Report on the ESO Workshop

# Baryons at Low Densities: The Stellar Halos around Galaxies

held at ESO Headquarters, Garching, Germany, 23–27 February 2015

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The workshop (Stellar Halos 2015) focused on theoretical and observational studies of the faint surface brightness envelopes surrounding luminous galaxies. This field of research has gained much attention in recent years owing to the availability of wide-field cameras, deep and large-area surveys, as well as advances in modelling galaxy formation and evolution. The comparison of the observational properties of stellar halos with the predictions from simulations provides important constraints on the formation of luminous galaxies and their assembly history. An overview of the topics covered at the workshop is presented.

Stellar halos are ubiquitous in luminous galaxies. On account of their low surface brightness, detailed study of their physical properties has been difficult and, until recently, confined largely to the Milky Way (MW) and Andromeda (M31). Since the advent of large cameras and surveys, both from ground and space, our knowledge of stellar halos has increased. For several late- and early-type galaxies, astronomers were able to measure the physical properties of their stellar halos out to hundreds of kiloparsecs, or beyond, revealing very low luminosity extended stellar structures, similar to the halos of the MW and its closest neighbouring spiral M31.

Observations show that these halos have complex morphologies with multiple stellar components, complex kinematics and substructures that indicate a history of merger and accretion events. These morphologies resemble the density maps from cosmological simulations of galaxy formation in a hierarchical Universe. Consequently a large amount of effort has been invested in trying to understand how we go from a qualitative resemblance to quantitative measurements of the fractions and frequencies of these substructures.



Figure 1. Participants of the Stellar Halos 2015 workshop in front of the ESO Headquarters building.

The Stellar Halos 2015 workshop brought together around 90 observers and theorists (see Figure 1), who discussed results from space- and ground-based surveys of stellar halos in late- and early-type galaxies and their comparison with the predictions from cosmological simulations. All the presentations were collected and are now posted on the workshop web page[1], under Programme. A short, non-exhaustive, summary of the highlights is presented here.

## What is a galaxy stellar halo?

Guinevere Kauffmann and Annette Ferguson set the stage for the workshop by addressing the question of what a galaxy stellar halo is from theoretical and observational perspectives. Kauffmann described the two main techniques for the theoretical studies of stellar halos: hybrid methods and full hydrodynamical simulations. According to the hierarchical cosmological model of Lambda Cold Dark Matter (ΛCDM), the Milky Way and other large galaxies of similar luminosity should have accreted and subsequently tidally destroyed ~ 200 low-mass galaxies in the past ~ 12 Gyr. The simulated stellar halo images produced by hybrid semi-analytic plus N-body models, such as those shown in Figure 2, from Bullock & Johnston (2005), display the complex structure of the halos as well as long-lived low surface brightness streams. Simula-

tions can now trace the build-up of stellar halos and the evolution of their properties. For example, the projected phase-space diagrams and plots of the line-of-sight velocity *vs*. radial distance relative to the host halo centre, can be used to identify the recent satellite disruption events both in simulations and in data (e.g., the talk by Alessia Longobardi on the extended substructure in the M87 halo — see also Longobardi et al., 2015).

However, not all halo stars are accreted. A fraction of the halo may be formed *in situ*, either by heating the disc stars to halo orbits, or by forming stars in the halo from in-falling gas. The in-falling gas may be stripped from sub-halos that merge with the host galaxy, or enter through direct infall. This dichotomy of "*in situ*" *vs*. "accreted" halos has led to discussions about the dual halo nature that was emphasised by Annalisa Pillepich, who showed results from a new set of simulations called Illustris. Andrew Cooper showed the power of the particle tagging method in making detailed predictions for the statistical properties of stellar halos that directly link CDM structure formation to photometric and spectroscopic halo observations.

Simulated images of stellar halos, like the one shown in Figure 2, can be compared with the observed surface brightness maps around nearby galaxies. Observationally, halos can be studied by stacking images of similarly bright objects, yielding deep photometry of integrated light, and by directly detecting individual stars and
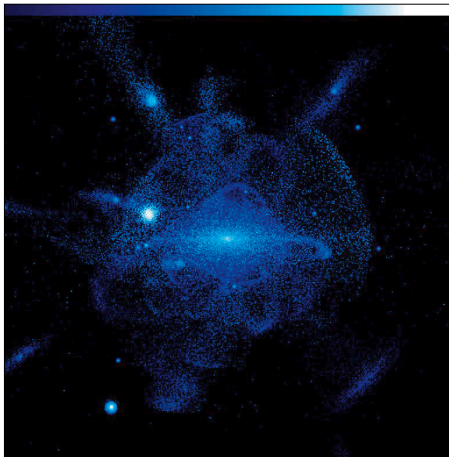
Figure 2. A simulated stellar halo surface brightness image[2] shown with a cut at 40 mag arcsec$^{-2}$ (image from Bullock et al., 2005).

other tracers. Yet, Annette Ferguson emphasised that in order to measure substructures in stellar halos, accurate surface brightness photometry down to $\mu_v \sim 30$ mag arcsec$^{-2}$, i.e., $\sim 9$–10 mag (0.05 %) below the surface brightness of the dark night sky, on angular scales equivalent to $\sim 100$–200 kpc around MW-sized galaxies, is required. This is observationally very challenging! Since different assembly histories for galaxies may lead to complex, heterogeneous and evolving structures, galaxy samples made up of a range of morphological types and environments are also necessary.

## Stellar halos of the Milky Way and Andromeda

The Milky Way and Andromeda are the two nearest large galaxies whose halos are being extensively studied. In his review of the Milky Way stellar halo, Wyn Evans quoted the fundamental observation from Eggen, Lynden-Bell and Sandage (1962): "The time required for stars in the halo to exchange their energies and angular momenta is very long compared with the age of the Galaxy. Hence, knowledge of their present energy and angular momenta tells us something of the initial conditions under which they formed." Such a statement, which is more than half a century old, illustrates very clearly the motivation for studying the dynamics of streams in galaxy halos. For example, the disrupted

Sagittarius dwarf provides ~ 20 % of all the debris of the stellar halo in the Milky Way, including multiple extended stellar streams and of the order of 20 globular clusters. The modelling of this stream constrains the Galaxy potential and its associated mass to ~ $5$–8 × $10^{11}$ $M_\odot$ within 200 kpc, in agreement with the kinematics of halo stars and satellites in the Local Group.

Paula Jofre reported on measurement of the ages of individual stars in the MW halo, demonstrating that they are very old, having been formed 10–12 Gyr ago. The more metal-rich component tends to have a higher fraction of younger stars. There is also a bifurcation in the age–metallicity relation seen in stellar clusters and in field stars at [Fe/H] = –1.4 dex. Giuseppe Bono presented a study of the Galactic Halo metallicity gradient based on a homogeneous set of RR Lyrae stars with accurate distances. The RR Lyrae stars are particularly suitable tracers of the old Galactic Halo, showing a linear shallow metallicity gradient. The younger *in situ* component however is not traced by RR Lyrae stars, which are all at least 10 Gyr old. Future spectroscopic surveys of RR Lyrae stars will also enable comparison with simulations that predict different kinematical signatures for the *in situ vs.* accreted components.

Two large surveys have investigated the stellar halo of M31: the Pan-Andromeda Archeological Survey (PAndAS) and the Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo (SPLASH). The PAndAS results, presented by Rodrigo Ibata, are based on a detailed photometric map extending beyond the 150 kpc radius around M31 and covering also M33, using the Canada-France-Hawaii Telescope (CFHT). The metal-poor halo of Andromeda is found to be smoother than the metal-rich part. Numerous dwarf galaxies and globular clusters as well as streams without clear progenitors, contribute to the network of rich substructure in the halo. Nicolas Martin, from the PAndAS survey, is comparing the Andromeda field of streams to Aquarius simulations, treating the observational and model datasets in a consistent way in order to reconstruct the assembly history of the halo.

Karoline Gilbert presented the SPLASH survey, which has traced the surface brightness profile out to ~ 180 kpc, finding a similar density profile to the PAndAS survey. The spectroscopic identification of more than 1500 M31 halo stars in the SPLASH survey has resulted in determination of the metallicity gradient out to large radii. The stellar density and metallicity profiles indicate that the M31 halo was largely built from one, or a few, relatively massive (> $10^9$ $M_\odot$) accretion events, but at large radii many low-mass accretions have contributed to the recent build-up of the halo. The kinematics of the inner halo stars is however consistent with their origin from the disc — these stars were likely kicked out in a collision with a system similar in size to the Large Magellanic Cloud that collided with M31 ~ 760 Myr ago. The MW and M31 metallicity and α-element abundance gradients provide datasets that can be used as constraints to the simulations, such as those presented, for example, by Andreea Font.

## Stellar halos in galaxies beyond the Local Group

Laura Greggio reviewed the current observational limitations and future opportunities for the studies of stellar halos. She made the case that resolved stellar population studies (single star photometry) should reach well below the red giant branch tip, hence arguing for deep observations. The shapes of the substructures and surface density profiles can then be used to assess the fraction of accreted halo stars and recover the individual galaxy accretion history. The European Extremely Large Telescope (E-ELT) and the James Webb Space Telescope (JWST) will open up the study of resolved stellar halos to ~ 30 Mpc distance, such as red giant stars in the halos of elliptical galaxies in Virgo. This advance will enable detailed studies of a statistically representative sample of large galaxies, and will connect the resolved stellar population to the integrated light studies.

Roelof de Jong and Antonella Monachesi presented detailed physical properties of individual galaxy halos beyond the Local Group for the spiral galaxies in the Hubble Space Telescope GHOSTS (Galaxy Halos

Outer disks Substructure Thick disks Star clusters) survey. The high angular resolution of the Hubble Space Telescope (HST) allows the detection of single stars in halos at larger distances and in denser regions — hence investigating the transition regions between the disc and halo. All MW-like galaxies observed by GHOSTS have extended stellar halos. Their power law profiles have a slope between $-2 < \alpha < -4.5$ over 10–70 kpc. The larger galaxies have fractionally larger envelopes and the inner halos are compact, with Sersic index $n \sim 5$, and are flat ($c/a \sim 0.3$).

Only a half dozen luminous early-type galaxies are close enough to resolve individual stars in the halos and study their properties. Marina Rejkuba summarised the previous studies, most of which concentrated on the nearest giant elliptical galaxy NGC 5128, known also as Centaurus A. The bulk of the stars in the halo of NGC 5128 formed at redshift $z > 2$, and these stars had very fast chemical enrichment, already reaching super-solar metallicity $\sim 12$ Gyr ago. This is the only early-type galaxy in which metallicity and stellar density gradients have been mapped to 25 effective radii, or 140 kpc distance. The halo appears to be elongated with a shallow metallicity gradient and some field-to-field variation in stellar density and metallicity, indicative of possible accretion events. This is not too surprising, since this galaxy is a known merger remnant.

On the other hand NGC 3379, a giant elliptical in the Leo group, has little or no indication of being disturbed or having recently accreted stars in its halo. Beyond $\sim 12$ effective radii in this galaxy there is a break in the metallicity distribution and the metal-poor component, which is typically associated with halos, starts to dominate. Mark Peacock presented the results from his HST study of NGC 3115, where there is also quite a high mean metallicity, extending to very large distances in the halo: the metallicity decreases from $-0.65$ to $-0.8$ dex between 15–60 kpc (6–23 effective radii). However, a distinct metal-poor population is identified in the two outer fields and its profile is found to trace the density profile of the metal-poor globular clusters. The metal-poor halo population mass fraction is $\sim 14$ % of the total halo mass in NGC 3115.
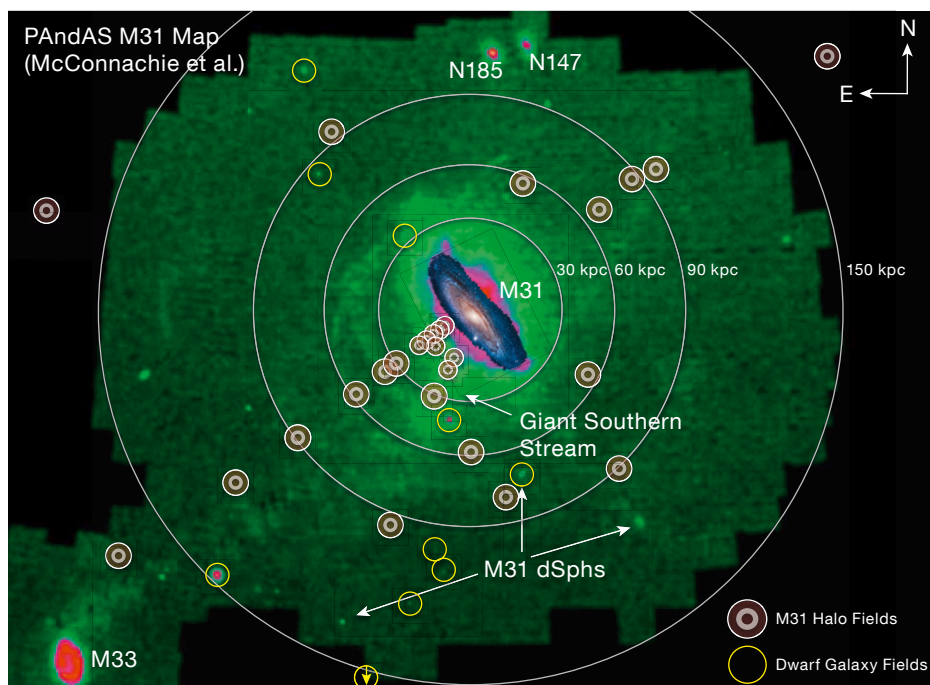


Figure 3. Map of the stellar counts in the Andromeda galaxy M31 from the PAndAS survey (McConnachie et al., 2009) with overlayed spectroscopic observation target fields from the SPLASH survey[3].

More distant early-type galaxies, in the Virgo and Fornax clusters, have too high a density of stars for accurate resolved stellar population studies, hence deep surface brightness observations are favoured for the study of their faint envelopes. Chris Mihos has traced the envelope of M49 at the centre of the Virgo subcluster B out to $\sim 150$ kpc. A steep bluer colour gradient has been measured in the outer regions indicating a very high fraction of metal-poor stars in its outskirts. Enrichetta Iodice and Marilena Spavone examined the extended envelopes of individual Virgo and Fornax cluster galaxies from VLT Survey Telescope and OmegaCAM guaranteed time observation programmes. The CFHT was used by Pierre-Alain Duc to systematically survey the extended regions around galaxies whose internal kinematics and stellar populations were observed by the ATLAS[3D] project. Several instrumental effects may limit the accuracy of these measurements: flat-fielding, scattered light, corrections due to the wings of the point spread function and halos due to internal reflections in the camera, as well as Galactic cirrus, must be taken into account.

Nevertheless tremendous progress has been achieved and there are ever-larger samples of galaxies where faint halos and streams are detected.

Particularly impressive accretion streams were presented by David Martinez-Delgado, based on imaging with small (0.1–0.5 metre) robotic telescopes. These observations reveal structures around galaxies with a striking resemblance to those shown by cosmological simulations of structure formation. Richard D'Souza presented the statistical properties of stellar halos. By carefully stacking a very large number of galaxies, he found that the stellar halos of late-type galaxies tend to be spherical, while those of early-type galaxies tend to be elliptical. The ellipticity increases with stellar mass, and also the fraction of light in the outskirts is higher in the more massive galaxies. The surface density profiles agree with the results from simulations using particle-tagging methods.

Magda Arnaboldi, Pat Durrell and Jean Brodie presented the use of discrete tracers, like planetary nebulae and globular clusters, to study the physical properties of the extended halos. Durrell and Brodie illustrated how red and blue globular clusters trace different components in the halos. The red globular

cluster populations have number density profiles similar to that of the stars, while the blue globular clusters are spatially more extended and seem to trace the metal-poor halo component. Arnaboldi showed the overlap of the M87 halo and the intracluster light in the radial range between 20 to 150 kpc from the centre of M87, and how the planetary nebulae luminosity function is used to identify the star-forming (metal-poor) stellar population *vs.* the old and metal-rich one. Michael Hilker showed that there are different sub-populations of globular clusters in the distant central galaxy in the Hydra cluster that trace different assembly epochs. The origin of ultra-compact dwarfs around NGC 1399, the central galaxy of the Fornax cluster was presented by Karina Voggel. Ortwin Gerhard, Nicola Napolitano and Eric Emsellem described the kinematics of stars, their angular momentum and orbital distribution in galaxies from the centre out to ten effective radii.

While the stellar mass is a strongly non-linear function of the galaxy halo mass, due to the large contribution of dark matter in the least and the most massive galaxies, the total mass of all globular clusters correlates linearly with the mass of the halo, as shown by Bill Harris. This is explained if globular cluster formation is largely immune to the feedback that affects star formation in the field, or if the formation of globular clusters is completed before the feedback starts.

## Prospects

During the final discussion, the obvious energy and enthusiasm testified that this field of research had gained substantial momentum! The observational samples are growing and we are starting to make quantitative comparison of the properties of halos inferred by different observational techniques with the simulations. The importance of consistent comparisons was emphasised yet again: there are different ways to define a stellar halo — including or excluding the streams and accreted material — which then lead to different halo properties. Hence the halo properties need to be studied in a homogeneous and unbiased way, by applying a consistent treatment to observations and theory/simulations. Lively discussions during the workshop, after every talk, during coffee breaks, and the vibrant atmosphere during the final gathering around *Bier und Bretz'n*, resulted in new ideas, new collaborations and projects for future advances in the field.

### References

Bullock, J. S. & Johnston, K. V. 2005, ApJ, 635, 931
Eggen, O. J., Lynden-Bell, D. & Sandage, A. R. 1962, ApJ, 136, 748
Longobardi, A. et al. 2015, A&A, in press, arXiv:1504.04369
McConnachie, A. W. et al. 2009, Nature, 461, 66

### Links

[1] Workshop programme: http://www.eso.org/sci/meetings/2015/StellarHalos2015/program.html
[2] Image of simulated stellar halo: http://www.physics.uci.edu/~bullock/StellarHalo/halo.html
[3] Annotated image of M31: https://blogs.stsci.edu/universe/2014/07/21/what-built-andromedas-stellar-halo/

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Report on the ESO Workshop

# Dissecting Galaxies Near and Far

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The workshop explored high-resolution perspectives for the understanding of star formation and the interstellar medium in the era of ALMA. Angular and spectral resolutions are fundamental limitations for our understanding of the properties of galaxies in the nearby and distant Universe. A new generation of instruments and powerful observatories, as well as planned future facilities, is pushing out the boundaries of what was previously possible over the entire electromagnetic spectrum. Held in the approach to ALMA Early Science Cycle 3, the workshop centred on discussing the scientific results and upcoming opportunities afforded by the new capabilities available in the era of ALMA. Some of the science highlights of the meeting are presented.

The advent of state-of-the-art facilities with high angular resolution and/or high spectral resolution capabilities, coupled with high sensitivity, such as the Atacama Large Millimeter/submillimeter Array (ALMA), allows the interstellar medium (ISM) and star formation properties of galaxies at intermediate redshift to be probed in unprecedented detail, along with their counterparts in the local Universe.

The aim of the workshop was to bring together astronomers whose interests further our understanding of star formation and ISM processes at high spatial and spectral resolution, both in nearby and distant galaxies. The theme of "dissecting galaxies" was intended not only to encompass what we can learn by going to higher spatial and spectral resolution, but also, in the true sense of the word "dissect", what we can learn about galaxies when we methodically break them down into their constituent