

Perseus I and the NGC 3109 association in the context of the Local Group dwarf galaxy structures

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ABSTRACT

The recently discovered dwarf galaxy Perseus I appears to be associated with the dominant plane of non-satellite galaxies in the Local Group (LG). We predict its velocity dispersion and those of the other isolated dwarf spheroidals Cetus and Tucana to be 6.5, 8.2 and 5.5 km s⁻¹, respectively. The NGC 3109 association, including the recently discovered dwarf galaxy Leo P, aligns with the dwarf galaxy structures in the LG such that all known nearby non-satellite galaxies in the northern Galactic hemisphere lie in a common thin plane (rms height 53 kpc; diameter 1.2 Mpc). This plane has an orientation similar to the preferred orbital plane of the Milky Way (MW) satellites in the vast polar structure. Five of seven of these northern galaxies were identified as possible backsplash objects, even though only about one is expected from cosmological simulations. This may pose a problem, or instead the search for local backsplash galaxies might be identifying ancient tidal dwarf galaxies expelled in a past major galaxy encounter. The NGC 3109 association supports the notion that material preferentially falls towards the MW from the Galactic south and recedes towards the north, as if the MW were moving through a stream of dwarf galaxies.

Key words: galaxies: dwarf – galaxies: groups: individual: NGC 3109 association – galaxies: individual: Perseus I – galaxies: kinematics and dynamics – Local Group – dark matter.

1 INTRODUCTION

The Milky Way (MW) is surrounded by a vast polar structure (VPOS) of satellite objects including the satellite galaxies, young halo globular clusters and several stellar and gaseous streams (Lynden-Bell 1976; Pawlowski, Pflamm-Altenburg & Kroupa 2012a). The proper motions of the 11 classical satellite galaxies reveal that these almost exclusively co-orbit in this VPOS, which allowed us to predict the proper motions of the remaining satellite galaxies (Pawlowski & Kroupa 2013).

Kroupa, Theis & Boily (2005) have first identified this planar alignment as being inconsistent with cosmological simulations based on the cold dark matter (CDM) paradigm with a cosmological constant, Λ CDM. This finding subsequently triggered an ongoing debate on whether such structures can be reconciled with cosmological expectations (e.g. Kang et al. 2005; Zentner et al. 2005; D’Onghia & Lake 2008; Li & Helmi 2008; Libeskind et al. 2009; Metz et al. 2009; Deason et al. 2011; Pawlowski et al. 2012b; Pawlowski & Kroupa 2013; Wang, Frenk & Cooper 2013) or rather point at a different origin such as the formation of phase-space correlated tidal dwarf galaxies (TDGs, e.g. Sawa & Fujimoto 2005; Metz & Kroupa 2007; Yang & Hammer 2010; Pawlowski, Kroupa

& de Boer 2011; Fouquet et al. 2012; Dabringhausen & Kroupa 2013; Hammer et al. 2013).

Ibata et al. (2013) and Conn et al. (2013) have recently discovered a similar ‘Great Plane of Andromeda’ (GPoA), a co-orbiting alignment consisting of about half of the satellite galaxies of the Andromeda galaxy (M31), the other major galaxy in the Local Group (LG). Motivated by this discovery that satellite galaxies appear to preferentially live in phase-space correlated structures, Pawlowski, Kroupa & Jerjen (2013) set out to search for similar structures on an LG scale. They have discovered that all but one of the 15 LG dwarf galaxies more distant than 300 kpc from the MW and M31 are confined to two narrow (short-to-long axis ratios of ≈ 0.1) and highly symmetric planes, termed Local Group Plane 1 and 2 (LGP1 and LGP2). LGP1 is the dominant plane both by number of objects (about nine), and alignment with additional features, such as the Magellanic Stream which traces the positions and line-of-sight (LOS) velocities of the LGP1 plane members in the southern Galactic hemisphere.

Given that the number of known dwarf galaxies in the LG more distant than 300 kpc from both major galaxies is still low, each additional detection poses a chance to test the existence of the planar LG structures and to potentially refine our understanding of these structures. Such an opportunity is now provided by the recent discovery of the dwarf spheroidal (dSph) galaxy Perseus I at a distance of 374 kpc from M31 (Martin et al. 2013). In the

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following, we test whether it can be considered to be associated with either LGP1 or LGP2.

In addition, we predict the velocity dispersion of Perseus I and two other non-satellite dSphs as expected in Modified Newtonian Dynamics (MOND; Milgrom 1983; Famaey & McGaugh 2012). Similar predictions have been made for other dwarf galaxies in M31's vicinity (McGaugh & Milgrom 2013a) and these have successfully passed the test of observations (McGaugh & Milgrom 2013b). Unfortunately, no similar predictions are possible in the Λ CDM framework.

Another recently discovered nearby dwarf galaxy, Leo P (Giovannelli et al. 2013; Rhode et al. 2013), has lead Bellazzini et al. (2013) to re-investigate the NGC 3109 association, a group of dwarf galaxies at a distance of about 1.3–1.4 Mpc from the MW that consists of NGC 3109, Antlia, Sextans A and Sextans B (van den Bergh 1999; Tully et al. 2006). They realized that Leo P aligns with the four other members of the association in a very narrow, linear structure. As the NGC 3109 association is very close to the LG and has a linear extent of 1.2 Mpc, similar to its distance from the MW, we will investigate its orientation in the context of the LG planes of non-satellite dwarf galaxies. This reveals an intriguing alignment with the other three nearby non-satellite galaxies in the Northern hemisphere of the MW and leads us to discuss suggested origins for the NGC 3109 association in light of the geometry of the LG.

The paper is structured as follows. In Section 2, we determine whether Perseus I is associated with one of the dwarf galaxy planes in the LG. In Section 3, we predict the velocity dispersion of the distant dSphs in the LG, Perseus I, Cetus and Tucana. In Section 4, we determine the orientation of the NGC 3109 association in the same coordinate system used in Pawlowski et al. (2013), discuss possible origins for the alignment and conclude that the association is likely part of the LG dwarf galaxy structures. In Section 5, we discuss how the search for cosmological backplash galaxies in the LG might give rise to two additional small-scale problems of cosmology and how it could falsely identify TDGs as backplash objects. In Section 6, we present a sketch of the LG dwarf galaxy structures and their preferred direction of motion and discuss open questions and limitations in Section 7. Finally, we summarize our results in Section 8.

2 PERSEUS I AND THE LG PLANES

Recently, Martin et al. (2013) reported the discovery of a dSph galaxy in the vicinity of Andromeda, Persus I. At a distance of 374 kpc from M31, it is a non-satellite galaxy according to the categorization of Pawlowski et al. (2013), which considers only galaxies closer than 300 kpc, i.e. within the typically assumed virial radii of the MW and M31, to be satellites. All but one of the 15 previously known non-satellite galaxies in the LG were found to be close to one of two thin, highly symmetric LG planes (LGP1 and LGP2). Is Perseus I a member of one of the two non-satellite galaxy planes in the LG?

To determine whether Perseus I lies close to one of the two LG planes as reported by Pawlowski et al. (2013) (see for example their table 3), we adopt the position and distance modulus of Perseus I from table 1 of Martin et al. (2013). In the Cartesian coordinate system of Pawlowski et al. (2013), this places Persues I at $(x, y, z) = (460, 94, -68)$ kpc, with a position uncertainty along the line connecting Perseus I and the Sun of 65 kpc.

Perseus I indeed lies in the vicinity of one of the planes, LGP1 [offset by 141 ± 15 kpc, compared to the plane's root-mean-square (rms) height of 55 kpc], as defined by the dwarf galaxies UGC

4879, Leo A, Leo T, Phoenix, Tucana, WLM, Cetus, IC 1613 and Andromeda XVI. All other dwarf galaxy planes, in particular LGP2, the second non-satellite galaxy plane in the LG, are more distant than ≈ 250 kpc.

While Andromeda XVI is considered a member of LGP1 for formal reasons in Pawlowski et al. (2013), this galaxy is perfectly aligned with the GPoA (offset of only 8 ± 3 kpc), its LOS velocity shows that the galaxy follows the co-orbiting trend of the other GPoA members and it is at a distance of only 323 kpc from M31. It is therefore more likely that Andromeda XVI belongs to the GPoA rather than the LGP1. Removing it from the plane-fit results in an rms height of $\Delta = 38 \pm 2$ kpc; short-to-long axis ratio of $c/a = 0.050 \pm 0.003$ and intermediate-to-long axis ratio of $b/a = 0.422 \pm 0.004$; offset from MW of $D_{\text{MW}} = 183.6 \pm 2.1$ kpc and from M31 of $D_{\text{M31}} = 209.9 \pm 4.4$ kpc. The normal to the best-fitting plane points to $(l, b) = (223^\circ, -22^\circ)$. Of the galaxies within 300 kpc of M31, Triangulum/M33 and its potential satellite Andromeda XXII are both very close to the best-fitting plane (11.2 ± 5.0 and 22.2 ± 15.7 kpc, respectively). Perseus I is at a considerably smaller offset (100 ± 14 kpc) from this plane fit than from the one including Andromeda XVI.

This warrants inclusion of the galaxy in the modified LGP1 sample (LGP1^{mod}), which now consists of UGC 4879, Leo A, Leo T, Phoenix, Tucana, WLM, Cetus, IC 1613 and Perseus I. The resulting parameters for LGP1^{mod} are compiled in Table 1. They are similar to the fit without Perseus I: rms height of $\Delta = 45 \pm 2$ kpc; short-to-long axis ratio of $c/a = 0.062 \pm 0.003$ and intermediate-to-long axis ratio of $b/a = 0.497 \pm 0.009$; offset from MW of $D_{\text{MW}} = 182.7 \pm 2.3$ kpc and from M31 of $D_{\text{M31}} = 247.2 \pm 5.8$ kpc.

Table 1. Parameters of the planes fitted to the LG dwarf galaxies, as discussed in Sections 2 and 4.3. These are: \mathbf{r}_0 : x -, y - and z -position of the centroid of the plane in the coordinate system introduced in Pawlowski et al. (2013). \mathbf{n} : the direction of the normal vector (minor axis) of the best-fitting plane in Galactic longitude l and latitude b . Δ_n : Uncertainty in the normal direction. This and all other uncertainties were determined by varying the galaxy positions within their uncertainties and then determining the standard deviation in the resulting plane parameters. D_{MW} and D_{M31} : offset of the planes from the MW and M31 position. Δ : rms height of the galaxies from the best-fitting plane. c/a and b/a : ratios of the short and intermediate axis to the long axis, determined from the rms heights in the directions of the three axes. N_{members} : Number of galaxies associated with the planes used for the fitting. In particular LGP1 and LGP2 might have additional satellite galaxies as members, but these were not included in the plane fits compiled here.

Name	LGP1 ^{mod}	Great Northern Plane
$r_0 \begin{pmatrix} x \\ y \\ z \end{pmatrix}$ (kpc)	$\begin{pmatrix} -52.1 \pm 4.6 \\ -242.1 \pm 3.2 \\ -51.4 \pm 5.5 \end{pmatrix}$	$\begin{pmatrix} -306.7 \pm 9.8 \\ -928.6 \pm 8.0 \\ 935.0 \pm 17.5 \end{pmatrix}$
$n \begin{pmatrix} l \\ b \end{pmatrix}$ ($^\circ$)	$\begin{pmatrix} 225.4 \\ -20.8 \end{pmatrix}$	$\begin{pmatrix} 197.6 \\ -31.5 \end{pmatrix}$
Δn ($^\circ$)	0.6	0.6
D_{MW} (kpc)	182.7 ± 2.3	162.6 ± 5.6
D_{M31} (kpc)	247.2 ± 5.8	143.8 ± 9.2
Δ (kpc)	44.5 ± 2.2	53.4 ± 1.5
c/a	0.062 ± 0.003	0.098 ± 0.004
b/a	0.497 ± 0.009	0.762 ± 0.067
N_{members}	9	8

The normal to the best-fitting plane points to $(l, b) = (225^\circ, -21^\circ)$ which is only 5° inclined relative to the normal of the original LGP1 $([l, b] = [220^\circ, -22^\circ])$. M33 and Andromeda XXII both remain close to the best-fitting plane (48.6 ± 6.1 and 23.6 ± 10.6 kpc, respectively).

As can be seen in Fig. 1, which shows an edge-on view of the LG planes LGP1^{mod} and LGP2, Perseus I is clearly aligned with this thin plane. The newly discovered galaxy therefore confirms the finding by Pawlowski et al. (2013) that essentially all non-satellite galaxies of the LG are confined to two very thin planes. Perseus I is offset by only 63 ± 6 kpc from the best-fitting plane, which is to be compared with the largest extent of LGP1^{mod} of 2.2 Mpc between Tucana and UGC 4879. The offset might in fact be a weak indication of a bending of the plane. As seen in Fig. 1, Perseus I and other nearby galaxies are offset to the right from the line indicating the edge-on view of the best-fitting plane in Fig. 1, while those at the top and bottom are offset to the left.

The significance of a satellite galaxy plane can be tested by comparing the observed distribution with an expected one, which in most cases is assumed to be isotropic. Due to the existence of a preferred axis in the LG (the MW–M31 line), this comparison cannot be easily adopted for planes spanning the whole LG. A proper determination of the plane significance therefore requires an expected model for the distribution of the non-satellite galaxies in the LG, which is not available. Furthermore, such a test has to take observational biases like the sky coverage of surveys searching for LG dwarf galaxies into account. Due to the very inhomogeneous nature of the galaxy data, this is currently not feasible. We nevertheless try to get a rough estimate for how likely it is to find two similarly thin planes of non-satellite galaxies in the LG. Assuming that Andromeda XVI is part of the GPoA, we use the following 15 LG dwarf galaxies for this test: Andromeda XVIII, Andromeda XXVIII, Aquarius, Cetus, IC 1613, Leo A, Leo T, NGC 6822, Pegasus dIrr, Perseus I, Phoenix, Sagittarius dIrr, Tucana, UGC 4879 and WLM. Instead of assuming a model for the expected galaxy distribution, we generate 1000 randomized realizations by rotating each of the dwarf galaxy positions by individual random angles around the MW–M31 axis. This preserves their distances from both the MW and from M31. For each realization, we then proceed as follows. Ignoring one of the LG galaxies (analogously to ignoring the Pegasus dIrr galaxy which is neither part of LGP1^{mod} consisting of nine dwarf galaxies nor of LGP2 consisting of five dwarf galaxies), we split the remaining galaxies into two samples, constructing all possible combinations of 9:5 objects. Planes are then fitted to both samples for each of these combinations. Both planes' rms heights Δ and axis ratios c/a are recorded for all 30 030 possible combinations for each of the 1000 realizations. Due to the large number of possible combinations, we refrain from varying the observed galaxy distances within their uncertainties and only use the most-likely values.

We then test how many of the randomized galaxy distributions contain planes which are similarly thin ($\Delta \leq 45$ kpc) or have similar axis ratios ($c/a \leq 0.062$) as the observed LGP1^{mod}. The mean of the minimum rms height for the nine-galaxy combinations over all realizations is 83 kpc, with a standard deviation of 22 kpc, while the mean minimum axis ratio is 0.140, with a standard deviation of 0.037. Thus, on average a plane of galaxies as narrow as the LGP1^{mod} is not expected. Of the 1000 realizations, 29 (2.9 per cent) contain a group of nine galaxies which can be fitted by a plane with an rms height at least as small as that of LGP1^{mod}. Only 10 (1.0 per cent) can be fitted by a plane with a sufficiently small axis ratio. If we simultaneously require that five out of the remaining six galaxies can be fitted by a plane having a similar rms height or axis ratio as

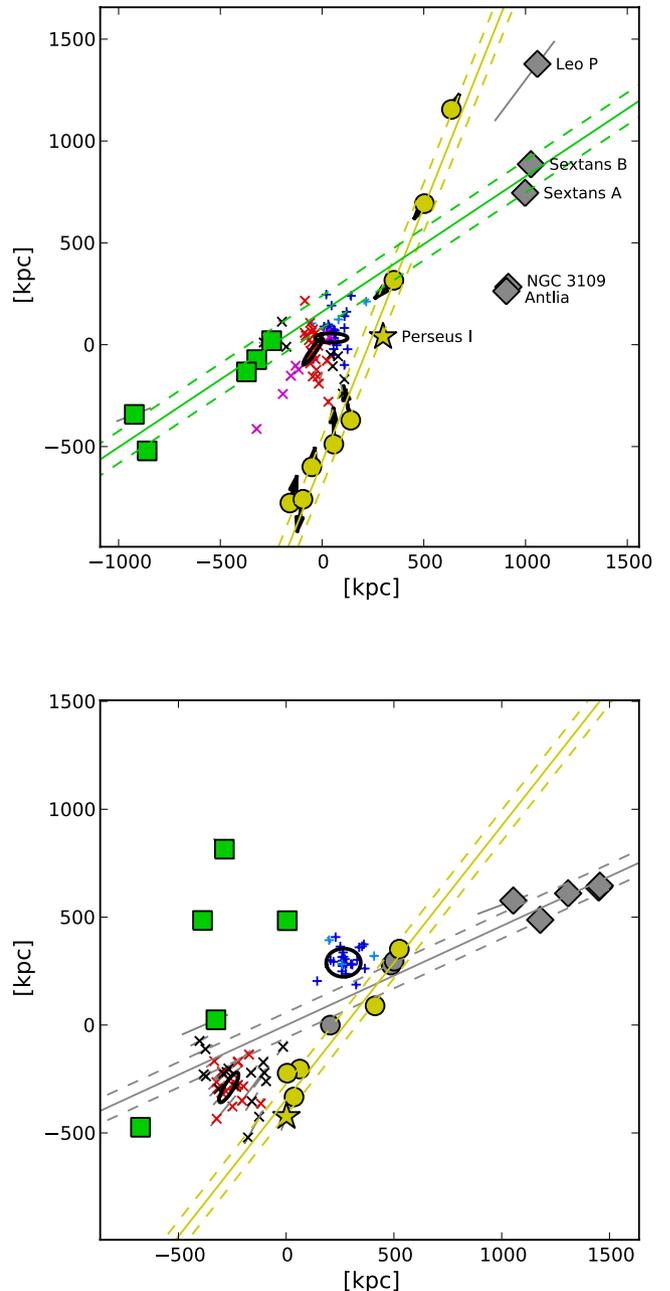


Figure 1. Top panel: edge-on view of the non-satellite dwarf galaxy planes LGP1^{mod} (yellow dots) and LGP2 (green squares) in the LG (looking along $[l, b] = [308^\circ 9', 16^\circ 8']$). The best-fitting planes are plotted as solid lines, the dashed lines denote their rms heights. The black ellipses indicate the positions and orientations of the MW and M31 and the blue plus signs (red and black crosses) indicate MW (M31) satellites. Grey lines mark the 1σ distance uncertainties. The newly discovered dwarf galaxy Perseus I (yellow star) is aligned with LGP1^{mod}. Compare to the similar plot shown as fig. 9 in Pawlowski et al. (2013). In addition, the plot shows the positions of the dwarf galaxies associated with the linear NGC 3109 association (grey diamonds) which is situated behind the LG in this view. The NGC 3109 association is almost parallel to the dominant non-satellite plane in the LG, but offset by 0.3–0.5 Mpc. Bottom panel: edge-on view of LGP1^{mod} and the plane fitted to the five members of the NGC 3109 association plus the LGP1^{mod} members Leo T, Leo A and UGC 4879 (looking along $[l, b] = [348^\circ 3', -54^\circ 9']$; the view of the upper panel would originate from approximately the lower left of this plot). The NGC 3109 association might be related to the dominant LG plane (LGP1^{mod}). The planes are inclined to it by only 27° and the intersection of the two planes lies close to the MW.

LGP2 ($\Delta \leq 66$ kpc, $c/a \leq 0.110$; Pawlowski et al. 2013), a situation similar to the one observed in the LG occurs in only 13 (1.3 per cent, rms height criterion) or three (0.3 per cent, axis-ratio criterion) of the 1000 random realizations. This test demonstrates that the LG planes are unexpected. We have not tested for the symmetry of the planes and their alignments, and varying the galaxy positions by only rotating them around the MW–M31 axis has a large chance of preserving information on the possible LG planes because they are parallel to the MW–M31 line. Our results should therefore be considered as upper limits.

3 PREDICTED VELOCITY DISPERSIONS FOR LG dSphs

In addition to the structures that dwarf galaxies trace in the LG, their internal kinematics are also of interest. These objects are generally inferred to be dark matter dominated, though there was no reason to anticipate this a priori. Λ CDM models can be constructed to match this observation, but do not provide the ability to predict the velocity dispersion of any particular dwarf. In contrast, it is possible to predict a dwarf’s velocity dispersion given its photometric properties using MOND.

We employ here the method described by McGaugh & Milgrom (2013a). Being quite remote from M31 (374 kpc), Perseus I is well into the isolated deep MOND regime for which the characteristic velocity dispersion follows directly from the stellar mass ($\sigma_{\text{iso}} = (4a_0 G/81)M_*^{1/4}$). This makes it one of the best test cases among the dwarfs of Andromeda. Most (though not all) of the other dwarfs are in the regime dominated by the external field effect so that the predicted velocity dispersions are less certain as they depend on the properties of M31 as well as those of the dwarfs themselves (see McGaugh & Milgrom 2013a).

Given the luminosity reported by Martin et al. (2013), we predict that Perseus I should have a velocity dispersion of $\sigma = 6.5_{-1.0}^{+1.2} \pm 1.1$ km s^{−1}. For consistency with McGaugh & Milgrom (2013a), we assume a stellar mass-to-light ratio of $2 M_{\odot}/L_{\odot}$. The first uncertainty reflects a factor of 2 variation in mass-to-light ratio while the second propagates the stated observational uncertainties. Predictions of this type have proven largely successful so far (McGaugh & Milgrom 2013b); Perseus I provides another opportunity to test this a priori prediction of MOND.

There exist two other dSphs in the LG that are far removed from both the MW and Andromeda: Cetus and Tucana. Being far from major perturbers, they should also be in the isolated MOND regime, and provide correspondingly good tests. However, they tend to be overlooked since they are not grouped together with the dwarfs that are obvious satellites. Applying the same procedure described above, given the luminosities and most-likely distances tabulated by McConnachie (2012), we predict for Cetus $\sigma = 8.2_{-1.3}^{+1.5} \pm 0.4$ km s^{−1} and for Tucana $\sigma = 5.5_{-0.9}^{+1.0} \pm 0.4$ km s^{−1}. As before, the first uncertainty represents the range of mass-to-light ratios $2_{-1}^{+2} M_{\odot}/L_{\odot}$. The second uncertainty represents the effect of the stated uncertainty in luminosity on the velocity dispersion for the nominal assumed mass-to-light ratio of $2 M_{\odot}/L_{\odot}$. Any systematic error in distance will have a strong effect, since $L \propto D^2$.

The predicted velocity dispersions of both Cetus and Tucana compare poorly with observed values. Lewis et al. (2007) observe $\sigma_{\text{Cet}} = 17 \pm 2$ km s^{−1} for Cetus and Fraternali et al. (2009) measure $\sigma_{\text{Tuc}} = 15.8_{-3.1}^{+4.1}$ km s^{−1} for Tucana. The observed values are a factor of ~ 2 and 3 higher than predicted, respectively. In terms of formal

significance, the observed velocity dispersions are 3.6σ (Cetus) and 3.0σ (Tucana) above the predicted range.

The velocity distributions of Cetus and Tucana are not particularly well described as Gaussians, so it is not obvious how to interpret their fitted velocity dispersions and uncertainties. The errors on the velocities of individual stars are typically ~ 8 km s^{−1}, so the velocity dispersions predicted here would not be resolved: improved observations are warranted. Nevertheless, in the absence of systematic errors, either in the overestimation of the velocity dispersion or the underestimation of the luminosity, these two dwarfs are problematic for MOND.

After the above text was written but shortly before we submitted this paper, Kirby et al. (2014) reported new observations of Cetus. They measure a velocity dispersion of 8.3 ± 1.0 km s^{−1}. This agrees well with our prediction of $8.2_{-1.3}^{+1.5} \pm 0.4$ km s^{−1}.

4 THE NGC 3109 ASSOCIATION AND THE LG

The dwarf galaxy Leo P has recently been discovered in the vicinity of the LG by the ALFALFA survey (Giovanelli et al. 2013; Rhode et al. 2013). It can be considered to be a member of the NGC 3109 association of galaxies (see e.g. van den Bergh 1999; Tully et al. 2006), consisting of NGC 3109, Antlia, Sextans A and Sextans B. Bellazzini et al. (2013) have shown that Leo P’s position and velocity is consistent with it belonging to the highly elongated, essentially linear association, as was also noted by McQuinn et al. (2013). Given the existence of correlated satellite galaxy planes and the recent discovery that essentially all LG dwarf galaxies are confined to one of two thin and highly symmetric planes (Pawlowski et al. 2013), it worthwhile to investigate how the NGC 3109 association relates to these structures.

4.1 Orientation of the NGC 3109 association

In the following, we use the galaxy positions as compiled by McConnachie (2012). However, like Bellazzini et al. (2013) we use the homogeneous set of tip of the red giant branch (TRGB) distance moduli from Dalcanton et al. (2009) for the members of the NGC 3109 association. For Leo P, we adopt the recent TRGB distance modulus by McQuinn et al. (2013), according to which the galaxy is at a distance of $1.72_{-0.40}^{+0.14}$ Mpc from the Sun.

The galaxies in the NGC 3109 association all have similar Galactocentric distances of 1.3–1.4 Mpc, and Leo P is also consistent with this distance range. The association is therefore oriented approximately perpendicular to our LOS, the angle between the long axis of the association and the line connecting the associations centroid with the position of the MW is 72° . The galaxies also have very similar distances from M31 and from the centre of the LG, such that the association is also oriented approximately perpendicular as seen from those points (85° and 80° , respectively). The NGC 3109 association is therefore almost perpendicular from the line connecting its centroid with the position of M31.

We have determined the associations’ orientation in the same Cartesian coordinate system used previously by employing the method used in Pawlowski et al. (2013). This effectively fits an ellipsoid to the points by determining the eigenvectors of the moments of inertia tensor defined by the non-mass-weighted galaxy positions. This gives the orientations of the major, intermediate and minor axes and the rms heights of the distribution along these axes. The resulting rms axis ratios of the NGC 3109 association are indicative for a very elongated distribution which is extremely flat in one direction (short-to-long axis ratio $c/a = 0.014 \pm 0.007$) and a

bit more extended along the intermediate axis ($b/a = 0.129 \pm 0.02$, still narrow compared to the long axis), like a ruler. The long axis points to $(l, b) = (319^\circ, -46^\circ)$ or $(139^\circ, 46^\circ)$, with an uncertainty of 7° . The association therefore aligns (being only 3° inclined) with the Supergalactic plane (de Vaucouleurs et al. 1991). It is also almost parallel to LGP1^{mod} (12° inclined), but offset by 0.3 (Leo P) to 0.5 Mpc (Antlia and NGC 3109), as can be seen in the upper panel of Fig. 1.

The LG is the closest major galaxy group to the NGC 3109 association and none of the other nearby galaxy groups listed in Pasetto & Chiosi (2009) are well aligned with the line defined by the main axis of the NGC 3109 association. The closest alignment, at an angle of $\approx 25^\circ$, is found for the M81 group, but at a distance of ≈ 3.5 Mpc from the association, two times as distant as the LG, this is most likely a chance alignment.

The short axis (normal direction if it were a plane) of the ellipsoid describing the NGC 3109 association points to $(l, b) = (230^\circ, 1^\circ)$ and $(50^\circ, -1^\circ)$. This is extremely close to the pole of the Supergalactic Plane ($[l, b] = [47:4, 6:3]$) and also similar to the normal to the LGP1^{mod} pointing to $(l, b) = (225^\circ, -21^\circ)$. Intriguingly, the normal to the GPoA has a similar orientation as well ($[l, b] = [206^\circ, 8^\circ]$, Pawlowski et al. 2013), even though it is defined by the co-orbiting satellite galaxies of M31 on the opposite side of the MW than the NGC 3109 association. However, the MW is offset by 0.8 Mpc and M31 by 0.9 Mpc from the NGC 3109 association along this short axis direction. Thus, while some hints for a connection exist it is not immediately obvious whether the NGC 3109 association is related to the dwarf galaxy planes in the LG. In the following, we will discuss additional indications why it might be part of the LG and its dwarf galaxy geometry.

4.2 Possible origins of the association's alignment

Bellazzini et al. (2013) mention several types of possible origins of the alignment of the NGC 3109 association. These include a tidal encounter with the MW which has stretched a pre-existing group of dwarf galaxies along its orbital plane, the formation of the galaxies as phase-space correlated TDGs, or the formation of the NGC 3109 association in a thin and cold cosmological filament which is just now starting to fall towards the LG. Here, we discuss these suggestions in more detail.

4.2.1 Common dark matter halo or infalling filament?

Assuming the NGC 3109 association to be bound and spherically symmetric, Bellazzini et al. (2013) estimate that it would have to have a mass of $M = 3.2 \times 10^{11} M_\odot$.¹ This is a significant fraction (up to one third) of the total mass of ≈ 1.0 to $2.4 \times 10^{12} M_\odot$ currently estimated for the MW halo (Boylan-Kolchin et al. 2013). If the NGC 3109 association were embedded in such a massive dark matter halo, this halo should significantly influence the dynamics of the LG. In addition, a past interaction with the massive dark matter content of the association would have likely lead to it merging with the MW because dynamical friction must be significant in this mass range. A spherical dark matter halo encompassing the whole association would furthermore have to have a radius of at least 600 kpc, half the association's diameter. This is twice as much as the virial radii assumed for the MW and M31 and would almost reach

¹ A spherical approximation is certainly a non-ideal assumption for such an extremely linear association.

Leo A at a distance of about 800 kpc from the NGC 3109 association. We therefore deem it unlikely that the NGC 3109 association is a distinct gravitationally bound entity.

Bellazzini et al. (2013) suggest a cosmological accretion scenario in which the NGC 3109 association is a 'thin and cold cosmological filament', assuming that the galaxies in the association have recently left the Hubble flow and are currently falling into the LG for the very first time. However, simulated dark matter filaments around MW-like haloes today have diameters which are larger than the virial radii of the major haloes they feed (Vera-Ciro et al. 2011). Due to its much narrower configuration, the NGC 3109 association cannot be identified with such a major dark matter filament. The dark matter hypothesis does, however, allow the freedom to propose that the NGC 3109 association is embedded in a dark matter 'sub-filament', which would have to be oriented almost perpendicular to its closest major mass concentration. While cosmological simulations might be searched for the existence of thin sub-filaments of this kind, as of now such a suggestion unfortunately remains non-testable via observations. However, one wonders how such a dark matter filament in the vicinity of the major dark matter halo potentials of the MW and M31 could have remained essentially a straight line over a length of 1.2 Mpc without being aligned towards the mass concentration.

The interpretation that the association is a filament falling towards the LG is in conflict with the orientation of the NGC 3109 association being almost perpendicular to the direction towards the MW or the LG barycenter. Simulated filaments of cold gas, which would be narrow enough to accommodate the thin association, point towards the central galaxy and are considered to be important at high redshifts of $z \gtrsim 2$ only (e.g. Dekel et al. 2009; Goerdt & Burkert 2013). More importantly, the NGC 3109 association does not fall towards but recedes from the MW with $\approx 170 \text{ km s}^{-1}$, a velocity similar to those of galaxies at larger distances of 1.6 to 2.2 Mpc (see e.g. fig. 5 of McConnachie 2012). The association appears to be situated beyond the zero-velocity surface of the LG (≈ 1 to 1.5 Mpc) and therefore should follow the Hubble flow. If it follows the Hubble flow, the galaxies should never have been close to the LG (except during the big bang). However, the members of the NGC 3109 association appear to recede faster than the expected Hubble flow velocity at their distance (see e.g. fig. 6 of Teyssier, Johnston & Kuhlen 2012). If this is the case and if they are on radial orbits (otherwise their motion is even faster), the galaxies must have been close to the MW in the past.

4.2.2 A past encounter with the LG?

Assuming that all galaxies in the NGC 3109 association are receding on radial orbits from the MW (i.e. the tangential velocity is zero), and that they have been travelling with their current Galactocentric velocity (no acceleration) gives a rough estimate for their travel time. If we transform the measured Heliocentric velocities to Galactocentric ones by assuming a circular velocity of the local standard of rest (LSR) of 220 km s^{-1} and a peculiar motion of the Sun as measured by Schönrich, Binney & Dehnen (2010), the travel times are 6.7 ± 0.1 Gyr for NGC 3109, 8.2 ± 0.2 Gyr for Sextans B, 8.6 ± 0.2 Gyr for Antlia and 8.6 ± 0.3 Gyr for Sextans A. Due to the large distance uncertainty for Leo P its travel time is in the range of 7.6–10.6 Gyr. The stated uncertainties are based on the distance uncertainties and an assumed uncertainty in the LOS velocities of the galaxies of 2 km s^{-1} . Of course, the major inaccuracy comes from the oversimplified assumption of radial orbits without acceleration.

Another major source of uncertainty is the LSR velocity. If we assume an LSR velocity of 240 km s^{-1} , instead of the previously used 220 km s^{-1} , the travel times become 0.75 Gyr longer on average.

If the galaxies in the NGC 3109 association do not have a significant tangential velocity, this timing estimate demonstrates that they have been close to the MW in the past. More importantly, the galaxies are consistent with all having been nearby at about the same time, $\approx 8.5 \text{ Gyr}$ ago. Only NGC 3109's timing appears to be off by $1.5\text{--}2 \text{ Gyr}$, but unaccounted-for tangential motion, gravitational acceleration by the LG galaxies and others and the possible interaction between members of the NGC 3109 association make this estimate unreliable on such time-scales.

That the NGC 3109 members have been close to the MW at a similar time in the past is also consistent with results by Shaya & Tully (2013). In their model of the dynamical history of the LG, the NGC 3109 association members had a close passage (pericentre $\approx 25 \text{ kpc}$) with the MW about 7 Gyr ago. However, at such a distance dynamical friction, in particular for massive objects such as NGC 3109 or the putative dark matter halo needed if one requires that the association as a whole is gravitationally bound, cannot be neglected. As Shaya & Tully (2013) do not consider dynamical friction in their study, the orbit of the association's members as derived from their study becomes unreliable as soon as they come close to the MW halo.

Another independent indication that the members of the NGC 3109 association have been close to the LG before is their identification as probable backplash galaxies, galaxies which have passed through the virial volume of the MW in the past but are now situated outside of it. By comparing the distances and LOS velocities of LG galaxies with sub-haloes in the Via Lactea II simulation, Teyssier et al. (2012) identify all four of the then-known galaxies in the NGC 3109 association as likely backplash haloes that have interacted with the MW before.

It therefore appears likely that the NGC 3109 association had a past encounter with the MW, in conflict with the interpretation as an infalling dark matter filament. A scenario in which a pre-existing group of dwarf galaxies collided with the MW and was tidally stretched along its orbit appears plausible, but the effects of dynamical friction in such a scenario will need to be assessed. It is currently not possible to discriminate such a scenario from one in which the galaxies were formed as TDGs in a past encounter in the LG, but there are additional coincidences which make a TDG origin look more appealing.

4.2.3 Consistent with a TDG origin?

As shown before, given their current distances and LOS velocities, the galaxies in the NGC 3109 association are consistent with having been in the vicinity of the MW at roughly the same time about 7 to 9 Gyr ago. This leads us to the other possible origin of the association discussed by Bellazzini et al. (2013): the galaxies might have been expelled as TDGs in a galaxy encounter. Interestingly, the estimated travel times are in good agreement with independent estimates for the timing of major galaxy encounters suggested as the origin of a population of TDGs in the LG:

(i) Based on the ages of the young halo globular clusters, the VPOS around the MW was estimated to have formed $9\text{--}12 \text{ Gyr}$ ago (Pawlowski et al. 2012a).

(ii) A major merger might have formed M31 $8\text{--}9 \text{ Gyr}$ ago. This event must have produced TDGs, some of which would constitute the GPoA today while others would have been expelled towards

the MW, may be forming the VPOS (Hammer et al. 2010, 2013; Fouquet et al. 2012).

(iii) In MOND, the observed baryonic masses of the MW and M31 and their relative velocity require a past encounter between the two major galaxies to have happened $7\text{--}11 \text{ Gyr}$ ago (Zhao et al. 2013).

The NGC 3109 association is therefore consistent with having formed in the same major galaxy encounter and thus such an origin cannot be ruled out at present. The star formation histories of the non-satellite galaxies do not provide conclusive information either, because most non-satellite galaxies in the LG are dwarf irregular (dIrr) galaxies which show ongoing star formation, consistent with expectations for gas-rich TDGs if the present high-resolution simulations of TDG formation and early evolution can be extrapolated to many Gyr (Recchi et al. 2007; Ploekinger et al. 2014). Differing environmental effects will furthermore diversify the evolutionary histories of TDGs born in the same event over time. The apparent dark matter content of some of these galaxies, unexpected for TDGs in a CDM universe (but nevertheless observed in young TDGs, see Bournaud et al. 2007; Gentile et al. 2007), is not a conclusive argument against the possible TDG nature of the NGC 3109 association either, as inflated velocity dispersions are expected in MOND as exemplified in Section 3.

To be consistent with a scenario in which a major fraction of the LG galaxies was formed in one common major encounter, the members of the NGC 3109 association must show signs of being related to the other dwarf galaxy structures known in the LG, in particular the VPOS, the GPoA and potentially the LG dwarf galaxy planes, because TDGs form as a phase-space correlated population, i.e. in a highly flattened tidal tail. If the NGC 3109 association shows alignments with other LG dwarf galaxies, this might indicate that the NGC 3109 association is, contrary to current belief, not an isolated entity and might share a common origin with other dwarf galaxy structures.

4.3 The NGC 3109 association as an extension of LGP1

Given that the total extent of the NGC 3109 association (the distance between Leo P and Antlia) is 1.2 Mpc , while the three LGP1 members UGC 4879, Leo A and Leo T are at distances of only $0.8\text{--}1 \text{ Mpc}$ from their respectively closest member of the NGC 3109 association, these eight galaxies might well constitute one common structure of square-megaparsec size. The difference in the Galactocentric LOS velocities between the NGC 3109 association (receding) and the other three galaxies (slowly approaching) might then be simply due to the stronger gravitational attraction acting on the more nearby galaxies. Indeed, as seen from the centre of the LG the members of the NGC 3109 association align along a similar band as defined by UGC 4879, Leo A and Leo T (see Fig. 2). This indicates that they are in a common plane running through the centre of the LG. Fitting a plane to the eight galaxy positions confirms that the galaxies are confined to a thin planar structure, which we will refer to as the *Great Northern Plane*. The parameters of the best-fitting plane are compiled in Table 1. The plane has a normal vector pointing to $(l, b) = (197^\circ.6, -31^\circ.5)$ and rms axis ratios of $c/a = 0.098 \pm 0.004$ and $b/a = 0.762 \pm 0.067$. As expected, it runs through the centre of the LG (see lower panel in Fig. 1). The galaxy with the largest offset of only 86 kpc from the best-fitting plane is UGC 4879. Compared to LGP1^{mod}, with which it shares three members, the plane has a similar offset from the MW ($162.6 \pm 5.6 \text{ kpc}$) and a similar rms height ($\Delta = 53.4 \pm 1.5 \text{ kpc}$). There is no other known dwarf galaxy in the Northern hemisphere of the MW and

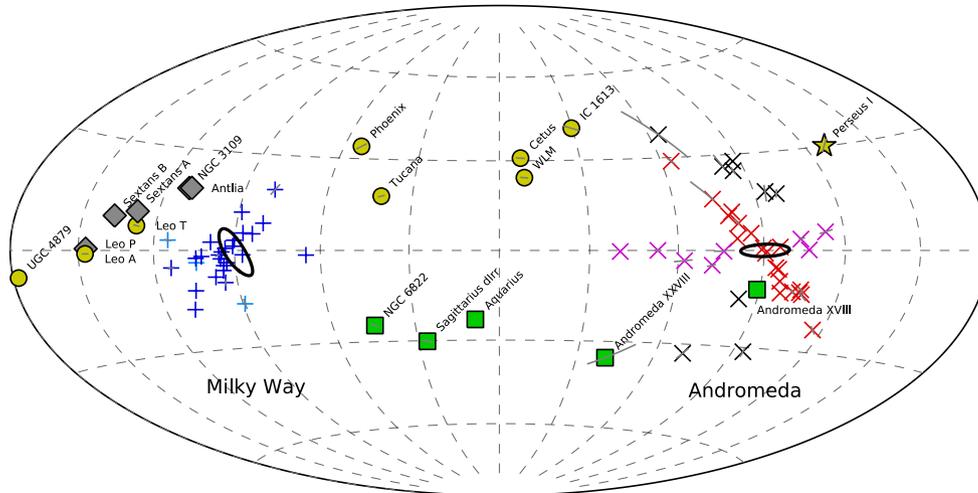


Figure 2. The positions of LG galaxies in an all-sky plot as seen from the mid-point between the MW and M31 (same symbols as in Fig. 1). Compared to fig. 6 in Pawlowski et al. (2013) this plot also includes the newly discovered dwarf galaxy Perseus I and the members of the linear NGC 3109 association (grey diamonds), which align with the LGP1^{mod} members Leo T, Leo A and UGC 4879, indicating that they lie in a common plane which passes through the centre of the LG.

between Galactocentric distances of 0.3 to 1.7 Mpc from the MW, such that all currently known nearby non-satellite dwarf galaxies to the north of the MW are confined to this one common plane.

To determine how significant this planar alignment is, we follow the same principle as in Section 2 (thus the same caveats apply here). We randomize the positions of the eight non-satellite galaxies in the Northern hemisphere of the MW and then determine the rms height of the planes fitted to these new positions. We generate 10^5 realizations for each of two randomization methods. The first method draws the galaxy positions randomly from an isotropic distribution, but we force the galaxies to be confined to $b \geq 20^\circ$. This make sure they are in the Northern Galactic hemisphere and in an area not obscured by the MW disc. This method conserves the distances from the MW, but not from M31. In this case, only five (0.005 per cent) of all realizations have $\Delta \leq 53.4$ kpc. In the second method, we instead conserve the distances from both the MW and from M31, by rotating the galaxy positions by a random angle around the MW–M31 axis. Again they are required to be at $b \geq 20^\circ$. In this case, only seven (0.007 per cent) of the realizations result in sufficiently thin best-fitting planes. However, Antlia might be interpreted as a satellite of NGC 3109 (van den Bergh 1999), such that these two galaxies might not be treated as two independent systems. If we exclude Antlia from this analysis (thus using only seven instead of eight galaxies), the probabilities to find a plane at least as narrow as the observed one increase to 0.079 per cent if the galaxy positions are chosen from an isotropic distribution and to 0.037 per cent if the galaxy positions are individually rotated by a random angle around the MW–M31 axis. A plane as narrow as the observed Great Northern Plane is therefore very unlikely to occur by pure chance.

The plane is inclined relative to LGP1^{mod} by only 27° . As can be seen in the lower panel of Fig. 1, which shows these two planes edge-on, the line at which they intersect passes close to the MW. Interestingly, the plane is also inclined by only 25° from the average orbital pole of the MW satellites with known proper motions, around which the individual satellite orbital poles scatter with a spherical standard distance of $\Delta_{\text{sph}} = 29^\circ$ (Pawlowski & Kroupa 2013). The plane is therefore consistent with being aligned with the preferred orbital plane of the MW satellites in the VPOS, but is

somewhat less polar than the VPOS. Relative to the GPoA of M31 satellites it is inclined by 40° . Interestingly, even though planes of satellite galaxies can be dynamically stable, depending on the galactic potential in which they are embedded their orientation can change due to precession and inclined planes can evolve into a more polar orientation (Klarman et al., in preparation).

It is possible that LGP1^{mod} bends close to the position of the MW, such that the NGC 3109 association is in fact a part of the same structure of non-satellite galaxies in the LG. For such a causal connection to be feasible, the NGC 3109 members must have been closer to the LG in the past, which appears to be supported by the timing estimate presented before. The NGC 3109 association therefore appears to be connected to the previously identified dwarf galaxy structures of the LG such that the LG geometry does not rule out the possibility of a TDG origin for its members.

5 DOES THE SEARCH FOR BACKSLASH GALAXIES IDENTIFY TDGS?

Interestingly, of the seven galaxies in the sample by Teyssier et al. (2012) which lie to the north of the MW ($b > 0^\circ$), five are identified as likely backslash galaxies and one of the remaining two (Leo A) has a non-negligible likelihood if sub-haloes close to an M31 analogue are excluded from the analysis. In the whole Northern hemisphere of the MW (the Southern hemisphere is more complicated due to the presence of M31 and its satellite galaxy population), the majority of dwarf galaxies are likely backslash objects, which is unexpected from cosmological simulations. According to Teyssier et al. (2012), overall only 13 per cent of all sub-haloes between 300 and 1500 kpc from the MW should be backslash haloes.

This can be expressed in another way, which might highlight a more curious coincidence: all galaxies in the Great Northern Plane except for UGC 4879² are possible backslash objects, posing the

² Including Leo P, which was not yet discovered when Teyssier et al. (2012) performed their analysis but has a similar distance and LOS velocity as the members of the NGC 3109 association identified as likely backslash galaxies.

question why they should all be in the same thin, planar structure. Even more puzzling is that most of the remaining five likely back-splash galaxies of Teyssier et al. (2012) situated in the Southern hemisphere of the MW are also close to the Great Northern Plane defined by the northern non-satellite galaxies only: NGC 185 at a distance of 45 kpc from the best-fitting plane,³ Phoenix at 87 kpc,⁴ Tucana at 113 kpc and maybe Cetus which is offset by 204 kpc. Only NGC 6822 has a much larger offset of 460 kpc. The distance uncertainties in the galaxy positions result in uncertainties in the offsets from the best-fitting plane of 8 to 11 kpc.

That all distant dwarf galaxies in the Northern hemisphere of the MW are confined to one single plane, which in addition is inclined by less than 30° from both the average orbital plane of the MW satellites co-orbiting in the VPOS and from the LGP1 might be more than a lucky coincidence. The study by Teyssier et al. (2012), according to which the distance and the LOS velocity makes five out of seven of these galaxies more consistent with being back-splash galaxies than infalling ones, whereas the latter type should be seven times more abundant, might indicate another small-scale problem for the current Λ CDM cosmology. To find at least 5 out of 7 galaxies to be back-splash objects, if only 13 per cent of all galaxies in this distance range should be back-splash objects has a likelihood of only 0.12 per cent. Even if half of the candidates are false positives, i.e. we would expect to find that 26 per cent of all galaxies are identified as candidates, the chance to draw 5 out of 7 candidates is still only 3 per cent. If Leo P is included as a back-splash object, these likelihoods drop even more. Unless cosmological simulations can show that there is a large excess of back-splash haloes in one hemisphere from a central galaxy, the Λ CDM model will face an ‘overabundant back-splash problem’ in the LG. Already now we have to wonder how, in a whole hemisphere, there can be more galaxies which have been close to the MW before and escaped to large distances than there are galaxies which are falling in, unless at least some of them have formed in and been expelled from the LG as TDGs.

In addition, if the identification as back-splash galaxies by Teyssier et al. (2012) is confirmed by other studies, we might even face a ‘planar back-splash problem’ as almost all of the current back-splash candidates lie within about 100 kpc of the same plane, which is defined by only the northern non-satellite galaxies and measures more than 1 Mpc in diameter. Again, this might be well understood in a TDG scenario where new galaxies form in a tidal tail as a phase-space correlated population, but there is no reason to anticipate a planar configuration among back-splash galaxies.

As illustrated in Fig. 3, TDGs expelled from a major galaxy encounter will have similar orbital properties as back-splash-sub-

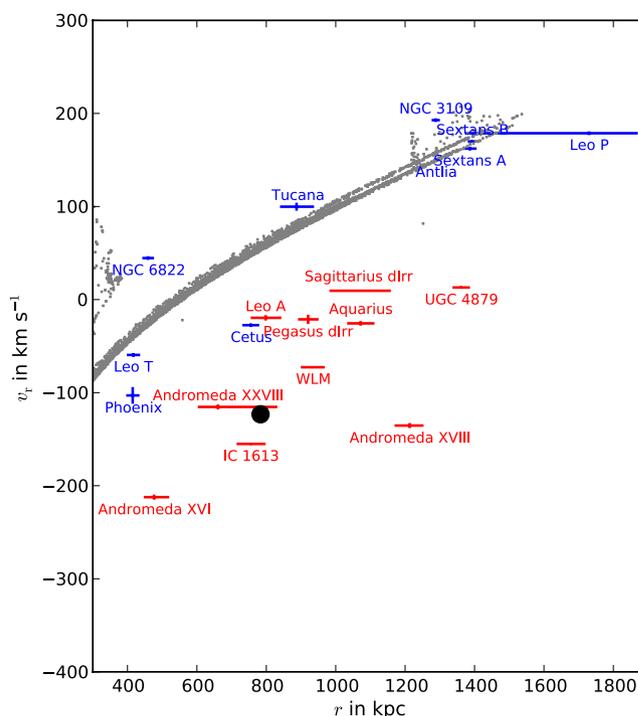


Figure 3. Galactocentric radial velocity v_r of LG dwarf galaxies is plotted against their Galactocentric distance r . Compare to fig. 6 of Teyssier et al. (2012). The black circle denotes M31. Dwarf galaxies identified as likely back-splash objects by Teyssier et al. (2012) are marked in blue, the others in red. Leo A has a non-negligible but below 50 per cent likelihood of being a back-splash galaxy. Leo P was discovered only after the study of Teyssier et al. (2012) and should also be interpreted as a back-splash candidate. The grey dots are tidal debris particles from an N -body model of a galaxy collision at about 9 Gyr after the first pericentre. Two disc galaxies embedded in $10^{12} M_\odot$ dark matter haloes merge, with one falling in on a polar, prograde orbit. The model parameters have not been fine-tuned to reproduce the MW or the surrounding LG galaxies, but the distribution of particles illustrates that tidal debris have similar properties as the back-splash galaxy candidates in this plot. This demonstrates that TDGs might be wrongly identified as back-splash galaxy candidates. Note that more than one tidal tail can be formed if there are several pericentre passages before the final merger and that a different origin of the TDGs, e.g. in M31 or at the barycenter of the LG in case of a past MW–M31 encounter, would result in a more complex distribution of tidal debris.

haloes. They are receding from the main galaxy with high velocities on almost radial orbits because they originate from material in the galactic disc. Their formation in a common event furthermore implies that the galaxies have similar travel times, in contrast to back-splash galaxies which might have been individually accreted. This could be a promising route to observationally discriminate between the two origins. Such a discrimination will be important because the search for back-splash galaxies in the LG might in fact be good at identifying ancient TDGs expelled in a past major galaxy encounter.

6 SCHEMATIC STRUCTURE OF THE LOCAL GROUP

The approximate alignment of the MW satellites co-orbiting in the VPOS (Pawlowski et al. 2012a; Pawlowski & Kroupa 2013), the M31 satellites co-orbiting in the GPoA (Ibata et al. 2013), the dominant non-satellite galaxy plane LGP1^{mod} in the LG and its

³ NGC 185 is a satellite galaxy of M31, situated in the GPoA and its LOS velocity indicates that it is also co-orbiting in the same sense as the other members of the satellite plane. This makes it unlikely that it is a dark matter sub-halo which has been close to the MW before, as it would have to end up in the unrelated satellite structure with the right velocity by chance. This case demonstrates that it is problematic to attempt an identification of back-splash galaxies based only on their Galactocentric distance and LOS velocity if one does include the galaxies in the direction of M31.

⁴ Note that the identification as a back-splash candidate by Teyssier et al. (2012) is based on the Heliocentric velocity for Phoenix reported in Cote et al. (1997) of 56 km s^{-1} , whereas more recent measurements yield $-13 \pm 9 \text{ km s}^{-1}$ (Irwin & Tolstoy 2002) or even $-52 \pm 6 \text{ km s}^{-1}$ (Gallart et al. 2001). These result in Phoenix approaching the MW much faster than assumed in the analysis by Teyssier et al. (2012), such that identification as a back-splash candidate will be less likely for this galaxy.

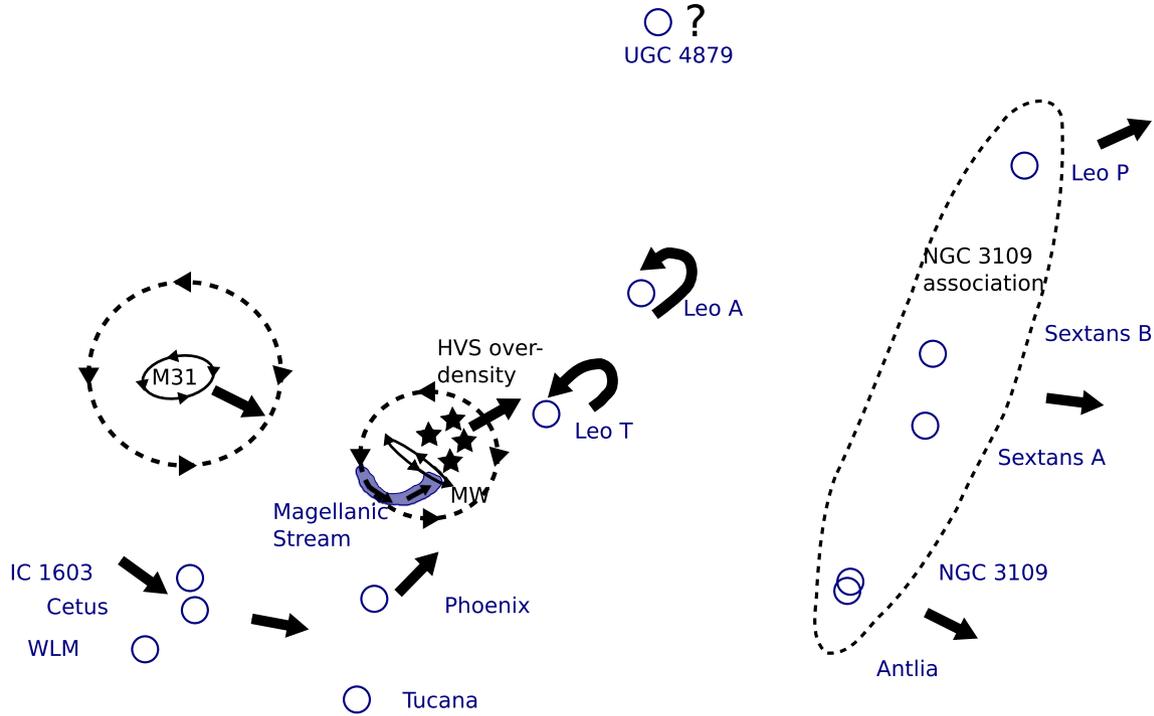


Figure 4. Schematic sketch of the LG looking approximately face-on on to the most pronounced dwarf galaxy structures. Not shown are the five non-satellite dwarf galaxies associated with the second LG plane LGP2. See Section 6 for a detailed description and discussion. Note that the size of the ellipses indicating the orientation of the galactic discs of the MW and M31, the circles indicating the dwarf galaxy positions, the Magellanic Stream and the HVSs are not to scale.

connection to the NGC 3109 association (this work) motivate our attempt to schematically sketch the geometry of the LG in Fig. 4. It shows the before-mentioned structures approximately face-on. Starting on the left, we see the orientation of M31 (solid ellipse) and the GPoA consisting of more than half its satellite galaxies (dashed circle). The arrow heads along the circles indicate the sense of rotation. M31 is moving towards the MW on an almost radial orbit (Sohn, Anderson & van der Marel 2012; van der Marel et al. 2012). Towards the bottom of the sketch, we see a number of dwarf galaxies belonging to LGP1^{mod} which appear to form a kind of bridge between the galaxies (small circles). As seen from the MW these are also approaching, except for Tucana (which, as one of the only two distant dSphs in the LG, is also morphologically different from most of the shown dwarf galaxies which are predominantly gas-rich dIrrs). These five ‘bridge’-galaxies have similar positions on the sky and similar LOS velocities like the Magellanic Stream (Pawlowski et al. 2013), which falls in towards the MW with the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) in the southern Galactic hemisphere.

The MW itself is oriented almost edge-on in this view (flatter black ellipse), but its polar structure of satellite galaxies is seen face-on (dashed circle). We can see that both satellite galaxy structures orbit in the same sense. In the north of the MW an overdensity of hypervelocity stars (HVSs) recede in the direction of the constellation of Leo (Brown et al. 2012) and opposite to the Magellanic Stream (Pawlowski et al. 2013), which is relevant in this context because the tidal disruption of a dwarf galaxy close to the Galactic centre has been suggested as a possible formation mechanism for grouped HVSs (Abadi, Navarro & Steinmetz 2009). Whether this overdensity continues to lower Galactic latitudes is currently unknown. The two galaxies at intermediate distance in the same constellation, Leo T and Leo A both have small approaching Galac-

tocentric LOS velocities. They might just have turned around, falling back towards the MW after having passed and receded from it some time ago. This is supported by their low velocities. Boylan-Kolchin et al. (2013) predict that to be on its first infall towards the MW, Leo A would have to have a large tangential velocity of two times its radial velocity. Furthermore, Phoenix on the other side of the MW is at essentially the same distance as Leo T (415 compared to 422 kpc), but it is falling towards the MW with a twice as large Galactocentric LOS velocity (-103 compared to -58 km s⁻¹). Finally, the members of the NGC 3109 association, starting with Leo P in the same constellation mentioned before and continuing to lower Galactic latitudes, are all receding with high velocities which indicate that they have been close to the MW in the past.

Not shown in the sketch is Leo I, the most distant of the classical MW satellite galaxies. It appears not to co-orbit in the VPOS and – in contrast to all other classical satellites – has a larger radial than tangential velocity (Pawlowski & Kroupa 2013). It moves away from the MW and might even be unbound to the MW, which would be unexpected if Leo I traces a dark matter sub-halo (Boylan-Kolchin et al. 2013; Sohn et al. 2013). Leo I’s 3D velocity vector (Pawlowski & Kroupa 2013) points into the direction of Leo T: as seen from Leo I, Leo T’s position is at $(l, b) = (202^\circ, 34^\circ)$ and Leo I’s most-likely velocity vector points to $(l, b) = (192^\circ, 29^\circ)$. In the future, the galaxy might therefore become a part of the Great Northern Plane.

UGC 4879, the topmost galaxy in the sketch, does not fit in. It has a very low LOS velocity and its free-fall time from its present position on to the LG is larger than a Hubble time (McConnachie 2012). It is therefore thought to have never interacted with a major LG galaxy (Kopylov et al. 2008). In addition, the galaxy has the largest offset from the Great Northern Plane (see Section 4.3) and according to Jacobs et al. (2011) almost all its stars appear to have

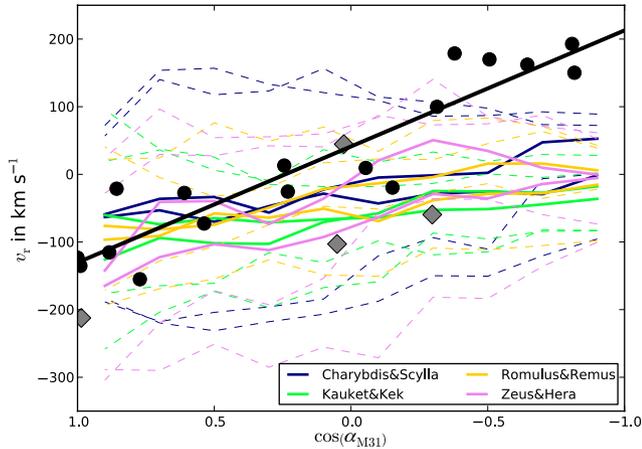


Figure 5. Cosine of the angle between a galaxy’s position and the position of M31 on the sky, $\cos(\alpha_{M31})$, against the Galactocentric radial velocity, v_r , of galaxies in the LG (within 1.8 Mpc from the MW). Black dots represent galaxies more distant than 600 kpc from the MW while grey diamonds represent galaxies at a distance between 300 and 600 kpc, which might be more affected by the gravitational pull of the Galactic potential. Galaxies closer than 300 kpc to the MW or M31, except for M31 itself, are not shown. The coloured lines represent sub-halo velocities measured from one major dark matter halo in the ELVIS suite of cosmological simulations of LG equivalents (Garrison-Kimmel et al. 2014), where α is measured from the position of the other major halo in the simulated group. The solid line is a fit to the observed galaxies at more than 600 kpc distance from the MW resulting in $v_r(\alpha_{M31}) \approx (40-170 \times \cos \alpha_{M31}) \text{ km s}^{-1}$.

formed more than 10 Gyr ago. Finally, of all galaxies in the Great Northern Plane, UGC 4879 has the lowest gas to star mass ratio (McConnachie 2012). UGC 4879 therefore seems to be the most unlikely galaxy to be associated with the dwarf galaxy structure in the LG.

Overall, there appears to be a trend that a variety of objects preferentially fall in from the Galactic South while those in the Galactic North recede. This is confirmed by Fig. 5, which plots the cosine of the angle between the position on the sky of a non-satellite LG galaxy and the position of M31, $\cos(\alpha_{M31})$, against the galaxy’s Galactocentric radial velocity v_r . For comparison, the coloured lines illustrate the average radial velocities of sub-haloes in the ELVIS suite of cosmological simulations modelling LG-like galaxy pairs (Garrison-Kimmel et al. 2014). They are measured in 10 bins in $\cos(\alpha)$, where α is the angle between a sub-halo position, as seen from one major dark matter halo (representing the MW), and the position of the other major dark matter halo (representing M31). All sub-haloes between 0.3 and 1.8 Mpc from the MW equivalent and outside of 300 kpc from the M31 equivalent are included. The dashed lines indicate the scatter in sub-halo velocities, 95 per cent of all sub-halo velocities are below the upper dashed lines and similarly 95 per cent are above the lower. Two sets of lines are shown for each pair of galaxies, each assuming a different main halo of each halo pair to be the MW equivalent. For clarity, only the four simulations with the largest volume uncontaminated by low-resolution particles are included, but the remaining 8 simulations in the ELVIS suite cover the same range in v_r .

Fig. 5 shows that the LG galaxies tend to approach from the direction of M31 and recede in the opposite direction. If the LG were simply collapsing towards the LG barycenter, the galaxies in the direction of M31 are expected to approach but those on the opposite side are expected to fall towards the LG barycenter together with the MW, resulting in radial velocities closer to zero. This is confirmed

by the cosmological simulations, which at $\cos(\alpha_{M31}) < -0.5$ scatter by $\approx \pm 100 \text{ km s}^{-1}$ around $v_r \approx 0 \text{ km s}^{-1}$. The observed velocities, however, continue to larger receding values of 150 to 190 km s^{-1} for the direction opposite to M31. Such high radial velocities are not found for dark matter sub-haloes in the simulations. While part of the velocity gradient will thus be due to the MW falling towards M31, the continuation of this trend in the direction opposite to M31 indicates that we might witness a larger scale flow of dwarf galaxies within a flattened structure. The linear trend of increasing velocities with decreasing $\cos(\alpha_{M31})$ can be interpreted as due to the MW moving through the LG dwarf galaxy population, such that its gravitational potential is deforming the structure (in addition to external tides, Raychaudhury & Lynden-Bell 1989; Pasetto & Chiosi 2009) and the MW might have accreted or is still accreting dwarf galaxies from it (such as the LMC if it is on its first infall), while others are leaving on the opposite side after having passed close to the MW (such as the potentially unbound Leo I). While this schematic representation currently is speculative (as we do not know the tangential motions) and does not prove any scenario right, the geometry presented in Fig. 4 might help to constrain attempts to model the LG.

7 OPEN QUESTIONS

Despite the intriguing alignments discovered among the currently known LG galaxies, it is to be expected that additional nearby galaxies will be discovered in the future. As our current knowledge is based on a large number of different sources, it is impossible to accurately consider selection effects and the possibility, however unlikely, that additional dwarf galaxies will preferentially be found outside of the structures does exist. We essentially do not know what we have not seen yet. Nevertheless, for searches for nearby dwarf galaxies, the northern Galactic hemisphere is generally considered the best-studied direction because the Sloan Digital Sky Survey (SDSS) sky coverage initially focused on this region. This might give some confidence in the significance of the Great Northern Plane. This is further supported by the present non-detection of new bright dwarf galaxy candidates in single-epoch data of the Pan-STARRS1 survey. While based on an approximately 1 mag shallower photometric depth than the SDSS, it covers a significantly larger fraction of the sky (away from the VPOS) and therefore supports the satellite galaxy anisotropy revealed by the presently known dwarf galaxies (Laevens, Martin & Rix 2013). However, despite being covered by the SDSS, Leo P was only found by the less extended ALFALFA H I survey, indicating that additional faint galaxies might hide in the LG.

Only once proper motions of the LG dwarf galaxies are known, will we be able to directly determine whether the planar structures are dynamically stable. This is so far only possible for the 11 classical MW satellites in the VPOS, of which nine are found to be consistent with moving within the structure (Pawlowski & Kroupa 2013), while one (Leo I) is moving towards the Great Northern Plane (as discussed in Section 6). Promising developments in this regard, such as the measurement of the proper motions of the M31 satellites M33 and IC 10 via water masers (Brunthaler et al. 2005, 2007) or the optical proper motion measurement of the MW’s most-distant classical satellite Leo I (Sohn et al. 2013) and of M31 (Sohn et al. 2012), indicate that acquisition of three-dimensional velocity data for a larger sample of LG galaxies might be feasible in the near future.

In addition to the tentativeness of the dynamical stability of the dwarf galaxy structures, all of the different scenarios of their

formation have yet to address serious issues. Most importantly, if the observed dwarf galaxies are identified with dark matter sub-halos such as those produced in cosmological simulations, these do not naturally result in the observed planar and co-orbiting structures. Most claims of the contrary (D’Onghia & Lake 2008; Li & Helmi 2008; Libeskind et al. 2009; Deason et al. 2011; Wang et al. 2013) have subsequently been addressed in the literature and shown to lack important aspects of the observed situation or to be inconsistent with additional observations (Metz et al. 2009; Pawlowski et al. 2012b; Pawlowski & Kroupa 2013, Ibata et al., in preparation, Pawlowski et al., in preparation). Furthermore, the inability of present simulations to reproduce the observed structures comes in addition to the other known small-scale problems of the Λ CDM cosmology (e.g. Kroupa et al. 2010; Kroupa 2012; Famaey & McGaugh 2013; Walker & Loeb 2014).

In the alternative TDG scenario phase-space correlated dwarf galaxies occur naturally, but there are two crucial questions that yet lack decisive answers: Why do the observed LG dwarf galaxies have large velocity dispersions that are classically interpreted as a strong indication for dark matter? And how could TDGs, born out of pre-processed material stripped from much larger galaxies, end up on the mass–metallicity relation? Modified gravity models (e.g. Gentile et al. 2007; Milgrom 2007; McGaugh & Milgrom 2013a) and non-equilibrium dynamics (e.g. Kroupa 1997; Metz & Kroupa 2007; Casas et al. 2012; Smith et al. 2013, Yang et al., in preparation) might provide answers to the first, and the early formation of TDGs at a redshift of $z \approx 2$ and out of less metal-rich material from the rim of interacting galaxies might indicate a possible approach to the second. However, none of these issues have yet been satisfactorily investigated in a full and self-consistent model forming an LG-like group of galaxies.

8 SUMMARY AND CONCLUSIONS

We have investigated how the recently discovered dSph galaxy Perseus I and the NGC 3109 association extended with the recently discovered dwarf galaxy Leo P are related to, and might fit in with, the dwarf galaxy structures present in the LG. Our work has shown that the NGC 3109 association cannot necessarily be interpreted as an independent group of galaxies, but might be related to the LG dwarf galaxy population and as such might provide important constraints on attempts to model the whole LG. The main results of our analysis are as follows.

(i) Perseus I is consistent with being part of the LGP1^{mod}, the dominant plane of non-satellite galaxies in the LG, at least if Andromeda XVI is associated with the GPoA.

(ii) In the context of MOND, we have predicted Perseus I’s velocity dispersion to be $\sigma = 6.5_{-1.0}^{+1.2} \pm 1.1 \text{ km s}^{-1}$. The corresponding prediction for Cetus ($\sigma = 8.2_{-1.3}^{+1.5} \pm 0.4 \text{ km s}^{-1}$) is in much better agreement with the more recent observational value ($\sigma = 8.3 \pm 1.0 \text{ km s}^{-1}$; Kirby et al. 2014) than with the previous measurement ($\sigma = 17 \pm 2.0 \text{ km s}^{-1}$; Lewis et al. 2007). The prediction for Tucana ($\sigma = 5.5_{-0.9}^{+1.0} \pm 0.4 \text{ km s}^{-1}$) is in conflict with the available measurement ($\sigma = 15.8_{-3.1}^{+4.1} \text{ km s}^{-1}$; Fraternali et al. 2009). We note that the observations of Fraternali et al. (2009) lack the spectral resolution to resolve the predicted velocity dispersion. Unfortunately, no similar predictions are possible in a Λ CDM context.

(iii) The orientation of the NGC 3109 association consisting of the dwarf galaxies NGC 3109, Antlia, Sextans A, Sextans B and Leo P has been determined in the same coordinate system used to

review the planes of co-orbiting satellite galaxies around the MW and M31 and the symmetric larger scale dwarf galaxy structure in the LG (Pawlowski et al. 2013). The association aligns with the Supergalactic Plane, is almost perpendicular to our LOS and parallel but offset by 300–500 kpc to LGP1^{mod}.

(iv) The members of the NGC 3109 association have large receding velocities which indicate that they have been close to the MW in the past, possibly at the same time about 7–9 Gyr ago. This is consistent with their orbits passing within ≈ 25 kpc of the MW suggested by Shaya & Tully (2013) and the identification as likely backsplash galaxies by Teyssier et al. (2012). Together with the association’s extremely narrow extent and perpendicular orientation this argues against the association tracing a thin and cold cosmological filament. The timing is consistent with independent timing estimates for several suggested major galaxy encounter scenarios in the LG, during which phase-space correlated populations of TDGs could have formed that would today give rise to the observed dwarf galaxy structures (Pawlowski et al. 2012a; Hammer et al. 2013; Zhao et al. 2013).

(v) The association aligns with the other three distant (> 300 kpc) LG galaxies in the Northern hemisphere of the MW in a narrow plane (rms height of $\Delta = 53$ kpc and axis ratios of $c/a = 0.10$ and $b/a = 0.76$). This ‘Great Northern Plane’ passes through the centre of the LG, is inclined to LGP1^{mod} by only 27° and to the GPoA by 40° and is consistent with being aligned with the preferred orbital plane of the MW satellites in the VPOS.

(vi) Five out of seven (six of eight if the later discovered Leo P would be included) of the galaxies in the Great Northern Plane have been identified as likely backsplash objects by Teyssier et al. (2012), and most of the remaining five backsplash candidates in the southern Galactic hemisphere are also situated close to the same plane. As only a small fraction of sub-halos in simulations are identified as backsplash objects, the finding of a majority of such galaxies in one hemisphere is extremely unlikely (≈ 0.1 per cent) and might constitute an ‘overabundant backsplash problem’ for Λ CDM. It would mean that more galaxies are receding in one direction from the MW than are being accreted on to the MW from that direction. A natural explanation for this would be the local formation of galaxies as TDGs, which, if expelled to large distances, have very similar orbital properties like cosmological backsplash galaxies. That the backsplash candidates preferentially lie in a common plane is also consistent with an interpretation as phase-space correlated TDGs.

(vii) LG galaxies are found to be preferentially infalling in the Galactic south and receding in the Galactic north, which possibly indicates that the MW is moving through a stream of dwarf galaxies. This would be in qualitative agreement with the M31-merger scenario by Hammer et al. (2010), in which our Galaxy passes through the tidal debris expelled in a past merger forming M31 (see also Yang & Hammer 2010; Fouquet et al. 2012; Hammer et al. 2013). However, the TDG origin would be in M31, such that the galaxies move away from M31 sufficiently fast which would imply that they have a tangential velocity component relative to the MW, rendering the timing estimate of Section 4.2.2 somewhat useless. The scenario should however be testable on LG scales if proper motion measurements of the distant dwarf galaxies could be obtained.

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