Publ. Astron. Obs. Belgrade No. 104 (2024), 59 - 65 *Invited Lecture*
https://doi.org/10.69646/aob104p059

PHASE-SPACE CORRELATIONS OF SATELLITE GALAXY SYSTEMS AND CHALLENGES TO ΛCDM COSMOLOGY

MARCEL S. PAWLOWSKI
Leibniz-Institute for Astrophysics (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
E–mail: mpawlowski@aip.de

Abstract. Driven by the increasingly complete observational knowledge of systems of satellite galaxies, mutual spatial alignments and relations in velocities among satellites belonging to a common host have become a productive field of research. The Planes of Satellite Galaxies issue is maybe the best-known type of such phase-space correlations, with an ongoing, controversial debate on how much of a challenge it poses for the ΛCDM model of cosmology. With the fast expansion of proper motion measurements in recent years, largely driven by the Gaia mission, other peculiar phase-space correlations have been uncovered among the satellites of the Milky Way. At the same time, more complete observational samples of satellite galaxies around more distant hosts now enable us to expand the study of such correlations to the Andromeda galaxy and beyond. This contribution briefly reviews the highly active field of phase-space correlations among satellite galaxy systems, mainly summarizing recent results concerning observed satellite structures and what formation scenarios have been suggested for these peculiar arrangements.

1. INTRODUCTION

The ΛCDM model of cosmology is broadly believed to be a good representation of the constituents of the universe and its evolution on large scales, driven by a dominant cold dark matter (CDM) component and dark energy parameterized by the cosmological constant Λ. However, comparing observed galaxies with expectations derived from the model, often via numerical simulations, have revealed a number of small-scale problems. In particular on the scale of dwarf galaxies, predominantly tested with the population of satellites of the Milky Way, apparent mismatches such as the Missing Satellites, Core-Cusp, or Too-Big-to-Fail problems have received broad attention.

These problems were initially identified using dark-matter-only simulations. Possible solutions were then found via the introduction of baryonic processes in simulations. Gas hydrodynamics, star formation prescriptions, feedback processes and their effects on heating or expelling surrounding gas, which in turn affects the gravitational potential the dark matter experiences, lead to a complex interplay of baryonic and dark matter distributions. These have been proposed to resolve the small-scale problems that are essentially internal to the galaxies. Similarly, changes to the nature of the dark matter particle (e.g. to warm, self-interactiong, or scalar field dark matter) mostly affect the inner dark matter halo structure only, and such alternatives are additionally severely limited by observational constraints (e.g. Júlio et al. 2023).

In contrast, the global positions and velocities of dwarf galaxies relative to their hosts are not directly affected by processes taking place within them. While introduction of baryons can affect e.g. the efficiency of tidal stripping for satellites in the

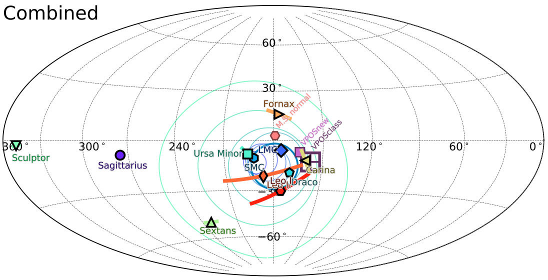

Figure 1: Distribution of the orbital poles of the 11 classical MW satellites, adopting the combined proper motions from Pawlowski & Kroupa (2020) for all but Leo I, for which the new multi-study average of Casetti-Dinescu et al. (2022) combining Gaia and HST data is adopted. The great-circle segments denote the orbital pole uncertainties, while the circles show the direction the spherical standard distance $\Delta_{\rm std}$, of the $k = [3, ..., 11]$ most concentrated orbital poles, with $k = 7$ emphasized.

inner region of a host galaxy's dark halo, influencing the overall radial profile of satellites around the host, their mutual distribution and motion on scales of ~ 100 kpc is robust against baryonic physics, in particular for dwarfs that are believed to be the most dark matter dominated galaxies. This makes the overall phase-space distribution and correlations therein a promising test of the underlying cosmological model, as it is more directly related to the model's inherent hierarchical formation scenario and much less affected by how simulations implement baryonic effects.

The flattened, polar arrangement of the Milky Way satellites, known as the Milky Way's plane of satellite galaxies or Vast Polar Structure (VPOS), was first reported by Lynden-Bell (1976). Similar structures were since discovered around the Andromeda galaxy M31 (Ibata et al. 2013), and Centaurus A (Müller et al. 2018). They have in common that available kinematic data indicate that these are rotating structures. Other phase-space correlations that have been studied include lopsided satellite systems, pairs of satellites, and groups of dwarfs (for a review see Pawlowski 2021).

Comparisons to ΛCDM have shown the known satellite planes to be unexpected, with studies indicating that planes of satellites as extreme as observed are rare in simulations at a level of 0.5 to 0.1%. Differences among studies can often be attributed to the chosen metrics of flattening and orbital coherence, as some of these bias towards apparent consistency with expectations. Coupled with the remarkable variety in opinions on what frequency of analogs in simulations is small enough to constitute a challenge for the model, this explains much of the ongoing controversy of this topic. Yet, it appears doubtful that major progress is to be expected from yet another simulation comparison, as ultimately most results are broadly consistent across different simulations. In the following, I therefore instead focus on recent developments in the empirical study of observed satellite galaxy planes and on attempts to understand the formation processes of these structures. This proceeding can thus act as an update and expansion on my review on planes of satellite galaxies (Pawlowski 2018).

2. OBSERVATIONAL PROGRESS

Our empirical understanding of known planes of satellite galaxies has made progress in recent years. For the Milky Way, an updated proper motion measurement for Leo I by Casetti-Dinescu et al. (2022), combining data from Gaia and the Hubble Space Telescope, has revealed that its orbit is plausibly much better aligned with the VPOS than previously thought (see Fig. 1). An initial concern was that the anisotropy of the observed Milky Way satellite was driven by the footprint of early surveys identifying new objects, in particular the Sloan Digital Sky Survey (SDSS). This concern has been alleviated by Pawlowski (2016), demonstrating that the anisotropy even persists when accounting for the survey footprint. Conversely, the aniosotropy due to the VPOS is now suggested as a possible reason for the overabundance of discovered satellites – compared to expectations assuming an isotropic satellite distribution – in the Hyper Suprime-Cam Subaru Strategic Program survey (Homma et al. 2023).

For a broader understanding of the VPOS constituents, Taibi et al. (2024) performed an in-depth analysis of the properties of on- and off-plane satellites, selected according to their orbital alignment. They showed that the two populations follow similar scaling relations, but that the known VPOS members tend to be brighter. Remarkably, they also identify a peculiar orbital phase distribution: most co-orbiting VPOS members are currently approaching the Milky Way, i.e. before pericenter, and might even be consistent with all having passed their apocenters at about the same time $\sim 1\,\mathrm{Gyr}$ ago (see Fig. 2).

For Andromeda, Sohn et al. (2020) have measured the first proper motions for two satellites on the Great Plane of Andromeda (GPoA). Their resulting orbits relative to M31 indicate that they indeed co-orbit along the GPoA, which might point to an enhanced tension of the M31 satellite plane with expectations from simulations (Pawlowski & Sohn 2021). It will require data on additional satellites to come to more firm conclusions. Projects in this direction are ongoing.

Kanehisa et al. (2023b) focused on the Centaurus A Satellite Plane (CASP) and classified the known satellites according to whether they could plausibly co-orbit along this structure. Interestingly, they found that excluding the five satellites which clearly can not co-orbit in the plane enhances the significance of the observed line-of-sight velocity coherence, in line with expectations of an intrinsically co-orbiting structure. This work also predicts the proper motions for all CASP members under the assumption that they co-orbit similar to satellites in the Local Group structures, predictions which might become testable once proper motion measurements can be extended beyond the Local Group.

Progress is also made in identifying satellite galaxy candidates around more distant hosts (e.g. Martínez-Delgado et al. 2021, Crosby et al. 2023). Yet, ultimately, it will be important to not only investigate specific hosts and their satellite systems, but to compare the overall distribution of satellite galaxies over a statistical sample of systems. This will require dealing with limited phase-space information. Proper motions are not available beyond the Local Group, and line-of-sight distances will be too uncertain to resolve the internal structure of a system of satellite galaxies around hosts beyond a few Mpc (assuming 5% distance uncertainties, the errors will be of order the host's virial radius of $\sim 250\,\mathrm{kpc}$ at distances beyond 5 Mpc). Even spectroscopically measured line-of-sight velocities are expensive to obtain and their

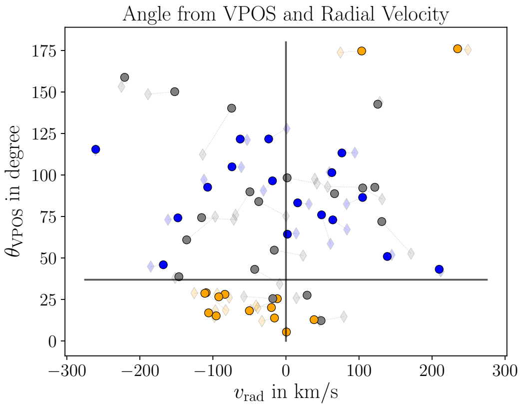

Figure 2: Galactocentric radial velocity $v_{\rm rad}$ vs. angle $\theta_{\rm VPOS}$ of orbital pole from VPOS normal. Satellites with orbits aligned along the VPOS (orange symbols) are predominantly approaching the Milky Way if they are co-orbiting (small $\theta_{\rm VPOS}$), the two counter-orbiting ones are receding. The filled symbols indicate the properties of observed Milky Way satellite galaxies after correcting for the center of mass offset and reflex motion induced by the Large Magellanic Clouds (as in Pawlowski et al. 2022).

availability will thus be severely limited. Thus, in the simplest (and thus most numerous) case only projected positions can be studied initially. The pioneering study of Heesters et al. (2021) shows the prospects of such attempts. Among 119 satellite systems around early-type galaxies from the MATLAS survey, they find one quarter display significantly flattened satellite distributions which have properties consistent with those of the observed satellite planes around M31 and Centaurus A. Comparisons of this sample to expectations from cosmological simulations in luminosity function and phase-space coherences are ongoing (Kanehisa et al. 2024).

3. POSSIBLE ORIGINS OF PHASE-SPACE CORRELATIONS RELATED TO INTERACTING GALAXIES

Among attempts to explain the emergence of planes of satellite galaxies, the accretion of dwarf galaxies along cosmic filaments and the infall of groups of satellite galaxies were discussed early on as possible formation scenarios. Yet, these mechanisms are already self-consistently included in cosmological simulations. They thus appear to be insufficient to boost the incidence of narrow coherent satellite planes to frequencies compatible with the observed satellite structures. However, for well-studied observed systems it can be a promising alternative approach to instead try to identify specific formation mechanisms in line with the system's individual history. In this context, in recent years a common theme has emerged according to which the formation of satellite planes might be linked, in a variety of proposed ways, to the interaction of major galaxies.

3. 1. GALAXY MERGERS

Both M31 and Centaurus A show indications of having experienced major merger events aligned with their observed satellite planes (Hammer et al. 2013, Wang et al.

2020). This offers a promising avenue to explain their coherent satellite systems, since it appears plausible that the angular momentum of major galaxy mergers could induce coherence, in particular in the orbital motion, of the remnant's satellite galaxy system. Via controlled simulations of interacting galaxies in the early universe, this effect was indeed shown to potentially lead to extended and coherent satellite planes in Smith et al. (2016). However, the initial setups were tailor-made and used rather compact, pre-aligned satellite systems around one of the major interacting galaxies only. They were thus not representative of interactions happening from a cosmological background, thereby limiting the interpretation of this scenario for realistic environments.

This concern was addressed by Kanehisa et al. (2023a), who studied the impact of major mergers on satellite galaxy systems in a full cosmological context. By investigating the satellite galaxy systems with respect to their host galaxy's merger history in the Illustris TNG simulations, they demonstrated that mergers do not induce strong phase-space coherence, nor do they substantially affect the presence or properties of satellite planes. In part this is due to the merger's destabilizing effect on pre-existing coherences, but another major factor is the continued accretion of satellites onto the hosts which quickly dilutes the satellite system with objects that have not experiences the earlier major encounter.

3. 2. THE INFLUENCE OF THE LARGE MAGELLANIC CLOUD

It has long been known that the orbit of the Large Magellanic Cloud (LMC) is closely aligned with the co-orbiting satellites in the VPOS (see Fig. 1). This suggests that it might have had an influence on the emergence of the satellite structure, a proposition already made by Lynden-Bell (1976). The presence of a massive satellite galaxy close to its pericenter, specifically the LMC for the Milky Way system, might enhance the incidence of planes of satellite galaxies in cosmological simulations (Samuel et al. 2021). One mechanism is the LMC bringing along some satellites of its own, which contribute to the population of orbitally coherent satellites. Yet none of the classical Milky Way dwarfs are certain former LMC satellites in the predominantly assumed scenario of the LMC falling into the Milky Way halo for the first time (Patel et al. 2020). Yet, it has recently been shown that if the LMC is passing the Milky Way for a second time, a still realistic alternative possibility, then some of the other observed satellites could have been stripped at the previous passage (Vasiliev 2024).

Another mechanism by which a massive LMC can affect the inferred orbits of satellite galaxies is related to its interaction with the Milky Way itself. Investigating dark matter halo particles of a Milky Way analog experiencing an interaction with a massive LMC analog, Garavito-Camargo et al. (2021) have demonstrated that the combined effect of center of mass shift of the central host galaxy with respect to its outer halo, and the reflex motion induced by the encounter, can result in an overabundance of orbital poles aligned with that of the infalling massive satellite. Yet, Pawlowski et al. (2022) showed that this effect is insufficient to affect the *observed* Milky Way satellite system. The orbital pole enhancement is rather mild, leading only to a few per cent increase in orbital pole density. This is particularly the case for particles on orbits more similar to the observed satellite galaxies, i.e. less eccentric ones. Due to their larger tangential velocities compared to highly radial orbits, their orbital poles are much less affected by a center of mass shift and reflex motion.

3. 3. TIDAL DWARF GALAXIES

During the interaction of disk galaxies, second-generation tidal dwarf galaxies (TDGs) can form out of the tidal debris expelled into intergalactic space. These would follow a similar orbital path defined by the tidal tail, motivating TDGs as a promising origin scenario for coherences in satellite galaxy systems. In the ΛCDM framework TDGs should be free of dark matter since they are formed out of the rotating galactic disk material ejected into tidal tails, while the pressure-supported dark matter halo does not participate in this process. TDGs are likely gas-rich and are expected to show higher metallicities than primordial dwarf galaxies since the former form from material that got pre-enriched in their parent galaxy.

Due to the lack of a stabilizing dark matter halo, it can be expected that TDGs are more susceptible to tidal disruption, in particular if they also lose their dominant mass component which resides in gas when they approach a major galaxy such as the Milky Way. The hot gaseous corona of the Milky Way then causes the gas to be stripped, which also makes it difficult to understand the leading arm of the Magellanic Stream as emanating from the Magellanic Clouds (Tepper-García et al. 2019). Simulations of dark-matter-free, gas-rich dwarfs accreted onto a host like the Milky Way show strong effects, with ram-pressure stripping of their gas in the galactic halo causing a deceleration and loss of gravity that leads to substantial expansion or even disruption, further exacerbated by tidal shocks at their orbital pericenters (Wang et al. 2024). Interestingly, this might be in line with the suggestion that many of the dwarfs have arrived in the Milky Way halo only recently (Hammer et al. 2023, 2024). This interpretation is further strengthened by the striking imbalance in the orbital phase of the on-plane satellites of the Milky Way (the co-orbiting ones predominantly approach, see Taibi et al. 2024 and Fig. 2) with most being currently before their pericenter. This appears consistent with the on-plane satellites originating as TDGs (as proposed by e.g. Hammer et al. 2013) which get preferentially destroyed as they pass their pericenter. However, they do not show a significant enhancement in metallicity over the off-plane systems (Taibi et al. 2024), contrary to expectations for pre-enriched material from a more massive galactic disk.

4. SUMMARY

Much of the debate around phase-space correlations among satellite systems is focused on planes of satellite galaxies. In this, most attention is spend on comparisons of observed structures to cosmological simulations, and these in turn mainly consider the VPOS of the Milky Way but not the other known satellite planes. Yet, the topic is much richer. Observational studies and empirical comparisons can teach us more about the nature of these structures. Such information will be essential in assessing the different, increasingly sophisticated, formation scenarios being proposed, many of which relate to galaxy encounters and non-equilibrium effects. Coupled with the range of other satellite-galaxy-related phase-space correlations, we can expect to gain new insights into the history of these nearby satellite galaxy structures.

Acknowledgements

MSP acknowledges funding of a Leibniz-Junior Research Group (project # J94/2020).

References

Casetti-Dinescu, D. I., Hansen, C. K., Girard, T. M., Kozhurina-Platais, V., Platais, I., & Horch, E. P.: 2022, *AJ*, **163**, 1.

Crosby, E., Jerjen, H., Müller, O., Pawlowski, M., Mateo, M., & Dirnberger, M.: 2023, *MNRAS*, **521**, 4009.

Garavito-Camargo, N., Patel, E., Besla, G., Price-Whelan, A. M., Gómez, F. A., Laporte, C. F. P., & Johnston, K. V.: 2021, *ApJ*, **923**, 140.

Hammer, F., Li, H., Mamon, G. A., Pawlowski, M. S., Bonifacio, P., Jiao, Y., Wang, H., Wang, J., & Yang, Y.: 2023, *MNRAS*, **519**, 5059.

Hammer, F., Wang, J., Mamon, G. A., Pawlowski, M. S., Yang, Y., Jiao, Y., Li, H., Bonifacio, P., Caffau, E., & Wang, H.: 2024, *MNRAS*, **527**, 2718.

Hammer, F., Yang, Y., Fouquet, S., Pawlowski, M. S., Kroupa, P., Puech, M., Flores, H., & Wang, J.: 2013, *MNRAS*, **431**, 3543.

Heesters, N., Habas, R., Marleau, F. R., Müller, O., Duc, P.-A., Poulain, M., Durrell, P., Sánchez-Janssen, R., & Paudel, S.: 2021, *A&A*, **654**, A161.

Homma, D., Chiba, M., Komiyama, Y., Tanaka, M., Okamoto, S., Tanaka, M., Ishigaki, M. N., Hayashi, K., Arimoto, N., Lupton, R. H., Strauss, M. A., Miyazaki, S., Wang, S.-Y., & Murayama, H.: 2023, arXiv:2311.05439.

Ibata, R. A., Lewis, G. F., Conn, A. R., Irwin, M. J., McConnachie, A. W., Chapman, S. C., Collins, M. L., Fardal, M., Ferguson, A. M. N., Ibata, N. G., Mackey, A. D., Martin, N. F., Navarro, J., Rich, R. M., Valls-Gabaud, D., & Widrow, L. M.: 2013, *Natur*, **493**, 62.

Júlio, M. P., Brinchmann, J., Zoutendijk, S. L., Read, J. I., Vaz, D., Kamann, S., Krajnović, D., Boogaard, L. A., Steinmetz, M., & Bouché, N.: 2023, *A&A*, **678**, A38.

Kanehisa, K. J., Pawlowski, M. S., & Müller, O.: 2023a, *MNRAS*, **524**, 952.

Kanehisa, K. J., Pawlowski, M. S., Müller, O., & Sohn, S. T.: 2023b, *MNRAS*, **519**, 6184.

Kanehisa, K. J., Pawlowski, M. S., Heesters, N., & Müller, O.: 2024, *A&A*, **686**, A280.

Lynden-Bell, D.: 1976, *MNRAS*, **174**, 695.

Martínez-Delgado, D., Makarov, D., Javanmardi, B., Pawlowski, M. S., Makarova, L., Donatiello, G., Lang, D., Román, J., Vivas, K., & Carballo-Bello, J. A.: 2021, *A&A*, **652**, A48.

Müller, O., Pawlowski, M. S., Jerjen, H., & Lelli, F.: 2018, *Science*, **359**, 534.

Patel, E., Kallivayalil, N., Garavito-Camargo, N., Besla, G., Weisz, D. R., van der Marel, R. P., Boylan-Kolchin, M., Pawlowski, M. S., & Gómez, F. A.: 2020, *ApJ*, **893**, 121.

Pawlowski, M. S.: 2016, *MNRAS*, **456**, 448.

—: 2018, *Modern Physics Letters A*, **33**, 1830004.

—: 2021, *Galaxies*, **9**, 66.

Pawlowski, M. S. & Kroupa, P.: 2020, *MNRAS*, **491**, 3042.

Pawlowski, M. S., Oria, P.-A., Taibi, S., Famaey, B., & Ibata, R.: 2022, *ApJ*, **932**, 70.

Pawlowski, M. S. & Sohn, S. T.: 2021, *ApJ*, **923**, 42.

Samuel, J., Wetzel, A., Chapman, S., Tollerud, E., Hopkins, P. F., Boylan-Kolchin, M., Bailin, J., & Faucher-Giguère, C.-A.: 2021, *MNRAS*, **504**, 1379.

Smith, R., Duc, P. A., Bournaud, F., & Yi, S. K.: 2016, *ApJ*, **818**, 11.

Sohn, S. T., Patel, E., Fardal, M. A., Besla, G., van der Marel, R. P., Geha, M., & Guhathakurta, P.: 2020, *ApJ*, **901**, 43.

Taibi, S., Pawlowski, M. S., Khoperskov, S., Steinmetz, M., & Libeskind, N. I.: 2024, *A&A*, **681**, A73.

Tepper-García, T., Bland-Hawthorn, J., Pawlowski, M. S., & Fritz, T. K.: 2019, *MNRAS*, **488**, 918.

Vasiliev, E.: 2024, *MNRAS*, **527**, 437.

Wang, J., Hammer, F., Rejkuba, M., Crnojević, D., & Yang, Y.: 2020, *MNRAS*, **498**, 2766.

Wang, J., Hammer, F., Yang, Y., Pawlowski, M. S., Mamon, G. A., & Wang, H.: 2024, *MNRAS*, **527**, 7144.