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Letter to the Editor

Dwarfs walking in a row

The filamentary nature of the NGC 3109 association

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ABSTRACT

We re-consider the association of dwarf galaxies around NGC 3109, whose known members were NGC 3109, Antlia, Sextans A, and Sextans B, based on a new updated list of nearby galaxies and the most recent data. We find that the original members of the NGC 3109 association, together with the recently discovered and adjacent dwarf irregular Leo P, form a very tight and elongated configuration in space. All these galaxies lie within $\sim$100 kpc of a line that is $\simeq$1070 kpc long, from one extreme (NGC 3109) to the other (Leo P), and they show a gradient in the Local Group standard of rest velocity with a total amplitude of 43 km s^{-1} Mpc^{-1}, and a rms scatter of just 16.8 km s^{-1}. It is shown that the reported configuration is exceptional given the known dwarf galaxies in the Local Group and its surroundings. We conclude that (a) Leo P is very likely an additional member of the NGC 3109 association, and (b) the association is highly ordered in space and velocity, and it is very elongated, suggesting that it was created by a tidal interaction or it was accreted as a filamentary substructure.

Key words. Local Group – galaxies: interactions – galaxies: individual: NGC 3109

1. Introduction

The identification of planar alignments of dwarf satellites (and globular clusters) of the Milky Way (MW) and M31 has a long history, starting from Lynden-Bell (1976) and Fusi Pecci et al. (1995), respectively; since Kroupa et al. (2005) it has become one of the most lively research fields in Galactic astronomy. Indeed, very significant large-scale structures have recently been recognized within the Local Group (LG). For example, Ibata et al. (2013) discovered that a large fraction of M31 dwarf satellites lie in a vast, thin planar structure that shows large-scale rotation. Pawlowski et al. (2013, hereafter P13), found that in addition to the already known thin planes of dwarf galaxies surrounding both M31 and the MW, most of the LG non-satellite dwarfs are also located in two very large planar structures (diameters 1−2 Mpc). Accretion along cold filaments (Dekel et al. 2009) has been proposed as a possible origin for these ordered structures (see, e.g., Lovell et al. 2011) within the generally accepted Λ-cold dark matter (Λ-CDM) paradigm for galaxy formation (Barkana & Loeb 2001). However several studies have reported that the Λ-CDM predictions are not compatible with the characteristics of the observed structures (see, e.g., Pawlowski et al. 2012, and references therein), proposing as an alternative that the planar alignments are the relics of huge tidal streams that arose from a major galaxy interaction that occurred in the LG (Hammer et al. 2013, P13).

In this context it seems very important to recall the discovery by Tully et al. (2006, hereafter T06) that a significant fraction of dwarf galaxies in the local volume belong to associations of dwarfs, i.e., small groups with strong correlation in space and velocity. T06 conclude that these associations are probably not in dynamical equilibrium, but they can be gravitationally bound, and, in this case, they are strongly dominated by dark matter, with mass-to-light ratios in the range $\sim$100−1000 $M_{\odot} L_{\odot}^{-1}$. Accretion of and/or interactions among dwarfs in associations may play a role in the formation of coherent structures around giant galaxies (Sales et al. 2007; D'Onghia & Lake 2008; but see also Metz et al. 2009).

The first bona-fide association discussed by T06 is the so called *NGC 3109 group*, from the gas-rich dwarf disk galaxy that is its most luminous member ($M_V = -14.9$, according to McConnachie 2012, hereafter M12). The group was previously discussed in detail by van den Bergh (1999). It lies just beyond the zero velocity surface of the LG, near the threshold between systems bound to the LG and the local Hubble flow (see Fig. 5 in M12), in a quite isolated location (more than 1 Mpc apart from both the MW and M31; see Fig. 3, below). In addition to NGC 3109, the other members of the association, recognized by T06 as lying at similar distance and with similar radial velocity in the LG standard of rest (V_{LG}), are the dwarf irregulars (dIrr) Sextans A, Sextans B, and Antlia, having $M_V = -14.3$, -14.5, and -10.4, respectively. T06 conclude that "...the NGC 3109 association is the nearest distinct structure of multiple galaxies to the Local Group". Recently Shaya & Tully (2013, hereafter ST13) noted that, since all the members lie at very similar distances from us and in the same portion of the sky (within $\sim$30° from NGC 3109) they effectively lie in a common plane, nearly perpendicular to the line of sight. It is interesting to note that none of the group members has been associated with the vast planar structures discussed by P13.

Triggered by the discovery of possible tidal tails in the outskirts of the group member Sex A (Bellazzini et al., in prep.), we reconsidered the NGC 3109 association in the light of the most recent data, summarized in the thorough catalogue of LG and nearby galaxies by M12 (in particular, all the known galaxies within 3 Mpc of the MW). Interactions within the group may be responsible for tidal features in some member (see, e.g., D'Onghia et al. 2009; Penny et al. 2012). We suddenly realized that the newly discovered faint dIrr Leo P (Giovanelli et al. 2013; Rhode et al. 2013) is a likely member of the group[1] and that all the known members, including Leo P, appear to be strictly clustered *along a line in space*. This finding strongly suggested the opportunity of a more systematical revision of the association: the results of this analysis are the subject of the present letter. It must be stressed that, in the following analysis, lines are adopted just as simple and convenient tools to parametrize and quantify the tightness of configurations that appear to be very elongated in one direction in space.

2. Analysis

All the data considered in the following analysis are drawn from the M12 compilation, except for (a) the distances to NGC 3109, Sex A, Sex B, and Antlia, and the associated uncertainties, that are from the homogeneous set by Dalcanton et al. (2009), and (b) the distance to Leo P that is still highly uncertain, since available estimates range from 1.3 Mpc (Giovanelli et al. 2013) to 1.5−2 Mpc (Rhode et al. 2013). Here we adopted $D = 1.5 \pm 0.5$ Mpc, for simplicity.

In the following, we will adopt a Cartesian reference frame (X_a, Y_a, Z_a) centered on NGC 3109, obtained by translating the origin of the classical Galacto-centric reference frame (as defined in Eqs. (3) and (4) by Thomas 1989, adopting $R_\odot$ = 8.0 kpc) to the position of NGC 3109. We also define

$$R = \begin{cases} \sqrt{X_a^2 + Y_a^2 + Z_a^2} & Y_a \geq 0 \\ -\sqrt{X_a^2 + Y_a^2 + Z_a^2} & Y_a < 0. \end{cases}$$

In case of aligned configurations, this is essentially a distance *along the line* in space, providing a more fundamental and general coordinate than X_a, Y_a, Z_a. For example, a velocity gradient along one of these coordinates would be just *a projection* of a correlation between velocity and spatial distance along the line. In the following we will always refer to velocity gradients (and corresponding rms velocity scatter about a best-fit line, rms_V) along this R coordinate, if not otherwise stated.

In the left panels of Fig. 1 we plot the positions of the galaxies in the M12 catalog that lie more than 300 kpc away from M31 or the MW (to avoid unnecessary confusion) in the principal planes of the NGC 3109-centric reference frame defined above. It is clear that NGC 3109+Antlia, Sex A, Sex B, *and* Leo P are strictly aligned in both planes, *implying that they are strongly clustered along a line in space*. The thick lines are linear fits to these five galaxies. For simplicity, in all the considered cases we perform independent fits in each plane (X_a vs. Y_a, and X_a vs. Z_a). Each linear fit defines a plane in space; the intersection of the two planes is a line in 3D space. In this context

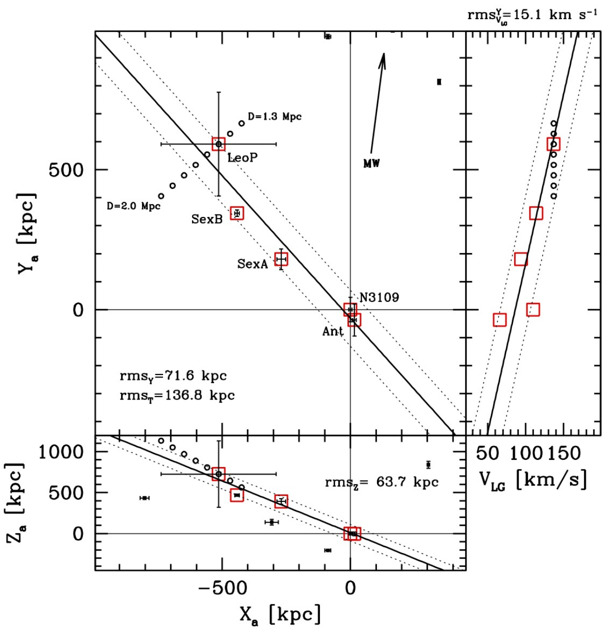

Fig. 1. Alignment within the NGC 3109 association including Leo P. The members of the association plus Leo P are plotted as large empty squares; other galaxies from the M12 catalog (more distant than 300 kpc from the MW or M31) are plotted as small filled squares in the left panels. Open circles mark the position of Leo P with different assumed values for its distance, from 1300 kpc to 2000 kpc, with steps of 100 kpc. Thick lines are linear fits to the data in each plane. The thin dotted lines enclose the ±100 kpc range about the best-fit lines (*left panels*) or the ±20 km s^{-1} range about the best-fit line (*right panel*). The arrow indicates the direction towards the MW.

we adopt the squared sum of the residuals of the two linear fits ($\mathrm{rms}_T = \sqrt{\mathrm{rms}_Y^2 + \mathrm{rms}_Z^2}$) as a measure of the global rms scatter about the line in space. The maximum distance from the line is 98 kpc in Y_a, 101 kpc in Z_a, and rms_T is 95.8 kpc, while the length of the structure is L = 1067 kpc, thus implying a length-to-thickness ratio $L/\mathrm{rms}_T = 11.1$.

The right panel of Fig. 1 shows that the five galaxies also display a very tight correlation between position along the line and V_{LG}, in the sense that galaxies farther from NGC 3109 have larger recession velocities with respect to the LG. The total amplitude of the gradient, as measured from the best-fit line in the R vs. V_{LG} plane, is 45 km s^{-1} from one extreme to the other. This corresponds to 43 km s^{-1} Mpc^{-1}, not compatible, at face value, with pure Hubble flow ($H_0 = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1}, see, e.g., Planck Collaboration 2013). The rms of the residuals is just 16.8 km s^{-1} (rms_V^Y = 15.1 km s^{-1} in the projection shown in Fig. 1), to be compared with a total velocity dispersion of $\sigma_{V_{\mathrm{LG}}}$ = 26.3 km s^{-1}. The effects of varying the distance to Leo P in the range 1.3−2.0 Mpc is also displayed in Fig. 1 (small open circles). Considering that the linear fits would adjust according to the adopted distance, it appears that a remarkable alignment is preserved over a large range of distances; the tightest alignment would be reached for $D \simeq$ 1700−1800[2] kpc.

[1] Thus the discovery of Leo P possibly vindicates the last sentence of van den Bergh (1999), although the Leo constellation was not explicitly mentioned: "...It would be of interest to search for additional faint members of the Ant-Sex group in Antlia, Hydra, and Sextans."

[2] While the first version of this paper was under the scrutiny of the Referee, a preprint was posted (McQuinn et al. 2013) reporting a more accurate estimate of the distance to Leo P, $D = 1.72^{+0.14}_{-0.40}$ Mpc, thus providing further support to the tightness of the alignment described here, and also suggesting Leo P as a likely member of the NGC 3109 group.

While considering the significance of spatial alignments it must be remembered that NGC 3109 and Antlia are probably interacting and they may be a bound couple (van den Bergh 1999; Penny et al. 2012); hence NGC 3109+Antlia should be considered a single system, in this sense[3]. van den Bergh (1999) suggested that Sex A and B may also have interacted in the past, but today they are more than 250 kpc apart and so we consider them to be individual galaxies. For the statistical analysis performed in Sect. 2.1, thus, it is worth reporting that rms_T = 110.2 kpc and rms_V = 13.8 km s^{-1}, if Antlia is excluded from the sample. The R vs. $V_{\rm LG}$ correlation remains strong, while the amplitude of the gradient reduces to 25 km s^{-1}Mpc^{-1}. None of the other galaxies in the left panels of Fig. 1 seems associated with the described alignment. The latter also does not appear to have any obvious relation with the known planar structures of the LG (P13). For brevity, in the following we will refer to the NGC 3109 group *plus* Leo P as the *extended NGC 3109 association*.

2.1. Can the observed alignment arise by chance?

What is the statistical significance of the configuration described above? This is very hard to assess in general, and in particular in the present case, given the sizable errors that affect the distance estimate of Leo P, and the effects of incompleteness as a function of distance and luminosity (Tollerud et al. 2008). In an attempt to overcome some of these issues we proceed in a fully non-parametric way.

Among the galaxies listed in the M12 catalog, we include in our analysis only those that have valid estimates of the distance and radial velocity, and that lie more than 300 kpc away from M31 or the MW, in order to avoid trivial alignments among dwarfs strongly clustered in the respective subsystems. Antlia and HIZSS3B were also removed as possible members of binary systems (Begum et al. 2005). Then we considered all the independent 66405 groups of four galaxies that can be extracted from the 37 galaxies remaining in the sample. For each group we perform the same change of reference system adopted for the NGC 3109 association above (selecting one of the four galaxies at random as the origin of the coordinates), we find the best fit lines in the same principal planes as in Fig. 1, and we compute rms_T and rms_V to check if values as low as those observed for the extended NGC 3109 association (without Ant) are common, and how frequently they could arise in this set of LG galaxies[4]. It turned out that alignments having $\mathrm{rms}_T \leq 130$ kpc and $\mathrm{rms}_V \leq$ 20.0 km s^{-1} occur only four times in 66405 cases. In addition to the case under scrutiny, there are two combinations of members of the NGC 55 subgroup (already recognized as a real association by T06; see also M12), i.e., NGC 55+NGC 300+ESO 294-G010 plus IC 5152 or IC 4662 (the only galaxy not classified as a member of the group). While interesting, these alignments appear dominated by three galaxies (NGC 55, NGC 300, and ESO 294-G010) having similar $V_{\rm LG}$ and enclosed within a radius of just ≃320 kpc (see Fig. 3), i.e., such a strict relation that they can be considered an individual triple system in this context. On the other hand, Sex A and Sex B are ≃510 kpc and ≃730 kpc from NGC 3109 (we recall that Ant is excluded from this analysis). The fourth configuration satisfying the conditions above is composed by NGC 3109+SexA+SexB plus IC 3104 instead of Leo P. We conclude that (a) the NGC 3109 linear group is unique in the surroundings of the LG, as illustrated in Fig. 2; (b) the very few cases of comparable tightness are not random at all, as they correspond to known associations; and (c) by transitive property, IC 3104 should also be approximately aligned with the *extended* NGC 3109 association.

The extended NGC 3109 association *plus* IC 3104 has rms_T = 136.8 kpc along its best-fit line, and the overall length of the structure is 2200 kpc, corresponding to a length-to-thickness ratio L = 16.0. While the line is virtually the same as that of Fig. 1, IC 3104 does not fit into the velocity gradient shown by the members of the extended NGC 3109 association. Moreover, Fig. 3 shows that, while NGC 3109+Ant, Sex B, Sex A, and Leo P are adjacent one to the other, IC 3104 is far away from all of them, on the other side of the LG with respect to M31 and the MW, at least in the $X_{\rm GC}$ vs. $Y_{\rm GC}$ direction; clearly it cannot be presently bound to the association, and it is unlikely to be physically associated. We are inclined to consider IC 3104 an individual chance match approximately along the direction of maximum elongation of a real structure, i.e., the filamentary *extended* NGC 3109 association.

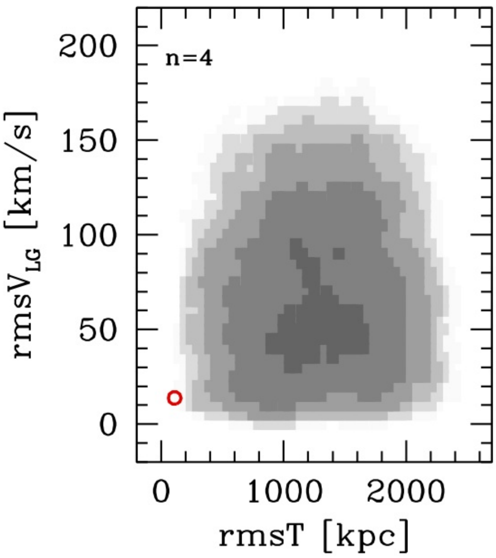

Fig. 2. Density distribution of all the explored configurations of groups of four galaxies in the rms_V vs. rms_T space, compared to the position of the extended NGC 3109 association without Antlia (n = 4). The density increases by a factor of two with each darker tone of gray. The contour of the lightest shade of gray includes more than 99.5 per cent of the cases.

3. Summary and discussion

In this Letter we re-considered the spatial distribution and the kinematics of the NGC 3109 association of dwarf galaxies. The main results of our analysis can be summarized as follows:

1. The distance and velocity of the recently discovered faint dIrr galaxy Leo P are compatible with the hypothesis that Leo P is an additional member of the well-known NGC 3109 association. According to Eq. (4) in Tully et al. (2002), the

[3] In Fig. 1 we consider each galaxy as a separate system for completeness and simplicity. This is a conservative approach since a bound pair will artificially inflate the velocity spread of a structure in analogy to what happens with binaries in stellar systems (Olszewski et al. 1996).

[4] We note that the vast majority of the randomly extracted groups do not correspond to real associations, hence the adopted procedure effectively compares the tightness of the considered structures against chance alignments that can occur in a sample including all the relevant selection effects, since it is the *real* sample. It would be impossible to implement these selection effects in mock catalogs, since they are not completely known.

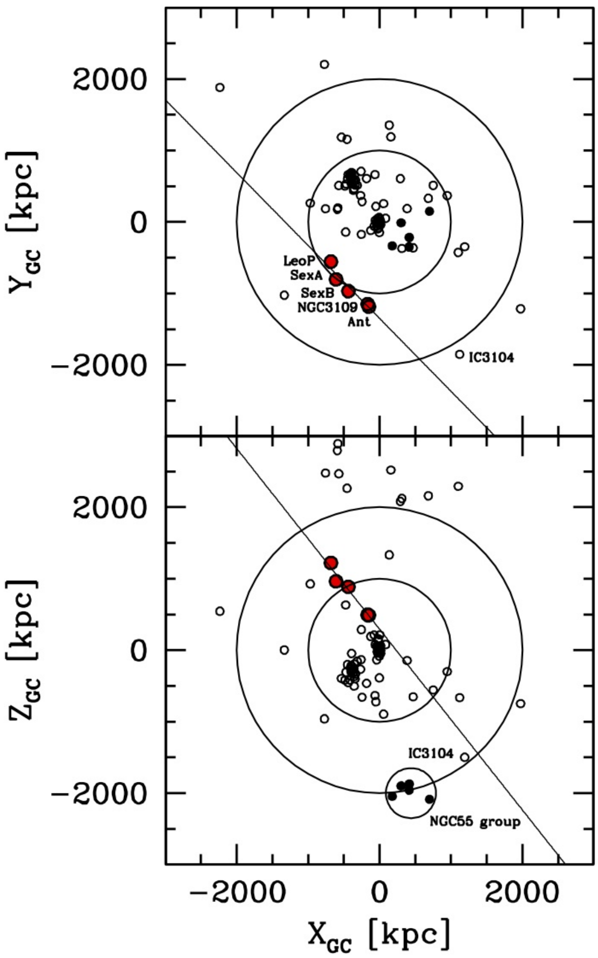

Fig. 3. Galaxies in the M12 list plotted in the Galactocentric Cartesian reference frame (small open circles). The dwarfs of the *extended* NGC 3109 association are plotted as large red filled circles (with labels); those belonging to the NGC 55 association are plotted as dark filled circles. The symbol corresponding to IC 3104 has also been labeled. The lines are the best-fit lines to the members of the *extended* NGC 3109 association (including Antlia). The wide concentric circles have radii of 1 Mpc and 2 Mpc.

mass of the extended association would be $M \simeq 3.2 \times 10^{11}$ $M_{\odot}$ (assuming that it is bound), quite typical for this kind of group (T06). According to Eq. (1) in T06, the turnaround diameter (in spherical approximation) is $2r^{1t}_{\rm dw} \simeq$ 980 kpc, comparable to the total side-to-side linear extension of the association ($\simeq$1070 kpc).

2. We found that the members of the *extended* NGC 3109 association are tightly aligned in space; the length of the configuration is $\simeq$11 times the global rms scatter about the line. The aligned galaxies also display a tight correlation between the distance along the best-fit line and their velocity in the LG standard of rest, with rms$_V$ = 16.8 km s^{-1}. Even if a member of the association (e.g., Leo P) is no longer bound to it, the alignment and the velocity gradient support the idea that they were all part of the same physical structure in the past.
3. Exploring all the possible alignments of groups of four galaxies, among those listed in the M12 catalogue and not strictly associated with the MW or M31, we find that alignments as tight as those described above are extremely rare and it appears very unlikely that they can occur by chance (see also Fig. 2).
4. A tidal interaction would be a quite natural explanation for the origin of the structure, either considering an encounter with the MW (as envisaged by ST13; see also Zhao et al. 2013) that may have stretched the intragroup distances of the original association in the plane of the orbit and produced the velocity gradient, or considering the members of the group to be *tidal* dwarfs (Duc 2012), from the fragmentation of a large-scale tidal arm formed during a major galaxy interaction in the LG (see, e.g., Hammer et al. 2013, P13). In the framework of Newtonian dynamics, the high dark matter content of at least some of the members (Carignan et al. 2013) would militate against the latter hypothesis, that can be a viable solution within other gravitation theories (McGaugh & Milgrom 2013). Instead, if we assume that the members of the extended NGC 3109 association have recently left the Hubble flow and are currently falling into the LG for the very first time, the possibility that the observed linear structure could have formed within a thin and cold cosmological filament (Dekel et al. 2009; Lovell et al. 2011) should be also considered.

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