Report on the ESO Workshop

Satellites and Streams in Santiago

held at ESO Vitacura, Santiago, Chile, 13–17 April 2015

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Galactic satellites and tidal streams are arguably the two most direct imprints of hierarchical structure formation in the haloes of galaxies. At this ESO workshop we sought to create the big picture of the galactic accretion process, and shed light on the interplay between satellites and streams in the Milky Way, Andromeda and beyond. The Scientific Organising Committee prepared a well-balanced programme with 60 talks and 30 poster contributions, resulting in a meeting which was greatly enjoyed by the more than 110 participants at the venue, and worldwide via Twitter (#SSS15).

Introduction

Near-field cosmology has become increasingly important over the past few decades. While the current concordance cosmological model (Lambda Cold Dark Matter [ΛCDM]) has been very successful in reproducing and predicting the properties of the Universe on large scales, several possible tensions have been identified on small scales (≤ 1 Mpc). Issues like the "missing satellite problem", the "core/cusp problem", "too big to fail", and detections of satellite discs around the Milky Way (MW) and M31 pose challenges to our understanding of structure and star formation in the early Universe, and the feedback between baryons and dark matter.

But how well do we understand what it means to be a satellite of the MW or M31? Even in the era of high-precision cosmology, we are still uncertain about the total masses of the two dominant galaxies in the Local Group, their assembly histories and the shape and extent of their dark matter haloes — key aspects for gaining a consistent picture of these galaxies and their satellite systems in a ΛCDM context. On the contrary, the discovery of transition objects at the star cluster–dwarf galaxy interface has made things more complicated. It has blurred the historical distinction between satellite classes, putting in question our understanding of tidal transformation and the census of small stellar systems.

Although these aspects of near-field cosmology have become more and more prominent in the age of surveys, there has not been a conference on both satellites and streams in over a decade. This five-day ESO workshop (see the workshop poster, Figure 1) therefore met with a great demand for presentation slots, and the registration had to close early due to the overwhelming interest.

Figure 1. Conference poster showing the Milky Way with its most prominent satellite, the Large Magellanic Cloud, over Santiago. The upper part of the poster shows a collection of tidal streams from the *Via Lactea Cauda* simulation.

Based on the scope of the meeting, the week was divided into three parts. First, satellites and the satellite systems of the Milky Way, M31 and other nearby galaxies were discussed. This was followed by presentations on observations and modelling of tidal streams, and the final part of the workshop was dedicated to the star cluster–dwarf galaxy divide. The grouping into these sessions was of course not strict, and, as intended, many presenters pointed out important connections between satellites and streams. The workshop programme, with links to many of the presentations, can

Stephane Courteau

Figure 2. Conference photo taken in the garden of the ESO Vitacura premises.

be accessed online[1]. The participants are shown in the gardens of ESO Vitacura in Figure 2.

The meeting was opened by the ESO Director General Tim de Zeeuw, giving an overview of the ESO facilities and an exciting outlook for the field into the European Extremely Large Telescope era, when it will be possible to resolve stellar populations out to the Virgo Cluster.

Satellite systems

Galactic satellites give us an account of low-mass substructures at the present day. However, in order to put these satellites into the context of structure formation within the ΛCDM framework, their masses, and especially their dark matter content, have to be understood. In the first talk of the satellite session, Jorge Peñarrubia discussed the advances, problems and challenges of mass modelling of dwarf galaxies. Although modelling might help to put constraints on the nature of dark matter (density cores/cusps), he clearly called for more (kinematic) data to inform the models. In the spirit of the meeting's title, and like many other speakers, he also presented an interesting new idea, using the streams of satellites to break the core/cusp degeneracy. Calling it a "diversity problem" rather than a cusp/core problem, Chervin Laporte demonstrated the large phenomenology of dark matter in galactic satellites due to a possible re-growth of cusps in cored galaxies via accretion of dark matter subhaloes or other dwarf galaxies — further complicated by baryonic effects on the central density profiles of satellites.

Michelle Collins then gave a recount of the dozens of newly discovered satellites in the Milky Way and M31 haloes from surveys like the Pan-Andromeda Archaeological Survey (PAndAS; see Figure 3). In her presentation, a mass–size diagram (Figure 4) made its first appearance and ended up being the plot shown most often during the meeting. In particular the divide between dwarf galaxies and globular clusters in this diagram is currently being populated with newly discovered objects, most of which cannot be classified by their photometry alone — which is why we had an entire session on this topic at the end of the meeting. Collins furthermore pointed out that kinematic data may often be ambiguous as some of the satellites seem to have had recent gravitational interactions and encounters, while others like Hercules and Willman 1 appear to be entirely out of equilibrium, making mass determinations hard, if not impossible.

Finding new satellites and following up the discoveries with deeper photometry and/or spectroscopy has become a sport. Yet only through this important exercise will we eventually get a complete census of substructure in the local Universe. After seeing the great successes of PAndAS, we heard further results and outlooks from ongoing and upcoming surveys with the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) by Jeff Carlin, on the Large Binocular Telescope (by Giacomo Beccari) and the Magellan Telescope (Denija Crnojevic), all looking for more substructure in the local Universe.

Eduardo Balbinot then presented the rich harvest from the Dark Energy Survey (DES) data release 1, giving us a detailed look at the structure and formation history of the Large Magellanic Cloud (LMC), as well as of the nine newly discovered satellites around the Magellanic Clouds. Later in the meeting, Vasily Belokurov talked more about the independent discovery of these satellites in the DES data. Both groups have follow-ups on one satellite, Reticulum II, confirming that it is in fact a dwarf galaxy. Similarly, Erik Tollerud presented his newest findings in the Galactic Arecibo *L*-band Feed Array (GALFA) survey. The two newly discovered, gas-rich, low-mass galaxies represent the progenitors of the dwarf galaxies that we find around larger host galaxies. Understanding this transformation from gas-rich to quenched galaxy is not straightforward, as Thorsten Lisker explained and Rachael Beaton later on confirmed.

Numerical simulations are getting up to speed with the flood of observational data. Coral Wheeler presented high-resolution hydrodynamical simulations of isolated dwarf galaxies to understand their satellites, finding a few ultra-faint satellites around each of these low-mass hosts and making them interesting testbeds for ΛCDM. Else Starkenburg showed results from her semi-analytical models of dwarf galaxies, which are particularly useful to test the physics inside the satellites and gain intuition about their evolution.

Accretion of satellites

Accretion and disruption of satellites can give us important insights into the build-up of bulges and haloes of galaxies. Benjamin Hendricks demonstrated this approach for globular clusters (GCs) in Fornax, and Ryan Leaman shed light on the accretion history of the Milky Way using its GCs as tracers of dwarf galaxy infalls. Similarly, tidal streams provide insights on the star formation histories of individual dwarf galaxies, as Thomas de Boer demonstrated in the example of Sagittarius.

But larger infalling galaxies, or major mergers, could also trigger the formation of new satellites — known as tidal dwarf galaxies. Pavel Kroupa argued that these satellites could be long-lived, and pollute (or entirely make up) the satellite populations of host galaxies. Kinematically correlated satellite populations in the Milky Way and M31 halo could point towards such a formation scenario. However, Pierre-Alain Duc argued that the formation of tidal dwarf galaxies through mergers is less likely than expected, and that the objects thus formed do not resemble the satellites found in the local Universe. From the numerical side, Sylvia Ploeckinger is developing the tools to perform full hydrodynamical simulations of tidal dwarf galaxies to study their long-term survivability.

Marcel Pawlowski, Rodrigo Ibata and Noam Libeskind then gave detailed descriptions of the co-rotating structures around the Milky Way, Andromeda and Centaurus A. The speakers pointed out that the chances of finding such planes in ΛCDM appears to be rather low, but may have to do with either larger mergers bringing in lots of satellites or infall of satellites along the cosmic web. Gurtina Besla added the Large and Small Magellanic Clouds to this picture, discussing different infall scenarios for the two satellite galaxies. She argued that if the LMC originally had a mass of $> 10^{11}$ $M_{\odot}$, it should have brought in at least seven massive satellites. Moreover, she pointed out that a massive LMC may have shifted the barycentre of the Milky Way, which could potentially affect all stream modelling. The satellite session thus concluded with lots of intriguing problems and open questions. In many cases, satellite orbits appear to be the missing ingredients to answer these questions, which is where tidal streams may come in handy.

Tidal streams

Tidal streams are tracers of how satellites get accreted and disrupted. They make up an as-yet unknown percentage of halo stars, complicating the modelling and interpretation of the stellar halo. But, due to their coherence in phase space, they also enable us to measure the shape of the gravitational potentials of their host galaxies, constrain the orbits of their progenitors, and provide insights into the chemo-dynamical evolution of satellites. As a first speaker of the session, Rodrigo Ibata presented modelling approaches and promising streams that need to be modelled, such as the Giant Southern Stream (GSS) in M31 (Figure 3). Karrie Gilbert then showed results from the Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo (SPLASH), shedding light on the merger event that created the GSS and related shells in the M31 halo. She pointed out that the halo of Andromeda shows clear signatures of further mergers with smaller galaxies. Edouard Bernard added insights on the GSS's star formation history from Hubble Space Telescope (HST) data, and possible links to a star formation event in M31.

Essential for our understanding of satellites, streams and their host galaxies are proper motion measurements. Tony Sohn presented HST observations, giving valuable insights on the internal kinematics, the gravitational potential of the Milky Way, and even the kinematics of streams. Iskren Georgiev presented first-epoch data from a Palomar 5 proper motion measurement with the HST. The data provide tight constraints on the distances to the cluster and its stream and their stellar mass functions, which significantly

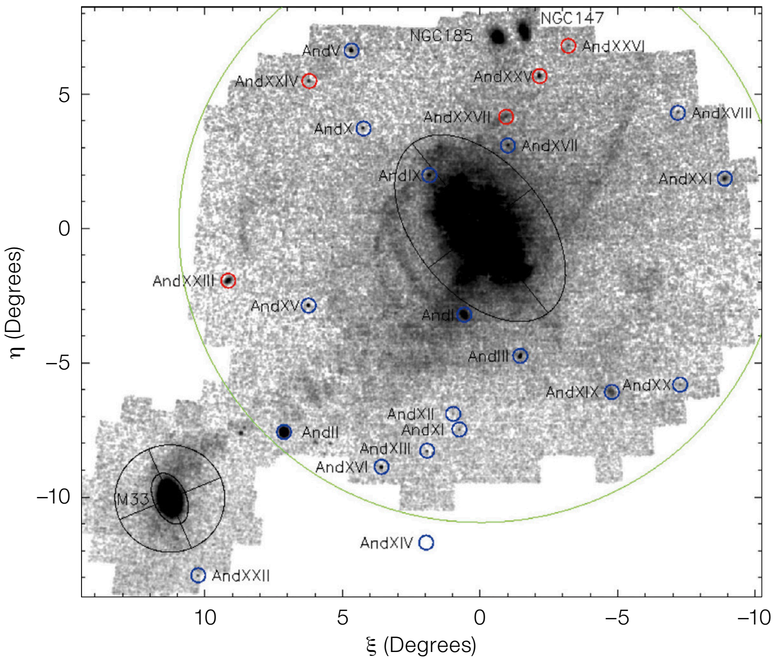

Figure 3. The surface density of colour-selected stars in the PAndAS footprint is shown. Andromeda and M33 are clearly visible, as well as lots of smaller satellites and a complex network of streams. From Richardson et al. (2011).

help to inform models of this system. Yet, most insights on streams have come, and are still coming, from wide-field imaging surveys. In this context, Blair Conn presented results from the PanSTARRS1 survey, concluding that the Monoceros overdensity could be either a stream, a flare or a ripple in the Galactic Disc. Heidi Newberg argued for the latter, backing up her arguments with signatures of such a density wave in Sloan Digital Sky Survey (SDSS) data. A different approach of finding and characterising halo substructure was presented by Kathy Vivas, who showed the extent of the Virgo overdensity as seen by RR Lyrae stars.

Putting all this into context, the "old cow" of the stream business (his words), Steven Majewski, gave an excellent historical overview of how tidal streams were discovered and modelled in the past twenty (forty?) years, and on how the discovery of the Sagittarius stream led to a paradigm shift in the astronomical community, since it was a striking confirmation of hierarchical structure formation. Carl Grillmair followed up with a complete census of the 21 currently known streams in the Halo of the Milky Way (most of which he discovered himself). Based on the present-day globular cluster population, Mark Gieles estimated that this number should be a factor of four times higher, whereas Grillmair estimates it to be a factor of ten higher. Grillmair pointed out that, although the northern sky looks like a "weaved carpet", there is a significant lack of stream detections on the southern hemisphere.

Aaron Romanowsky extended this census to M31 and beyond, emphasising that streams are found in basically any galaxy with deep enough photometry. He pointed out that for distant galaxies, since stars are too faint for spectra, globular clusters or planetary nebulae have to be used to get kinematic data for investigating stream-like substructures. With the example of M87, he then demonstrated that these tracers can in fact be used to detect accretion events. Michael West followed up on that with the investigation of halo substructure using computer-vision techniques, that is, by applying the versatile Hough transformation to globular cluster maps.

Modelling tidal streams

Fast and efficient ways of modelling tidal streams have become available in recent

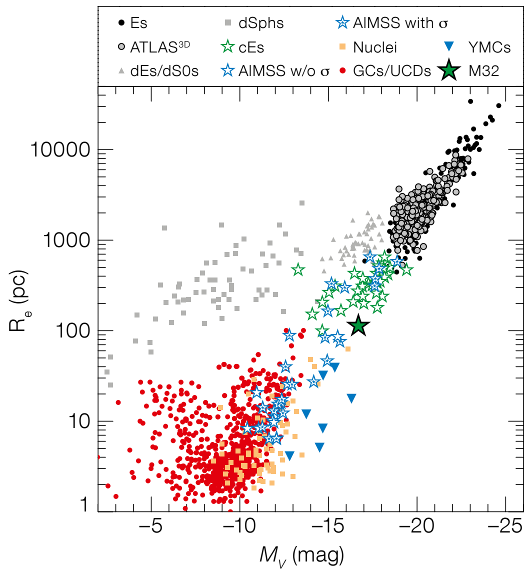

Figure 4. This mass–size plot from Norris et al. (2014) depicts absolute magnitude, as a tracer of stellar mass, versus effective radius, as a proxy for size. It contains nearly all known satellites in the local Universe. Globular clusters (red) and dwarf galaxies (grey squares) form two distinct sequences, which merge onto a common mass–size sequence defined by elliptical galaxies. Newly found objects close this gap between the two satellite populations.

years. Yet, applications to real data are still the exception. With the flood of kinematic data in mind, which will soon come from the Gaia satellite (mid 2016/early 2017), Amina Helmi gave an excellent overview of action-angle modelling of streams and phase-space substructure. She emphasised that streams are significantly simpler structures in action-angle space than in phase space, which makes this formalism a promising technique to model large numbers of streams. Based on the Aquarius simulations, she estimated that Gaia should be able to detect about 400 streams in the Solar Neighbourhood. Building on Helmi's talk, Jo Bovy introduced his Python galpy software, which can be used to efficiently generate stream models, and which is entirely based on the simple nature of streams in action-angle space. Then Robyn Sanderson demonstrated how this framework can be used to disentangle stream memberships of stars in the (messy) Galactic Halo, and in this way constrain the potential of the Milky Way.

The kinematically cold streams detected in the Milky Way Halo, such as GD-1 and Palomar 5, are very thin — surprisingly thin. In this context, Raymond Carlberg demonstrated the effects of a realistic, i.e., triaxial and substructured, dark matter halo on the width of tidal streams. He concluded that the potential of the Milky Way should rather be filled with streams looking like "overcooked spaghetti". In this context, Sarah Pearson presented her modelling results, showing that the only triaxial halo model currently known for the Milky Way dark matter profile that can successfully reproduce the Sagittarius stream, fails in reproducing the thin and curved morphology of the Palomar 5 stream. She explained that the triaxiality of the gravitational potential leads to significant stream fanning, resulting in puffy streams that do not resemble the SDSS observations of Palomar 5. Andreas Küpper followed up on Pearson's talk, by identifying (probable epicyclic) substructures within the stream of Palomar 5. He demonstrated how these, when modelled correctly, turn globular cluster streams into high precision scales, constraining models of Palomar 5, the Milky Way and the Solar position and motion within the Galaxy.

But substructure in tidal streams may also arise from dynamical encounters with dark matter subhaloes. Denis Erkal explained within a mathematical framework how these dark satellites affect stellar streams and what we can learn about dark matter from a single gap in a stream. This will certainly be an important use for tidal streams in the future, since ΛCDM predicts thousands of satellites around Milky-Way-size galaxies, whereas our current number count of luminous satellites lingers around 40–50. Why some satellites contain luminous matter and why most others are probably devoid of baryons has to be understood, if the ΛCDM model of cosmology is to prevail.

With this outlook we ended the streams session and moved on to satellite properties and tidal transformation. From the variety of tidal features around satellites seen in the stream session it became clear that we have to expect many satellites to be tidally affected, altering properties like mass, size and velocity dispersion.

The star cluster–dwarf galaxy interface

Properties of satellites differ substantially, from compact, relatively low-mass globular clusters to extended, high-mass dwarf galaxies with complex chemical compositions. The discovery of transition objects at the star cluster–dwarf galaxy interface has blurred the historical distinction between these satellite classes. Exploring this interesting region in the mass–size plane was therefore an integral part of this workshop.

One of the main questions was the nature of ultra-compact dwarf galaxies (UCDs). Are they massive globular clusters, compact dwarf galaxies or disrupting satellites? In an attempt to answer this question, Carolin Wittman presented imaging data to search for tidal features around low-mass galaxies in galaxy clusters. She found signs of tidal disruption around one UCD. Similarly, Michael West presented data on the M31 satellite G1, which shows clear signs of tidal disruption, and G1 may therefore be a nucleated dwarf galaxy rather than a globular cluster.

Oleg Gnedin showed that globular clusters are fundamentally different from dwarf galaxies. These dense systems formed during galaxy mergers — from the early gas-rich Universe to the present day — following a universal log-normal mass function. Dissolving GCs in the inner regions of galaxies may spiral into the centres and form nuclear star clusters; dissolving GCs in the outer regions of galaxies, such as the Milky Way satellite Crater (the true nature of which is actually still under debate), may appear like ultra-faint dwarf galaxies. Relying on results from numerical simulations, Mike Fellhauer then added that GCs, when brought completely out of virial equilibrium through tidal shocks, can mimic ultra-faint dwarf galaxies (UFDs) like Hercules and Segue 1. In a similar fashion, but with opposite sign, Filippo Contenta presented results from N-body simulations showing that dissolving GCs are unlikely to contribute to the UFD population. But not all star clusters that fall into in the gap between the bulk of GCs and dwarf galaxies within the mass–size plane (Figure 4) are necessarily ultra-faint. Extended outer-halo clusters like Palomar 14 or Crater have half-light radii that are a factor of ten times higher than usual for GCs. Paolo Bianchini weighed the hypothesis that these extended clusters could have been formed as compact within the weaker tidal fields of dwarf galaxies, and then fallen into the Milky Way Halo. He found that such clusters do indeed expand, but not enough to resemble the extended GCs in the Milky Way, leaving their origin as an open question.

What exactly is a galaxy? Several speakers tried to answer this controversial question. Jay Strader defined it as a bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's law of gravity. Referring to previous speakers, he pointed out that a mass-to-light ratio is not a well-defined quantity for systems that are not in virial equilibrium, and, hence, should not be used for this distinction. Instead, he proposed to use metallicity spread as a diagnostic to distinguish a star cluster from a galaxy. It was noted, however, that the existence of a mass–metallicity relation detected in extragalactic GC systems (the blue tilt) suggests metallicity spreads to be a natural feature of massive GCs. Thus, not even a metallicity spread may be a sufficient criterion to define a galaxy. Strader suggested that, until enough data exists, newly found objects should not be named, since otherwise star clusters like Crater end up having names following the Local Group dwarf galaxy naming convention.

In a series of excellent presentations, Dougal Mackey, Duncan Forbes, Jean Brodie and Mark Norris reviewed how the mass–size diagram has filled up over the last few decades (or rather centuries since the first discovery of a GC in 1665). Many of these new objects have been found in M31, and most of those through the PAndAS survey. These data also show that the GCs in the outer halo of M31 are highly correlated with streams, strengthening the accretion scenario. It was also shown that, even though new discoveries of extended clusters have slowly filled up the mass–size plane, the two dominant populations of satellites are still "regular" GCs and dwarf galaxies. Many more of these exotic, extended systems have been found outside the Local Group by the SAGES Legacy Unifying Globulars and GalaxieS (SLUGGS) survey.

Ultra-compact dwarf galaxies

UCDs were, again, the topic of the final day of the meeting. Even after the previous sessions, their origin was still unclear: are they the massive end of the globular cluster mass function, or are they stripped nuclei of dwarf galaxies? The session was a back-and-forth of good arguments for each hypothesis. Michael Hilker pointed out that nuclear star clusters and UCDs fall into the same region of the mass–size plane. He also showed observations of UCDs with clear signs of tidal disruption. Yet he concluded that the number and properties of UCDs seem to be incompatible with them being entirely made up of stripped nuclei. In an attempt to resolve the cluster/galaxy question, Matthias Frank put forward the provocative definition that "a globular cluster is something that is made up of globular cluster stars". With this definition in mind, he found that X-shooter spectra of UCDs put them on the same sequence with GCs, when looking at them in the CN–MgFe plane. With even more ESO data, Karina Voggel found, from a large sample of > 100 Fornax UCDs imaged with the FOcal Reducer and low dispersion Spectrograph (FORS), that their distribution around Fornax follows the distribution of the GCs. She finds an overabundance of GCs in the vicinity of UCDs, which she interprets as support for the stripping scenario — even though less than 20 % show signs of tidal disruption in the form of an extended stellar halo. Mark Norris, furthermore, reasoned that UCDs with an absolute magnitude $M_V < 13$ have to be stripped nuclei, since they lie 5σ away from the cluster luminosity function.

No matter what they are, UCDs are among the most extreme stellar systems. Jean Brodie presented observations of the densest stellar systems in the local Universe. M60-UCD1 and M59-UCD3, being typical examples of these hypercompact clusters, even showing signs of central supermassive black holes. Anil Seth presented integral field unit observations of M60-UCD1, showing that this massive UCD indeed hosts a supermassive black hole that makes up about 15 % of the galaxy's mass. Such overly massive black holes could be explained through tidal stripping of larger dwarf galaxies in a host galaxy potential.

In further presentations on the kinematics of GCs, UCDs, and compact ellipticals (cEs), Mark Norris and Adrien Gouérou demonstrated how important integral field units have become for the investigation of extragalactic compact stellar systems, as they should all be called. In the final presentation of the meeting, Florent Renaud gave a fascinating outlook on how the formation of UCDs and GCs can be traced in high-resolution numerical simulations. He demonstrated how compact stellar systems can expand during galaxy mergers, and form UCD-like objects. The meeting was concluded by the honorary conference photographer Stephane Courteau, who gave an entertaining summary in pictures (and kindly made his conference photos available to the public[2]).

Based on the success of this workshop, the organisers hope that there will be many more Satellites and Streams meetings in the future.

Acknowledgements

The organisers would like to thank Maria Eugenia Gómez, Paulina Jirón, the team of ESO IT and General Services, and the entire Local Organising Committee. Heartfelt thanks go also to ESO's Directorate for Science for supporting this workshop.

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Links

[1] Workshop programme with access to presentations: http://www.eso.org/sci/meetings/2015/Satellites2015/program.html
[2] Gallery of conference photos: http://www.astro.queensu.ca/people/Stephane_Courteau/gallery.php