The Structure and Content of Galaxy Outskirts

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Abstract. The outer regions of galaxies are expected to contain important clues about the way in which galaxies are assembled. Although quantitative study of these parts has been severely limited in the past, breakthroughs are now being made thanks to the combination of wide-area star counts, deep HST imagery and 8-m class spectroscopy. I review here several recent results concerning substructure, star clusters and stellar halos in the outer regions of our nearest large neighbours, M31 and M33.

1. The Outskirts of Galaxies: Motivation and History

The study of the faint outskirts of galaxies has become increasingly important in recent years. From a theoretical perspective, it has been realised that many important clues about the galaxy assembly process should lie buried in these parts. Cosmological simulations of disk galaxy formation incorporating baryons now yield predictions for the large-scale structure and stellar content at large radii – for example, the abundance and nature of stellar substructure and the ubiquity, structure and content of stellar halos and thick disks. These models generally predict a wealth of (sub)structure at levels of \( \mu_V \sim 30 \text{ mag }/\text{arcsec}^2 \) and fainter (e.g. Bullock & Johnson 2005); their verification thus requires imagery and spectroscopy of galaxies to ultra-faint surface brightness levels.

Since Malin first applied his photographic stacking and amplification technique (e.g. Malin et al. 1983), it has been known that some galaxies possess unusual low surface brightness (LSB) structures – shells, loops, asymmetric envelopes – in their outer regions. Although limited to \( \mu_B \lesssim 28 \text{ mag }/\text{arcsec}^2 \), these images were sufficient to demonstrate that even the most “normal” nearby galaxies could become very abnormal when viewed at faint light levels (e.g. Weil et al 1997). Follow-up study of Malin’s LSB features, and several more recently-discovered examples (e.g. Shang et al. 1999), has been severely limited due to the technical difficulties associated with detecting and quantifying diffuse light at surface brightnesses \( \sim 10 \) magnitudes below sky. The currently most viable technique to probe the very low surface brightness regions of galaxies is that of wide-area resolved star counts. I review here recent results from studies of the resolved populations in the outer regions of M31 and M33, focusing on substructure, star clusters and stellar halos.
2. Stellar Substructure in the Outskirts of Galaxies

Figure 1 (left panel) shows a map of the red giant branch (RGB) population (age $\gtrsim 1-2$ Gyr) in M31 made with the INT Wide-Field Camera (see Ferguson et al. 2002 and Irwin et al. 2005 for details); the right panel indicates regions of prominent stellar substructure in the inner halo. The faintest features visible by eye in the M31 map have effective V-band surface brightnesses of $\mu_V \sim 28-31$ mag/′′. An ongoing survey with Megacam on CFHT extends the INT coverage in the south-east quadrant of M31 to a projected radius of $\sim 150$ kpc and has already led to the discovery of three new dwarf spheroidal galaxies and the most remote currently known M31 globular cluster (Martin et al. 2006). A map of the RGB population around the low mass spiral M33 has also been made. Despite reaching the same limiting depth ($\approx 3$ magnitudes below the tip of the RGB) as the M31 map, no visible substructure can be discerned around M33 (Ferguson et al. 2007, in prep); if substructure is present in this system, it must be of significantly lower surface brightness.

Various distinct features can be seen around M31, including a giant stream in the south-east, stellar overdensities at large radii along the major axis, a
diffuse structure in the north-east and a loop of stars projected near NGC 205. It is of obvious importance to establish the origin of this substructure. Bullock & Johnston (2005) predict substructure in the outer regions of galaxies due to tidal debris from the accretion and disruption of an expected population of $\sim 100-200$ luminous satellites. It has long been recognized that satellite accretion will also heat and restructure the thin disk, generating additional “low latitude” debris (e.g. Quinn et al. 1993, Gauthier et al. (2006). I summarize here our current understanding of the substructure seen around M31:

- Deep HST/ACS CMDs reaching well below the horizontal branch have been obtained for 8 regions in the far outskirts of M31, including seven regions of visible substructure (see Figure 1). Many of the CMDs exhibit different morphologies, suggesting variations in the mean age and metallicity of the constituent stars (Ferguson et al. 2005, Richardson et al., these proceedings). In all cases, the metallicity inferred from the RGB colour is significantly higher ([Fe/H] $\gtrsim -0.7$) than that of typical present-day low mass Local Group dwarf satellites ([Fe/H] $\sim -1.5$), implying that such objects are unlikely to be the progenitors of the observed substructure.

- All substructure fields lying near the major axis contain stars of age $\lesssim 1.5$ Gyr (Faria et al 2007; Richardson et al.,these proceedings); this includes the NE clump field, which lies at a projected radius of 40 kpc. Additionally, the major axis substructure fields are dominated by a strong rotational signature, similar to the HI disk, with a modest velocity dispersion (Ibata et al. 2005). Taken together, these results suggest that the “low-latitude” substructure in M31 originates primarily from perturbed thin disk and not from an accreted satellite (e.g. Peñarrubia et al. 2006).

- The combination of line-of-sight distances and radial velocities for stars at various locations along the giant stream constrains the progenitor orbit (e.g. Ibata et al. 2004; Fardal et al. 2006). Currently-favoured orbits do not easily connect the more luminous inner satellites (e.g. M32, NGC 205) to the stream however this finding leaves some remarkable coincidences (e.g. the projected alignment on the sky, similar metallicities) yet unexplained. The giant stream is linked to another overdensity, the diffuse feature lying north-east of M31’s centre, on the basis of nearly identical CMD morphologies and RGB luminosity functions (Ferguson et al. 2005); orbit calculations suggest this connection is indeed likely.

3. Star Clusters

Our INT and Megacam surveys of the outskirts of M31 and M33 have facilitated a search for new globular clusters in these regions (Huxor et al. 2005, Martin et al. 2006, Huxor 2007, Huxor et al. 2007, in prep). To date, almost 40 new clusters have been identified in M31 and 5 in M33. Of particular interest has been the discovery of a new class of extended, luminous globular clusters in M31 (Huxor et al. 2005). These objects have large half-light radii ($\approx 30$ pc) yet luminosities ($M_V \approx -7$) which place them near the peak of the globular cluster luminosity function. Such a combination of luminosity and size has rarely been
observed within the star cluster population. When placed on the $M_V-R_h$ plane, these extended clusters encroach on the gap in parameter space between classical globular clusters and dwarf spheroidal galaxies (e.g. Belokurov et al. (2007)).

In order to gain further insight into these objects, deep HST/ACS observations were obtained for a small sample of extended clusters lying within 60 kpc of M31 (see Figure 1 and Mackey et al. 2006). Figure 2 shows images of these objects and their associated CMDs. In all cases, the CMD morphology is described by a narrow steep RGB and a clear horizontal branch. Three of the clusters possess horizontal branches extending to the blue and display broadened regions at intermediate colour, suggestive of the presence of RR Lyrae stars. A second parameter effect can also be discerned within the sample.

The extended clusters thus appear to be composed of old ($\geq 10$ Gyr) single stellar populations. Metallicities, estimated from fitting Galactic globular cluster fiducials, indicate these objects are also metal-poor with $-2.2 \leq [Fe/H] \leq -1.8$. Despite their unusual structures and special location in the $M_V-R_h$ plane, these systems appear to be genuine globular clusters as opposed to the stripped cores of dwarf galaxies. Studies of their internal kinematics will be required to test for the presence of dark matter and thus confirm this interpretation.

We have also obtained deep HST/ACS observations of a sample of newly-discovered classical globular clusters in the far outskirts of M31 (15 $\leq R_{proj} \leq 100$ kpc, see Figure 1). Figure 3 shows their CMDs with Galactic globular cluster fiducials overlaid (see also Mackey et al. 2007). The bulk of the sample appears old and metal-poor ($-2.2 \leq [Fe/H] \leq -1.8$). The very outermost clusters ($R_{proj} \geq 40$ kpc) are particularly compact ($R_h \approx 5$pc) and luminous ($M_V \approx -8.5$) when compared to their counterparts in the outermost halo of the Milky Way. They are also considerably more metal-poor than the kinematically-selected field halo population in M31 (see below), again in contrast to the Milky Way where the field halo and globular clusters both peak at $[Fe/H] \sim -1.5$. These
disparities are intriguing and must reflect differences in the early formation and evolution of the two galaxies or in their subsequent accretion histories.

4. Diffuse Stellar Halos

Tidal debris from accretion events will disperse over time and streams from ancient events will have long merged to produce a diffuse stellar halo (e.g. Abadi et al. 2005; Bullock & Johnston et al. 2005). If hierarchical growth is the main mode of mass assembly then such halos should be a generic feature of galaxies. Unfortunately, few observational constraints exist on the nature and ubiquity of stellar halos around galaxies (see however Zibetti et al. 2004 and Zibetti & Ferguson 2004). Even our understanding of the M31 and M33 stellar halos has been extremely poor until recently. I summarize some key results here:

4.1. M31

Using data from the INT/WFC survey, Irwin et al. (2005) combined diffuse light surface photometry with resolved star counts to probe the minor axis profile of M31 to a radius of \( \sim 55 \) kpc (effective \( \mu_V \sim 32 \text{ mag/}^2 \)). The profile shows an unexpected flattening (relative to the inner \( R^{1/4} \) decline) at a radius of \( \sim 30 \) kpc, beyond which it can be described by shallow power-law (index \( \approx -2.3 \)), possibly extending out to 150 kpc (Kalirai et al. 2006). This compares favourably with the Milky Way halo, which exhibits a power-law index of \( -3.1 \) in volume density (Vivas et al. 2006). The discovery of a power-law component which dominates
the light at large radii in M31 has profound implications for the interpretation of all prior studies of the M31 “stellar halo”. Since these studies generally targeted regions lying within 30 kpc along the minor axis, they most likely probed the extended disk/bulge region of the galaxy and not the true stellar halo.

Keck/DEIMOS spectroscopy has been used to study the kinematics and metallicities of stars in the far outer regions of M31. By windowing out the stars which corotate with the HI disk, Chapman et al. (2006) have detected an underlying metal-poor ([Fe/H] ∼ −1.4), high velocity dispersion (σ ∼ 100 km/s) component (see also Kalirai et al. 2006). Although it has yet to be proven that this component is the same one that dominates the power-law profile at very large radius, the evidence is highly suggestive. Despite previous views to the contrary, it thus appears that M31 does indeed have a stellar halo which resembles that of the Milky Way in terms of structure, metallicity and kinematics.

4.2. M33

Studies of the M33 stellar halo have also had a checkered history. Mould & Kristian (1986) measured [M/H] ∼ −2.2 in a field located at 7 kpc along the minor axis of M33 and, for the better part of two decades, this metallicity was generally assumed to reflect that of the M33 halo. Recent work has found a significantly higher metallicity for stars in this same field and, at the same time, suggested that the field is actually dominated by the outer disk and not the stellar halo (e.g. Tiede et al. 2004, Ferguson et al. 2007 in prep). The detection of a power-law structural component in the outskirts of M33 has so far proved elusive, although the RGB clearly becomes narrower and more metal-poor in these parts (Ferguson et al. 2007 in prep). A recent Keck/DEIMOS spectroscopic study has targeted two fields in the outskirts of the galaxy, located at ∼ 9 kpc along the major axis (McConnachie et al. 2006). Although the dominant kinematic component in these fields is rotating, there is tentative evidence for an additional low-level metal-poor ([Fe/H] ∼ −1.5) component centered at the systemic velocity (see also Smecker-Hane, these proceedings). While more work is needed to confirm this detection, the estimated velocity dispersion (σ ∼ 50 km/s) supports an association with M33’s true stellar halo.

4.3. Stellar Halos and Host Galaxies

Based on the RGB colours at projected distances of 2-13 kpc along the minor axes of 8 nearby spirals, Mouhcine et al. (2005) found evidence for a correlation between stellar halo metallicity and parent galaxy luminosity. Specifically, they found that more luminous galaxies possessed more metal-rich halos (and with a higher metallicity spread). The existence (or otherwise) of such a correlation would place extremely interesting constraints on the galaxy assembly process. Mouhcine et al. (2005) found the Milky Way to lie more than 1 dex off their observed relation; somewhat disconcertingly, they suggested that the Milky Way halo may be more “the exception than the rule” for large spiral galaxies.

Figure 4 presents the data from Mouhcine et al. (2005) along with our new spectroscopic measurements of the stellar halo metallicity in M31 and M33. The metallicity of the Milky Way halo is also shown, as well a recent spectroscopic metallicity derived for the high velocity dispersion RR Lyrae component in the LMC (Borissova et al. 2006). With the addition of these new data points, the
correlation observed between stellar halo metallicity and host galaxy luminosity is substantially diminished. Indeed, if one focuses solely on spectroscopic metallicities that have been determined for kinematically-selected halo stars, there is no trend whatsoever between metallicity and host luminosity.

5. Future Outlook

Quantitative study of the faint outskirts of galaxies provides important insight into the galaxy assembly process. Much recent work has focused on our nearest large neighbours, M31 and M33. While both appear to show evidence for metal-poor, pressure-supported stellar halos (similar to that of the Milky Way), only M31 shows evidence for recent accretion. Globular cluster populations offer additional clues to the formation and evolution of M31. This galaxy provides one of the very few systems in which we can infer the assembly history from both resolved field stars and globular clusters; it will be of great importance to determine if a unified picture emerges from these rather different approaches.

In order to put our Local Group results in context, it is necessary to establish the properties of a larger sample of galaxies, spanning a range in both host galaxy luminosity and Hubble type. With 8-m class telescopes, it is possible to obtain wide-field maps of the RGB populations in galaxies to distances of \( \lesssim 5 \) Mpc; with HST, this work can feasibly be extended to \( \gtrsim 10 \) Mpc. However, in this latter case, one must be mindful of the vagaries of inferring global properties from small field-of-view studies of components which have large angular extents.
on the sky. Spectroscopic characterization of resolved RGB populations beyond the Local Group is far harder and must await the arrival of 30-m class telescopes.

Acknowledgments. I thank the organizers for a very enjoyable meeting. Scott Chapman, Daniel Faria, Rodrigo Ibata, Mike Irwin, Avon Huxor, Rachel Johnson, Kathryn Johnston, Geraint Lewis, Dougal Mackey, Nicolas Martin, Alan McConnachie, Jenny Richardson and Nial Tanvir are thanked for their collaboration. Support from a Marie Curie Excellence Grant is acknowledged.

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