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A whirling plane of satellite galaxies around Centaurus A challenges CDM cosmology

Oliver Müller

Departement Physik, Universität Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland
email: oliver89.mueller@unibas.ch

Abstract. The phase-space correlation of dwarf galaxies around the Milky Way and the Andromeda galaxy pose a serious challenge to our understanding of structure formation. Recently, another planar structure was discovered around Cen A, the major galaxy of the Centaurus group. We have surveyed this galaxy group for new dwarf galaxies and presented the discovery of 57 new dwarf member candidates. Furthermore, we have studied the kinematics of previously known dwarfs and again found a kinematic coherence in their movement, similar to the Local Group satellites. In CDM simulations, such an alignment appears in less than 0.5 percent.

Keywords. galaxies: dwarf, galaxies: kinematics and dynamics, (cosmology:) large-scale structure of universe.

1. Introduction

In the Local Group, several cosmological problems have been identified on the scale of dwarf galaxies: the long standing "missing satellite problem" (Moore *et al.* 1999), the "too-big-to-fail problem" (Boylan-Kolchin *et al.* 2011), and the the "cusp/core problem" (de Blok 2010). This trinity of problems might be attributable to an incomplete understanding of baryonic physics (e.g., Simon & Geha 2007) and is thus potentially solvable. However, recently, another challenge for the standard ΛCDM model of structure formation has emerged: the dwarf galaxy satellites in the Local Group are distributed in planar structures, the so-called "plane-of-satellites problem" (Kroupa *et al.* 2005). There are the Vast Polar Structure (VPOS) of the Milky Way (Pawlowski *et al.* 2012, 2015) and the Great Plane of Andromeda (GPoA, Ibata *et al.* 2013) which are structures that extend over ∼500 kpc, are as thin as 13−20 kpc, and display coherent kinematics. To summarize, these are highly phase-space correlated structures, best explained by a co-rotation of the satellites within a plane. For many Milky Way satellites proper motion measurements are available thanks to Hubble Space Telescope (HST) and Gaia (DR2) measurements. These observations indicate coherent motions of the satellites, even though their significance is debated (e.g. Pawlowski & Kroupa 2013, Gaia Collaboration *et al.* 2018, Fritz *et al.* 2018). For the Andromeda galaxy only line-of-sight velocities are available to study the kinematics, and again, most (13 out of 15) satellites share a coherent motion. In the standard ΛCDM concordance model these structures are thought to be rare (e.g. Pawlowski *et al.* 2014, Cautun *et al.* 2015, see also Pawlowski 2018 for a recent review). Galaxy groups are expected to have a close-to isotropic distribution of the satellites with random motions. Most importantly, baryonic physics is expected to play only a minor role: the distribution and orbits of satellite galaxies on scales of a Megaparsec must be largely driven by gravity alone, hence the solutions for the previously mentioned cosmological probes cannot help solve the "plane-of-satellites problem". Thus a key question for small-scale cosmology is given by: Is the Local Group just a statistical outlier in the otherwise successful ΛCDM model of structure formation, i.e. is it a typical galaxy group to study cosmology?

2. Search for new dwarf galaxies

To answer this question, many teams have taken up the effort to search for and study hitherto undetected dwarf galaxies outside of the Local Group (e.g. Chiboucas *et al.* 2009, Merritt *et al.* 2014, Javanmardi *et al.* 2016b, Müller *et al.* 2017, 2018). In the nearby Centaurus group, which consists of two aggregates around the massive elliptical galaxy Cen A ($D = 3.7$ Mpc) and the spiral galaxy M 83 ($D = 4.9$ Mpc), we have conducted a large survey covering 550 square degrees with the Dark Energy Camera, where we found 57 new dwarf galaxy candidates (Müller *et al.* 2015, 2017a) – doubling the number of known galaxies in this group. Their morphology and derived surface brightness photometry resemble those of the Local Group dwarfs. The surface brightness limit reached in this survey is $r = 29$ mag arcsec^{-2} and the faintest suspected member candidates found have an absolute magnitude of $M_r = -8.8$ mag at a putative mean distance of 4.5 Mpc.

We have started to follow-up these dwarfs using ground based observations with the FORS2 instrument mounted at the Very Large Telescope (VLT). In our pilot study (Müller *et al.* 2018b), we have confirmed two out of three candidates. For one galaxy, dw1335-29, HST data is available (Carrillo *et al.* 2017) and the estimated distances agree well within the errors. This result is intriguing as it shows the feasibility to measure tip of the red giant branch distances up to a distance of 5.5 Mpc within reasonable observation times with ground-based instruments. However, as the Centaurus association extends up to 6.5 Mpc, not all dwarfs can be followed up by ground-based measurements and thus ultimately space-based observations will be necessary to trace the whole dwarf population of the group.

3. The case of Centaurus A

Tully *et al.* (2015) reported two planes of satellites around Cen A, already suggesting similarities to the Local Group of galaxies. Our new dwarf galaxies, as well as the addition of a deep survey by Crnojević *et al.* (2016), start to fill the gap between the two planes such that a unimodal interpretation becomes apparent (Müller *et al.* 2016). Recently, by using archival line-of-sight velocities, we studied the kinematics of the known dwarf galaxies around Cen A (Müller *et al.* 2018b) and indeed, we found the same kinematic coherence as in the Local Group planes: 14 out of 16 dwarf galaxies share a common motion, i.e. to the North they are blueshifted, to the South they are redshifted– which is again best explained by co-rotation of the satellites, see Figure 1. We have compared this phase-space alignment to cosmological dark matter simulations with and without the inclusion of baryons (Millennium-II and Illustris) and we found that the probability to form such a structure is very low to a similar degree as in the Local Group (<0.5%). This gives the third case of such an unlikely structure in the third studied system. Undoubtedly, this poses a serious challenge to the standard model of structure formation, as neither filamentary accretion, dwarf galaxy group infall, nor tidal dwarfs can satisfactory explain the appearance of the three observed planes-of-satellites in the nearby universe.

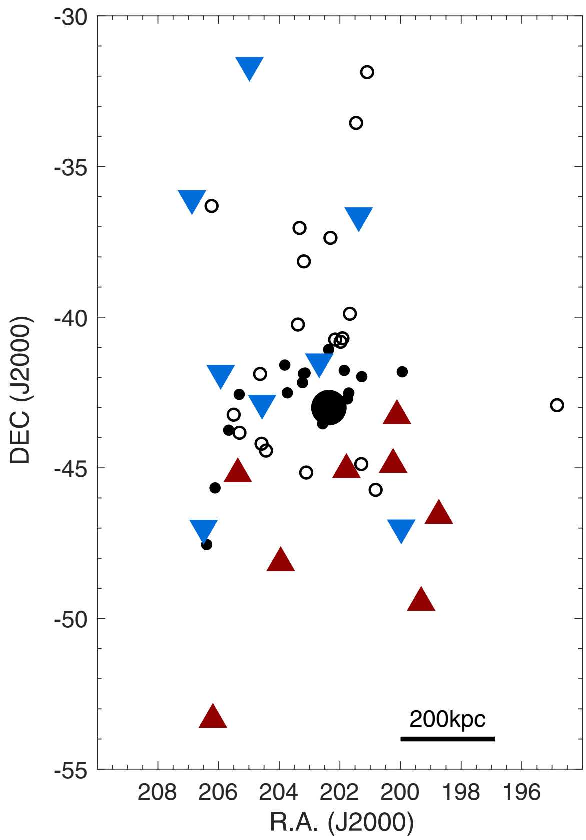

Figure 1. The phase-space alignment of the Cen A subgroup. Red upward pointing triangles are redshifted dwarf galaxies with respect to Cen a, blue downward pointing triangles are blueshifted dwarfs. The big black point is Cen A, the small black points are confirmed Cen A satellites without velocity measurements, the open circles are dwarf candidates.

References

Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2011, *MNRAS*, 415, L40
Carrillo, A., Bell, E. F., Bailin, J., *et al.* 2017, *MNRAS*, 465, 5026
Cautun, M., Bose, S., Frenk, C. S., *et al.* 2015, *MNRAS*, 452, 3838
Chiboucas, K., Karachentsev, I. D., & Tully, R. B. 2009, *AJ*, 137, 3009
Crnojević, D., Sand, D. J., Spekkens, K., *et al.* 2016, *APJ*, 823, 19
de Blok, W. J. G. 2010, Advances in Astronomy, 2010, 789293
Fritz, T. K., Battaglia, G., Pawlowski, M. S., *et al.* 2018, arXiv:1805.00908
Gaia Collaboration, Helmi, A., van Leeuwen, F., *et al.* 2018, arXiv:1804.09381
Ibata, R. A., Lewis, G. F., Conn, A. R., *et al.* 2013, *Nature*, 493, 62
Javanmardi, B., Martinez-Delgado, D., Kroupa, P., *et al.* 2016, *A&A*, 588, A89
Kroupa, P., Theis, C., & Boily, C. M. 2005, *A&A*, 431, 517
Merritt, A., van Dokkum, P., & Abraham, R. 2014, *APJL*, 787, L37
Moore, B., Ghigna, S., Governato, F., *et al.* 1999, *APJL*, 524, L19
Müller, O., Jerjen, H., & Binggeli, B. 2015, *A&A*, 583, A79
Müller, O., Jerjen, H., Pawlowski, M. S., & Binggeli, B. 2016, *A&A*, 595, A119
Müller, O., Jerjen, H., & Binggeli, B. 2017, *A&A*, 597, A7
Müller, O., Scalera, R., Binggeli, B., & Jerjen, H. 2017, *A&A*, 602, A119
Müller, O., Pawlowski, M. S., Jerjen, H., & Lelli, F. 2018, *Science*, 359, 534
Müller, O., Rejkuba, M., & Jerjen, H. 2018, *A&A*, 615, A96

Müller, O., Jerjen, H., & Binggeli, B. 2018, *A&A*, 615, A105
Pawlowski, M. S., Pflamm-Altenburg, J., & Kroupa, P. 2012, *MNRAS*, 423, 1109
Pawlowski, M. S., & Kroupa, P. 2013, *MNRAS*, 435, 2116
Pawlowski, M. S., Famaey, B., Jerjen, H., *et al.* 2014, *MNRAS*, 442, 2362
Pawlowski, M. S., Famaey, B., Merritt, D., & Kroupa, P. 2015, *APJ*, 815, 19
Pawlowski, M. S. 2018, Modern Physics Letters A, 33, 1830004
Simon, J. D., & Geha, M. 2007, *APJ*, 670, 313
Tully, R. B., Libeskind, N. I., Karachentsev, I. D., *et al.* 2015, *APJL*, 802, L25

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