

Chapter 2

Resolved Stellar Populations as Tracers of Outskirts

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Abstract Galaxy haloes contain fundamental clues about the galaxy formation and evolution process: hierarchical cosmological models predict haloes to be ubiquitous and to be (at least in part) the product of past merger and/or accretion events. The advent of wide-field surveys in the last two decades has revolutionized our view of our own Galaxy and its closest “sister”, Andromeda, revealing copious tidal streams from past and ongoing accretion episodes, as well as doubling the number of their known faint satellites. The focus shall now be shifted to galaxy haloes beyond the Local Group: resolving individual stars over significant areas of galaxy haloes will enable estimates of their ages, metallicities and gradients. The valuable information collected for galaxies with a range of masses, morphologies and within diverse environments will ultimately test and quantitatively inform theoretical models of galaxy formation and shed light onto the many challenges faced by simulations on galactic scales.

2.1 The Importance of Haloes

Our understanding of galaxy formation and evolution has dramatically evolved in the past 50 years. The first and simplest idea for the formation scenario of our own Milky Way (MW) Galaxy was put forward by Eggen et al. (1962), who proposed the bulk of a stellar halo to be formed in a rapid collapse of gas in the protogalaxy. This scenario, often referred to as “monolithic” collapse, is a dissipative process and takes place on dynamical timescales of the order of $\sim 10^8$ years. This process gives birth to a metal-poor stellar component in the halo outer regions, while the inner regions end up being more metal rich due to the reprocessing of the gas as it collapses deeper into the protogalaxy potential well. This idea was later challenged by an alternative explanation, based on the observation that globular clusters (GCs) at different galactocentric distances have a wide range of metallicities. In this scenario, the halo

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is formed on longer timescales ($\sim 10^9$ years), and instead of being a self-contained system, it comes together as the product of several protogalactic fragments (Searle and Zinn 1978). These fragments can be pre-enriched before they are accreted. While both scenarios are capable of explaining many observed quantities of the Galactic halo, they cannot individually give a comprehensive picture (Norris and Ryan 1991; Chiba and Beers 2000), which has led to the development of hybrid “two-phase” models. In the latter, the inner Galaxy regions are formed in a first phase as a result of a monolithic-like process, while the outer halo regions are built up over the Galaxy’s lifetime through dissipationless accretion events (Freeman and Bland-Hawthorn 2002).

In the past couple of decades, the most widely accepted paradigm of the hierarchical Lambda-Cold Dark Matter (Λ CDM) structure formation model has prevailed, favouring the predominance of merger and accretion events in the build-up of galactic haloes (White and Frenk 1991; Bullock and Johnston 2005; Springel et al. 2006; Johnston et al. 2008). These models predict the ubiquitous presence of haloes, which are characterized by old and metal-poor populations and often show signs of recent interactions, in contrast with the smooth haloes predicted by dissipative models (Bullock and Johnston 2005; Abadi et al. 2006; Font et al. 2006). The interaction events provide a mine of information on the assembly of haloes: dynamical timescales become relatively long (up to several Gyr) in the outer regions of a galaxy, and thus accretion/merger events that occurred a long time ago are often still visible as coherent structures like disrupting galaxies or streams, which readily testify the past assembly history of their host. The assembly itself depends on a variety of factors, such as number, mass, stellar content and structural properties of the accreted satellites, as well as orbital properties, timing and energy of the accretion event. Even when the progenitor is completely dissolved in the host’s halo (which is particularly true in the inner halo regions where dynamical timescales are relatively short), its stripped stellar content still retains a characteristic coherence in velocity space as well as in metallicity content, thus giving important clues about the progenitor’s properties. Observing the stellar “fossils” that populate galaxy haloes thus offers a unique opportunity to reconstruct the modes, timing and statistics of the halo formation process.

Besides being tellers of their host system’s merger history, the shape and size of haloes also hold vital clues to the process of galaxy formation. In particular, they can teach us about the primordial power spectrum of density fluctuations at the smallest scales, about the reionization process that shall lead to faint and concentrated haloes for an early suppression of star formation in low-mass dark matter (DM) subhaloes or about the triaxiality of DM haloes, which are predicted to be more flattened for dissipationless formation scenarios (Abadi et al. 2006). Despite only accounting for a mere $\sim 1\%$ of a galaxy’s total mass (e.g. Morrison 1993), extended haloes are clearly extremely valuable to test and refine theoretical predictions on the halo assembly process. Due to their extreme faintness, however, haloes have not been as fully exploited as they should have been as key tests of galaxy formation models: they are not easily detected above the sky level, i.e.

surface brightness values of $\mu_V \sim 25 \text{ mag arcsec}^{-2}$, posing a serious observing challenge to their investigation. Cosmological simulations predict the majority of past and ongoing accretion events to have surface brightness values well below this value (e.g. Bullock and Johnston 2005). According to some models, reaching a surface brightness of $\mu_V \sim 29 \text{ mag arcsec}^{-2}$ should allow the detection of at least one stream per observed galaxy (Johnston et al. 2008; Cooper et al. 2010). How is it then possible to extract the information locked in the faint outskirts of galaxies?

2.1.1 Resolved Stellar Populations

The best method to study faint haloes and their substructure in nearby galaxies is to resolve individual stars. Even when sparse and faint, resolved stars can be individually counted, and a stellar number density can easily be converted into a surface brightness value. When the Galactic extinction presents a high degree of spatial inhomogeneity (possibly mimicking faint irregular substructures), and the sky level is higher than the integrated light signal coming from extremely faint sources, resolved populations provide a very powerful means to trace them. This method is not free from complications: there will always be contamination coming both from foreground Galactic stars and from background unresolved galaxies. This can be accounted for statistically, by observing “field” regions away from the main target and quantifying the contaminants, while a direct confirmation of a star’s membership requires spectroscopy. At the same time, resolving individual stars poses constraints on the inherent nature and on the distance of the putative targets: for systems where the stellar density is so high that stars fall on top of each other on the sky, the “crowding” prevents the resolution of individual objects. This can of course occur also in the case of a relatively sparse galaxy which has a large line-of-sight distance, so that the stars are packed in a small region of the sky. Distance is also the principal enemy of depth: the larger the distance, the brighter the detection limit, i.e. the absolute magnitude/surface brightness that we can reach for a fixed apparent magnitude. Nonetheless, resolved stellar populations are able to deliver powerful information for galaxies located within $\sim 10 \text{ Mpc}$, i.e. within the so-called Local Volume.

The discovery of the Sagittarius dwarf galaxy by Ibata et al. (1994) from the identification of a co-moving group of stars opened the door to the era of halo studies and their substructure: a galaxy resembling the properties of classical dwarf spheroidals was clearly in the process of being disrupted by its giant host, our own MW. This evidence was the first to support theoretical predictions for the hierarchical assembly models and the existence of observable accretion events. Soon thereafter, stellar density maps allowed the discovery of a prominent low surface brightness stream around the MW’s closest giant spiral Andromeda (M31), the so-called giant stellar stream (Ibata et al. 2001). This feature, invisible to the naked eye, is a clear example of the elusive nature of haloes and their substructure: the surface

brightness of the giant stellar stream is $\mu_V \sim 30 \text{ mag arcsec}^{-2}$, which is prohibitive for integrated light images.

As challenging as it is, the mere detection of haloes and their substructures is not enough to provide quantitative constraints on models of galaxy evolution. From the stars' photometry and thus position in the colour-magnitude diagram (CMD), i.e. the observational counterpart of the Hertzsprung-Russell diagram, it is possible to characterize the properties of the considered stellar system. First and foremost, in contrast to integrated light, accurate distance measurements can be obtained from CMD features that act as standard candles, e.g. the luminosity of the tip of the red giant branch (TRGB) or of the horizontal branch (HB). Another key advantage of resolved populations is the possibility to constrain ages and metallicities more tightly than with integrated light alone. The CMD is used to quantify the star formation rate as a function of lookback time and thus derive the star formation history (SFH) of a composite stellar population (e.g. Gallart et al. 2005, and references therein). Spectroscopy of individual stars is the ultimate method to constrain their metallicity content and kinematical properties, such as radial velocity and proper motion, which allows for the full six-dimensional phase space to be investigated. The latter cannot, for the moment, be achieved beyond the LG limits and still only occasionally for M31.

Besides giving precious insights into galaxy haloes and their accretion histories, resolved stellar populations can help us in characterizing the “surviving” low-mass galaxies that have not been accreted to date and reside in the outskirts of giant hosts.

2.1.2 The Low-Mass End of the Galaxy Luminosity Function

The low-mass end of the galaxy luminosity function (LF) is of no less interest than haloes themselves. Besides the MW and M31, the Local Group (LG) contains tens of smaller galaxies which can be studied in detail due to their proximity (see Tolstoy et al. 2009 for a review). While the Λ CDM cosmological model has provided a convincing match to the large-scale structures observed in the high-redshift Universe, it falls short at the smallest, galactic scales, indicating an incomplete understanding of the physics involved in the evolution of galaxies: for example, the “missing-satellite problem” has been highlighted for the first time by Moore et al. (1999) and Klypin et al. (1999). Briefly, the number of DM subhaloes predicted in simulations exceeds the observed number of MW satellites by almost two orders of magnitude. The shape of the DM profile in the innermost regions of dwarf galaxies is also a matter of debate (the “cusp-core” problem; Walker and Peñarrubia 2011). In addition, the more massive among the MW satellites are less dense than what is expected from simulations, which is puzzling because they should be affected by fewer observational biases than their smaller, sparser siblings (the “too-big-to-fail” problem; Boylan-Kolchin et al. 2011). In addition, the fact that many of the

MW and M31 satellites are distributed along planes does not have a straightforward explanation in Λ CDM models (e.g. Pawlowski et al. 2014).

From the theoretical point of view, the inclusion of baryonic physics in DM-only simulations is key to reconcile predictions with observations of the smallest galaxies. In particular, effects such as supernova feedback, stellar winds, cosmic reionization and tidal/ram pressure stripping all concur to reduce star formation efficiency in the least massive DM haloes. Tremendous progress is being made on this front, taking into account realistic physics as well as increasing the resolution of simulations (e.g. Stinson et al. 2009; Brooks et al. 2013; Sawala et al. 2016; Wetzel et al. 2016). At the same time, new observational discoveries keep offering intriguing challenges at the smallest galactic scales, as further described in Sects. 2.2.1.3 and 2.2.2.3.

2.2 Local Group

The galaxies closest to us give us the most detailed information because of the large number of stars that can be resolved. Here, I will summarize what we have learnt in the past two decades about our own Galaxy (even though an extensive picture of the MW outskirts goes beyond the scope of this contribution and can be found in Figueras 2017), about its closest spiral neighbour M31 and about their lower-mass satellites.

2.2.1 Milky Way

The MW is traditionally divided into discrete components, i.e. the bulge, the disks (thin and thick) and the halo. The spheroidal portion of the MW is given by the central bulge, which consists mainly of metal-rich populations, and an extended diffuse component, which has a lower mean metallicity. Overall, stars and GCs in the halo have ages $\sim 11\text{--}13$ Gyr (Carollo et al. 2007). The halo can be further deconstructed into an inner halo and an outer halo, even though the distinction could partly arise from observational biases (Schönrich et al. 2014). The inner and outer haloes also seem to have different chemical composition ($[\text{Fe}/\text{H}] \sim -1.6$ and $[\text{Fe}/\text{H}] \sim -2.2$, respectively; Ryan and Norris 1991; Carollo et al. 2007). According to simulations, the two halo components should also have formed on different timescales: the inner halo (<20 kpc) is partly constituted by early-formed in situ stars, partly due to a violent relaxation process and partly assembled from early, massive merging events that provide metal-rich populations (Abadi et al. 2006; Font et al. 2011; Tissera et al. 2013; Pillepich et al. 2014; Cooper et al. 2015); the outer halo is assembled more recently, with its mass beyond ~ 30 kpc being mainly accreted in the past ~ 8 Gyr (Bullock and Johnston 2005; Cooper et al. 2010). These predictions are, however, still not sufficient at a quantitative level and unconstrained

as to the exact ratio of accreted stars versus in situ populations. At the same time, observations of the MW halo with better statistics and precision are needed to inform them.

Our position within the MW puts us at a clear disadvantage for global studies of its outskirts: the distant and sparse halo stars are observed from within the substantial disk component, which produces contamination both in terms of extinction and numerous disk stars along the line of sight, which completely “obscure” the sky at low Galactic latitudes. Nonetheless, thanks to the advent of wide-field imagers, the past two decades have revolutionized the large-scale view of our Galaxy. Several stellar tracers can be used to dig into the MW halo at different distance ranges: old main sequence turnoff (MSTO) stars are identified mostly out to ~ 20 kpc and brighter RGB stars out to ~ 40 – 50 kpc, while RR Lyrae and blue horizontal branch (BHB) stars can be detected out to 100 kpc. Spatial clustering of these stellar components indicates non-mixed substructure, which is often confirmed to be kinematically coherent.

2.2.1.1 The Emergence of Streams

After the cornerstone discovery of the disrupting Sagittarius dwarf, it became clear that substructure is not only present in the MW halo, but it also might constitute a big portion of it. To put it in Majewski’s words (Majewski 1999),

There is good reason to believe that within a decade we will have a firm handle on the contribution of satellite mergers in the formation of the halo, as we move observationally from serendipitous discoveries of circumstantial evidence to more systematic surveys for the fossils left behind by the accretion process.

In the following decade, several streamlike features have indeed emerged from a variety of multiband photometric and spectroscopic surveys, and the Sloan Digital Sky Survey (SDSS) proved to be an especially prolific mine for such discoveries around the northern Galactic cap. The Sagittarius Stream has been traced further, including in the Galactic anti-centre direction (e.g. Mateo 1998; Majewski et al. 2003), and independent substructures have been uncovered (Ivezić et al. 2000; Yanny et al. 2000; Newberg et al. 2002; Grillmair 2006; Jurić et al. 2008), most notably the Monoceros Ring, the Virgo Overdensity, the Orphan Stream and the Hercules-Aquila Cloud. Some of these have later been confirmed to be coherent with radial velocities (Duffau et al. 2006). Note that most of these substructures are discovered at galactocentric distances > 15 kpc, while the inner halo is smooth due to its shorter dynamical timescales.

During the past decade, one of the most stunning visualizations of the ongoing accretion events in the MW halo was provided by the Field of Streams (Belokurov et al. 2006), reproduced in Fig. 2.1. The stunning stellar density map is derived from SDSS data of stars around the old MSTO at the distance of Sagittarius, with a range of magnitudes to account for a range in distances. This map not only shows the Sagittarius Stream and its distance gradient but also a plethora

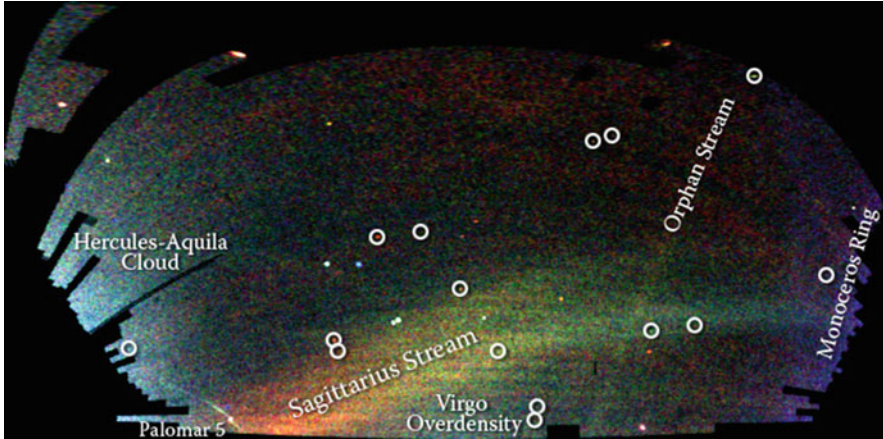


Fig. 2.1 Spatial density of SDSS stars around the Galactic cap, binned in $0.5 \times 0.5 \text{ deg}^2$; the colour scale is such that *blue* indicates the nearest stars, while *red* is for the furthest ones. *Labelled* are the main halo substructures, which are in some cases streams associated with a GC or a dwarf galaxy; the *circles* show some newly discovered dwarf satellites of the MW. Plot adapted from Belokurov et al. (2006) (http://www.ast.cam.ac.uk/~vasily/sdss/field_of_streams/dr6/)

of less massive streams, as well as an abundance of previously unknown dwarf satellites (see Sect. 2.2.1.3). The Field of Streams has been now complemented with results from the latest state-of-the-art surveys, most notably the all-sky Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), which covers an area significantly larger than that of SDSS. In Fig. 2.2 the first stellar density maps from Pan-STARRS are shown, obtained in a similar way as the Field of Streams (Bernard et al. 2016). The map highlights the fact that the deeper and wider we look at the Galaxy halo, the more substructures can be uncovered and used to constrain its past accretion history and the underlying DM halo properties. From this kind of maps, for example, the halo stellar mass that lies in substructures can be estimated, amounting to $\sim 2\text{--}3 \times 10^8 M_{\odot}$ (see Belokurov 2013). Using SDSS, Bell et al. (2008) also highlight the predominant role of accretion in the formation of the MW’s halo based on MSTO star counts, adding to up to $\sim 40\%$ of the total halo stellar mass (note that, however, different tracers could indicate much smaller values, e.g. Deason et al. 2011).

Many of the known halo streams arise from tidally disrupting GCs, of which Palomar 5 is one of the most obvious examples (Odenkirchen et al. 2001). This demonstrates the possible role of GCs, besides dwarf satellites, in building up the halo stellar population and additionally implies that some of the halo GCs may be stripped remnants of nucleated accreted satellites (see Freeman and Bland-Hawthorn 2002, and references therein). In order to discern between a dwarf and a cluster origin of halo stars, we need to perform chemical “tagging”, i.e. obtain spectroscopic abundances for tens of elements for these stars (e.g. Martell and Grebel 2010): stars born within the same molecular cloud will retain the same

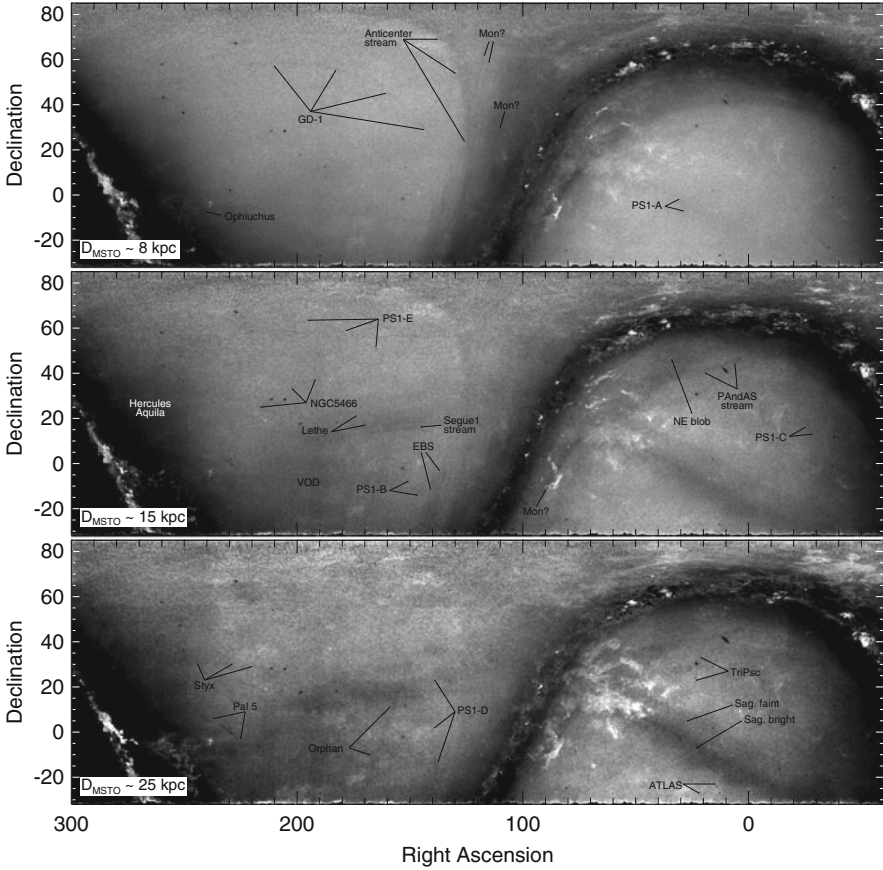


Fig. 2.2 Stellar density maps of the whole Pan-STARRS footprint, obtained by selecting MSTO stars at a range of heliocentric distances (as indicated in each panel). The map is on a logarithmic scale, with *darker areas* indicating higher stellar densities. The many substructures are highlighted in each panel. Reproduced from Bernard et al. (2016), their Fig. 1, with permission of MNRAS

chemical composition and allow us to trace the properties of their birthplace. A number of ambitious ongoing and upcoming spectroscopic surveys (SEGUE, APOGEE, Gaia-ESO, GALAH, WEAVE, 4MOST) are paving the path for this promising research line, even though theoretical models still struggle to provide robust predictions for the fraction of GC stars lost to the MW halo (e.g. Schiavon et al. 2016, and references therein).

2.2.1.2 The Smooth Halo Component

Once the substructure in the halo is detected, it is important that it is “cut out” in order to gain insights into the smooth, in situ stellar component (note that, however,

the latter will inevitably suffer from residual contamination from accreted material that is now fully dissolved). The stellar profile of the Galactic halo is, in fact, not smooth at all: several studies have found a break at a radius ~ 25 kpc, with a marked steepening beyond this value (Watkins et al. 2009; Sesar et al. 2013), in qualitative agreement with halo formation models. Some of the explanations put forward suggest that a density break in the halo stellar profile is the likely consequence of a massive accretion event, corresponding to the apocentre of the involved stars (Deason et al. 2013).

The kinematics of halo stars, of GCs and of satellite galaxies, as well as the spatial distribution of streams and tidal features in satellites, can be further used as mass tracers for the DM halo. The total MW mass is to date still poorly constrained, given the difficulty of evaluating it with a broad range of different tracers. The general consensus is for a virial mass value of $\sim 1.3 \pm 0.3 \times 10^{12} M_{\odot}$, even though values discrepant up to a factor of two have recently been suggested (see Bland-Hawthorn and Gerhard 2016 for a compilation of estimates). Besides providing estimates for the total MW mass, studies of SDSS kinematical data, of the Sagittarius Stream and of GC tidal streams have provided discording conclusions on the shape of the MW DM halo: nearly spherical from the modelling of streams or strongly oblate from SDSS kinematics at galactocentric distances < 20 kpc, while nearly spherical and oblate based on stream geometry or prolate from kinematical arguments for distances as large as ~ 100 kpc (see Bland-Hawthorn and Gerhard 2016 for details). These constraints need a substantial improvement in the future to be able to inform cosmological models: the latter predict spherical/oblate shapes once baryons are included in DM-only flattened haloes (see Read 2014).

2.2.1.3 Dwarf Satellites

As mentioned above, the SDSS has revolutionized our notions of dwarf satellites of the MW. Bright enough to be easily recognized on photographic plates, a dozen “classical” MW dwarf satellites has been known for many decades before the advent of wide-field surveys (Mateo 1998; Grebel et al. 2000). Starting with the SDSS, an entirely new class of objects has started to emerge with properties intermediate between the classical dwarfs and GCs (see Willman 2010, and references therein). The so-called ultra-faint satellites have magnitudes higher than $M_V \sim -8$ and surface brightness values so low that the only way to find them is to look for spatial overdensities of resolved main sequence/BHB stars. Their discovery 10 years ago doubled the number of known MW satellites and revealed the most DM-dominated galaxies in the Universe, with mass-to-light ratios of up to several times $10^3 M_{\odot}/L_{\odot}$ (Simon and Geha 2007).

More recently, the interest in the low end of the galaxy LF has been revitalized once again with deep, wide-field surveys performed with CTIO/DECam, VST/OmegaCAM and Pan-STARRS: these have led to the discovery of more than 20 southern dwarfs in less than 2 years (Bechtol et al. 2015; Koposov et al. 2015; Kim et al. 2015; Drlica-Wagner et al. 2015; Torrealba et al. 2016, and

references therein). Some of these discoveries represent extremes in the properties of MW satellites, with surface brightness values as low as $\sim 30 \text{ mag arcsec}^{-2}$, total luminosities of only a few hundred L_{\odot} and surprisingly low stellar density regimes. One of the perhaps most intriguing properties of the newly discovered dwarfs is that many of them appear to be clustered around the Large Magellanic Cloud (LMC): this might be the smoking gun for the possible infall of a group of dwarfs onto the MW, which is predicted by simulations (D’Onghia and Lake 2008; Sales et al. 2016). Low-mass galaxies are expected to have satellites on their own and to provide a large fraction of a giant galaxy’s dwarf companions (e.g. Wetzel et al. 2015). The properties of the possible LMC satellites will give us a glimpse onto the conditions of galaxy formation and evolution in an environment much different from the LG as we know it today.

These faintest galaxies, or their accreted and fully dispersed counterparts, are also excellent testbeds to look for the very most metal-poor stars and to investigate the star formation process in the early stages of the Universe (e.g. Frebel and Norris 2015). The study of the lowest mass galaxies holds the promise to challenge our knowledge of galaxy physics even further and pushes us to explore unexpected and exciting new limits.

2.2.2 M31 (*Andromeda*)

Our nearest giant neighbour has received growing attention in the past decade. Having a remarkable resemblance with the MW and a comparable mass (e.g. Veljanoski et al. 2014), it is a natural ground of comparison for the study of spiral haloes. In terms of a global perspective, the M31 halo is arguably known better than that of the MW: our external point of view allows us to have a panoramic picture of the galaxy and its surrounding regions. The other side of the medal is that, at a distance of $\sim 780 \text{ kpc}$, we can only resolve the brightest evolved stars in M31, and we are mostly limited to a two-dimensional view of its populations. Its proximity also implies a large angular size on the sky, underlining the need for wide field-of-view imagers to cover its entire area.

At the distance of M31, ground-based observations are able to resolve at best the uppermost $\sim 3\text{--}4$ magnitudes below the TRGB, which is found at a magnitude $i \sim 21$. The RGB is an excellent tracer for old ($> 1 \text{ Gyr}$) populations, but suffers from a degeneracy in age and metallicity: younger, metal-rich stars overlap in magnitude and colour with older, metal-poor stars (Koch et al. 2006). Despite this, the RGB colour is often used as a photometric indicator for metallicity, once a fixed old age is assumed (VandenBerg et al. 2006; Crnojević et al. 2010). This assumption is justified as long as a prominent young and intermediate-age population seems to be absent (i.e. as judged from the lack of luminous main sequence and asymptotic giant branch, AGB, stars), and it shows very good agreement with spectroscopic metallicity values where both methods have been applied.

The very first resolved studies of M31's halo introduced the puzzling evidence that the M31 halo stellar populations along the minor axis have a higher metallicity than that of the MW at similar galactocentric distances (e.g. Mould and Kristian 1986). This was further confirmed by several studies targeting projected distances from 5 to 30 kpc and returning an average value of $[\text{Fe}/\text{H}] \sim -0.8$: in particular, Durrell et al. (2001) study a halo region at a galactocentric distance of ~ 20 kpc and underline the difference between the properties of M31 and of the MW, suggesting that our own Galaxy might not represent the prototype of a typical spiral. In fact, it has later been suggested that the MW is instead fairly atypical based on its luminosity, structural parameters and the metallicity of its halo stars when compared to spirals of similar mass (Hammer et al. 2007). This result was interpreted as the consequence of an abnormally quiet accretion history for the MW, which apparently lacked a major merger in its recent past.

The wide-area studies of M31's outskirts were pioneered ~ 15 years ago with an Isaac Newton Telescope survey mapping $\sim 40 \text{ deg}^2$ around M31, reaching significantly beyond its disk out to galactocentric distances of ~ 55 kpc (Ibata et al. 2001; Ferguson et al. 2002). As mentioned before, the southern Giant Stream was first uncovered with this survey, and the halo and its substructures could be studied with a dramatically increased detail. A metal-poor halo component ($[\text{Fe}/\text{H}] \sim -1.5$) was finally uncovered for regions beyond 30 kpc and out to 160 kpc (Irwin et al. 2005; Kalirai et al. 2006; Chapman et al. 2006), similar to what had been observed for the MW both in terms of metallicity and for its stellar density profile. These studies do not detect a significant gradient in metallicity across the covered radial range. Nonetheless, the properties of the inner halo remained a matter of debate: while Chapman et al. (2006) found a metal-poor halo population within 30 kpc above the disk, Kalirai et al. (2006) analysed a kinematically selected sample of stars within 20 kpc along the minor axis and derived a significantly higher value of $[\text{Fe}/\text{H}] \sim -0.5$. At the same time, Brown et al. (2006) used deep, pencil-beam *Hubble Space Telescope* (HST) pointings in M31's inner halo to conclude that a significant fraction of its stellar populations have an intermediate age with an overall high metallicity. These results were later interpreted by Ibata et al. (2007) in light of their wider-field dataset: the samples from Kalirai et al. (2006) and Brown et al. (2006) are simply part of regions dominated by an extended disk component and with a high contamination from various accretion events, respectively. This underlines, once again, the importance of wide-field observations to reach a global understanding of halo properties.

The M31 INT survey was further extended out to 150 kpc (200 kpc in the direction of the low-mass spiral M33) with the Canada-France-Hawaii Telescope/Megacam and dubbed Pan-Andromeda Archaeological Survey (PAndAS; Ibata et al. 2007; McConnachie et al. 2009). This survey contiguously covered an impressive 380 deg^2 around M31, reaching 4 mag below the TRGB. The PAndAS RGB stellar density map (see Fig. 2.3) is a striking example of an active accretion history, with a copious amount of tidal substructure at both small and large galactocentric radii. PAndAS also constituted a mine for the discovery of a number of very faint satellites and GCs (see below; Richardson et al. 2011; Huxor et al. 2014; Martin et al. 2016).

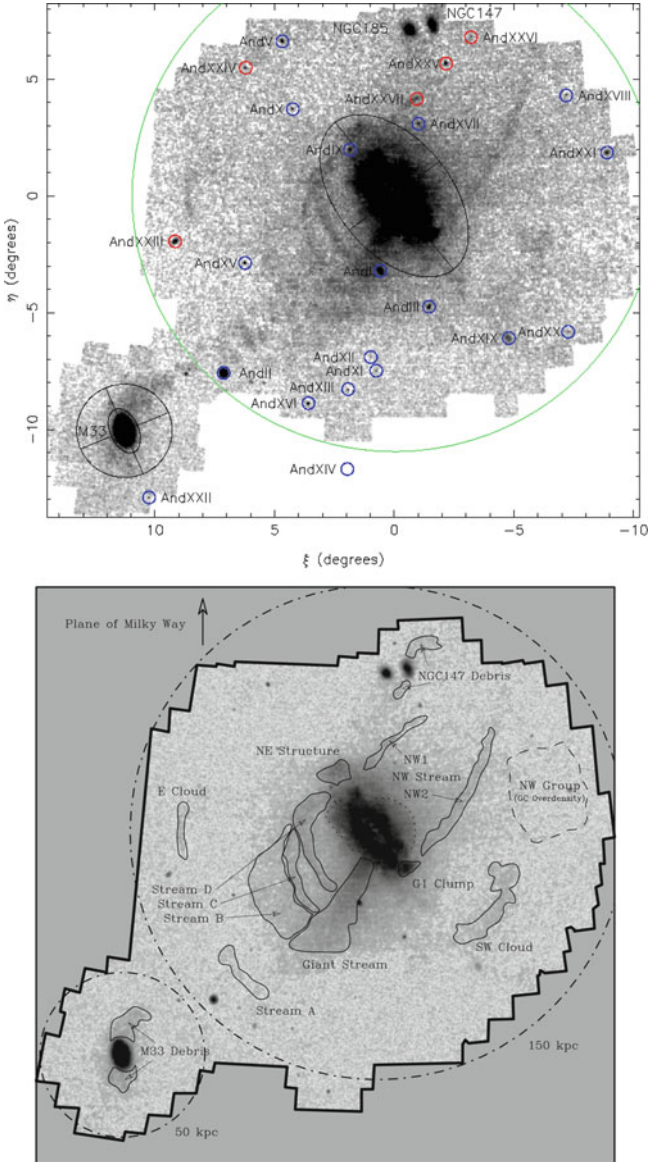


Fig. 2.3 Stellar density maps of metal-poor RGB populations at the distance of M31, as derived from the PAndAS survey. The *large circles* lie at projected radii of 150 kpc and 50 kpc from M31 and M33, respectively. *Upper panel*: The Andromeda satellites are visible as clear overdensities and are marked with *circles*. The vast majority of them were uncovered by the PAndAS survey. Reproduced by permission of the AAS from Richardson et al. (2011), their Fig. 1. *Lower panel*: The main substructures around M31 are highlighted, showcasing a broad range of morphologies and likely progenitor type. Tidal debris is also present in the vicinities of the low-mass satellites M33 and NGC 147, indicating an ongoing interaction with M31. Reproduced by permission of the AAS from Lewis et al. (2013), their Fig. 1

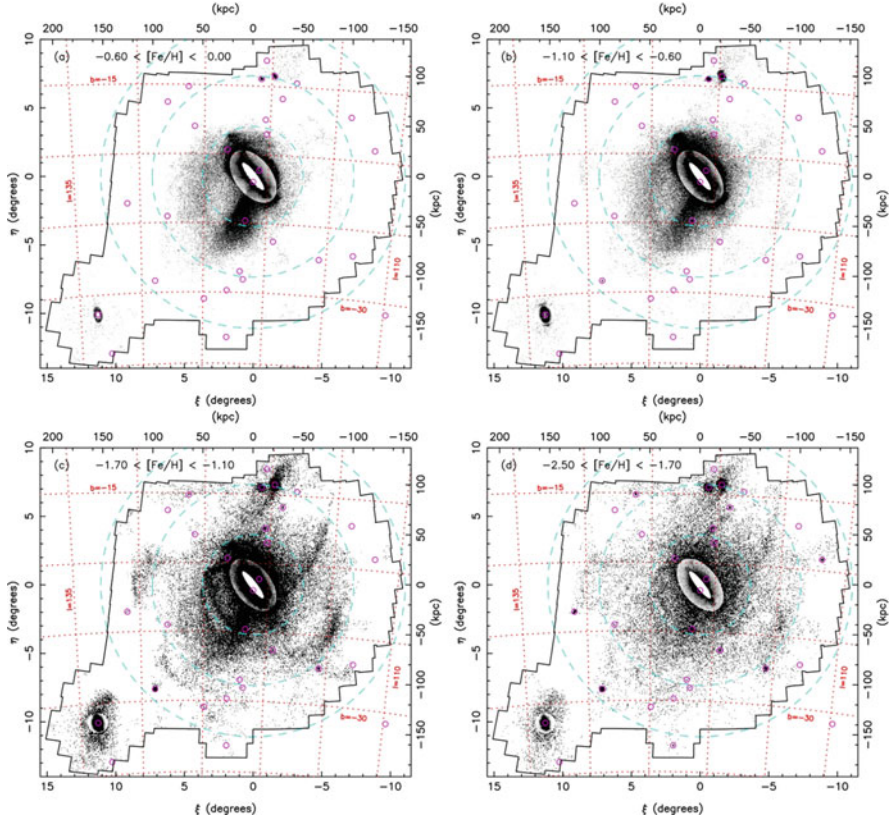


Fig. 2.4 Stellar density map of M31 (akin to Fig. 2.3), this time subdivided into photometric metallicity bins (as indicated in each subpanel). The *upper panels* show high metallicity cuts, where the Giant Stream and Stream C are the most prominent features; note that the shape of the Giant Stream changes as a function of metallicity. The *lower panels* show lower metallicity cuts: the *lower left* panel is dominated by substructure at large radii, while the most metal-poor panel (*lower right*) is smoother and believed to mostly contain in situ populations. Reproduced by permission of the AAS from Ibata et al. (2014), their Fig. 9

Figure 2.4 further shows the RGB stellar map broken into bins of photometric metallicity. The parallel Spectroscopic and Photometric Landscape of Andromeda’s Stellar Halo (SPLASH) survey (Guhathakurta et al. 2006; Kalirai et al. 2006) provides a comparison dataset with both photometric and spectroscopic information, the latter obtained with Keck/DEIMOS. The SPLASH pointings are significantly smaller than the PAndAS ones but strategically cover M31 halo regions out to ~ 225 kpc. Deeper, pencil-beam photometric follow-up studies have further made use of the *HST* to target some of the substructures uncovered in M31’s outskirts, resolving stars down to the oldest MSTO (e.g. Brown et al. 2006; Bernard et al. 2015). These observations reveal a high complexity in the stellar populations in M31, hinting at a high degree of mixing in its outskirts. Overall, M31 has evidently

had a much richer recent accretion history than the MW (see also Ferguson and Mackey 2016).

2.2.2.1 Streams and Substructures

As seen from the maps in Figs. 2.3 and 2.4, while the inner halo has a flattened shape and contains prominent, relatively metal-rich substructures (e.g. the Giant Stream), the outer halo (>50 kpc) hosts significantly less extended, narrow, metal-poor tidal debris.

The features in the innermost regions of M31 can be connected to its disk populations (e.g. the north-east structure or the G1 clump): kinematic studies show that a rotational component is present in fields as far out as 70 kpc, and they retain a fairly high metallicity (Dorman et al. 2013). This reinforces the possible interpretation as a vast structure, which can be explained as disk stars torn off or dynamically heated due to satellite accretion events. Deep *HST* pointings of these features indeed reveal relatively young populations, likely produced from pre-enriched gas in a continuous fashion, comparable to the outer disk (Ferguson et al. 2005; Brown et al. 2006; Bernard et al. 2015).

The most prominent feature in M31's outer halo, the Giant Stream, was initially thought to originate from the disruption of either M32 or NGC 205, the two dwarf ellipticals located at only ~ 25 – 40 kpc from M31's centre (Ibata et al. 2001; Ferguson et al. 2002). While both these dwarfs show signs of tidal distortion, it was soon clear that none of them could produce the vast structure extending ~ 100 kpc into M31's halo. Great effort has been spent into mapping this substructure both photometrically and spectroscopically, in order to trace its orbit and define its nature: a gradient in its line-of-sight distance was first highlighted by McConnachie et al. (2003), who found the outer stream regions to be located behind M31, the innermost regions at about the distance of M31 and an additional stream component on the opposite (northern) side of M31 to be actually in front of M31. The stream presents a metallicity gradient, with the core regions being more metal-rich and the envelope more metal-poor (see also Fig. 2.4), as well as a very narrow velocity dispersion, with the addition of a puzzling second kinematic component (Gilbert et al. 2009); possible interpretations for the latter may be a wrap or bifurcation in the stream, as well as a component from M31's populations.

A number of increasingly sophisticated theoretical studies have tried to reproduce the appearance of the Giant Stream and picture its progenitor, which is undetected to date. The general consensus seems to be that a relatively massive ($\sim 10^9 M_\odot$) satellite, possibly with a rotating disk, impacted M31 from behind with a pericentric passage around 1–2 Gyr ago (most recently, Fardal et al. 2013; Sadoun et al. 2014). In particular, simulations can reproduce the current extension and shape of the stream and predict the progenitor to be located to the north-east of M31, just beyond its disk (Fardal et al. 2013). This study also concludes that some of the substructures linked to M31's inner regions are likely to have arisen from the same accretion event, i.e. the north-east structure and the G1 clump (Fig. 2.3): these shelf features

would trace the second and third passage around M31, which is also supported by their radial velocities. CMDs of the Giant Stream populations are in agreement with these predictions: its stellar populations have mixed properties, consistent with both disk and streamlike halo features (Ferguson et al. 2005; Richardson et al. 2008). Detailed reconstruction of its SFH indicates that most star formation occurred at early ages and was possibly quenched at the time of infall in M31’s potential (around 6 Gyr ago) (Bernard et al. 2015). Again, these studies deduce a likely origin of these populations as a dwarf elliptical or a spiral bulge.

Besides the Giant Stream, the only other tidal feature with a relatively high metallicity is Stream C (see Figs. 2.3 and 2.4), which appears in the metal-poor RGB maps as well. The origin of this feature is obscure, even though it is tempting to speculate that it could be part of the Giant Stream event. The lower left panel of Fig. 2.4, showing metal-poor populations, encompasses all of the narrow streams and arcs beyond 100 kpc, which extend for up to several tens of kpc in length. All these substructures are extremely faint ($\mu_V \sim 31.5 \text{ mag arcsec}^{-2}$), and their origin is mostly unknown because of the difficulty in following up such faint and sparse populations. As part of the *HST* imaging of these features, Bernard et al. (2015) find that their populations are mainly formed at early ages and undergo a more rapid chemical evolution with respect to the disk populations. Despite the metal-poor nature of these features, the hypothesis of a single accretion event producing most of the tidal features observed in the outer halo is not that unlikely, given the metallicity gradient present in the Giant Stream itself.

An efficient alternative to investigate the nature of these streams is to study the halo GC population: the wide-field surveys of M31 have allowed to uncover a rich population of GCs beyond a radius of ~ 25 kpc (e.g. Huxor et al. 2014, and references therein), significantly more numerous than that of the MW halo. Mackey et al. (2010) first highlighted a high spatial correlation between the streams in M31’s halo and the GC population, which would be extremely unlikely in a uniform distribution. Following the hypothesis that the disrupting satellites might be providing a high fraction of M31’s halo GCs, Veljanoski et al. (2014) obtained spectroscopic follow-up: they were able to confirm that streams and GCs often have correlated velocities and remarkably cold kinematics. This exciting result gives hope for studies of more distant galaxies, where halo populations cannot be resolved and GCs could be readily used to trace possible substructure.

2.2.2.2 Smooth Halo

One of the first spatially extended datasets to investigate the halo of M31 in detail is described in Tanaka et al. (2010): their Subaru/SuprimeCam photometry along the minor axis in both directions is deeper, even though less extended, than PAndAS. The stellar density profile derived in this study extends out to 100 kpc and shows a consistent power law for both directions. The authors also suggest that, given the inhomogeneities in the stellar populations, the M31 halo is likely not fully mixed.

In the most metal-poor (lower right) panel of Fig. 2.4, the substructures in the outer halo fade away, displaying a smoother component that can be identified with the in situ M31 halo. Once the substructures are decoupled based on the lack of obvious spatial correlation and with an additional photometric metallicity cut, Ibata et al. (2014) derive a stellar density profile out to 150 kpc. Again, the profile follows a power law, which turns out to be steeper when increasingly more metal-rich populations are considered. Ibata et al. (2014) also conclude that only 5% of M31's total halo luminosity lies in its smooth halo, and the halo mass is as high as $\sim 10^{10} M_{\odot}$, significantly larger than what is estimated for the MW.

The SPLASH survey extends further out than PAndAS and benefits from kinematical information that is crucial to decontaminate the studied stellar samples from foreground stars and decreases the scatter in the radial profiles. Based on this dataset, Gilbert et al. (2012) find that the halo profile does not reveal any break out to 175 kpc. This is somewhat surprising given the prediction from simulations that accreted M31-sized stellar haloes should exhibit a break beyond a radius of ~ 100 kpc (Bullock and Johnston 2005; Cooper et al. 2010). Beyond a radius of 90 kpc, significant field-to-field variations are identified in their data, which suggests that the outer halo regions are mainly comprised of stars from accreted satellites, in agreement with previous studies. At the outermost radii probed by SPLASH (~ 230 kpc), there is a tentative detection of M31 stars, but this is hard to confirm given the high contamination fraction. Finally, the Gilbert et al. (2012) stellar halo profile suggests a prolate DM distribution, which is also consistent with being spherical, in agreement with Ibata et al. (2014).

Both Ibata et al. (2014) and Gilbert et al. (2014) investigate the existence of a metallicity gradient in the smooth halo of M31: they found a steady decrease in metallicity of about 1 dex from the very inner regions out to 100 kpc. This might indicate the past accretion of (at least) one relatively massive satellite. At the same time, a large field-to-field metallicity variation could mean that the outer halo has been mainly built up by the accretion of several smaller progenitors.

2.2.2.3 Andromeda Satellites

Similarly to the boom of satellite discoveries around the MW, the vast majority of dwarfs in M31's extended halo have been uncovered by the SDSS, PAndAS and Pan-STARRS surveys in the past decade (see Martin et al. 2016, and references therein). The M31 satellites follow the same relations between luminosity, radius and metallicity defined by MW satellites, with the exception of systems that are likely undergoing tidal disruption (Collins et al. 2014). Once more, the characterization of the lowest-mass galaxies raises new, unexpected questions: from the analysis of accurate distances and kinematics, Ibata et al. (2013) conclude that half of the M31 satellites lie in a vast (~ 200 kpc) and thin (~ 12 kpc) corotating plane and share the same dynamical orbital properties. The extreme thinness of the plane is very hard to reconcile with Λ CDM predictions, where such structures should not survive for a Hubble time. While several theoretical interpretations have been

offered (e.g. Fernando et al. 2016), none is conclusive, and this reinforces the allure of mystery surrounding low-mass satellites.

2.2.3 *Low-Mass Galaxies In and Around the Local Group*

Besides the detailed studies of the two LG spirals, increasing attention is being paid to lower-mass galaxies and their outskirts. Given the self-similar nature of DM, low-mass galaxies should naively be expected to possess haloes and satellites of their own; however, our difficulty in constraining star formation efficiency and physical processes affecting galaxy evolution at these scales blurs these expectations. In the last couple of years, the increasing resolution of cosmological simulations has allowed to make quantitative predictions about the halo and substructures in sub-MW-mass galaxies and about the number of satellites around them (Wheeler et al. 2015; Dooley et al. 2016). Observations are thus much needed to test these predictions.

Since the late 1990s, numerous studies of star-forming dwarfs within or just beyond the LG have claimed the detection of an RGB component extending beyond the blue, young stars (see Stinson et al. 2009, and references therein), hinting at a generic mode of galaxy formation independent on galaxy size. Such envelopes, however, were not characterized in detail and in fact could not be identified uniquely as the product of hierarchical merging without, e.g. accurate age and metallicity estimates.

The presence of extended haloes in the most luminous satellites of the MW and M31, i.e. the irregular LMC and the low-mass spiral M33, respectively, has not been confirmed to date despite the availability of exquisite datasets. Gallart et al. (2004) demonstrate how, out to a galactocentric distance of 7 kpc, the stellar density profile of the LMC disk does not show a clear break, in contrast to previous tentative claims. Clearly, the question is complicated by the fact that the LMC is undergoing tidal disruption, and stripped stellar material could easily be misinterpreted as a halo component. Nonetheless, McMonigal et al. (2014) suggest to have found a sparse LMC halo population from a wide-field dataset around the nearby dwarf galaxy Carina, at galactocentric distances as large as 20 deg. The question might be settled in the near future with the help of wide-field surveys such as the Survey of MAgellanic Stellar History (Martin et al. 2015). With regard to possible low-mass satellites, there is now tantalizing indication that the LMC might have fallen onto the MW with its own satellite system, as mentioned in Sect. 2.2.1.3. As part of the PAndAS survey, deep imaging of M33 has revealed prominent substructure in its outer disk reminiscent of a tidal disturbance and a faint, diffuse substructure possibly identified as a halo component (Cockcroft et al. 2013). This result was, however, carefully reconsidered by McMonigal et al. (2016), who claim that a definitive sign of a halo structure cannot be confirmed, and if present it must have a surface brightness below $\mu_V \sim 35 \text{ mag arcsec}^{-2}$.

Besides the investigation of haloes and satellites, deep and wide-field views of low-mass galaxies are crucial to, for example, assess the presence of tidal disturbances, which in turn are key to estimate mass values and constrain DM profiles (e.g. Sand et al. 2012). As demonstrated by Crnojević et al. (2014), a striking similarity in the global properties (luminosity, average metallicity, size) of two low-mass galaxies, such as the M31 satellites NCG 185 and NGC 147, can be quite misleading: once deep imaging was obtained around these galaxies (within PAndAS), NCG 147 revealed extended, symmetric tidal tails, returning a much larger extent and luminosity for this dwarf than what was previously thought. This dataset further showed a flat metallicity gradient for NGC 147, in contrast with the marked gradient found in NGC 185. All these pieces of evidence point at an ongoing interaction of NGC 147 with M31. Large-scale studies of LG dwarfs also provide useful insights into their evolutionary history: by studying CMDs reaching below the MSTO, Hidalgo et al. (2013) trace significant age gradients that advocate an outside-in mode of star formation for dwarf galaxies.

Clearly, systematic deep searches are needed to detect and characterize the outskirts of low-mass satellites. With this goal in mind, wide-field surveys of nearby (<3 Mpc) dwarfs have started to be pursued. The first of these efforts targets NGC 3109, a sub-LMC-mass dwarf located just beyond the boundaries of the LG: several candidate satellites of NGC 3109 are identified from a CTIO/DECam survey targeting regions out to its virial radius (Sand et al. 2015). One of them, confirmed to be at the distance of NGC 3109, is relatively bright ($M_V \sim -10$) and is already in excess of the predicted number by Dooley et al. (2016) for this system. Other ongoing surveys are similarly looking for halo substructures and satellites in several relatively isolated dwarfs, e.g. the Solitary Local Dwarfs survey (Higgs et al. 2016) and the Magellanic Analog Dwarf Companions and Stellar Halos survey (Carlin et al. 2016), by using wide-field imagers on large telescopes such as CFHT/MegaCam, Magellan/Megacam, CTIO/DECam and Subaru/HyperSuprimeCam. These datasets will constitute a mine of information to constrain the role of baryonic processes at the smallest galactic scales.

2.3 Beyond the Local Group

The ground-breaking photometric and kinematic surveys carried out in the past two decades have significantly advanced our knowledge of haloes and their substructures within LG galaxies. Nonetheless, the MW and M31 may not be representative of generic MW-sized haloes, given the stochasticity of the hierarchical assembly process: several marked differences in the stellar populations of their haloes underline the need for observations of a statistically significant sample of galaxy haloes with different morphologies, with surveys targeting large portions of their haloes.

Cosmological simulations of MW-mass analogues show a wide variation in the properties of their haloes. As already mentioned, the relative contribution of in situ star formation and disrupted satellites remains unclear: depending on the models

(e.g. full hydrodynamical simulations, N -body models with particle tagging), they can vary from a negligible number of accretion events for a MW-sized halo to making up for most of a stellar halo content (e.g. Lu et al. 2014; Tissera and Scannapieco 2014). Even within the same set of simulations, the number, mass ratio and morphology of accretion and merger events span a wide range of possible values (Bullock and Johnston 2005; Johnston et al. 2008; Garrison-Kimmel et al. 2014). The chemical content of extended haloes can provide useful insights into their assembly history: mergers or accretion events of similar-mass satellites will generally tend to produce mild to flat gradients; in situ populations will feature increasingly metal-poor populations as a function of increasing galactocentric radius, similarly to the accretion of one or two massive companions (e.g. Cooper et al. 2010; Font et al. 2011). More extended merger histories are also expected to return younger and relatively metal-rich populations with respect to those coming from a shorter assembly and to produce more massive stellar haloes, with the final result that the mean halo metallicities of MW-mass spirals can range by up to 1 dex (e.g. Renda et al. 2005).

Comprehensive observational constraints are key to guide future simulations of galaxy haloes: the past decade has seen a dramatic increase in the observational census of resolved galaxy haloes beyond the LG, thanks to deep imaging obtained with space facilities, as well as to the advent of wide-field imagers on large ground-based telescopes.

While the increasing target distance means that it is easier to survey larger portions of their haloes, the drawback is that the depth of the images decreases dramatically, and thus we are only able to detect the brightest surface brightness features in the haloes, i.e. the uppermost ~ 2 – 3 mag below the TRGB in terms of resolved stars (see Fig. 6 in Radburn-Smith et al. (2011) for a schematic visualization of the different stellar evolutionary phases recognizable in such shallow CMDs). A number of studies have surveyed relatively nearby and more distant galaxy haloes in integrated light despite the serious challenges posed by sky subtraction at such faint magnitudes, masking of bright stars, flat fielding and scattered light effects, point spread function modelling and/or spatially variable Galactic extinction.

A few early studies have been able to uncover a halo component and tidal debris in the target galaxies (e.g. Malin et al. 1983; Morrison et al. 1994; Sackett et al. 1994), without, however, settling the questions about their existence, nature or ubiquity. Different approaches have been adopted to detect haloes and their substructures, i.e. targeting either individual galaxies (e.g. Zheng et al. 1999; Pohlen et al. 2004; Jablonka et al. 2010; Janowiecki et al. 2010; Martínez-Delgado et al. 2010; Adams et al. 2012; Atkinson et al. 2013) or stacking the images of thousands of objects (e.g. Zibetti et al. 2004; van Dokkum 2005; Tal et al. 2009). A precise quantification of the occurrence of faint substructure in the outskirts of nearby galaxies seems as uncertain as it can be, ranging from a few percent to $\sim 70\%$ (see, e.g. Atkinson et al. 2013, and references therein). This is perhaps unsurprising given the heterogeneity of methods used, target galaxy samples and surface brightness limits in such studies. Besides the identification of such features,

the characterization of unresolved halo stellar populations constitutes an even harder challenge: integrated colours and spectra can at most reach a few effective radii, thus missing the outer haloes. Even for the available datasets, the degeneracies between age, metallicity and extinction are generally challenging to break (e.g. de Jong et al. 2007); in addition, tidal features can rarely tell us about the mass ratio of a merger event or its orbit (with the exception of tails). Here, we do not intend to discuss the detection of haloes and the variety of fractions and morphologies for tidal features observed in integrated light studies; Knapen and Trujillo (2017) treat this topic in detail, while this contribution focusses on resolved populations.

Obtaining resolved photometry beyond the LG is a daunting task as well, due to the very faint luminosities involved—the brightest RGB stars for galaxies at ~ 4 – 10 Mpc have magnitudes of $I \sim 24$ – 28.5 , and thus this approach is so far really limited to the Local Volume. Early attempts to perform photometry of individual stars in the outskirts of nearby galaxies have been made using large photographic plates and the first CCDs (e.g. Humphreys et al. 1986; Davidge and Jones 1989; Georgiev et al. 1992). The brightest populations (i.e. the youngest) could often be reconciled with being members of the parent galaxy, but the critical information on the faint, old stars was still out of reach. With the advent of wide-format CCDs in the mid-1990s, photometry finally became robust enough to open up new perspectives on the resolved stellar content of our closest neighbours.

The first studies of this kind date back to 20 years ago and mainly focus on the inner regions of the target galaxies, most commonly their disks or inner haloes, with the goal of studying their recent star formation and of deriving TRGB distances (see, e.g. Soria et al. 1996 for CenA, Sakai and Madore 1999 for M81 and M82). Elson (1997), in particular, resolved individual stars in the halo of the S0 galaxy NGC 3115 with *HST*. By analysing the uppermost 1.5 mag of the RGB at a galactocentric distance of 30 kpc, they derived a distance of ~ 11 Mpc and additionally discovered for the first time a bimodality in the photometric metallicity distribution function of this early-type galaxy. Tikhonov et al. (2003) studied for the first time the resolved content of the nearest (~ 3.5 Mpc) S0 galaxy NGC 404 with combined ground-based and *HST* imaging. Their furthest *HST* pointings (~ 20 kpc in projection) contain RGB stars that are clearly older than the main disk population, with similar colour (metallicity). The authors conclude that the disk of NGC 404 extends out to this galactocentric distance, but they do not mention a halo component.

Beyond these early studies of individual galaxies, the need for systematic investigations of resolved stellar haloes was soon recognized. Next we describe the design and results of some systematic surveys targeting samples of galaxies in the Local Volume.

2.3.1 Systematic Studies

A decade ago, Mouhcine et al. (2005a,b,c) started an effort to systematically observe the haloes of eight nearby (< 7 Mpc) spiral galaxies with the resolution of *HST*. In

particular, they utilized WFPC2 to target fields off of the galaxies' disks (2–13 kpc in projection along the minor axis) with the goal of investigating their stellar populations and obtaining accurate distance estimates as well as photometric metallicity distribution functions, to gain insights into the halo formation process. Mouhcine et al. (2005c) find the haloes to predominantly contain old populations, with no younger components and little to no intermediate-age populations. Interestingly, Mouhcine et al. (2005b) find a correlation between luminosity and metallicity for the target galaxies, where the metallicity is derived from the mean colour of the resolved RGB. Both the spiral galaxies from their sample (NGC 253, NGC 4244, NGC 4945, NGC 4258, NGC 55, NGC 247, NGC 300 and NGC 3031 or M81) and the two ellipticals (NGC 3115 and NGC 5128 or Centaurus A, included in their comparison from previous literature data) fall on the same relation, indicating that haloes might have a common origin regardless of the galaxy morphological type. Interestingly enough, the MW halo turns out to be substantially more metal-poor than those of the other galaxies of comparable luminosity, based on kinematically selected pressure-supported halo stars within ~ 10 kpc above the disk (see also Sect. 2.2.2). This relation is consistent with a scenario where halo field stars form in the potential well of the parent galaxy in a gradual way from pre-enriched gas. Moreover, the relatively high metallicities of the target haloes seem to suggest that they likely originate from the disruption of intermediate-mass galaxies, rather than smaller metal-poor dwarf galaxies (Mouhcine et al. 2005c).

Interestingly, the dataset presented and studied in Mouhcine et al. (2005a,b,c) is further analysed by Mouhcine (2006) to find that each spiral of the sample presents a bimodal metallicity distribution. In particular, both a metal-poor and a metal-rich component are present in the outskirts of the target galaxies, and both components correlate with the host's luminosity. This is taken as a hint that these populations are born in subgalactic fragments that were already embedded in the dark haloes of the host galaxy; the metal-poor component additionally has a broader dispersion than that of the metal-rich population. These properties show similarities with GC subpopulations in the haloes of early-type galaxies (e.g. Peng et al. 2006). Mouhcine (2006) argues that the metal-poor component may arise from the accretion of low-mass satellites, while the metal-rich one could be linked to the formation of the bulge or the disk.

The shortcoming of this ambitious study is, however, twofold: first, the limited field of view (FoV) of *HST* hampers global conclusions on the galaxies' haloes, and the stellar populations at even larger radii may have different properties than those in the observed fields; second, perhaps most importantly, it is not obvious what structure of the galaxy is really targeted, i.e. the halo, the outer bulge or disk or a mixture of these.

Along the same lines of these studies, Radburn-Smith et al. (2011) present an even more ambitious *HST* survey of 14 nearby disk galaxies within 17 Mpc, with a range of luminosities, inclinations and morphological types. The Galaxy Halos, Outer disks, Substructure, Thick disks, and Star clusters (GHOSTS) survey aims at investigating radial light profiles, axis ratios, metallicity distribution functions (MDFs), SFHs, possible tidal streams and GC populations, all to be considered as

a function of galaxy type and position within the galaxies. The 76 ACS pointings of the survey are located along both major and minor axes for most of the targets, and reach $\sim 2\text{--}3$ mag below the TRGB, down to surface brightness values of $V \sim 30$ mag arcsec $^{-2}$. This dataset thus represents a very valuable resource for testing hierarchical halo formation models. Monachesi et al. (2016) investigate six of the galaxies in this sample (NGC 253, NGC 891, M81, NGC 4565, NGC 4945 and NGC 7814) and conclude that all of them contain a halo component out to 50 kpc, and two of them out to 70 kpc along their minor axis. The colour (i.e. photometric metallicity) distribution of RGB stars in the target haloes is analysed and reveals a non-homogeneity which likely indicates the presence of non-mixed populations from accreted objects. The average metallicity out to the largest radii probed remains relatively high when compared to the values of the MW halo; metallicity gradients are also detected in half of the considered galaxies. Surprisingly, and in contrast to the results presented by Mouhcine et al. (2005b), the spiral galaxies in this sample do not show a strong correlation between the halo metallicity and the total mass of the galaxies, highlighting instead the stochasticity inherent to the halo formation process through accretion events (e.g. Cooper et al. 2010). The advantage of the GHOSTS dataset over the one from Mouhcine et al. (2005b) is that the GHOSTS fields are deeper, there are several pointings per galaxy, and they reach significantly larger galactocentric distances, thus offering a more global view of the haloes of the targets.

In an effort to increase the sample of nearby galaxies for which stellar haloes are resolved and characterized, several groups have individually targeted Local Volume objects with either ground-based or space-borne facilities: the low-mass spirals NGC 2403 (Barker et al. 2012, with Subaru/SuprimeCam), NGC 300 (Vlajić et al. 2009, with Gemini/GMOS) and NGC 55 (Tanaka et al. 2011, with Subaru/SuprimeCam.), the ellipticals NGC 3379 (Harris et al. 2007b, with *HST*) and NGC 3377 (Harris et al. 2007a, with *HST*) and the lenticular NGC 3115 (Peacock et al. 2015, with *HST*). In most of these galaxies, a resolved faint halo (or at least an extended, faint and diffuse component) has been detected and is characterized by populations more metal-poor than the central/disk regions. Most of these haloes also show signs of substructure, pointing at past accretion/merger events as predicted by a hierarchical galaxy formation model. Even galaxies as far as the central elliptical of the Virgo cluster, M87 (~ 16 Mpc), are starting to be targeted with *HST*, although pushing its resolution capabilities to the technical limits (Bird et al. 2010).

While spectroscopically targeting individual RGB stars to obtain radial velocity and metallicity information is still prohibitive beyond the LG (see Sect. 2.2.3), some cutting-edge studies have pushed the limits of spectroscopy for dwarf galaxies within ~ 1.5 Mpc (e.g. Kirby et al. 2012, and references therein). At the same time, novel spectroscopic techniques are being developed to take full advantage of the information locked into galaxy haloes. One example is the use of co-added spectra of individual stars, or stellar blends, to obtain radial velocities, metallicities and possibly gradients in galaxies within ~ 4 Mpc, as robustly demonstrated by Toloba et al. (2016a). The development of new analysis methods and the advent of high-resolution spectrographs will soon allow for systematic spectroscopic

investigations of nearby galaxy haloes which will importantly complement the available photometric studies, similarly to the studies of LG galaxies.

Besides the systematic studies presented here, which mostly involve deep space observations, an increasing effort is being invested in producing spatial density maps of outer haloes in some of the closest galaxies with ground-based observations, akin to the panoramic view of M31 offered by PAndAS. In the following section, we describe some of these efforts.

2.3.2 Panoramic Views of Individual Galaxies

Panoramic views of nearby galaxies can be obtained with the use of remarkable ground-based wide-field imagers such as Subaru/SuprimeCam and HyperSuprime-Cam and CFTH/MegaCam in the northern hemisphere, and Magellan/Megacam, CTIO/DECam and VISTA/VIRCAM in the southern hemisphere. Clearly, such CMDs cannot reach the depth of those obtained for M31; these studies nevertheless represent cornerstones for our investigation of global halo properties and serve as precursor science cases for the next generation of telescopes that will open new perspectives for this kind of studies to be performed on a significantly larger sample of galaxies. As mentioned in Sect. 2.2.3, the haloes of low-mass galaxies are also starting to be systematically investigated, to gain a more complete picture of galaxy formation at all mass scales. Here we further describe the few examples of spatially extended imaging obtained to date for some of the closest spiral and elliptical galaxies.

2.3.2.1 NGC 891

Despite its relatively large distance (~ 9 Mpc, Radburn-Smith et al. 2011), the “MW-twin” NCG 891 (van der Kruit 1984) is one of the first spirals to be individually investigated in resolved light. Its high inclination and absence of a prominent bulge make it an appealing target for halo studies.

Mouhcine et al. (2007) exploit three *HST* pointings located approximately 10 kpc above the disk of NGC 891 to investigate the properties of this galaxy’s halo. The broad observed RGB indicates a wide range of metallicities in this population, with metal-rich peaks and extended metal-poor tails. The three fields also show a decreasing mean metallicity trend as a function of increasing distance along the major axis. The mean metallicity of this sample of RGB stars ($[Fe/H] \sim -1$) falls on the halo metallicity-galaxy luminosity relation pointed out by Mouhcine et al. (2005b): this, together with the gradient mentioned before, is in contrast with the lower metallicities and absence of a gradient for non-rotating stars in the inner haloes of the MW and M31 (Chapman et al. 2006; Kalirai et al. 2006). Mouhcine et al. (2007) thus suggest that not all massive galaxies’ outskirts are dominated by metal-poor, pressure-supported stellar populations (because of the inclination and

absence of a bulge, the studied RGB sample is thought to be representative of the true halo population). A possible explanation is suggested with the presence of two separate populations: a metal-rich one that is present in the most massive galaxies' outskirts and one constituting the metal-poor, pressure-supported halo, coming from the accretion of moderate-mass satellites. For smaller-mass galaxies, the halo would instead be dominated by debris of small satellites with lower metallicities.

Follow-up analysis on the same *HST* dataset has been carried out by Ibata et al. (2009) and Rejkuba et al. (2009). After careful accounting for the internal reddening of the galaxy, a mild metallicity gradient is confirmed in NGC 891's spheroidal component, which is surveyed out to ~ 20 kpc (assuming elliptical radii), and suggested to arise from the presence of a distinct outer halo, similarly to the MW (Ibata et al. 2009). Most importantly, and for the first time, this refined analysis reveals a substantial amount of substructure not only in the RGB spatial distribution but also as metallicity fluctuations in the halo of NGC 891. This evidence points at multiple small accretion events that have not fully blended into the smooth halo.

Motivated by these studies, Mouhcine et al. (2010) provide the first attempt to derive a PAndAS-like map of a MW-analogue beyond the LG: their wide-field map of NGC 891's halo is shown in Fig. 2.5. The panoramic survey, performed contiguously with Subaru/SuprimeCam, covers an impressive $\sim 90 \times 90$ kpc² in the halo of NGC 891 with the *V* and *i* filters, reaching ~ 2 mag below the TRGB. Among

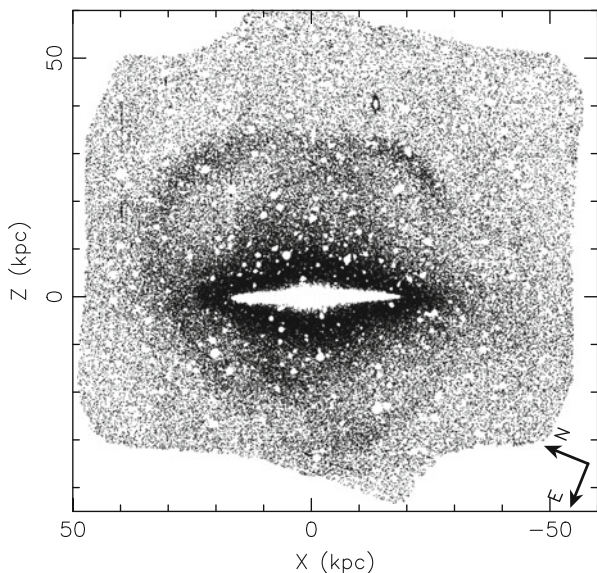


Fig. 2.5 Surface density map of RGB stars in the halo of NGC 891, obtained with Subaru/SuprimeCam. The overdensities of old RGB stars reveal a large complex of arcing streams that loops around the galaxy, tracing the remnants of an ancient accretion. The second spectacular morphological feature is the *dark cocoon-like structure* enveloping the high surface brightness disk and bulge. Figure 1 from Mouhcine et al. (2010), reproduced by permission of the AAS

the abundant substructures uncovered by the RGB map around NGC 891, a system of arcs/streams reaches out some ~ 50 kpc into the halo, including the first giant stream detected beyond the LG with ground-based imaging. The latter's shape does not rule out a single accretion event origin, but a possible progenitor cannot be identified as a surviving stellar overdensity. These structures appear to be old, given the absence of corresponding overdensities in the luminous AGB (i.e. intermediate-age populations) maps. Another surprising feature highlighted by the RGB map is a flattened, superthick envelope surrounding the disk and bulge of NGC 891, which does not seem to constitute a simple extension of its thick disk but is instead believed to generate from the tidal disruption of satellites given its non-smooth nature (Ibata et al. 2009).

2.3.2.2 M81

Located at a distance of 3.6 Mpc (Radburn-Smith et al. 2011) and with a dynamical mass inside 20 kpc of $\sim 10^{11} M_{\odot}$, M81 is one of the closest MW-analogues and has thus been among the first targets for extended halo studies beyond the LG. The earliest HI imaging of the galaxy group dominated by this spiral unambiguously shows a spectacular amount of substructure, most prominently a bridge of gas between M81 and its brightest companions NGC 3077 and M82, located at a projected distance of ~ 60 kpc (van der Hulst 1979; Yun et al. 1994).

Given the high level of interaction and HI substructure in a group that can be considered as a LG-analogue, it is natural to pursue the investigation of this complex environment even further. The intergalactic gas clouds embedding this environment are traced by young stellar systems identified in resolved stellar studies (Durrell et al. 2004; Davidge 2008; de Mello et al. 2008). Some of them are classified as tidal dwarf galaxies, such as Holmberg IX and the Garland (Makarova et al. 2002; Karachentsev et al. 2004; Sabbi et al. 2008; Weisz et al. 2008), characterized by a predominance of young stellar populations. This type of galaxy has no counterpart in our own LG, and it is believed to be DM-free (see, e.g. Duc et al. 2000).

The first detailed look into the resolved populations in the outskirts of M81 is through the eye of *HST*: the predominantly old halo RGB stars show a broad range of metallicities and a radial gradient (Tikhonov et al. 2005; Mouhcine et al. 2005c). The radial stellar counts (along several different directions) also reveal a break at a radius of ~ 25 kpc, which is interpreted as the transition point between thick disk and halo (Tikhonov et al. 2005). In a similar fashion, the ground-based wide-field imager Subaru/SuprimeCam has been used to uncover a faint and extended component beyond M81's disk with a flat surface brightness profile extending out to ~ 0.5 deg (or ~ 30 kpc) to the north of M81 (Barker et al. 2009). This low surface brightness feature (~ 28 mag arcsec $^{-2}$) traced by the brightest RGB star counts appears bluer than the disk, suggesting a metallicity lower than that of M81's main body, but its true nature remains unclear. The authors suggest this component to have intermediate properties between the MW's halo and its thick disk, but the limited surveyed area (0.3 deg 2) precludes any robust conclusions.

As part of a campaign to obtain panoramic views of nearby galaxy haloes, Mouhcine and Ibata (2009) present a $0.9 \times 0.9 \text{ deg}^2$ view of M81's surroundings obtained with the CFHT/MegaCam imager. The images resolve individual RGB stars down to ~ 2 mag below the TRGB, but this study focusses on the younger, bright populations such as massive main sequence stars and red supergiants, which reveal further young systems tracing the HI tidal distribution between M81 and its companions. These systems are younger than the estimated dynamical age of the large-scale interaction and do not have an old population counterpart, suggesting that they are not simply being detached from the main body of the primary galaxies but are instead formed within the HI clouds.

Durrell et al. (2010) recently conducted a deeper, albeit spatially limited, *HST* study of a field at a galactocentric distance of ~ 20 kpc. This field reveals an $[M/H] \sim -1.15$ population with an approximate old age of ~ 9 Gyr. This field thus contains the most metal-poor stars found in M81's halo to that date, which led the authors to the conclusion that they were dealing with an authentic halo component. This study is extended by Monachesi et al. (2013) with the *HST* GHOSTS dataset (see Sect. 2.3.1): they construct a colour profile out to a radius of ~ 50 kpc, and this dataset does not show a significant gradient. The mean photometric metallicity derived is $[Fe/H] \sim -1.2$, similarly to Durrell et al. (2010). This result is found to be in good agreement with simulations, and the authors suggest that the halo of M81 could have been assembled through an early accretion of satellites with comparable mass (e.g. Cooper et al. 2010; Font et al. 2006).

As a further step in the investigation of M81's halo, the Barker et al. (2009) and Mouhcine and Ibata (2009) ground-based imaging of M81 is being improved by means of the Subaru/HyperSuprimeCam. The first $\sim 2 \times 2 \text{ deg}^2$ ($\sim 100 \times 115 \text{ kpc}^2$) resolved stellar maps from different subpopulations (upper main sequence, red supergiants, RGB and AGB stars) are presented in Okamoto et al. (2015) and constitute a preview of an even wider-field effort to map the extended halo of this group. These first maps (see Fig. 2.6) confirm a high degree of substructure, most interestingly: the youngest populations nicely trace the HI gas content, confirming previous small FoV studies; the RGB distributions are smoother and significantly more extended than the young component and show streamlike overlaps between the dominant group galaxies, e.g. M82's stars clearly being stripped by M81; a redder RGB distribution is detected for M81 and NGC 3077 compared to M82, indicating a lower metallicity in the latter; and, in addition, M82 and NGC 3077's outer regions present S-shaped morphologies, a smoking gun of the tidal interaction with M81 and typical of interacting dwarf galaxies with larger companions (e.g. Peñarrubia et al. 2009).

Not less importantly, the widest-field survey to date ($\sim 65 \text{ deg}^2$) of the M81 group has been performed by Chiboucas et al. (2009) with CFHT/MegaCam, although with only one filter. The main goal of this survey was to identify new, faint dwarf galaxies and investigate the satellite LF in a highly interacting group environment as compared to the LG. This is the first survey to systematically search for faint dwarfs beyond the LG. Resolved spatial overdensities consistent with candidate dwarfs have been followed up with two-band *HST*/ACS and *HST*/WFPC2 observations.

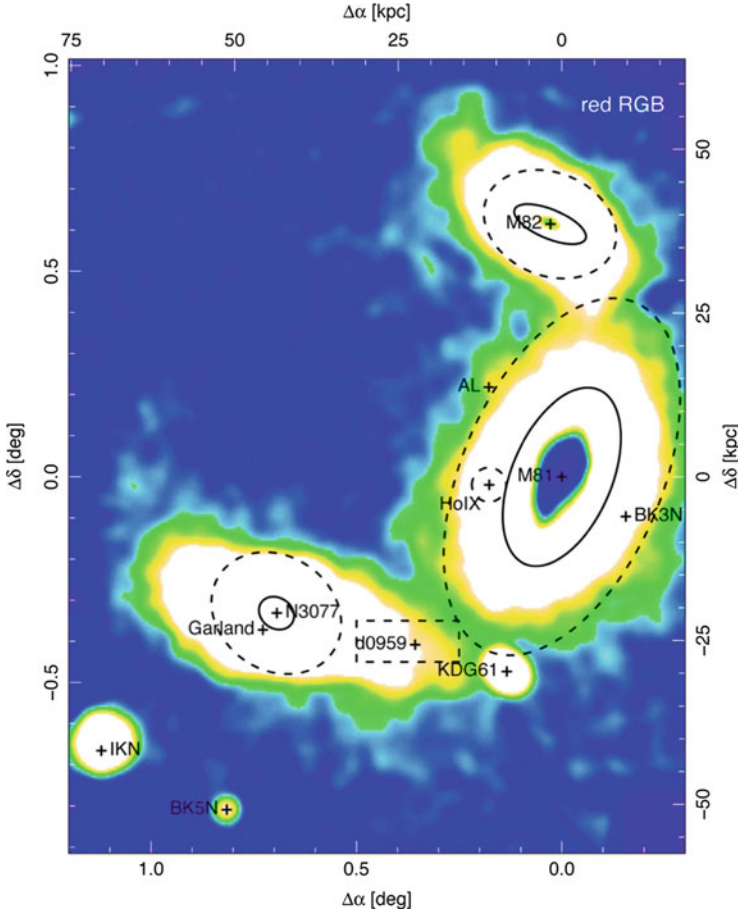


Fig. 2.6 Isodensity contour map of red RGB stars in the M81 group, as observed by Subaru/HyperSuprimeCam. Structures up to 20σ above the background level are visible; the *cross marks* represent the centres of known M81 group members, while *solid lines* are R_{25} of galaxies. The high degree of substructure underlines the ongoing tidal interactions in this group; note in particular the S-shape of the outer regions in NGC 3077 and M82. Figure 4 from Okamoto et al. (2015), reproduced by permission of the AAS

Fourteen of the 22 candidates turned out to be real satellites of M81 based on their CMDs and TRGB distances, extending the previously known galaxy LF in this group by three orders of magnitude down to $M_r \sim -9.0$ (Chiboucas et al. 2013), with an additional possibly ultra-faint member at $M_r \sim -7.0$. The measured slope of the LF in the M81 group appears to be flatter than cosmological predictions ($\alpha \sim -1.27$, in contrast to the theoretical value of $\alpha \sim -1.8$), similar to what has been found for the MW and M31 satellites.

2.3.2.3 NGC 253

Another obvious MW-mass spiral target for halo studies is NGC 253 (~ 3.5 Mpc, Radburn-Smith et al. 2011). Its role of brightest object within the loose Sculptor filament of galaxies makes it ideally suited to investigate the effects of external environment on the assembly of haloes. As already apparent from old photographic plates, NGC 253's outskirts show faint perturbation signs, such as an extended shelf to the south of its disk (Malin and Hadley 1997), pointing at a possible accretion event. This spiral galaxy, despite its relative isolation, is experiencing a recent starburst and a pronounced nuclear outflow: the latter is believed to host local star formation extending as high as ~ 15 kpc above the disk in the minor axis direction (see Comerón et al. 2001, and references therein).

The resolved near-infrared study of Davidge (2010) allowed them to detect bright AGB stars, but not RGB stars, extending out to ~ 13 kpc from the disk plane in the south direction: these are interpreted as being expelled from the disk into the halo as consequence of a recent interaction. Subsequently, Bailin et al. (2011) exploited a combination of *HST* data from the GHOSTS survey and ground-based Magellan/IMACS imaging, the former being deeper while the latter have a more extended FoV (out to ~ 30 kpc in the halo NGC 253 in the south direction). The authors are able to estimate NGC 253's halo mass as $\sim 2 \times 10^9 M_{\odot}$ or 6% of the galaxy's total stellar mass: this value is broadly consistent with those derived from the MW and M31 but higher reminiscent of the halo-to-halo scatter seen in simulations. A power law is fit to the RGB radial profile which is found to be slightly steeper than that of the two LG spirals and appears to be flattened in the same direction as the disk component. This is one of the few studies to date to quantitatively measure such parameters for a halo beyond the LG, and it sets the stage for the possibilities opened by similar studies of other nearby galaxies. The RGB density maps derived in Bailin et al. (2011) from IMACS imaging confirm the early detection of a shelf structure and uncover several additional kpc-scale substructures in the halo of this spiral.

A more recent wide-field study of NGC 253 is presented by Greggio et al. (2014), who exploit the near-infrared VISTA/VIRCAM imager to study the RGB and AGB stellar content of this galaxy out to ~ 40 – 50 kpc, covering also the northern portion which was not included in previous studies. This portion, in particular, reveals an RGB substructure symmetric (and likely connected) to the one in the south. A prominent arc (~ 20 kpc in length) to the north-west of the disk is detected and estimated to arise from a progenitor with a stellar mass of roughly $\sim 7 \times 10^6 M_{\odot}$. The RGB radial density profile shows a break at a radius of ~ 25 kpc, indicative of the transition from disk to halo. The elongated halo component already discussed in Bailin et al. (2011) is confirmed here, but is considered to be an inner halo: an outer, more spherical and homogeneous component extends at least out to the galactocentric distances covered by this survey. Intriguingly, the AGB density map reveals that 25% of this intermediate-age (i.e. up to a few Gyr old) population is spread out to ~ 30 kpc above the disk: this component cannot easily be explained with either an in situ or an accreted origin.

NGC 253 is also one of the two targets of the Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS), recently initiated with the wide-field imager Magellan/Megacam. This ambitious survey aims at obtaining RGB stellar maps of this galaxy and of the elliptical Centaurus A (Cen A; see next section) out to galactocentric radii of ~ 150 kpc, similarly to the PAndAS survey of M31. Early results from this survey include the discovery of two new faint satellites of NGC 253, one of which is clearly elongated and in the process of being disrupted by its host (Sand et al. 2014; Toloba et al. 2016b).

2.3.2.4 NGC 5128 (Centaurus A)

It is important to target galaxies of different morphologies and environments to thoroughly investigate the assembly of haloes. The closest (~ 3.8 Mpc; Harris et al. 2010) elliptical galaxy is Centaurus A (Cen A; technically speaking, Maffei 1 is slightly closer, but it lies behind the Galactic disk and is thus heavily reddened; see Wu et al. 2014). Cen A is the dominant galaxy of a rich and dense group, which also has a second subgroup component centred on the spiral M83 (e.g. Karachentsev et al. 2007).

Despite having often been referred to as a peculiar galaxy, due to its pronounced radio activity, its central dust lanes and a perturbed morphology, the luminosity of Cen A is quite typical of field elliptical galaxies: a recent (< 1 Gyr) merger event is believed to be the culprit for its peculiar features (see Israel 1998, and references therein). Besides this main merger event, Peng et al. (2002) uncover a system of faint shells and an arc within ~ 25 kpc of Cen A's centre from integrated light observations; the arc is believed to have been produced by the infall of a low-mass, star-forming galaxy around ~ 300 Myr ago.

This elliptical galaxy has been the subject of a systematic study conducted with *HST*/ACS and *HST*/WFPC2 throughout the past couple of decades: a number of pointings at increasingly large galactocentric radii (from a few out to ~ 150 kpc) have been used to investigate the properties and gradients of Cen A's halo populations (Rejkuba et al. 2014, and references therein). The considered pointings out to 40 kpc reveal metal-rich populations ($[\text{Fe}/\text{H}] > -1.0$), not dissimilar to what has been observed for the haloes of spiral galaxies. The deepest CMD to date of this elliptical is presented by Rejkuba et al. (2011) for the *HST* field at 40 kpc: this study concludes that the vast majority of Cen A's halo population is old (~ 12 Gyr), with a younger (~ 2 – 4 Gyr) component accounting for $\sim 20\%$ of the total population.

The first wide-field study of Cen A was performed with the ground-based VLT/VIMOS imager, reaching out to ~ 85 kpc along both minor and major axes (Crnojević et al. 2013). Cen A's halo population seems to extend all the way out to this large radius. This study confirms the relatively high metallicity for halo populations found by the *HST* studies, although with a considerable presence of metal-poor stars at all radii; the authors also highlight the absence of a strong metallicity gradient from a ~ 30 kpc radius out to the most distant regions probed.

This study suggests that the outer regions of Cen A's halo show an increase in ellipticity as a function of radius, which could, however, be interpreted as the presence of substructure contaminating the observed fields. A subsequent study exploits additional *HST* pointings out to a remarkably large radius of ~ 150 kpc: the edge of Cen A's halo is not reached even by this study (Rejkuba et al. 2014). This dataset, analysed together with the previous *HST* pointings, confirms that a very mild metallicity gradient is present, with median metallicities remaining high out to the largest distances probed. Rejkuba et al. (2014), however, also detect a significant pointing-to-pointing variation in both the RGB star counts and the median metallicity, which is likely indicative of non-mixed accreted populations.

Recently, the PISCeS survey (see previous section) has sketched a PAndAS-like picture of Cen A's halo out to ~ 150 kpc: the RGB stellar density map derived from a mosaic of Magellan/Megacam images is presented in Fig. 2.7. This map, very much like the ones obtained for M31 and NGC 891, uncovers a plethora of faint substructures, both in the inner regions of the target galaxy and in its outskirts. The morphological variety of these features is reminiscent of that observed in PAndAS,

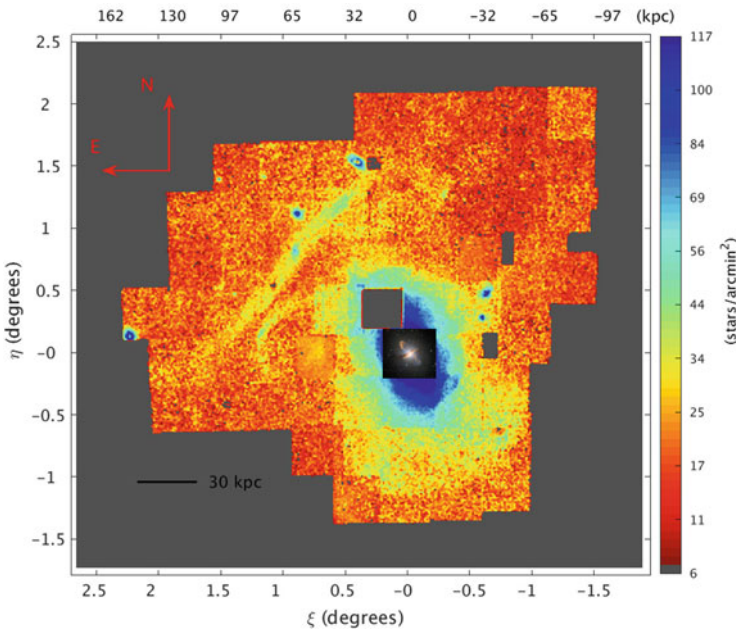


Fig. 2.7 Surface density map of RGB stars in the halo of Cen A, obtained with Magellan/Megacam as part of the PISCeS survey. The map extends out to a radius of 150 kpc in the north and east directions (physical and density scales are reported). Several tidal features are easily recognized, including a stunning disrupting dwarf with tails 2 deg long in the outer halo, an extended sparse cloud to the south of the galaxy, as well as arcs and plumes around the inner regions, tracing both ongoing and past accretion events. Figure 3 from Crnojević et al. (2016), reproduced by permission of the AAS

with shells, plumes, an extended cloud and long tidal streams. In particular, one of the newly discovered dwarf satellites of Cen A is clearly in the process of being disrupted, with ~ 2 deg long tails: taking into account the stellar content of these tails, this galaxy's pre-disruption luminosity could have been similar to that of Sagittarius in the LG. This survey also led to the discovery of nine (confirmed) dwarf satellites down to $M_V \sim -7$. Their properties are consistent with those of faint LG satellites, but some of them lie at the faint/diffuse end of the LG luminosity/surface brightness/radius distribution: this indicates that we might be looking at previously unexplored physical regimes for these faintest satellites, which opens new exciting perspectives for future studies.

2.4 Summary and Future Prospects

In a Λ CDM hierarchical model, all galaxies are predicted to have experienced mergers, of which many should be recognizable as debris/streams that make up for a large fraction of their haloes. Haloes and their substructures thus provide a unique glimpse into the assembly history of galaxies and can inform the models at the smallest galactic scales, where they still fall short in reproducing observations. The time is now ripe for in-depth systematic studies of the resolved stellar populations in galaxy haloes, which will dramatically increase our understanding of galaxy evolution over the next decade.

The challenges for this type of studies are of a different nature: for our own Galaxy, state-of-the-art results on its halo shape, profile and mass inevitably suffer from assumptions on underlying density models and extrapolations of the available data to radii larger than observed. The major current limitation of MW halo studies lies in observational biases due to small field-of-view samples, which preclude the identification of possible substructure contamination. Future surveys hold the promise to advance the knowledge of our Galaxy by obtaining significantly larger samples of tracers, especially in areas so far not covered. Most notably, the astrometric *Gaia* mission (which will provide unprecedented six-dimensional phase space information for two billion stars out to the inner MW halo) and the Large Synoptic Survey Telescope (LSST, designed to provide a southern sky counterpart to SDSS and reaching ~ 4 magnitudes fainter than its predecessor for a total sample of tens of billions of stars) are going to revolutionize our view of the MW. At the same time, the current and future generation of high-resolution spectrographs will follow up these surveys from the ground, providing comprehensive kinematic and chemical information to assess the origin of halo stars and characterize their birthplaces (see also Figueras 2017).

The pioneering studies of an increasing number of haloes beyond the LG, and across a range of masses, will soon be extended by the next generation of ground-based extremely large telescopes (E-ELT, GMT, TMT), as well as space-borne missions (*JWST*, *Euclid*, *WFIRST*). The PAndAS survey of M31 has extensively demonstrated that only the synergy of wide-field ground-based observations, deep

(but spatially limited) observations from space and spectroscopy can return a truly global understanding of haloes made up of a complex mixture of in situ and accreted populations. The aforementioned facilities will open new perspectives with wide-field optical and infrared imagers in concert with high-resolution spectrographs, which will allow us to systematically survey hundreds of galaxies within tens of Mpc in the next decade or two. For example, with the E-ELT/MICADO and *JWST*/NIRCam imagers (the former having higher resolving power and the latter a wider field of view), we should resolve stars down to the HB within ~ 10 Mpc, thus identifying and characterizing the SFHs of streams and faint satellites; derive radial profiles, MDFs and stellar population gradients in haloes within 20 Mpc from the uppermost few magnitudes of the RGB; and trace the halo shape and possible overdensities down to $\mu_V \sim 33$ mag arcsec $^{-2}$ from the uppermost ~ 0.5 mag of the RGB out to 50 Mpc (Greggio et al. 2016).

These observational constraints will be crucial to inform increasingly sophisticated theoretical models and ultimately answer intriguing open questions (as well as possibly unexpected ones that will likely be raised by these observations themselves), such as:

- Do all galaxies have haloes?
- What are the relative fractions of in situ versus accreted populations in galaxy haloes, and how does this depend on galactocentric distance, galaxy morphology and environment?
- What are the properties of the objects currently being accreted, i.e. mass, chemical content, SFH and orbital properties, and how do they relate to those of the present-day low-mass satellites?
- Do low-mass galaxies possess haloes/satellites of their own, and what is their fate and contribution upon infall onto a massive galaxy?
- How extended really are the haloes of massive galaxies?
- What is the shape and mass of the DM haloes underlying galaxies?
- What is the relation between the outer halo and the bulge/disk of a galaxy?
- What is the role of internal versus external processes in shaping a galaxy's properties, especially at the low-mass end of the galaxy LF?
- What is the relation between the present-day haloes/satellites and their unresolved, high-redshift counterparts?

The era of resolved populations in galaxy haloes has just begun, and it holds the promise to be a golden one.

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