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Understanding planes of satellites.

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Abstract

Planes of satellites are observed in the Milky Way and Andromeda, and recent observations claim their presence as well in other nearby galactic systems. Moreover, recent proper motion data of MW satellites allege an important fraction of satellites are co-orbiting within the plane they define.

However, the quality and degree of co-orbitation of the planes of satellites reported so far from simulations within a ΛCDM context have been insufficient to explain the observational data.

In order to further understand the origin of planes of satellites we have carried out a detailed study of planes of satellites in zoom-in cosmological hydro-simulations of disc galaxies, focusing on plane-finding methods and plane quality analyses. We report on a method to identify kinematically-coherent satellites based on their orbital angular momentum vectors. We find a group of co-orbiting satellites in the PDEVA-5004 simulation that forms a persistent planar structure across cosmic time, with characteristics compatible with those of the observed planes in the MW and M31.

1 Introduction

The satellite galaxies of the Milky Way (MW) show a very anisotropical distribution. Their positions trace a plane that is approximately perpendicular to the Galactic disc [14, "VPOS"], and in addition, a high fraction of satellites present a common orbitation within the plane [4]. Planar configurations of satellites have also been found in Andromeda (M31) [7], and recently claimed for in other nearby galactic systems like Centaurus A, though still with high uncertainties [13]. Theoretical studies within the ΛCDM cosmological context have tried to link these observations with the large scale structure in which the system is embedded. In particular, dark matter-only simulations have shown that an anisotropical spatial distribution of satellites is indeed expected: satellite accretion occurs along preferential directions given by the velocity field shear tensor, following the filamentary structure of the cosmic web [8]. Hydrodynamical simulations have recently also studied this issue showing the important influence of baryons on the final number and distribution of the satellite sample [1, 10]. Despite these findings, the quality of the planes and the degree of co-orbitation found in previously reported simulations has been insufficient to explain observational data. Therefore this topic has been considered as one of the most challenging small-scale problems in ΛCDM.

The ultimate motivation of this study is to further understand the origin of planes of satellites within a ΛCDM context with baryons, addressing whether the observed planes of satellites in the MW and M31 are a unique occurrence in nature or if there are certain fundamental physical and evolutionary conditions that may favour their emergence. To this end, first a detailed analysis of planes in simulations and their evolution is needed. Here we report on one such detailed study, focusing on plane-finding methods and plane-quality analyses.

2 The simulation

We have analyzed a set of zoom-in cosmological hydrodynamical simulation of disc galaxies. We present here the results for PDEVA-5004 [17]. This simulation has been run with an entropy conserving AP3M-SPH code whose primary concern is that conservation laws (like angular momentum) hold accurately. It includes an inefficient star formation scheme working at sub-grid scales to mimick the regulation effects of stellar feedback, as well as detailed chemical enrichment and feedback methods implemented by [11]. As a result, the simulation gives a defined stellar and gaseous disc at all redshifts, with properties that match observational constraints (see [3] and references therein). The mass resolution of baryonic and dark matter particles is $m_{\rm bar} = 3.94 \times 10^5\,{\rm M}_\odot$, and $m_{\rm dm} = 1.98 \times 10^6\,{\rm M}_\odot$, respectively.

Satellite galaxies have been selected at redshifts $z = 0$ and also $z = 0.5$ to include objects that may end up accreted by the central disc galaxy later on. All selected objects are above a resolution limit of at least ~ 50 baryonic particles and have been checked to be bound to the host galaxy by following the orbit during the analysis period ($z = 1.4 - 0$, $\equiv$ $T_{\rm uni} = 4.7 - 13.7\,$Gyr). The tool used for the selection of satellites has been `IRHYS` (by H. Artal). In order to accurately compare our results to the observational data of the MW, in the analysis that follows we have taken into account the effects of Galactic obscuration (which prevents us from observing satellites orbiting in the plane of the Galactic disc). We apply a bias that hinders objects at latitudes $|b| < 12^\circ$ when projected on the sphere [16]. A total number of 35 satellites have been identified, 30 surviving until $z = 0$. When the obscuration bias is applied the numbers range from 32-20.

The satellites of the sample present very different evolutionary histories that reflect in a variety of orbits. Some lose angular momentum and are eventually accreted by the

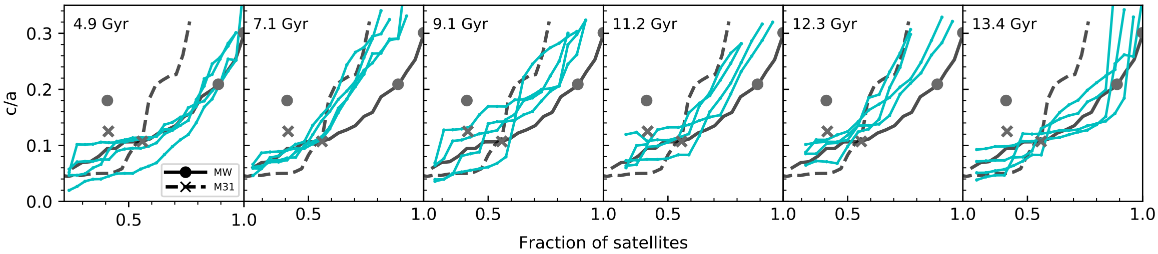

Figure 1: Quality analysis of the planar structures found in PDEVA-5004 with the *4-galaxy-normal* density plot method at certain timesteps: Variation of the short-to-long axis ratio (c/a) with the fraction of satellites included in the plane. Gray solid and dashed lines show the result for the MW and M31 at $z = 0$. Points show the specific values for observed planes of satellites mentioned in the literature [15].

disc, some follow regular orbits, and some have just been captured by the halo and orbit at long distances, sometimes even outside the virial radius. The distribution of satellite radial distances at different timesteps reveals that the system contracts and expands as it evolves. In fact, when the orbits of all satellites are plotted together, it is clear that there are certain moments where many satellite pericenters coincide (i.e., resonances). Interestingly, PDEVA-5004's satellite radial distribution is very similar to that of the MW at $z = 0$.

3 Finding planes of satellites from a positional analysis

We have started searching for planes of satellites by following the *4-galaxy-normal* density plot method [15]. In short, this method consists in fitting a plane (through the Tensor of Inertia, ToI, technique [12]) to every combination of 4 satellites and drawing a density map with the projection of the resultant normal vectors on the sphere. An over-density signals the normal direction to a predominant planar arrangement of satellites. When applied to PDEVA-5004 at each timestep, we obtain different density plots that reflect an anisotropic distribution. We have developed an extension to this method that consists in an iterative plane-fitting process, starting with the 7 satellites that contribute most to each over-density (at each timestep) and then continuously adding one more satellite at a time by contribution order. This allows for a study of the quality of the prominent planar arrangements found, through, for example, the variation of the c/a parameter (short-to-long axis ratio of the ToI) with the number of satellites included in the plane. Results for PDEVA-5004 at representative timesteps are shown in Fig. 1. Note the gray solid and dashed lines, which show the same analysis for the MW and M31 galaxies, respectively. The two galaxies have very different satellite distributions: while the MW satellites form a regular structure that remains a fairly thin plane ($c/a < 0.3$) even when including all of them, only approximately half of M31's satellites form a thin plane, the structure breaking down when including more objects in the plane. PDEVA-5004 presents at every timestep planes of satellites that are both thin and populated, compatible with the observed structures.

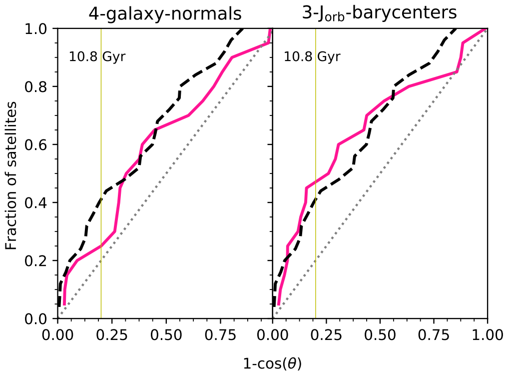

Figure 2: Fraction of co-orbiting satellites in the best planar structure with 70% of satellites found at $\mathrm{T_{uni}} = 10.8$ Gyr in PDEVA-5004 using the *4-galaxy-normals* and *3-Jorb-barycenters* methods. The dashed line shows the result for the MW and the dotted line an isotropic distribution. A yellow vertical line marks an angle of 36.78° which represents 10% the area of the sphere [4].

We now study if the very thin and populated planes of satellites found with the 4-galay-normal method are kinematically-coherent structures that contain a relevant fraction of co-orbiting satellites. To this aim we compute the orbital angular momentum vectors $\vec{J}_{\rm orb}$ of satellites and check the fraction of them that are aligned with the normal vector to the plane they define[1]. In [4] the MW satellites with $\vec{J}_{\rm orb}$ vectors within 36.78° (area of 10% of the sphere) around the VPOS are defined as co-orbiting. We therefore compute the angle $\theta(\vec{J}_{\rm orb}, \vec{n}_{\rm plane})$ between each satellite's $\vec{J}_{\rm orb}$ and the normal $\vec{n}_{\rm plane}$ to the best plane found at that timestep including 70% of satellites. This is shown in the left panel of Fig. 2 at a given timestep as an example, where only $\sim$ 23% of the total number of satellites co-orbit. We find that in general the very high quality planes found at all timesteps with the *4-galaxy-normal* method do not contain a high fraction of co-orbiting satellites. This is indicating that satellites align by chance and the planes they form are therefore *transient* (see also [5, 2]).

4 Finding kinematically-coherent structures

In view of the previous results we have developed a new method that makes use of the full 6D-space-phase information of satellites: the *3-$\vec{J}_{\rm orb}$-barycenter method.* It consists in calculating the barycenter of the minimal spherical triangle formed by the projections of every combination of 3 $\vec{J}_{\rm orb}$ vectors. As before, we project the resultant barycenters on the sphere and draw density maps. In this case, over-densities or accumulation areas indicate the presence of a kinematically-coherent group of satellites. When measuring now the angular distance between the center of the main over-density at a given timestep and each satellite's $\vec{J}_{\rm orb}$ vector, we find at all timesteps that at least 40% of satellites are co-orbiting about the direction given by the 3-$\vec{J}_{\rm orb}$-barycenter over-density, matching the MW value at $z = 0$ [4,

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[1] Note that we do not differentiate between co-rotation and counter-rotation with the disc of the central galaxy.

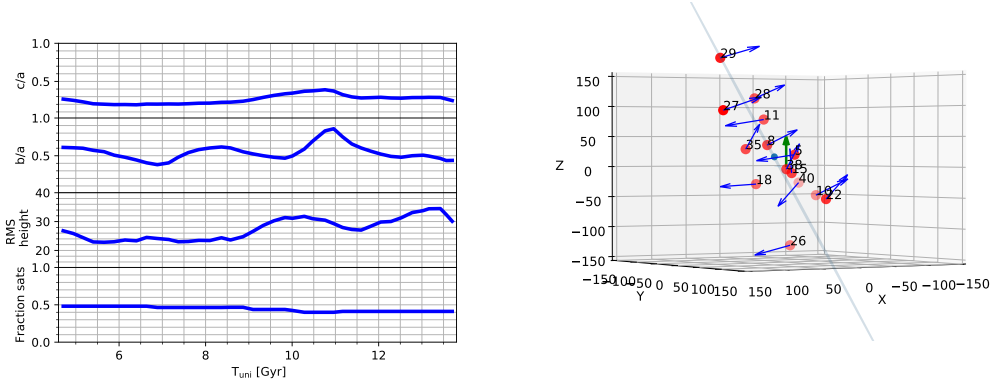

Figure 3: Left: Evolution with time of the properties (i.e., short-to-long axis ratio c/a, intermediate-to-long axis ratio b/a, root-mean-square thickness RMS-height, and fraction of satellites involved) of the plane of kinematically-coherent satellites. Right: Edge-on view of the plane of kinematically-coherent satellites at $T_{\rm uni}$=12.5 Gyr. Blue arrows represent the orbital angular momentum vectors of satellites.

~40%]. An example is shown in the right panel of Fig. 2. Note it is at the same timestep as the results on the left panel obtained with the *4-galaxy-normal* method.

A group of co-orbiting satellites across time In order to identify a group of satellites with aligned $\vec{J}_{\rm orb}$ during a long period of time, at each timestep we iteratively fit planes to groups of satellites as ordered by smaller angular distance between their $\vec{J}_{\rm orb}$ and the peak of each over-density. Specifically, to delimit such a persistent group of kinematically-coherent satellites, we have followed a criteria of choosing those that contribute most to the best planes with 40% of the satellites at each timestep. A group of 14 satellites has been singled out in PDEVA-5004.

We fit a plane to the positions of these satellites at each timestep, finding that they form a persistent planar structure that remains fairly thin across cosmic time (see Fig. 3 for the evolution of some plane properties). Moreover, these satellites represent the 48% of the total number of satellites at $z = 0$, proving this as the best plane+kinematics structure found with hydro-simulations so far (see Fig. 3 for an edge-on view of the plane at a given moment). Finally, the projection of the normal vectors on the sphere are shown in Fig. 4, color-coded by redshift. The reference frame is such that the central disc galaxy lies at latitud=0°. They appear very much clustered at latitud $\sim 0°$, which indicates that the plane of kinematically-coherent satellites is approximately perpendicular to the galactic disk, as occurs with the VPOS in the MW.

Possible origin? Previous studies have suggested a common large scale structure origin for persistent planes of co-orbiting satellites. We therefore trace the baryonic particles of the kinematically-coherent satellites back in time until redshift $z \sim 2.80$. We observe that co-orbiting satellites originate at different locations of the local cosmic web at high redshift

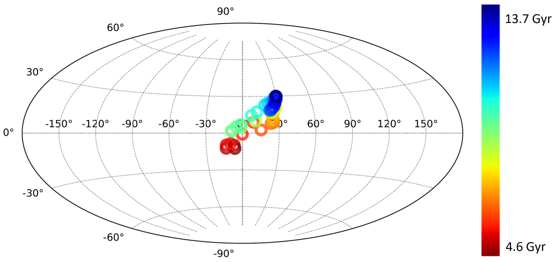

Figure 4: Projection on the sphere of the normal vectors to the plane of kinematically-coherent satellites. The colorbar indicates the corresponding age of the Universe.

but are accreted onto the central main halo through common entrace channels. Although more statistics and a proper numerical quantification of these effects is needed, results seem to support that found in [9] obtained by measuring the velocity field shear tensor: the bulk of the mass (i.e, a higher fraction of satellites) will follow the main direction of local collapse at high redshift (as expected from the Adhesion Model [6]). After, substructure will be accreted to virialized halos following the direction of weakest collapse depending on the given local cosmic web structure in which it is embedded, gaining in the process a common dynamics. In addition, an overall quiet merger history at late times prevents the destabilization of the system and allows angular momentum conservation, what possibly favors these kinematically-coherent groups to persist in time (Santos-Santos et al. in prep.).

Acknowledgments

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