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The orbital distribution of satellite galaxies: cosmological correlations and origin

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Abstract

The knowledge of the distribution, the number and the characteristics of satellite galaxies can provide important informations about the cosmological phenomena involved in the formation of their hosts. The observational data on the distribution of satellite galaxies in the Local Group show that some dwarfs and globular clusters orbit the main galaxies in common planes. The origin of these co-planar orbits is still unknown. In this paper we report on some results from hydrodynamical cosmological simulations about the orbital distribution of satellite galaxies, focusing in their correlations and the cosmological origin of co-planar orbits.

1 Introduction

The distribution of satellite galaxies relative to their hosts at $z = 0$ is an important issue. Indeed, it could reflect, for example, the manner in which large galaxies have accreted their mass, or the time-scales for the accretion processes. Observations of the Milky Way dwarf satellites and globular clusters show that a large percentage of them seem to share orbital planes with each other, also known as "great circles" [8, 13, 11]. A similar behaviour has been found for some satellite galaxies of the Andromeda galaxy [3, 4, 10, 12]. The origin of this correlation is still unknown. One hypothesis is that low mass objects such as globular clusters or small dwarf galaxies are tidal debris from larger satellite galaxies disruption, that after past tidal events remain on the same orbital plane [7]. However, the different chemical enrichments and star-formation histories found in the objects belonging to the same plane [2], cannot be explained within this hypothesis. Another possible origins of this anisotropic distribution could be that satellite galaxies are cold dark matter sub-structures that are accreted onto the main halo bundled as infalling groups [6, 1], or that dwarfs form in chain structures tracing the dark matter filaments [14]. Finally, another possibility is that such a planar alignments have occured by chance, although the probability of this is very low [5].

In order to discriminate among the different scenarios described above, we have run hydrodynamical cosmological simulations and analysed the systems formed by a disk galaxy and its satellite dwarf galaxies, focusing on the orbital distribution of the bound satellites and the cosmological origin of the coplanar orbits.

2 Methodology

We have used two different numerical codes in our simulations. The first one is DEVA, a Lagrangian SPH-AP3M code using particles to sample dark matter (DM) and baryonic (i.e., gaseous and stellar) mass elements, where particular attention has been paid to assure that the conservation laws (energy, entropy and angular momentum) hold as accurately as possible (see [16] for details on the simulation code). The second code is P-DEVA, an OpenMP version of the previous one [9, 17], with the same characteristics as DEVA concerning the general performances of the code but with new computation algorithms. Several sets of simulations have been run: i) using DEVA in a periodic box of 10 Mpc side, with 64^3 DM particles and 64^3 baryonic particles and the following sets of cosmological parameters: $(\Omega_{\rm m}, \Omega_{\rm b}, h) = (0.35, 0.06, 0.65)$ or $(0.3, 0.04, 0.7)$, and ii) using P-DEVA with a periodic box of 20 Mpc side, 128^3 DM particle, 128^3 baryonic particles and $(\Omega_{\rm m}, \Omega_{\rm b}, h) = (0.3, 0.04, 0.7)$.

Galaxies of different morphologies are formed in these simulations. Disk-like galaxies (DLGs) have been identified as those objects having an extended rotating disk and a central, dynamically relaxed spheroid component or bulge.

We have analyzed the host-satellite systems of 200 DLGs with baryonic mass $M_{\rm host} > 4 \times 10^{10}$ solar masses. DLGs have structural and dynamical properties consistent with observations [15]. These hosts have a population of 3210 satellites with $M_{\rm sat} > 4 \times 10^8$ solar masses within projected distance to the main DLG $d_{\rm p} < 500$ kpc, identified at $z = 0$ in the simulations. Among these host-satellite systems, we have selected the isolated ones (the host is at least 2.5 more massive than any other galaxy within 700 kpc in projected distance), having two or more bound satellites. After this selection, we end up with 45 hosts and 175 bound satellites. Summarizing the statistics of the host-satellites systems, we have got in our simulations: 17 systems having 2 bound satellites, 7 having 3 bound satellites, 7 with 4 bound satellites, 5 with 5 bound satellites, 4 with 6 bound satellites, 1 with 7 bound satellites, 1 with 8 bound satellites, 2 with 9 and 1 with 10 bound dwarfs. It is important to remark that with the satellite mass limit we used here, the Milky Way would be a system with only two bound satellites (the Magellanic Clouds). In fact, its lower mass satellites are under the mass resolution limit of our simulations.

After selecting the bound satellite galaxies associated to a host, we have looked for common orbital planes using the orbital poles, such as described in [8]. The orbital pole is the point projected on the sky where the angular momentum of the satellite orbit points to. Therefore, the orbits of the satellites having the same orbital pole are coplanar. We have considered that two satellites are in the same orbital plane if the angular distance between their poles is smaller than 15°. Finally, we have analysed the statistical significance of the coincidences in the orbital poles. To this end, we have taken into account the number of bound satellites of the host and the number of dwarfs in the common orbital plane. Furthermore, as our simulations provide the whole information of the 6-D phase space (position and kinematics) of the satellite orbits as a function of time, we can test the stability of the pole alignments by tracing the orbits back in time from $z = 0$ up to high redshifts.

3 Results

We have analysed our simulations using the procedure described in Section 2 and we have obtained the following results:

- In our simulations, 17 of the 45 systems present orbital planes with two or more satellites. Six of the systems have two different orbital planes, and another system has three different orbital planes, while the remaining ten have only one.
- We have observed 25 "great circles" in our simulations, 23 with two satellites, one with three satellites and another one with four.
- Among the systems having two bound satellites, we have observed aligned poles in 4 over 17 systems, that is, a 23.5%. If the satellites were randomly distributed, we would expect that only a 1.7% of the systems with two bound satellites have aligned poles (within 15°). Therefore, using these data, we can reject an isotropic distribution with a confidence level higher than 99.99%.
- Among the 7 systems having 4 bound satellites, five of them have planes with two satellites (two with one plane and three with two planes of two satellites each). The probability for a bound system with 4 dwarfs to have one orbital plane with two satellites in a random distribution is 10.2%. Hence, by doing a statistical analysis of our results we can reject the hypothesis of an isotropic distribution of satellites in this case with a confidence level higher than 99.99%
- In the only system of our simulations having 7 bound satellites, there are 3 dwarfs with aligned poles. This result allows us to reject this configuration to be an isotropic distribution with a confidence level higher than 99.99%.
- In one of our systems having 9 bound satellites, there are 4 dwarfs with aligned poles. This allows us to reject the isotropic distribution hypothesis with a confidence level higher than 99.99%.
- We have also found other systems with more than two bound satellites having orbital planes with two satellites, but when analysed one by one the isotropic distribution hypothesis cannot be rejected at a confidence level of 99%. However, by doing a statistical

analysis of the whole set of data (that is, 17 over 45 system having a total number of 25 "great circles") we have obtained that the high number of co-planar orbits in our simulations allows us to reject an isotropic distribution with a confidence level higher than 99.99%.

These results on the number of coplanar planes are summarized in the Table 1

Table 1: Number of common orbital planes given the number of bound satellites in the systems, $N_{\rm bound}$, and the number of dwarfs in the plane, $N_{\rm sat}$

$N_{\rm bound}$	2	3	4	5	6	7	8	9	10
($N_{\rm Systems}$)	(17)	(7)	(7)	(5)	(4)	(1)	(1)	(2)	(1)
$N_{\rm sat}=2$	4	0	8	3	2	0	1	3	2
$N_{\rm sat}=3$	–	0	0	0	0	1	0	0	0
$N_{\rm sat}=4$	–	–	0	0	0	0	0	1	0

Additionally, when the stability of the poles is analyzed as a function of time, we have observed that the planes are quite stable in most of the cases since, at least, $z = 1$. This result is a confirmation that the pole alignments have a cosmological origin and they are not produced by chance. An example of this result is illustrated in Fig. 1. In this Figure, we have plotted in red the evolution of the orbital poles of two co-planar galaxies as a function of the redshift (from $z = 1$ to $z = 0$). As can be seen, the correlation between the two poles is stable along time. The same behaviour is observed for two other satellite galaxies in another orbital plane (in blue).

The origin of the orbital planes is shown up when the orbits of the satellites with aligned poles are traced back in time. In our cosmological simulations we have observed that, sometimes, the dwarfs are accreted joint together in groups and, therefore, their orbits have the same orientations. However, other times the satellite dwarfs sharing the orbital plane are accreted individually, but they have travelled along the same filament before been accreted onto the host. In this case, the satellite galaxies are formed in the same spatial region, then they reach the filament and travel along it until they reach the host.

4 Conclusions

In the present paper we have analysed the existance of satellite galaxies orbiting in the same plane around disk galaxies in hydrodynamical cosmological simulations. We have obtained that almost a 38% of the systems have orbital planes with two or more satellites with baryonic mass larger than 4×10^8 $M_\odot$. Among these systems having orbital planes, more than a 40% have two or more "great circles". The large fraction of this kind of phenomenon allows us to reject a random distribution of the satellites orbiths around the host galaxies, with a confidence level higher than a 99.99%. We would like to remark that if the mass resolution of the simulations increases, in order to detect fainter dwarf satellites, the percentage of common

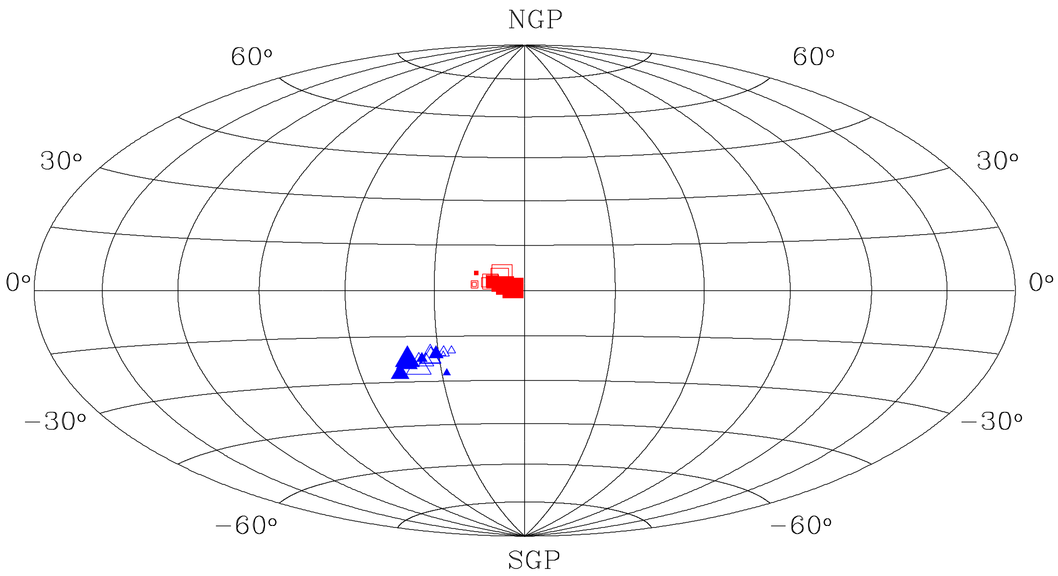

Figure 1: Aitoff projection of the orbital poles of four bound satellites of a disk galaxy as a function of the time (since $z = 0$ to $z = 1$). Each symbol represent a dwarf. The dot sizes decrease with the look-back time. Two orbital planes having two satellites each can be observed.

orbital planes will be probably higher as observed in the Milky Way. This would make these events more significant.

The origin of the satellite pole alignments can be found by studying the cosmological evolution of the satellite accretion processes onto the host. Some of the satellite galaxies are accreted buldled in groups and, therefore, they share the same orbital plane. However, some others are accreted individually, following separated accretion processes, but sharing the same cosmological filament in their trajectory towards the host galaxy. In this case, the dwarf galaxies are formed in regions close to each other, then they travel to the cosmological filament individually (even at different time epoch) and follow the filament to reach, finally, the halo of the host galaxy. As they are accreted following the same filament, that is, with a given orientation with respect to the disk of the main galaxy, their orbits have the same orientation and, therefore, their poles are aligned.

The results presented in this paper allow us to understand the existence of "great circles" in the Milky Way (see, for example, [8]) and in the Andromeda Galaxy [3], either as common groups of satellites accreted onto the main or as satellite dwarfs travelling along the same cosmological filament in their accretion process onto the halo of the host. In any of these two scenarios, it is possible to understand that two satellites with aligned poles have different star formation histories since they have evolved independently to each other. However, if the satellite galaxies in the same orbital have only in common the cosmological filament that drived the accretion process, then they could have different velocities, different orbital energies and different orbits, but the same orbital pole. Therefore, it is very important that the whole kinematics and positions (the six coordinates of the phase-space) of the dwarfs are provided in order to distinguish between the two accretion scenarios decribed above.

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