Does the dwarf galaxy system of the Milky Way originate from Andromeda?

Sylvain Fouquet, François Hammer, Yanbin Yang, Mathieu Puech and Hector Flores

1 Univ Paris Diderot, Sorbonne Paris Cité, GEPI, UMR 8111, F-75205 Paris, France
2 Laboratoire GEPI, Observatoire de Paris, CNRS-UMR8111, Univ Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France
3 National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

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ABSTRACT

The Local Group is often seen to be a quiescent environment without significant merger events. However, an ancient major merger may have occurred in the most massive galaxy as suggested by the M31 classical bulge and its halo haunted by numerous stellar streams. Numerical simulations have shown that tidal tails formed during gas-rich major mergers are long-lived and could be responsible for old stellar streams and likely induce the formation of tidal dwarf galaxies (TDGs). Using several hydrodynamical simulations we have investigated the most prominent tidal tail formed during the first passage, which is gas rich and contains old and metal-poor stars. We discovered several striking coincidences after comparing its location and motion to those of the Milky Way (MW) and of the Magellanic Clouds (MCs). First, the tidal tail is sweeping a relatively small volume in which the MW precisely lies. Because the geometry of the merger is somehow fixed by the anisotropic properties of the giant stream (GS), we evaluate the chance of the MW to be at such a rendezvous with this gigantic tidal tail to be 5 per cent. Secondly, the velocity of the tidal tail matches the Large Magellanic Cloud (LMC) proper motion, and reproduces quite well the geometrical and angular momentum properties of the MW dwarfs, that is, the so-called disc of satellites, also known as the vast polar structure (VPOS). Thirdly, the simulation of the tidal tail reveals one of the formed TDGs with the mass and location almost comparable to those of the LMC. Our present modelling is, however, too limited to study the detailed interaction of gas-rich TDGs with the potential of the MW, and a complementary study is required to test whether the dwarf intrinsic properties can be accounted for by our scenario. Nevertheless this study suggests a causal link between an expected event, an ancient, gas-rich major merger at the M31 location, and several enigmas in the Local Group, namely the GS in the M31 outskirts, the VPOS almost perpendicular to the MW disc, and the presence of the MCs, two Irr galaxies near the MW.

Key words: galaxies: dwarf – Local Group.

1 INTRODUCTION

Despite their proximity, the properties of Milky Way (MW) dwarf galaxies are far from being unanimously interpreted. They are often considered as remnants of primordial galaxies that would have escaped to the numerous merger events expected in the hierarchical scenario. Within the cold dark matter (LCDM) paradigm, they are believed to be DM-dominated subhaloes that are gravitationally trapped in the MW halo and have not yet merged completely with their hosts (White & Rees 1978). As the LCDM predicted a considerable number of massive subhaloes relative to the small number of observed dwarf galaxies surrounding the MW and other giant spirals, this leads to objects considerably dominated by their DM content. Such objects, including ultrafaint dwarf galaxies (UFDs), are currently followed to search for DM annihilation, without any positive detection yet (see e.g. Ackermann et al. 2012; Geringer-Sameth & Koushiappas 2011).

However, some dwarf galaxies may be tidally formed during the numerous merger events expected in the frame of the LCDM scenario (Kroupa 2012), leading to objects mainly free of DM. Okazaki & Taniguchi (2000) claimed that most dwarf galaxies could be of tidal origin, although this is disputed by Bournaud (2010) and Wen et al. (2012). A full description of the number density of tidal
dwarf galaxies (TDGs) is still lacking, as it has to account for gas-rich mergers that likely occurred in the past, as well as consider a representative sampling of (major) merger orbital parameters and describe the production and destruction rate with time of TDGs within evolving tidal tails. A significant part of our knowledge of dwarf galaxy properties is based on the Local Group content, including irregular dwarf galaxies (dIrrs) with the two Magellanic Clouds (MCs), spheroidal dwarf galaxies (dSphs) and UFDs, which have been recently discovered (Willman et al. 2005; Belokurov et al. 2006; Sakamoto & Hasegawa 2006; Zucker et al. 2006; Belokurov et al. 2007; Walsh, Jerjen & Willman 2007). Einasto et al. (1974) pointed out that dSphs lie close to the MW (mean distance 193 kpc), whereas the dIrrs are more distant (572 kpc), except the MCs. In order to explain this distance-dependent morphological bias, Mayer (2011) suggested that the closest dwarf galaxies undergo physical phenomena that changed their morphology from dIrr to dSph, such as stripping, stirring or tidal force.

Kallivayalil et al. (2009) have re-estimated the proper motion of the Large Magellanic Cloud (LMC) to a significantly larger value than previous estimates, that is, a velocity of 378 km s$^{-1}$ relatively to the MW. Thus, either MCs are passing for the first time close to the MW (Besa et al. 2007) or one needs to assume a quite large DM content for the MW with $M_{\text{DM}}$ = $(2.7 \pm 0.5) \times 10^{12}$ M$_\odot$ (Watkins, Evans & An 2010), that is, a value 50 times larger than its baryonic content and even larger than that of M31. A recent measurement of the Leo II proper motion (Lépine et al. 2011) provides a similar constraint, raising the question of whether some of the MW dwarf galaxies may be unbound, and as such, would not be MW satellites.

In addition, most of the MW dwarf galaxies seem to belong to a plane-like structure, the plane of satellites (also known as the vast polar structure, hereafter VPOS), which is found to be roughly perpendicular to the MW disc (Kunkel & Demers 1976; Lynden-Bell 1976). Kroupa, Theis & Boily (2005) updated this idea by using the 11 classical dwarf galaxies and compared the satellite spatial distribution with the isotropic spatial distribution expected from ACDM simulations. They concluded that the dwarf galaxy distribution cannot derive from the expected ACDM distribution, and Metz, Kroupa & Jerjen (2007) deduced that their spatial distribution is neither spherical nor mildly prolate with a confidence of more than 99 per cent. Moreover, the VPOS could be a somewhat permanent structure as the angular momenta of five dSphs plus the MCs indicate a coherent motion within the VPOS (Metz, Kroupa & Libeskind 2008).

Metz et al. (2009b) summarized the different possible concepts to explain the concordance between the spatial and angular momentum (AM) distribution of the VPOS galaxies. They investigated the scenario of a dwarf galaxy group surrounding the MCs (D’Onghia & Lake 2008), possibly coming from a filament (Libeskind et al. 2005; Zentner et al. 2005), which would be entering the MW halo in ordered motions. None of these explanations seems fully satisfactory, because it requires a quite unexpected compact group as a progenitor, and because the supergalactic plane is almost perpendicular to the VPOS (Metz et al. 2009b).

A fully different alternative would be that MW dwarf galaxies originate from an ancient tidal tail (see a detailed discussion on the possible tidal origin in Kroupa 1997; Metz et al. 2009b), which would explain their ordered motion. In fact such an alternative was suggested quite early (Lynden-Bell 1976) and Pawlowski, Kroupa & de Boer (2011) have recently investigated the possibility of a major merger or a flyby interaction (mass ratio 1:1 or 4:1) that would have occurred in the early history of the MW, producing tidal tails and then TDGs. Assuming an orbital AM aligned to the VPOS, the tidal tail associated with this early interaction in the MW history would have formed TDGs that could further populate the VPOS. While this is an interesting suggestion, perhaps the MW is not the best candidate for being a merger remnant, which are generally associated with classical bulge galaxies (Kormendy & Kennicutt 2004). Moreover, as mentioned by Pawlowski et al. (2011), the flyby alternative would have allowed the interloper well detectable, at the fringes of the Local Group.

All the above ideas are very imaginative and they may resolve the origin of the VPOS and why dwarf galaxies are part of it. However, this is at the cost of introducing another ad hoc assumption. Alternatively, we may consider the past history of the MW in the whole context of the Local Group, in which the baryonic content is dominated by M31. Quoting van den Bergh (2005): ‘Both the high metallicity of the M31 halo, and the $L^{1/4}$ luminosity profile of the Andromeda galaxy, suggest that this object might have formed from the early merger and subsequent violent relaxation, of two (or more) relatively massive metal-rich ancestral objects’. As further noticed by Yang & Hammer (2010), the disc plane of M31 is seen almost perpendicular, implying that tidal tails possibly formed after a gas-rich merger in the M31 history could be part of a hyperplane that includes the MW. By tracing back in time the position of the LMC, Yang & Hammer (2010) have showed that the LMC could be near M31, 5–8 Gyr ago. Moreover, Hammer et al. (2010) have proposed that M31 could be the result of a major, gas-rich merger because it provides a simple and common interpretation of most of its exceptional properties, including the giant stream (GS), the outer thick disc, as well as the giant ring. Constraints from stellar population ages in these different halo substructures imply a first close passage 8–9 Gyr ago and a fusion time 5.5–6 Gyr ago (Hammer et al. 2010).

This paper intends to verify whether or not the ordered motion of the MW dwarf galaxies could be entirely due to their origin as TDGs formed from a tidal tail caused by an ancient interaction in the history of M31. The goal is to verify whether this alternative may explain two exceptional features in the Local Group: the VPOS and the MW–LMC–SMC proximity (where SMC stands for Small Magellanic Cloud). Robotham et al. (2012) estimate the occurrence of the MW–LMC–SMC configuration for 414 MW-like galaxies in a local volume of $1.8 \times 10^3$ Mpc$^3$ ($0.01 \leq z \leq 0.055$). The chance to found out a galaxy having two close companions at least as massive as the SMC within a projected separation of 70 kpc and a radial separation of 400 km s$^{-1}$ is only 0.4 per cent (two examples). Moreover, in each of these configurations there is another $L^\star$ luminosity galaxy within 1 Mpc from the MW-like galaxy. This may support the importance of M31 for the MC formation, and then, accounting for the VPOS, for all the MW dwarfs.

In Section 2, we present the VPOS properties and refine their statistical significance by including additional constraints on the dwarf angular momenta. In Section 3, we describe both the physical and numerical models that we adopt for reproducing the VPOS. In Section 4, we try to reproduce the VPOS with a simple tidal tail toy model. Then, in Section 5, the model is improved to closely match the work done by Hammer et al. (2010), providing more realistic initial conditions for the tidal tail. Section 6 summarizes the
observational coincidences that support the M31 scenario, discusses the possible falsifications, and describes the further studies required for testing them.

In this paper, we use two coordinate systems. One is the Galactocentric coordinate which is centred on the MW (van der Marel et al. 2002). This system is used in Sections 2 and 4. In Section 5, we use a ‘projection’ coordinate which is centred on the current position of M31 with the z-axis pointing from M31 to the Sun, and the x-axis and y-axis parallel to the east and the north of the celestial coordinate, respectively, at the position of M31. In this projection coordinate, the MW is located at \((x, y, z) = (6.42, −2.72, 788.85)\) kpc and the Sun at \((0, 0, 785)\) kpc, assuming that the distance of M31 from the Sun is 785 kpc.

2 VPOS PROPERTIES

2.1 Defining the VPOS dwarf galaxies

The distances between the dwarf galaxies and the MW can be used as a simple criterion to verify whether dwarf galaxies are MW companions. The gravitational force of the Galaxy becomes weaker for distances larger than the virial radius, which ranges from 150 to 300 kpc. Following Metz, Kroupa & Jerjen (2009a), we consider as companions only the galaxies in a sphere with a radius of 300 kpc (see Fig. 1). With this simple criterion, all the dIrrs but the MCs are discarded, while most of the dSphs and UFDs are taken into account. The next task is to get a complete sample of dwarf galaxies within this sphere with a cut in absolute V-band magnitude. Two factors make this task difficult: the 11 classical dwarf galaxies were discovered by different sets of observations and the Zone of Avoidance hides a part of the sky. Thus, in principle, our sample may be affected by strong observational biases. The fact that the newly discovered satellites by the SDSS are systematically fainter than the classical dwarf galaxies is, however, reassuring. Even Canes Venatici I with \(M_V = −7.5 ± 0.5\) (Zucker et al. 2006) is fainter than the faintest classical dwarf, suggesting that no classical dwarf could have been missed in the sky not sampled by the SDSS (80 per cent of the sky, see Koposov et al. 2008), except maybe in the Zone of Avoidance. Accounting for the UFDs found by the SDSS which includes a significant part of the VPOS could therefore bias the resulting statistics.

![Figure 1. Distribution function of the satellite–MW distances. The large red points represent the dSphs, small red ones the UFDs, while blue squares represent the dIrrs. A line separates the MW companions considered in this study (closer than 300 kpc) from the other dwarf galaxies.](https://example.com/figure1.png)

Table 1. Basic properties of the 11 classical dwarf galaxies. From the left-hand to right-hand side: galactic longitude \(l\), galactic latitude \(b\) (both in degrees), heliocentric distance \(R\) (kpc), V-band absolute magnitude \(M_V\), and references: (1) = McConnachie (2012), (2) = Mateo (1998) and (3) = van den Bergh (1999).

| Name   | \(l\)       | \(b\)       | \(R\)  | \(M_V\) | Reference |
|--------|-------------|-------------|-------|---------|-----------|
| LMC    | 280.46      | −32.88      | 50 ± 2| −18.1 ± 0.1| (1), (3)  |
| SMC    | 302.80      | −44.32      | 60 ± 4| −16.2 ± 0.2| (1), (3)  |
| Fornax | 237.10      | −65.65      | 138 ± 12| −13.4 ± 0.3| (1), (2)  |
| Leo I  | 225.98      | 49.11       | 250 ± 15| −12.0 ± 0.3| (1), (2)  |
| Leo II | 220.16      | 67.22       | 210 ± 14| −9.8 ± 0.3  | (1), (2)  |
| Sextans| 243.49      | 42.27       | 86 ± 5 | −9.3 ± 0.5  | (1), (2)  |
| Carina | 260.11      | −22.22      | 102 ± 6| −9.1 ± 0.5  | (1), (2)  |
| Draco  | 86.36       | 34.72       | 82 ± 6 | −8.8 ± 0.3  | (1), (2)  |
| UMi    | 104.95      | 44.80       | 66 ± 7 | −8.8 ± 0.5  | (1), (2)  |
| Sagittarius | 5.60 | −14.08      | 24 ± 2 | −13.5 ± 0.3 | (1), (2)  |
| Sculptor | 287.53    | −83.15      | 87 ± 5 | −11.1 ± 0.5 | (1), (2)  |

Table 2. Results of the VPOS fit. From the left-hand to right-hand side: galactic longitude and latitude of the vector perpendicular to the VPOS, \(l_{\text{VPOS}}\) and \(b_{\text{VPOS}}\) (‘), uncertainty due to the plane-fitting method, Error1 (‘), uncertainty due to the uncertainty associated with the VPOS dwarf galaxy distance, Error2 (‘), minimal distance from the MW centre to the VPOS plane, D-centre (kpc), standard deviation of the minimal distance from the VPOS dwarf galaxy position to the VPOS and thickness \(T\) (kpc).

| \(l_{\text{VPOS}}\) | \(b_{\text{VPOS}}\) | Error1 | Error2 | D-centre | \(T\)  |
|---------------------|---------------------|--------|--------|----------|-------|
| 157.4               | −12.5               | 16.4   | 1.03   | 8.07     | 18.5  |

Thus, we will consider only the 11 classical dwarf galaxies grouped in a sample named ‘dSphMC’: LMC, SMC, Sagittarius, Fornax, Leo I, Leo II, Sculptor, Sextans, Carina, Draco and Ursa Minor, following Kroupa et al. (2005) and Metz et al. (2007). Their basic properties are listed in Table 1.

2.2 Spatial properties of the VPOS

We follow the methodology of Metz et al. (2007, 2009a) who have studied in detail the spatial properties of the VPOS, by fitting the position of the VPOS using a least-squares method. They investigated the uncertainties associated with the direction perpendicular to the VPOS due both to the uncertainties on the distances between the MW and the satellites (using Monte Carlo simulations) and to the fitting model (using bootstrap resampling).

Using the data listed in Table 1, we confirm that the dominant source of uncertainty is due to the fitting model (see Table 2). Fig. 2 shows the resulting VPOS fit, which is found to be very similar to that derived by Metz et al. (2007).

2.3 Kinematic properties of the VPOS

In addition to spatial correlations, Metz et al. (2008) have robustly confirmed that most of the individual dwarf motions lie close to the VPOS. We have extended and confirmed their study by adding two dwarf galaxies: Leo II and Sextans (see Table 3). In the left-hand panel of Fig. 3, we show that the AM directions of all the dwarf galaxies except Ursa Minor and Sagittarius lie close to the uncertainty range of the VPOS perpendicular direction (notice that Carina and Draco are only marginally consistent). Besides this, the Sculptor motion is found to be lying in the VPOS but counter-rotating. Indeed, its AM is shifted by 180°.
However, amongst the MW companions, nine VPOS position derived from the 11 classical dwarf galaxies can also be reproduced. Using simulations, Strigari et al. (2008) showed that young stellar objects, star clusters and TDGs further shown that some of the classical dwarf galaxies of the MW (e.g. 7 out of 10) were found to have orbital poles aligned with the normal to the disc of satellites, then this would be inconsistent with the results of our simulations. As shown by Metz et al. (2007) this is because the VPOS is particularly thin which requires the accretion of a large, hypothetic group of dwarf galaxies that is otherwise naturally brought by remnant tidal tails. Thus, additional data on the proper motions are still required, though the present data favour an exceptional MW–satellite alignment of their locations and motions (see Figs 2 and 3).

3 FORMING THE VPOS AS A REMNANT OF A TIDAL TAIL

3.1 Physical model

Hammer et al. (2010) have proposed that a gas-rich major merger occurred during the history of M31. They used an N-body, hydrodynamical simulation (gadget2, Springel 2005) to reproduce most of the M31 structures such as the bulge, the thin and thick discs, the GS, and the 10-kpc ring. In their model, the first passage between the galaxies occurred more than 8 Gyr ago, and the fusion time 2.5–3 Gyr later. A significant part of the matter ejected during the first passage lies in a tidal tail. As we will show in Section 5.1, for most of the models reproducing M31, this tidal tail is found to pass close to the MW.

Several observations and simulations have suggested that dwarf galaxies, named TDGs, can form in such tidal tails (see Okazaki & Taniguchi 2000, and references therein). Bournaud & Duc (2006) have run 96 major merger simulations in order to better understand TDG properties and their formation mechanisms. Most of their simulations revealed the formation of TDGs with stellar masses larger than $10^5 M_\odot$. However, amongst the MW companions, none of the 11 classical dwarf galaxies have stellar masses ranging from $\sim10^5$ to $\sim10^7 M_\odot$ (Strigari et al. 2008). Using simulations with higher resolution, Bournaud, Duc & Emsellem (2008) have further shown that young stellar objects, star clusters and TDGs with masses ranging from $10^5$ to $10^6 M_\odot$ can also be reproduced. All these simulations suggest that it is possible to form TDGs with a relatively large range of mass, as a result of a major merger event.

In the following sections, we investigate whether the remnant of such a tidal tail could be at the origin of the VPOS dwarf galaxies. Pawlowski et al. (2011) were the first to study in detail such a hypothesis. They simulated the evolution of tidal tails created by major mergers or flybys in the MW past, $\sim10$ Gyr ago. They explored the orbital parameters of the progenitors to match the properties of the remnant. They also used simulations that avoid an overefficient tidal stripping of the disc of satellites, then this would be inconsistent with the results of our simulations. As shown by Metz et al. (2007) this is because the VPOS is particularly thin which requires the accretion of a large, hypothetic group of dwarf galaxies that is otherwise naturally brought by remnant tidal tails. Thus, additional data on the proper motions are still required, though the present data favour an exceptional MW–satellite alignment of their locations and motions (see Figs 2 and 3).
Table 3. Proper motions of 10 classical dwarf galaxies. From the left-hand to right-hand side: radial velocity (km s$^{-1}$), proper motion (mas yr$^{-1}$), both in the heliocentric rest frame, total velocity, radial velocity and transverse velocity (all in km s$^{-1}$ in the galactocentric rest frame), and references: (1) = Vieira et al. (2010), (2) = Piatek et al. (2007), (3) = Lépine et al. (2011), (4) = Walker, Mateo & Olszewski (2008), (5) = Piatek et al. (2003), (6) = Scholz & Irwin (1994), (7) = Piatek et al. (2005), (8) = Ibata et al. (1997) and (9) = Piatek et al. (2006).

| Name       | $V_{\text{rad}}$ | $\mu_\delta$ | $\mu_\alpha \cos(\delta)$ | $V_{\text{tot}}$ | $V_{\text{rad}}$ | $V_{\text{trans}}$ | Reference |
|------------|-----------------|--------------|--------------------------|-----------------|-----------------|-------------------|-----------|
| LMC        | 278             | 0.39 ± 0.27  | −1.89 ± 0.27             | 347$^{+73}_{-69}$ | 103$^{+11}_{-11}$ | 331$^{+73}_{-69}$ | (1)       |
| SMC        | 158             | −1.01 ± 0.29 | 0.98 ± 0.30              | 221$^{+110}_{-120}$ | 29$^{+14}_{-14}$ | 219$^{+110}_{-121}$ | (1)       |
| Fornax     | 53              | −0.36 ± 0.041| 0.476 ± 0.046            | 188$^{+38}_{-39}$ | −31$^{+2}_{-2}$ | 185$^{+38}_{-39}$ | (2)       |
| Leo II     | 79              | −0.033 ± 0.151| 0.104 ± 0.113            | 268$^{+171}_{-184}$ | 22$^{+5}_{-5}$ | 267$^{+172}_{-186}$ | (3)       |
| Sextans    | 224             | 0.10 ± 0.44  | −0.26 ± 0.41             | 260$^{+211}_{-182}$ | 88$^{+20}_{-20}$ | 241$^{+216}_{-230}$ | (4)       |
| Carina     | 229             | 0.15 ± 0.09  | 0.22 ± 0.09              | 131$^{+60}_{-60}$ | 27$^{+4}_{-4}$ | 128$^{+65}_{-65}$ | (5)       |
| Draco      | −292            | 1.1 ± 0.3   | 0.6 ± 0.4                | 563$^{+174}_{-180}$ | −6$^{+12}_{-12}$ | 559$^{+176}_{-184}$ | (6)       |
| UMi        | −247            | 0.22 ± 0.16  | −0.50 ± 0.17             | 161$^{+52}_{-53}$ | −76$^{+8}_{-8}$ | 141$^{+61}_{-61}$ | (7)       |
| Sagittarius| 140             | −0.88 ± 0.08 | −2.65 ± 0.08             | 303$^{+10}_{-10}$ | 138$^{+1}_{-1}$ | 269$^{+11}_{-11}$ | (8)       |
| Sculptor   | 110             | 0.02 ± 0.13  | 0.09 ± 0.13              | 227$^{+65}_{-65}$ | 79$^{+6}_{-6}$ | 212$^{+69}_{-72}$ | (9)       |

VPOS. However, a flyby seems unlikely, since no other massive galaxy but M31 is observed in the Local Group. In this study, we investigate the formation of the VPOS as a result of a tidal tail ejected during a merger that occurred in the past history of M31 rather than in that of the MW. Indeed, Yang & Hammer (2010) have shown that the position of the LMC could be traced back towards M31, ~6 Gyr ago, assuming an appropriate choice for the M31 tangential velocity and the MW halo shape. This suggests that all VPOS dwarf galaxies could have formed as TDGs resulting of a major merger event in the M31 history.

3.2 Numerical models

To investigate this scenario, we developed a code that simulates the trajectories of tidal tails populated with TDGs. They are formed and ejected during a major merger, and eventually interact with the MW.

The small mass of the TDGs, as well as the large distance between M31 and the MW, renders the tidal effects on the two spiral galaxies negligible. This allows us to assume that their gravitational potentials are static, and to model them analytically. Following Yang & Hammer (2010), we assume Navarro–Frenk–White haloes (Navarro, Frenk & White 1997), Hernquist bulges (Hernquist 1990) and exponential discs (Yang & Hammer 2010) for M31 and the MW, while dwarf galaxies and the LMC are assumed to be point masses.

In the simulations, we first trace back the position of the LMC, the MW and M31 backwards in time until the LMC reaches the outskirts of M31. The unknown tangential velocity of M31 is taken out of the MW and M31 backwards in time until the LMC reaches the VPOS as a result of a tidal tail ejected during a major merger, and eventually interact with the MW.
is just equal to its baryonic mass, ~3 × 10^9 M_☉. We have verified that the dynamical friction is negligible in the computation of the LMC trajectory.

Secondly, we used numerical models of tidal tail formation to set up initial conditions for the positions and velocities of the TDGs in the surrounding of M31. The position of the LMC back in time in the surrounding of M31 is used to constrain the tidal tail properties. Finally, we allow the TDGs to evolve until the present time. At the end of the simulation, we analyse the TDG positions and angular momenta, and test whether they match the present-day VPOS properties.

4 A TIDAL TAIL TOY MODEL CONSTRAINED BY THE LMC TRAJECTORY

4.1 Initial conditions for the TDGs

The goal of the proposed toy model is to verify whether or not the gross properties of the VPOS can be described by particles linked to the overdensities found in tidal tails. As described in Section 3.2, we first trace back in time the position of the LMC, MW and M31, 5.5 Gyr ago. This corresponds to the epoch when the LMC was found to be at 50 kpc from M31 according to Yang & Hammer (2010, see their table 3). To be consistent with their study, the MW and M31 total masses are, respectively, chosen to be 10^{12} and 1.6 × 10^{12} M_☉, while the LMC velocity is taken from the study conducted by Kallivayalil et al. (2009), that is, \( V = 384 \text{ km s}^{-1} \).

The position and velocity profiles of the tidal tail are extracted from the work of Wetzstein, Naab & Burkert (2007). Indeed, they studied the formation of TDGs produced in a major merger and estimated the effects of initial conditions on the TDG properties. Two snapshots separated in time by 262 Myr are extracted from their simulation EG2 (see Fig. 4). Five density peaks are found to be prominent within the tidal tail. We assume that the third peak represents the LMC location in the past. This arbitrary choice implies that the part of the tidal tail which is located farther than the LMC position will escape from M31, which is quite expected during the typical evolution of a tidal tail.

We use the relative positions of the five prominent peaks to set up initial positions of five groups of TDGs. Each group, even that with the LMC, is assumed to contain six TDGs, which are modelled as point masses with a total mass equals to 10^8 M_☉, that is, close to that of the SMC. We choose six particles per peak in order to populate enough the outskirts of the MW at the end of the simulation. The mass distribution in each group of particles is assumed to follow a Plummer density mass profile with a typical radius of 10 kpc, which constrains the internal velocity dispersion to be ~16 km s^{-1} in order to have a static group. The bulk velocity of the TDG groups is roughly estimated by comparing the positions of the peaks in the two snapshots (see Fig. 4). The tidal tail plane that encompasses the positions and motions of the TDGs is rescaled, rotated and translated in order for the third density peak to match both the position and velocity of the LMC, 5.5 Gyr ago.

4.2 The results

A set of 100 simulations have been run by randomly generating internal positions and velocities for the TDGs in the five groups, consistent with a Plummer model. For each simulation, we only kept particles for which the trajectories end within 300 kpc from the MW centre, that is, the distance limit used in Section 2.1 to define a dwarf galaxy as a MW companion. The VPOS properties and the mean AM direction are calculated following the same method as the one used for the observations (see Section 2.2). The resulting plane thickness distribution for the 100 simulations has an average of 18.3 ± 6 kpc, which is consistent with the observed value (see Table 2).

Fig. 5 shows typical trajectories of simulated TDGs. Particles are found to travel on both sides of the MW disc plane, although most of them, including the LMC, pass below it. There are some particles passing above the MW disc plane, with an AM direction shifted by 180° relative to the simulated VPOS direction. This configuration is similar to the counter-rotation of Sculptor in the MW environment.

In Fig. 6, we plot for the 100 simulations the resulting mean AM directions and the directions perpendicular to the simulated VPOS. These directions populate the region occupied by the uncertainty range corresponding to the observed dwarf galaxies. We find that the mean AM direction of the 100 simulations is consistent within uncertainties with the mean direction of the observed AM. The mean perpendicular direction for the 100 simulated VPOSs is also close to that derived from observations, although not strictly within the uncertainty range. However, for some simulations, the perpendicular direction is encouragingly found to lie within this range.

This very simple model illustrates how TDGs associated with a tidal tail can easily reproduce most of the VPOS properties. By varying the radius of the Plummer model and the LMC position in the tidal tail, one can reproduce the fraction of dwarf galaxies having the same AM direction as that of the LMC (eight dwarf galaxies) and those having it inverted as Sculptor, that is, a very similar optimization to that done by Pawlowski et al. (2011).

It is clear that such a model is quite ad hoc since the dominant motion of the simulated TDGs is that of the LMC, which is a part of the VPOS. The LMC velocity measurement used is larger than that found by Vieira et al. (2010). Using their value would increase the look-back time needed by the LMC to reach M31 by more than 2.5 Gyr. This time could match the formation epoch of the first tidal tail according to the model of Hammer et al. (2010) described in
5 A TIDAL TAIL GENERATED BY AN ANCIENT MERGER AT THE M31 LOCATION

5.1 M31 modelling as a remnant of a major merger

Hammer et al. (2010) have run a series of gas-rich, major-merger simulations designed to reproduce both the M31 galactic substructures and the extended structures in its outskirts. The orbital geometry of the interaction is close to be polar, driven by the need to reproduce the giant 10-kpc ring, while stellar ages in the M31 halo substructures constrain the pericentre radius. In this family of models, two tidal tails systematically form during the first passage, as well as additional ones during the second passage and/or fusion. Each tidal tail is made of material stripped off each M31 progenitor, resulting in an AM that combines that of the corresponding galaxies with the orbital AM, which is the dominant component. We have tested a significant series of models from Hammer et al. (2010, see their table 3) and found that the first-passage tidal tail, associated with the minor encounter, passes systematically close to the MW, that is, generally at 50 kpc and always at less than 200 kpc (see Fig. 8). In other words, the MW lies within the past M31 merger orbital plane, and the large area swept by the tidal tail motion leads to a significant chance for a tidal tail–MW interaction. In fact the first-passage tidal tail is the most extended one. It contains the largest amount of baryons expelled during the merger, the largest amount of gas, and the lowest metal abundance compared to other tidal tails.

In the Hammer et al. (2010) model, the GS is linked to the tidal tail formed during the second passage, and caused by stars returning to the remnant galaxy leading to the formation of loops (see their fig. 8 as well as a complete description of the loop mechanism in Wang et al. 2012).

The model used in this study is a refined version of Hammer et al. (2010, 10th column in their table 3) with a slightly higher mass ratio (3.5 instead of 3), and an improvement of the initial conditions, that is, the two interlopers at \( t = 0 \) are separated by 200 kpc instead of 80 kpc. The most significant change is due to the use of a larger number of particles (2.4 millions instead of 540 thousands), which allows us to generate gravitational instabilities within the tidal tail, under the assumption of a softening length of 0.1 and 0.12 kpc for baryons and DM, respectively. A more subtle change is about the GS modelling, which is associated with the second-order loop instead of the first-order loop (see fig. 8 in Hammer et al. 2010). This results in a rotation within the orbital plane by approximately 50°, which only slightly impacts the relative angle between the first tidal tail and the assumed GS. This updated model now reproduces both the GS and the Northern loop discovered by the PAndAS team (Mackey et al. 2010), those being related to the material stripped off in the loop formed at the fusion and at the first passage, respectively (see Yang et al., in preparation, for details).

5.2 Initial conditions for the TDGs

Instead of relying on the simulations of Wetzstein et al. (2007) as in Section 4, we now use the Hammer et al. (2010) merger model for M31 (as updated above) to set up initial conditions for the position and velocity of the TDGs in the outskirts of M31.

We adopt a baryonic-to-total mass ratio of 20 per cent as used by Hammer et al. (2010) instead of 6 per cent as in Yang & Hammer (2010), as well as in Section 4. Following Yang & Hammer (2010), the DM scalelength is tuned to fit the rotation curve. A total mass of \( 5.5 \times 10^{11} M_\odot \) (\( 3.3 \times 10^{11} M_\odot \)) provides \( R_{vir} = 70 \) kpc and \( c = 10 \) (\( R_{vir} = 60 \) kpc and \( c = 6 \)) for M31

![Figure 5. Comparison between the positions of the simulated TDGs (diamonds) and the observed satellites (squares). The upper and lower panels show the projection in the \( y-z \) and \( x-y \) galactic coordinate planes, respectively. The MW is represented by a red spiral. The grey lines represent the trajectories of each simulated TDG. The inset panels give a global view of the trajectories of the simulated TDGs (grey lines) as well as that of M31 (black line). The trajectory of the LMC is also shown as a red line. The green line illustrates a counter-rotating trajectory, which may explain the motion of Sculptor.](https://academic.oup.com/mnras/article-abstract/427/2/1769/977592)
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Figure 6. Aitoff map comparing the VPOS and AM directions between simulations and observations. The red square and the blue dots indicate the direction of the mean AM and the direction of the VPOS, respectively, as derived from observations (Metz et al. 2007, 2008). Their uncertainties are represented by the red circle (AM) and by the blue dashed circle (VPOS). The open triangles and circles represent the directions of the VPOS and the mean AM, as resulting from 100 simulations (see Section 4.2). Their mean values are indicated by a green square (VPOS) and a green dot (AM).

Figure 7. Schematic illustration of the VPOS formation as a result of a tidal tail ejected by the M31 major merger. The tidal tail sweeps space for 4.5 Gyr followed by the LMC and finally passes through the MW trajectory. The green dots represent the initial and final positions of the tidal tail, while the white dots represent intermediate steps. The M31 and MW discs are represented with a size of 100 kpc, as well as the observed VPOS (blue rectangular) and the y- and z-axis of the M31 rest frame (green and red lines).

5.3 Simulated VPOS properties

The conditions for reproducing the VPOS using a merger model for M31 are considerably more constrained than in Section 4 because of the required match between the tidal tail velocity and that of the LMC. In fact, we realize that for most models in Hammer et al. (2010) such a condition is verified as illustrated in Fig. 7. Besides the choice of the model reproducing most accurately the properties of M31 (Yang et al., in preparation), the location of the tidal tail can be fine-tuned using a rotation by less than ±20°.
along the M31 rotational axis (see Hammer et al. 2010). Such a
fine-tuning preserves the modelling of the GS and is required for
matching the look-back time at which both the LMC and tidal tail
are found at a common position in the outskirts of M31. Fig. 7
shows the evolution of the tidal tail together with the LMC, and the
MW trajectories relative to M31. It illustrates that for a given set of
transversal velocities for the MW relative to M31, the LMC is found
to travel between the two galaxies. Without more than fine-tuning,
its trajectory matches the predicted tidal tail trajectory formed after
the first encounter between the two progenitors of M31.

Let us now consider the first-passage tidal tail, which is the best
candidate for inducing TDGs passing near the MW. Fig. 8 shows the
formation of clumps due to gravitational instabilities in the gaseous
 tidal tail at discrete locations. The five prominent overdensities have
mass profiles consistent with that of dwarf galaxies with half-mass
radii from 0.9 to 4 kpc, and total masses from $1.7 \times 10^8$ to $8.6 \times
10^8 \, M_\odot$ (see Table 4). Our 2.4 million particle simulation generates
TDGs similar in location, for example, the so-called ‘beads on a
string’ appearance, to those found in the Wetzstein et al. (2007)
EG2 model with 6 million particles, but with larger masses. This is
surprising, since larger the resolution in the simulation, the larger
the mass of the formed TDGs (see Section 3.1). As suggested
by Wetzstein et al. (2007), this could be due to the initial gas fraction,
which is in our simulation twice that adopted in the Wetzstein et al.
(2007) EG2 model (30 per cent) and could result in the formation
of more massive TDGs. However, the simulation does not have a
resolution large enough to sample the lowest mass dwarf galaxies
(see Table 4). A higher resolution and a smaller softening length
are required to generate such TDGs (Bournaud et al. 2008), and one
may expect a larger number of TDGs with masses similar to those
of the MW companions.

Given our absence of knowledge about the detailed internal struc-
ture of the tidal tail, we have arbitrarily selected particles within
a 40-kpc section of the tidal tail (300 particles) at the region inter-
acting with the MW (see the red arrow in Fig. 8). In Fig. 9, for
the sake of the visualization, we have randomly selected only 25
particles amongst the 300 particles. They are all included into a
thick plane, whose orientation is found to be similar to the VPOS
within $13^\circ$, a value smaller than the observational uncertainty (see
Table 2). Finally, almost all their AM directions are found to be
close to the direction perpendicular to the observed VPOS, except
for some of them which have an opposite direction such as Sculptor
(see Fig. 10).

However, even if this tidal tail gives some promising results, it
does not match the spatial distribution extension of the 11 classical
dwarf galaxies (see Fig. 9, top panels). We notice that in the sim-
ulations reproducing M31 the first tidal tail may vary by a factor
of 1–5 in width. This variation is due to the sensitivity to the ini-
tial conditions: the size of the gas disc in the progenitors and the
orbital parameters. For example, orbital parameters associated with
conditions close to the resonance (between the disc rotation and the
orbital motion) at the first passage provide very narrow first tidal
tails. Because being close to the resonance is not a requirement for
the M31 model (in fact such conditions are mostly required at the
second passage), we have used another model of M31 to generate a
wider tidal tail. As the clump locations within the tidal tail have no
other constraints than the actual spatial distribution of the classical
dwarf galaxies, we have used three clumps instead of one to mimic
the extension of the tidal tail and the results are shown in Fig. 9
(bottom panels).

We emphasize that this model is in sharp contrast with Section 4
and Pawlowski et al. (2011) studies that use all free parameters to
optimize the tidal tail. In other words, the formation of the VPOS
is predicted by the merger model of M31, as shown in Fig. 7.

Table 4. Physical parameters of the five TDGs identified in the tidal tail
generated during the first passage between the M31 merger progenitors. The
masses are given in units of $10^8 \, M_\odot$. From the left-hand to right-hand side:
gaseous mass, stellar mass, total mass, gas fraction and half-mass radius
(kpc).

| No. | $M_{\text{gas}}$ ($10^8 \, M_\odot$) | $M_{\text{star}}$ ($10^8 \, M_\odot$) | $M_{\text{total}}$ ($10^8 \, M_\odot$) | $f_{\text{gas}}$ | $r_h$ (kpc)$^a$ |
|-----|----------------------------------|----------------------------------|-----------------------------------|-------------|----------------|
| 1   | 1.67                             | 0.056                            | 1.72                              | 0.97        | 4.3            |
| 2   | 6.20                             | 2.41                             | 8.62                              | 0.72        | 1.5            |
| 3   | 3.49                             | 0.027                            | 3.76                              | 0.93        | 1.1            |
| 4   | 4.11                             | 2.58                             | 6.70                              | 0.61        | 0.75           |
| 5   | 4.09                             | 2.93                             | 7.02                              | 0.58        | 0.85           |

$^a r_h$ is the half-mass radius of the TDG for the 2D projected mass profile.
6 DISCUSSION

6.1 A surprising series of ‘coincidences’ supporting an M31 origin

At first sight, a possible causal link between a possible merger in the history of M31 and the MW dwarf galaxies might appear at odds with many years of studies of the Local Group. To our knowledge such a proposition has never been made, probably because it appears far too unlikely for geometrical reasons: why the MW would be precisely at a rendezvous with a tidal tail formed during the first passage, 8–9 Gyr ago, of a merger that occurred at more than 780 kpc away?

Let us consider three galaxies of similar masses, two of them being involved in a merger process. What is the chance that a tidal tail produced during the event reaches the third galaxy? Assuming a merger in the history of M31, it should be rather small, given the fraction of the volume swept by a tidal tail. The corresponding conic volume is shown in Fig. 11, drawing a solid angle of 2000 deg², that is, 5.5 per cent of the 4π sr sphere. In principle, this argument should suffice to falsify or reject a possibility to associate M31 to the MW dwarf galaxies. In practice, the MW lies precisely within this small volume, because both the M31 disc is seen edge-on and the geometry of the GS (and of the Northern loop) fixes the progenitors inclinations, and then the properties of the tidal tail induced after the first passage. We have considered a very large number of models from Hammer et al. (2010) as well as more recent ones. In these models, \( r_{\text{peri}} \) ranges from 24 to 30 kpc, the mass ratio from 2.5 to 3.5, the dark-to-baryonic matter ratio from 10 to 25 per cent, and a significant range of initial progenitor inclinations are explored, which result in an uncertainty on the angular location of the first tidal tail that is smaller than 20°. Of course we cannot claim having

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Figure 9. Face-on (left-hand panels) and edge-on (right-hand panels) views of the observed VPOS populated by the tidal tail particles (green diamonds). The 11 classical dwarf galaxies are represented by red points (dSphs) and blue open squares (MCs). The top panel corresponds to the tidal tail with a small extension and the bottom one to the extended tidal tail. For both, there are 25 particles randomly selected into the clumps which interact with the MW (green diamonds).
investigated all the numerous parameters of a merger model for M31, although the number of constraints just describing the M31 galaxy and its outskirts is quite impressive (Hammer et al. 2010). We have also verified that for all geometrical configurations studied by Barnes (2002), the disc plane is close within less than 25° to the orbital plane. This favourable configuration applies well to the M31 disc (see Fig. 11), which is supported by an AM that is found to be slightly larger than the average of similar local spiral galaxies (see Hammer et al. 2007).

Perhaps all of the above is just a coincidence and other properties would easily falsify a causal link between the M31 merger and the MW dwarf galaxies. Fig. 7 shows that the tidal tail velocity matches well that of the LMC, in amplitude and orientation. This is ensured using the most recent results compiled by Vieira et al. (2010) with quite large uncertainties (see their fig. 10), while the amplitude of the LMC velocity would be too large using the Kallivayalil et al. (2009) values. Such a match with the LMC velocity is another intriguing coincidence. While Yang & Hammer (2010) have shown that the LMC past trajectory may have passed near M31 for a precise range of M31 transverse velocities, why would the velocity of the modelled tidal tail follow such an amplitude and orientation? This coincidence naturally ensures that our model can reproduce the VPOS orientation and dwarf angular momenta (see Fig. 9).

Possibly the most astonishing, completely unexpected coincidence is the fact that the part of the tidal tail shown in Fig. 8 which interacts with the MW is very close to the most massive simulated tidal dwarf, TDG2, whose mass almost reaches that of the LMC. This is very encouraging for pursuing this study with higher resolution simulations.

6.2 Could the MW dwarf galaxies be descendants of TDGs?

6.2.1 Global properties

First we acknowledge that a robust proof of a dominant DM component in MW dwarf galaxies would provide a definitive falsification of the scenario proposed in this paper. It may come from the detection of DM annihilation in MW dwarf galaxies. In fact, the non-detection of DM annihilation in MW dwarf galaxies could provide the strongest up-to-date constraint on the nature of the DM particles, excluding for some annihilation channels thermal DM for masses below 30 GeV or so (see e.g. Ackermann et al. 2012). On the other hand, a tidal origin for the MW dwarf galaxies would discard a significant DM content in these galaxies. It was considered very early (e.g. Lynden-Bell 1976) and was revived by Kroupa (1997) and Kroupa et al. (2005). Support for this assumption is enormous and well summarised by Kroupa et al. (2010) and Kroupa (2012). Their old stellar populations are perhaps inherited from the merger progenitors. Their long lifetime in the tidal tail could have allowed them in various environments providing a diversity in star formation histories that could explain their different behaviours. Kroupa et al. (2010) summarized that ‘the physics of TDG formation and evolution is sufficiently well understood to conclude that (1) once formed at a sufficient distance from the host, TDGs will take an extremely long time to dissolve, if at all; and (2) the TDGs formed will naturally lead to a population of ancient TDGs that resemble dSph satellites’.

However, to be plausible, our scenario (as well as that of Pawlowski et al. 2011) requires an alternative explanation of the large mass-to-light ratios of the MW dwarf galaxies. Recently, Casas et al. (2012) have simulated DM-free satellites that after several orbits around the MW are out-of-equilibrium bodies with high apparent mass-to-light ratios. According to their claim, if such progenitors of MW satellites have reached the MW potential at the same time along a few specific orbits, they may reproduce most of their intrinsic kinematics and surface brightness. Although similar simulations are beyond the scope of this paper, we noticed that the Casas et al. (2012) progenitors are far more compact than the TDGs that are formed from our modelling. In other words, it is likely that realistic TDGs are more fragile and they may be even more easily disrupted than in the Casas et al. (2012) study. In a forthcoming paper, we will study a more realistic TDG infalling into the MW potential and verify whether or not such an event may reproduce the MW dwarf galaxies. Such a study is mandatory to verify whether or
not the large mass-to-light ratios of the MW dwarf galaxies falsify the M31 scenario.

6.2.2 Could the LMC be a descendant of a TDG?

The above-mentioned studies do not apply to the MCs and one may wonder whether or not the most massive Ir galaxy of the Local Group could also be TDGs. In the M31 scenario, both the LMC and the SMC have arrived for the first time in the MW halo, and as such they are not stripped of their gas, conversely to other MW dwarf galaxies. The stellar mass of the LMC has been properly estimated by van der Marel et al. (2002) assuming an LMC V-band absolute magnitude of $M_V = -18.5$, an extinction of $A_V = 0.4$ and an extinction-corrected colour $(B - V)_0 = 0.43$. Following Bell et al. (2003), the stellar mass for the LMC is estimated to be $2.6 \times 10^9 M_\odot$ for a diet Salpeter initial mass function (IMF). Based on a full reconstruction of the star formation history, Harris & Zaritsky (2009) found a stellar mass ranging from $1.7$ to $3.5 \times 10^8 M_\odot$ (see their fig. 12) for a Salpeter IMF. To be compared with a diet Salpeter IMF value, one has to subtract 0.15 dex (Bell et al. 2003) to these values, reaching a range of $(1.2–2.5) \times 10^9 M_\odot$. Other IMFs generally provide a lower stellar mass, by subtracting an additional 0.15 dex, for example, a Kroupa (2002) or a Kennicutt (1983) IMF. According to Kim et al. (1998), the LMC gas mass is $0.5 \times 10^9 M_\odot$ and thus the baryonic mass ranges from $1.7 \times 10^9$ to $3.1 \times 10^9 M_\odot$, assuming a diet Salpeter IMF for the stellar mass estimate. These values are larger than those of Table 4 by a factor of 2–3, which could be a serious difficulty for a tidal origin of the LMC. More detailed and resolved simulations of gas-rich tidal tails with more realistic physical conditions may help to further investigate this issue. On the observational side, Kaviraj et al. (2012) found several TDGs (approximately 15 per cent of them) with a mass larger than $10^9 M_\odot$, after a wide TDG search in the SDSS data through the Galaxy Zoo project. The fact that these local mergers are certainly less gas rich than the assumed ancient M31 merger progenitors suggests the latter may lead to TDGs as massive as the LMC.

To investigate whether a tidal origin related to a merger at the M31 location is realistic or not would require to compare it with the numerous results provided by studies on the Local Group and dwarf galaxies. It also requires to firmly assess the model properties and its predictions before any conclusion. For example, the recent determination of the Fe/H abundance of old stars in the LMC may not be a falsification of this scenario (see e.g. Haschke et al. 2012). The fact that the old globular clusters in M31 are relatively Fe/H richer can be explained by our model. The LMC is predicted to be formed within the first-passage tidal tail with stars stripped off the less massive interloper 8–9 Gyr ago, while old globular clusters could have been formed from material stripped off the most massive interloper, that is, expected to be more metal-rich. The search for further falsification tests has to continue.

6.2.3 MW dwarf velocities and angular momenta

It is unclear yet whether all classical dwarf galaxies are part of the VPOS. Sagittarius is clearly off the VPOS in Fig. 3. Could it be due to the fact that it is strongly tidally disrupted by the MW potential? Fig. 12 provides a crucial test of the M31 scenario by comparing the dwarf velocities to the escape velocities, assuming two values for the MW mass. However, this exercise is limited by the accuracy of the proper motion data: this excludes Draco, Sextans and Leo II for which the uncertainties are so large that their bound or unbound nature remains unknown. For example, the Sextans proper motion was not measured but derived, and the Draco proper motion was calculated by a ground-based telescope more than 10 years ago providing an extremely high value, $V = 556$ km s$^{-1}$. It shows that Sagittarius, UMi and Carina are certainly bound for any values of the MW mass, while all other dwarf galaxies are lying in a region where the measurement accuracy does not allow us to...
7 CONCLUSION: A CAUSAL LINK BETWEEN THE M31 MAJOR MERGER AND THE VPOS?

It is widely accepted that the classical bulge of M31 is due to an ancient major merger (Kormendy & Kennicutt 2004; van den Bergh 2005). Quoting John Kormendy (private communication): ‘don’t we already know with some confidence that M31 was formed in at least one (in fact: very probably exactly one) major merger?’ Perhaps its consequences have not been fully investigated, whereas it occurred in the galaxy that represents almost two-thirds of the Local Group baryonic mass. The immediate question is: where are the relics of the most energetic event that occurred in the whole Local Group history? One may investigate the most anomalous and difficult-to-explain features discovered in the Local Group. Among them are the M31 haunted halo (Ibata et al. 2007), the GS (Ibata et al. 2001), the VPOS and also the unusual proximity of two massive Irrs near the MW (see e.g. van den Bergh 2010).

In principle an ~1 Gyr old minor merger may reproduce the GS (e.g. Fardal et al. 2008) although this may be problematic (see e.g. Font et al. 2008) because stars in the GS have ages from 5.5 to 13 Gyr (Brown et al. 2007). Hammer et al. (2010) have been able to reproduce the GS as well, assuming a major merger and using the stellar ages in the outskirts of M31 as clocks to date a major merger, providing a first passage and a fusion occurring 8.75 ± 0.35 and 5.5 ± 0.5 Gyr ago, respectively. Having M31 involved in a merger at these epochs may be quite common, as demonstrated by detailed studies of intermediate-redshift galaxies from the IMAGES sample (Hammer et al. 2009; Puech et al. 2012). This model is quite challenging in reproducing many other properties of the M31 galaxy (disc, bulge, thick disc and 10-kpc ring) together with the GS. A noticeable feature of gas-rich major mergers is that they produce long-lived tidal tails that can reproduce many structures discovered in the halo of giant spiral galaxies (see e.g. Wang et al. 2012).

This paper is the first of a series aiming at investigating the consequences of such a major merger occurring in the Local Group. The main weakness of the present modelling is the oversimplification in considering tidal tail particles as point masses. To reproduce the properties of the MW dwarf galaxies requires a full modelling of extended, gas-rich TDGs entering into the potential of the MW. It is highly desirable to verify whether or not the MW dwarf galaxies and the VPOS can be fully modelled by the interaction between a gas-rich tidal tail, its associated TDGs and the MW. Such a study will aim at verifying whether or not the intrinsic properties of dwarf galaxies may be reproduced, including their apparent large mass-to-light ratios.

Our modelling of the M31 major merger is getting more and more mature since Hammer et al. (2010) and it is able to provide some predictions that can be tested for falsification purposes. The modelling of an anisotropic feature like the GS and further of the Northern loop (Yang et al., in preparation) almost fixes the location and velocity of the tidal tails associated with the merger. Here we have concentrated our efforts to examine the largest tidal tail, which is formed during the first passage, stripping the minor encounter stars, 8–9 Gyr ago. This tidal tail is bringing the largest amount of baryonic material expelled by this event towards the Local Group. It results in a series of ‘coincidences’ that considerably strengthen our preliminary conjecture. The MW is found precisely at the meeting point with the tidal tail, at present time. Moreover, the velocity of the tidal tail matches well that of the LMC providing a good fit of the VPOS, including its spatial orientation and the AM, even to some details such as the inverted AM of Sculptor.
Having this in mind we conclude that a link between the VPOS and the major merger at the location of M31 is plausible. Compared to the MW merger or encounter hypothesis of Pawlowski et al. (2011), it has the advantage of resulting from a testable prediction that could be falsified or supported by many observations of the Local Group. Besides this, the present modelling is made within the ΛCDM scenario and there is no peculiar need to account for other physics to describe the above-noticed unusual properties of the Local Group, that is, the VPOS, the presence of two massive Ir galaxies near the MW and most features found in the M31 halo. In fact, Knebe et al. (2011) have been the first to show that within ΛCDM, there should be a renegade subhalo, that is, a subhalo of M31 that could have migrated towards the MW. However, they could not explain either the VPOS or the LMC and its large velocity, conversely to our prediction that leads to an external origin for most MW dwarf galaxies. If the latter is true, it strengthens the tension between the predicted number of DM subhaloes and observations, that is, the so-called missing satellite problem, which might then be reconsidered as an excess of subhaloes in the ΛCDM paradigm.

NOTE ADDED IN PROOF

Pawlowski et al. (2012b) recently showed that filamentary infall is excluded to explain the VPOS.

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APPENDIX A: STATISTICAL METHOD TO TEST THE ISOTROPY

The statistical test proposed by Metz et al. (2007) assesses whether the MW dwarf galaxy positions or velocities derive from an isotropic distribution. 50 000 random samples are generated using Monte Carlo simulations. Each sample is isotropic and follows a radial density distribution \( \rho(r) \propto 1/r^2 \), consistent with the radial distribution of the MW dwarf galaxy positions (Kroupa et al. 2005) and velocities. A plane is fitted for each sample, and the associated uncertainty is estimated using bootstrap resampling as follows. Each sample is resampled 1000 times and the perpendicular vector for each of the corresponding fitted plane is stored in a matrix \( \mathbf{M} \).

The 3D symmetric matrix \( \mathbf{S} = \mathbf{M}^T \mathbf{M} \) is computed and its three eigenvalues (\( \tau_1 < \tau_2 < \tau_3 \)) calculated. To characterize the 1000 vector distribution, that is, to characterize the plane fit uncertainty, two numbers are defined using the eigenvalues

\[
\gamma = \log \left( \frac{\tau_3}{\tau_2} \right) \log \left( \frac{\tau_2}{\tau_1} \right),
\]

\[
\zeta = \log \left( \frac{\tau_3}{\tau_1} \right).
\]

\( \gamma \) describes how clustered the vector distribution is, while \( \zeta \) indicates how the vector distribution focuses towards one direction. If \( \gamma \) and \( \zeta \) are small (~1), the vector distribution is close to isotropic (the plane fit uncertainty is thus large), whereas if \( \gamma \) and \( \zeta \) are large (>2), the vector distribution clearly defines one direction (the plane fit is then well defined). The resulting statistics of \( \gamma \) and \( \zeta \) are plotted in Fig. 3. For the 10 classical dwarf galaxy position and velocity set, \( \gamma \) and \( \zeta \) are also derived. The distribution function \( D(\gamma_0, \zeta_0) \), defined by the probability that \( \gamma > \gamma_0 \) and \( \zeta > \zeta_0 \), can be used to estimate the probability for a sample to derive from an isotropic law.

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