The Tucana dwarf spheroidal: a distant backsplash galaxy of M31?

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We use the APOSTLE Local Group (LG) cosmological hydro-simulations to examine the properties of “backsplash” galaxies, i.e., dwarfs which were within the virial boundaries of the Milky Way (MW) or M31 in the past, but are today outside their virial radius ($r_{200}$). More than half of all dwarfs between $1 - 2r_{200}$ of each primary are backsplash. More distant backsplash systems, i.e., those reaching distances well beyond $2r_{200}$, are typically close to apocentre of nearly radial orbits, and, therefore, essentially at rest relative to their primary. We use this result to investigate which LG dwarfs beyond $\sim 500$ kpc of either primary could be a distant backsplash satellite of MW or M31. Tucana dSph, one of the few known quiescent LG field dwarfs, at $d_{M31} \approx 1350$ kpc and $d_{MW} \approx 880$ kpc, is a promising candidate. Tucana’s radial velocity is consistent with being at rest relative to M31. Further, Tucana is located close to M33’s orbital plane around M31, and simple orbit integrations indicate that Tucana may have been ejected during an early pericentric passage of M33 $\sim 11$ Gyr ago, a timing which approximately coincides with Tucana’s last episode of star formation. We suggest that Tucana may have been an early-infalling satellite of M31 or M33, providing a compelling explanation for its puzzling lack of gas and ongoing star formation despite its isolated nature. In this scenario, M33 should have completed some orbits around M31, a result that may help to explain the relative dearth of M33 satellite-candidates identified so far.

Key words: galaxies: dwarf – galaxies: Local Group – galaxies: individual: M31 – galaxies: individual: Tucana

1 INTRODUCTION

In the Lambda Cold Dark Matter (LCDM) cosmological paradigm galaxies form at the centre of dark matter halos which grow hierarchically, continuously accreting smaller systems. Of all accreted systems, the most massive ones quickly spiral to the centre and merge with the main halo, but lower mass systems may remain in orbit for a long time and are today identified with satellite galaxies (see; e.g., Wang et al. 2011, and references therein).

Satellites are strongly affected by their host, both gravitationally, as tides gradually pull away matter, and hydrodynamically, as the circumgalactic gas of the primary rams pressure strips away the gaseous envelopes of subhalos, depriving them of star formation fuel and eventually extinguishing their star formation activity (Tolstoy et al. 2009).

This scenario leads naturally to differences between the properties of satellite galaxies compared with dwarf galaxies of similar mass in the field. In particular, it successfully explains the origin of the environmental dependence of dwarf galaxy types in the Local Group: the majority of satellites are quiescent, gas-free dwarf spheroidal systems whereas field dwarfs are typically gas-rich dwarf irregulars with ongoing star formation (see; e.g., Grebel 1998; Weisz et al. 2014).

Given the importance of these environment-driven processes, it is important to establish how far away from a galaxy they may operate. Early work on galaxy clusters led to the realization that environmental effects may extend well beyond the nominal virial boundary of a system (Balogh et al. 2000), conventionally defined as the radius $r_{200}$, where the circular orbit timescale is comparable to the age of the Universe.

The reasons for the unexpectedly large “radius of influence” of a primary system on its associated subsystems is twofold. One reason is that many subhalo orbits are fairly radial, and may reach outside the virial radius during their first trip to apocentre after accretion (Mamon et al. 2004; Gill et al. 2005; Knebe et al. 2011). Indeed, most subhalos first accreted 2-3 Gyr ago into a halo like that of the Milky Way are expected to be at present outside the virial radius (Barber et al. 2014). These so-called “backsplash” galaxies are especially abundant just outside the virial radius, representing a fraction of that may exceed $\sim 50\%$ of subhalos with $1 < d/r_{200} < 2.5$ (Garrison-Kimmel et al. 2014; Buck et al. 2019; Simpson et al. 2018; Applebaum et al. 2021; Bakels et al. 2021).

More precisely, the virial radius is defined as the radius where the mean enclosed density equals $200\times$ the critical density for closure. We shall use the subscript “200” to identify quantities measured at or within the virial boundary.

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The second reason is that many subhalos come as members of virialized groups which are tidally dissociated soon after first infall into the primary halo. As discussed in detail by Sales et al. (2007) and Ludlow et al. (2009), some subhalos may gain enough energy during the disruption of their group to be expelled much further away, to distances as far as 5 virial radii or beyond (see also Teffsier et al. 2012). Systems on these extreme orbits are typically a small fraction of the low-mass members of the group, whose heavier members typically stay tightly bound to the primary. Identifying these “extreme backslash” cases therefore requires not only some evidence for dynamical association, but also the existence of a more massive “parent” progenitor to help propel them into highly energetic orbits.

In the cosmological context of the Local Group, the above discussion suggests the existence of a rare population of low-mass field dwarfs, located far away (out to ∼ 1.5 Mpc) from the Milky Way (MW) and Andromeda (M31), but showing properties consistent with satellites of either of them, such as lack of ongoing star formation. These galaxies are indeed unusual, since most isolated galaxies discovered so far in the Local Group field and beyond are currently star-forming (Geha et al. 2012).

To date, the only known examples of field dSph galaxies within 1.5 Mpc of the LG midpoint are Cetus, Tucana, and And XVIII, currently at ∼ 755 (674), ∼ 877 (1345), and ∼ 1330 (580) kpc from the MW (M31), respectively (Whiting et al. 1999; Lavery & Mighell 1992; McConnachie et al. 2008). All three show little to no gas content and predominantly old stellar populations formed roughly ∼ 9-10 Gyrs ago (Castellani et al. 1996; Monelli et al. 2010a;b; Savino et al. 2019; Makarova et al. 2017). Further away, at ∼ 2 Mpc, the only other examples of quiescent dwarfs known are KKR25 and KK53 (Karachentsev et al. 2015, 2001), plus the recent discoveries of Tucana B (Sand et al. 2022) and COSMOS-dw1 in the COSMOS-CANDELS field beyond the LG (Polzin et al. 2021).

The origin of isolated dwarf galaxies with no recent star formation activity remains poorly understood, but it has been argued that, in the case of Cetus and Tucana, they may have resulted from either a backslash interaction with the MW (e.g. Sales et al. 2007; Fraternali et al. 2009; Teffsier et al. 2012) or from ram-pressure stripping with the cosmic web (e.g. Benitez-Llambay et al. 2013). More recently, a novel proposal associating them with the effects of the photoionizing background has been put forward by Pereira Wilson et al. (2022).

We use in this paper distant backslash dwarfs in the APOSTLE cosmological hydrodynamical simulations (Sawala et al. 2016; Fattahi et al. 2016) to characterize the kinematic properties of such systems in the Local Group. We focus on seemingly isolated galaxies at distances larger than ∼ 500 kpc from the MW and M31, noting as well that, as reported in earlier work, many dwarfs between \( r_{200} < d < 2.5 r_{200} \) (roughly out to ∼ 500 kpc of the MW or M31) are indeed backslash galaxies.

This paper is organised as follows. In Sec. 2 we describe the APOSTLE simulations and the observational data used. Our results on distant backslash galaxies in APOSTLE are presented in Sec. 3.1. Section 3.2 shows our analysis of Local Group dwarfs in light of the simulation results. Finally in Sec. 3.3 we focus on the Tucana dSph and provide evidence supporting a hypothetical backslash origin. Sec. 4 summarizes our conclusions.

2 METHODS

2.1 Numerical simulations

The APOSTLE simulations are a set of cosmological volumes chosen to include two massive primary halos with masses, relative distance, relative radial velocity and surrounding Hubble flow similar to that observed for the Milky Way (MW) and M31 pair (Fattahi et al. 2016). In this work we have used 4 volumes run at the highest resolution in APOSTLE (labelled ‘L1’ level in previous literature). These runs have initial dark matter and gas particle masses of \( m_{DM} \sim 5 \times 10^4 M_\odot \) and \( m_{gas} \sim 1 \times 10^4 M_\odot \), respectively, and a gravitational softening length of 134 pc at \( z = 0 \). The zoom-in region of each APOSTLE volume fully contains a sphere of radius \( r \approx 3.5 \) Mpc from the midpoint of the MW and M31 “primary” halos.

APOSTLE used the EAGLE galaxy formation code (Schaye et al. 2015; Crain et al. 2015). This model includes subgrid physics prescriptions for star formation in gas exceeding a metallicity-dependent density threshold, radiative cooling of gas, stellar feedback (from stellar winds, radiation pressure and supernovae), homogeneous X-ray/UV background radiation, supermassive black hole growth and AGN feedback (the latter have negligible effects on dwarf galaxies).

APOSTLE assumes a flat ΛCDM cosmological model following WMAP-7 parameters (Komatsu et al. 2011): \( \Omega_m = 0.272; \Omega_k = 0.728; \Omega_b = 0.0455; H_0 = 100 \) km s\(^{-1}\) Mpc\(^{-1}\); \( \sigma = 0.81; h = 0.704 \).

2.1.1 Simulated galaxies

Dwarfs and subhalos in APOSTLE have been identified using the friends-of-friends (FoF) groupfinding algorithm (Davis et al. 1985) (with linking length equal to 0.2 times the mean interparticle separation) and the SUBFIND halo finder (Springel et al. 2001; Dolag et al. 2009).

Simulated galaxies are halos where star formation has led to the formation of a luminous component. In APOSTLE, this restricts galaxy formation to field halos more massive than \( M_{200} \sim 10^9 M_\odot \). Satellite galaxies may exist in subhalos with lower mass, because of tidal stripping; see for details Fattahi et al. (2018).

We shall define galaxies associated with each APOSTLE primary as those that have been within the virial radius of the primary’s most massive progenitor at some time during its evolution. Associated galaxies include satellites (i.e., galaxies within \( r_{200} \) at \( z = 0 \)) and backslash galaxies (i.e., associated galaxies located today outside the virial radius of the primary). Backslash systems were identified by tracking back in time all galaxies found outside the virial radius of both main primaries at \( z = 0 \). Each of the main APOSTLE primaries present halo masses \( M_{200} \) ranging from 0.78 to \( 2.05 \times 10^{12} M_\odot \), with primary-secondary mass ratios in the range ∼ 0.33-0.96.

In this work we do not distinguish galaxies which are today satellites of one of the primaries, but were associated with the other primary at an earlier time (see, e.g. Newton et al. 2021).
2.2 Observational data

In this work we consider the currently known Local Group dwarf galaxies within \( \sim 1.5 \) Mpc of the midpoint between the MW and M31. We use the latest position and velocity data in the McConnachie (2012) compilation of nearby galaxies\(^3\). We refer to dwarf galaxies within 300 kpc of the MW or M31 as “satellites” of that primary; the rest are considered “isolated” or “field” dwarfs.

For M31 and its satellite M33 (i.e., Triangulum) we adopt the positions and velocities derived from the combined Gaia DR2 and HST proper motions by van der Marel et al. (2019).

Galactocentric positions and velocities have been computed assuming a Galactocentric distance for the Sun of \( R_\odot = 8.29 \) kpc, a peculiar velocity with respect to the LSR of \( (U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \) km/s (Schönrich et al. 2010), and a circular velocity for the local standard of rest (LSR) of \( V_0 = 239 \) km/s (McMillan 2011).

We make use of updated Gaia EDR3 systemic proper motions for a set of distant Local Group dwarf galaxies for which such data has been measured (McConnachie et al. 2021). For dwarfs without proper motion measurements we convert the heliocentric line-of-sight velocities to the Galactic standard of rest (GSR) as \( V_{\text{GSR}} = \vec{V}_{\text{hel}} + \vec{V}_{\odot,\text{proj}} \); where \( \vec{V}_{\odot,\text{proj}} \) is the projection of the Sun’s motion \( (V_0 + \vec{V}_{\text{pec}}) \) along the Galactocentric radial direction to the dwarf galaxy.

Tables 1 and 2 present the specific data values used for M31, M33 and Tucana, the objects which we will focus on later in the paper (see Sec. 3.3).

3 RESULTS

3.1 Backsplash galaxies in APOSTLE

Fig. 1 shows the radial velocity versus distance from the primary for all galaxies identified in the 4 APOSTLE high-resolution volumes studied. This figure is centered on each of the 8 available primaries and shows a stack of all luminous galaxies in each of the simulated volumes.

“Associated” galaxies are shown in red, being either satellites (small circles) or backslash galaxies (big circles with black edges). A vertical shaded area delimits the 10-90 percentile range of \( r_{200} \) values for the 8 primaries, 196-261 kpc, which separates the overall satellite and backslash populations.

“Isolated” dwarfs are shown as gray open circles. Note that because of the binary nature of the Local Group, some of the isolated galaxies could be backslash galaxies of the other primary in the same volume. For reference, the radial distance to the other primary, \( r_{p2} \), is marked with an arrow.

We find an average of \( \sim 43 \) satellites and \( \sim 9 \) backslash per primary, down to a limit of one star particle, or roughly \( M_* \sim 10^4 M_\odot \). This is best regarded as a lower limit, as the raw number is very likely affected by numerical limitations. There are actually more associated subhalos outside than inside the virial radius (Ludlow et al. 2009), but the vast majority of them are low-mass subhalos without stars in them.

The upper panel in Fig. 1 shows the fraction of associated galaxies over all dwarfs in the simulated Local Group, as a function of radial distance from the primary. In APOSTLE, more than \( > 80\% \) (50\%) of dwarfs within 300 (400) kpc of a primary are associated to it, emphasizing that the virial radius does not represent a true physical boundary separating objects that have or have not been influenced dynamically by the primary. At 550 kpc, only 25\% of dwarfs are associated; at 700 kpc, fewer than 10\% are. The furthest backslash case we find is at a distance of \( \sim 1.2 \) Mpc from its primary, roughly \( 6 \times r_{200} \).

Figure 1. Radial velocity vs distance for galaxies in the APOSTLE Local Group simulations in the reference frame of one of its primaries. Results for all 8 primaries are stacked. Associated galaxies are shown in red, being either satellites (i.e., within \( r_{200} \), smaller circles) or backslash galaxies (i.e., outside \( r_{200} \), larger circles). Field dwarfs not associated with the primary are shown as open gray circles. Satellites of the other primary in the volume are shown as small gray dots. For reference, a vertical gray band indicates the 10-90 percentile range of \( r_{200} \) values for all 8 APOSTLE primaries. The \( \pm 1\sigma \) radial velocity dispersion of associated galaxies as a function of distance is shown with a red shaded area. The radial distance to the second primary in each APOSTLE volume, \( r_{p2} \), is marked with an arrow for reference. An upper auxiliary panel indicates the average fraction of associated galaxies, over all galaxies in the volume, as a function of radial distance from the primary.

\(^3\) see \( \text{https://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/community/nearby/} \), and references therein.

\(^4\) See also Taiibi et al. (2020); Savino et al. (2022). Note that some of our conclusions are changed by using these alternative data values.
Table 1. Observational data used in this work for M31, M33 and Tucana. Columns show right ascension and declination, distance from the Sun, heliocentric line-of-sight velocity and proper motions. References: McConnachie (2012); van der Marel et al. (2012, 2019). In red are our predicted proper motions for Tucana if it is a backsplash galaxy of M31, computed by assuming it is at rest with respect to M31 (see Sec. 3.3).

| Galaxy | RA (deg) | Dec (deg) | $D_{\odot}$ (kpc) | $V_{hel}$ (km/s) | $\mu_{RA*}$ (mas/yr) | $\mu_{Dec}$ (mas/yr) |
|--------|----------|-----------|-------------------|-----------------|----------------------|----------------------|
| M31    | 10.684   | 41.269    | 770±40            | -301±1          | 0.049±0.011          | -0.038±0.011         |
| M33    | 23.462   | 30.660    | 794±23            | -180±1          | 0.024±0.007          | 0.003±0.008          |
| Tucana | 340.456  | -64.419   | 887±50            | 194±4.3         | 0.0206               | -0.0754              |

Table 2. Galactocentric position and velocities for M31, M33 and Tucana derived from data in Tab 1.

| Galaxy | $X$ (kpc) | $Y$ (kpc) | $Z$ (kpc) | $V_{rad}$ or $V_{GSR}$ (km/s) | $V_X$ (km/s) | $V_Y$ (km/s) | $V_Z$ (km/s) |
|--------|-----------|-----------|-----------|-----------------------------|--------------|--------------|--------------|
| M31    | -378.95   | 612.66    | -283.12   | -108.91                     | 34.99        | -123.82      | -17.02       |
| M33    | -476.09   | 491.06    | -412.86   | -35.17                      | 44.34        | 90.95        | 125.10       |
| Tucana | 470.99    | -652.71   | -362.36   | 91.42                       | -             | -            | -            |

3.2 Distant backsplash candidates in the Local Group

Figure 2 shows the radial distance to the MW versus the radial distance to M31, for observed LG dwarf galaxies within ~1.5 Mpc from the LG midpt.

The shaded areas in Figure 2 highlight distances within 500 kpc of the MW (cyan) or M31 (red). Objects within these boundaries are likely associated to that primary, and are colored accordingly. In each case, this includes the satellites (i.e., those with $d < 300$ kpc, shown as star symbols for MW satellites or ‘x’ symbols for M31 satellites) and dwarfs with $300 < d/kpc < 500$ which, according to APOSTLE, have fairly high probability of being backsplash galaxies, shown as circles. One galaxy, And XVI, overlaps both samples as it is located at $r_{MW} = 450$ kpc and $r_{M31} = 310$ kpc. We assume it is associated to M31, to which it is closer.

Eight dwarf galaxies are at larger distances (i.e. Aquarius, Cetus, IC1613, LeoA, Sagittarius dIrr, Tucana, UGC4879, WLM), and we will consider them as potential distant backsplash candidates for the rest of our study.

Any galaxy from this subsample which is a backsplash of the MW or of M31 should be essentially at rest relative to its primary. We illustrate this idea in Fig. 3. This figure shows the Galactocentric radial velocity of each of these galaxies ($V_{rad}$) versus the Galactocentric radial velocity they would have if they were at rest relative to M31 ($V_{pred}$). Note that we only use the radial velocity component in this diagnostic because proper motions for most distant dwarfs are unknown.

To compute $V_{pred}$, we simply assume that, relative to the MW, the 3D velocity vector of the dwarf galaxy is the same as that of M31, and project accordingly. $V_{pred}$ for a certain
Figure 3. Observed Galactocentric radial velocity vs that predicted if the galaxy was at rest with respect to M31. Only Local Group field galaxies within 1.5 Mpc from the Local Group’s midpoint and outside 500 kpc of the MW and M31 are considered. The cyan and red shaded bands mark an area of ±1σ in $V_{\text{rad}}$, as measured for distant backsplash galaxies from the APOSTLE Local Group simulations (see Fig. 1). Galaxies within the horizontal cyan band present radial velocities compatible with being backsplash galaxies of the MW. Galaxies within the red diagonal band present radial velocities compatible with being backsplash galaxies of M31. The dotted line marks the 1:1 correspondence. Error bars indicate the minimum and maximum “predicted” $V_{\text{rad}}$ values when considering the uncertainties in M31’s proper motion data. For reference, M33 and M31 are shown as gray squares.

The dwarf is thus calculated by projecting M31’s Galactocentric 3D velocity vector along the MW-dwarf radial direction as:

$$V_{\text{pred}} = \frac{V_{\text{M31,MW}} \cdot \vec{r}_{\text{dwarf,MW}}}{|\vec{r}_{\text{dwarf,MW}}|}. \quad (1)$$

A cyan shaded area indicates a region of ±1σ around $V_{\text{rad}} = 0$ km/s in the y-axis, where $\sigma_{\text{rad}} = \pm 29$ km/s, the radial velocity dispersion of distant ($d > 500$ kpc) backsplash systems in APOSTLE (see Fig. 1).

Dwarfs in the cyan area are compatible with being backsplash galaxies of the MW and have been colored in cyan. Alternatively, dwarfs falling in the red shaded area around the 1:1 line—with a width also equal to ±1σ—have observed radial velocities compatible with being backsplash galaxies of M31 and are colored in red.

For reference, M31 and M33 (Triangulum) are shown as grey squares. M31 falls exactly on the 1:1 line by construction. Error bars correspond to the minimum and maximum $V_{\text{pred}}$ obtained when considering the uncertainties in M31’s proper motion data.

Six out of eight dwarfs are plausible backsplash candidates according to this criterion. UGC4879, Sagittarius dIrr, Aquarius and Cetus could have been associated to the MW. The last three, plus possibly Leo A, are also compatible with being backsplash candidates of M31. The Tucana dSph, on the other hand, stands out as a clear M31 distant backsplash candidate, with a Galactocentric radial velocity in very close agreement with that expected for an object at rest relative to M31.

### 3.3 Cetus and Tucana as distant backsplash candidates

The case of Cetus and Tucana as backsplash candidates are of particular interest given that they are two of the few Local Group field dSphs. Because of their low gas content, as well as their predominantly old stellar populations, these systems resemble MW or M31 satellites rather than field dwarfs (Monelli et al. 2010a,b; Fraternali et al. 2009), and it is therefore tempting to associate them with backsplash systems.

Are there any other further hints that Tucana or Cetus may actually be distant backsplash systems? Both seem to satisfy the low radial velocity dispersion criterion (see Fig. 3), but so do several other distant LG dwarfs. As discussed in Sec. 1, further evidence for a backsplash origin may include the identification of a plausible “parent” satellite system whose tidal dissolution may have expelled the dSph. Both the MW and M31 have satellites massive enough to be plausible parents of either Tucana or Cetus; in particular, the Magellanic Clouds in the case of the MW and the Triangulum galaxy (M33) in the case of M31.
For the Clouds, there is now robust evidence that they are just past the first pericentric approach of their orbit around the MW (Besla et al. 2012; Kallivayalil et al. 2013). This disfavors them as possible parents of distant backsplash systems, as these objects are ejected after a pericentric passage, and they would require several Gyr to travel to their current location. A similar reasoning disfavors the Sagittarius dSph as a potential parent, since the latest orbital modeling suggests that Sagittarius first approach to the MW happened only ~ 5-6 Gyr ago (Laporte et al. 2018). As we shall see below, reaching the large distances of Cetus and Tucana require that the ejection must have occurred much earlier than that.

It is in principle possible that a massive progenitor could have merged with the central galaxy soon after pericentre, but there is little evidence that the MW has undergone a substantial merger in the recent past. The lack of an obvious parent system therefore suggests that none of the MW distant backsplash candidates in Fig. 3 (i.e., those in the cyan band) have actually been associated with the MW in the past.

Could some of the distant candidates be associated with the accretion of M33 into M31? Since proper motions and radial velocities are available for both of these systems, it is possible to estimate the 3D relative velocity of the M31-M33 pair using the data compiled in Table 1. The resulting velocity, $V_{\text{M31-M33}} \sim 258$ km/s, is not much higher than the rotation speed of M31 ($V_{\text{max}} \sim 226$ km/s, Carignan et al. 2006) and likely well below the M31 escape velocity at M33’s location. M33 is thus likely to be on a fairly bound orbit and may have completed a few pericentric passages in the past (see; e.g., McConnachie et al. 2009; Patel et al. 2017; van der Marel et al. 2019), making it a plausible “parent” for backsplash systems.

We investigate further a possible connection between the distant LG dwarfs and the M31-M33 pair in Fig. 4, where we show, in an Aitoff projection, the position of various LG galaxies in an M31-centric reference frame. We choose the “equatorial plane” of the projection ($b = 0^\circ$) to coincide with the MW plane, and the N-S direction of the polar axis so that MW is in the northern hemisphere of the projection. The MW-M31 orbital plane is shown by the thick grey curve in Fig. 4; the M33 orbital plane around M31, on the other hand, is shown by the thick red curve.

The latter plane is especially significant, since we would expect that systems that may have been expelled during the accretion of M33 into M31 to share the same orbital plane of the main progenitor and to remain close to it after ejection (see; e.g., Sales et al. 2011; Santos-Santos et al. 2021). This reasoning singles out the Tucana dSph in Fig. 4 as the most promising candidate of them all. Indeed, Tucana is only 6.6$^\circ$ (< 150 kpc) away from the M33 orbital plane, which is only about a tenth of its current distance from M31 (see right-hand panel of Fig. 4).

This could be, of course, just an extraordinary coincidence, but it motivates us to examine further a potential association between Tucana and M33/M31. A powerful extra constraint may be placed by requiring that the “flight time” from M31 to Tucana’s present location is shorter than the Hubble time. We may estimate this by assuming that Tucana is a test particle presently at the apocentre of a nearly radial orbit, and integrating backwards in time to find when it was propelled into such orbit. The estimate requires an assumption for the gravitational potential of M31, for which we adopt a standard NFW halo (Navarro et al. 1997) with virial mass $M_{200} = 3 \times 10^{12} M_\odot$ (van der Marel et al. 2012; Fardal et al. 2013, about 3 times more massive than the MW according to...
We choose such a setup for simplicity, as it is enough for our purposes here, but acknowledge that the actual orbits of Tucana and M33 would look differently in detail when including a proper treatment for dynamical friction, the evolution of M31’s potential and the influence of an evolving cosmic web at early times.

We adopt $M_{\text{Tuc}} = 5.6 \times 10^{9} M_{\odot}$ and $M_{\text{M33}} = 2 \times 10^{10} M_{\odot}$, computed by applying a mass-to-light ratio to the V-band luminosities in McConnachie (2012)’s database. We assumed $M_{*}/L_{V} = 1$ for Tuc and 0.7 for M33 (see Woo et al. 2008).
4 SUMMARY

We have used the APOSTLE cosmological simulations to characterize the population of galaxies dynamically associated with the two primary galaxies (MW and M31) of the Local Group. “Associated” systems are defined as those which have been, at some time during their evolution, within the virial radius of one of the primaries. Associated galaxies outside the virial radius at $z=0$ are denoted as “backsplash”; those inside $r_{200}$ are defined as “satellites”.

The fraction of dwarfs associated to a primary in APOSTLE drops quickly outside its virial radius; from $\sim 50\%$ at 400 kpc (roughly $2 \times r_{200}$), to roughly 10% at 600 kpc. The most distant backsplash galaxy in all 4 APOSTLE volumes analysed is located at $\sim 1.2$ Mpc, roughly 6$x$ the average virial radius of APOSTLE primaries.

Distant backsplash galaxies originate during the tidal disruption of an accreted “parent” group of dwarfs, when they are propelled into highly energetic orbits. Today they are found mainly close to apocentre of nearly radial orbits (i.e., essentially at rest) relative to their primaries, with a radial velocity dispersion of only $\pm 29$ km/s beyond $\sim 600$ kpc.

We use this feature to examine which, if any, of the isolated Local Group dwarfs could be a distant backsplash of the MW or M31. We focus, in particular, on M31 backsplash candidates linked to the accretion of M33, given the lack of obvious “parent” in the MW. (The Magellanic Clouds are at present on first approach, and therefore could not have caused backsplash systems as distant as the ones we examine here.)

There are at present eight LG dwarfs known outside 500 kpc from the MW and M31, and within $\sim 1.5$ Mpc from the Local Group midplane: Aquarius, Cetus, IC1613, LeoA, Sagittarius dIrr, Tucana, UGC4879 and WLM. Several of these have low relative radial velocities relative to M31, but none of them stands out: the Tucana dSph.

Therefore, a natural consequence of our proposed scenario for Tucana as a backsplash of an early-infalling M33 onto M31, is that M33 is likely to have lost its satellite population by now. This prediction agrees with the current observational data where only one satellite candidate is found within $\sim 100$ kpc around M33 (AndXXII, Martin et al. 2009).

ACKNOWLEDGEMENTS

We thank the referee for useful comments. ISS acknowledges support from the Arthur B. McDonald Canadian Astroparticle Physics Research Institute and from the European Research Council (ERC) through Advanced Investigator grant to C.S. Frenk, DMIDAS (GA 786910). We wish to acknowledge the generous contributions of all those who made possible the Virgo Consortium’s EAGLE/APOSTLE simulation projects. This work used the DiRAC6Durham facility managed by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The equipment was funded by BEIS capital funding via STFC capital grants ST/K00042X/1, ST/P002293/1, ST/R002371/1 and ST/S002502/1. Durham University and STFC operations grant ST/R000832/1. DiRAC is part of the National e-Infrastructure. This research made use of Astropy (http://www.astropy.org) a community-developed core Python package for Astronomy.

DATA AVAILABILITY

The simulation data underlying this article can be shared on reasonable request to the corresponding author. The references for the observational data for Local Group dwarfs used in this article are listed in Sec. 2.2.

REFERENCES

Applebaum E., Brooks A. M., Christensen C. R., Munshi F., Quinn T. R., Shen S., Tremmel M., 2021, ApJ, 906, 96
Bakels L., Ludlow A. D., Power C., 2021, MNRAS, 501, 5948
Balogh M. L., Navarro J. F., Morris S. L., 2000, ApJ, 540, 113
Barber C., Starkenburg E., Navarro J. F., McConnachie A. W., Fattahi A., 2014, MNRAS, 437, 959
Benítez-Llambay A., Navarro J. F., Abadi M. G., Gottlüber S., Yepes G., Hoffman Y., Steinmetz M., 2013, ApJ, 763, L41
Besla G., Kallivayalil N., Hernquist L., van der Marel R. P., Cox T. J., Kereś D., 2012, MNRAS, 421, 2109
Buck T., Macciò A. V., Dutton A. A., Obreja A., Frings J., 2019, MNRAS, 483, 1314
Carignan C., Chemin L., Huchtmeier W. K., Lockman F. J., 2006, ApJ, 641, L109
Castellani M., Marconi G., Buonanno R., 1996, A&A, 310, 715
Crain R. A., et al., 2015, MNRAS, 450, 1937
Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371
Tucana dSph: a distant backsplash galaxy of M31?

Deason A. J., Belokurov V., Sanders J. L., 2019, MNRAS, 490, 3426

Dolag K., Borgani S., Murante G., Springel V., 2009, MNRAS, 399, 497

Fardal M. A., et al., 2013, MNRAS, 434, 2779

Fattahi A., et al., 2016, MNRAS, 457, 844

Fattahi A., Navarro J. F., Frenk C. S., Oman K. A., Sawala T., Schaller M., 2018, MNRAS, 476, 3816

Fraternali F., Tolstoy E., Irwin M. J., Cole A. A., 2009, A&A, 499, 121

Garrison-Kimmel S., Boylan-Kolchin M., Bullock J. S., Lee K., 2014, MNRAS, 448, 2578

Geha M., Blanton M. R., Yan R., Tinker J. L., 2012, ApJ, 757, 85

Gill S. P. D., Knebe A., Gibson B. K., 2005, MNRAS, 356, 1327

Grebel E. K., 1998, Highlights of Astronomy, 11A, 125

Karachentsev I. D., van der Marel R. P., Besla G., Anderson J., Alcock C., 2013, ApJ, 764, 161

Karachentsev I. D., Kniazev A. Y., Sharina M. E., 2015, Astronomische Nachrichten, 336, 707

Knebe A., Libeskind N. I., Knollmann S. R., Martinez-Vaquero L. A., Yepes G., Gottlöber S., Hoffman Y., 2011, MNRAS, 412, 529

Komatsu E., et al., 2011, ApJS, 192, 18

Laporte C. F. P., Johnston K. V., Gómez F. A., Garavito-Camargo N., Besla G., 2018, MNRAS, 481, 286

Lavery R. J., Mighell K. J., 1992, AJ, 103, 81

Ludlow A. D., Navarro J. F., Springel V., Jenkins A., Frenk C. S., Helmi A., 2009, ApJ, 692, 931

Ludlow A. D., Bose S., Angulo R. E., Wang L., Hellwing W. A., Navarro J. F., Cole S., Frenk C. S., 2016, MNRAS, 460, 1214

Makarova L. N., Makarov D. I., Karachentsev I. D., Tully R. B., Rizzi L., 2017, MNRAS, 464, 2281

Mamon G. A., Sanchis T., Salvador-Solé E., Solanes J. M., 2004, A&A, 414, 445

Martin N. F., et al., 2009, ApJ, 705, 758

McConnachie A. W., 2012, AJ, 144, 4

McConnachie A. W., et al., 2008, ApJ, 688, 1009

McConnachie A. W., et al., 2009, Nature, 461, 66

McConnachie A. W., Higgs C. R., Thomas G. F., Venn K. A., Côté P., Battaglia G., Lewis G. F., 2021, MNRAS, 501, 2363

McMillan P. J., 2011, MNRAS, 414, 2446

Monelli M., et al., 2010a, ApJ, 720, 1225

Monelli M., et al., 2010b, ApJ, 722, 1864

Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493

Newton O., et al., 2021, arXiv e-prints, p. arXiv:2104.11242

Patel E., Besla G., Sahlmann J., Watkins L. L., 2019, MNRAS, 501, 2363

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