RESOLVING THE STELLAR OUTSKIRTS OF M31 AND M33

Annette Ferguson[1], Mike Irwin[2], Scott Chapman[3], Rodrigo Ibata[4], Geraint Lewis[5] and Nial Tanvir[6]

[1] *Institute for Astronomy, University of Edinburgh, UK*

[2] *Institute of Astronomy, University of Cambridge, UK*

[3] *California Institute for Technology, Pasadena, USA*

[4] *Observatoire de Strasbourg, Strasbourg, France*

[5] *Institute of Astronomy, University of Sydney, Australia*

[6] *Centre for Astrophysics Research, University of Hertfordshire, UK*

Abstract Many clues about the galaxy assembly process lurk in the faint outer regions of galaxies. The low surface brightnesses of these parts pose a significant challenge for studies of diffuse light, and few robust constraints on galaxy formation models have been derived to date from this technique. Our group has pioneered the use of extremely wide-area star counts to quantitatively address the large-scale structure and stellar content of galaxies at very faint light levels. We highlight here some results from our imaging and spectroscopic surveys of M31 and M33.

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1. Introduction

The study of galaxy outskirts 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 have now been carried out by several groups and have led to testable predictions for the large-scale structure and stellar content at large radii – for example, the abundance and nature of stellar substructure (e.g., Bullock & Johnston 2005, Font et al. 2005), the ubiquity, structure and content of stellar halos and thick disks (e.g., Abadi et al. 2005, Governato et al. 2004, Brook et al. 2005) and the age distribution of stars in the outer regions of thin disks (e.g., Abadi et al. 2003).

Bullock & Johnston (2005) find that Milky Way-like galaxies will have accreted 100-200 luminous satellites during the last 12 Gyr and that the

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signatures of this process should be readily visible at surface brightnesses of V $\sim$ 30 magnitudes per square arcsec and lower. Although traditional surface photometry at such levels (roughly 9 magnitudes below sky) remains prohibitive, star count analyses of nearby galaxies have the potential to reach these effective depths (e.g., Pritchet & van den Bergh 1994). The requirement of a large survey area (to provide a comprehensive view of the galaxy) and moderate-depth imagery can now be achieved in a relatively straightforward manner using wide-field imaging cameras attached to medium-sized telescopes.

2. The INT WFC Surveys of M31 and M33

In 2000, we began a program to map the outer regions of our nearest large neighbour, M31, with the Wide-Field Camera equipped to the INT 2.5m. The success of this program led us to extend our survey to M33 in the fall of 2002. To date, more than 45 and 7 square degrees have been mapped around these galaxies respectively. Our imagery reaches to V$\sim$24.5 and $i$$\sim$23.5 and thus probes the top 3 magnitudes of the red giant branch (RGB) in each system. The raw data are pipeline-processed in Cambridge and source catalogues are produced containing positions, magnitudes and shape parameters. The M31 survey currently contains more than 7 million sources, and the M33 survey more than 1 million. Magnitude and colour cuts are applied to point-like sources in order to isolate distinct stellar populations and generate surface density maps (see Figure 1). The faint structures visible by eye in Figure 1 have effective V-band surface brightnesses in the range 29-30 magnitudes per square arcsec. Early versions of our M31 maps have been discussed in Ibata et al. (2001), Ferguson et al. (2002) and Irwin et al. (2005).

Results for M31

The left-hand panel of Figure 1 shows the distribution of blue (i.e. presumably more metal-poor) RGB stars in and around M31. A great deal of substructure can be seen including the giant stream in the south-east, various overdensities near both ends of the major axes, a diffuse extended structure in the north-east and a loop of stars projected near NGC 205.

Origin of the Substructure: Do the substructures in M31 represent debris from one or more satellite accretions, or are they simply the result of a warped and/or disturbed outer disk? We are addressing these issues with deep ground-based imagery from the INT and CFHT, Keck-10m spectroscopy and deep HST/ACS colour-magnitude diagrams (CMDs). Our findings to date can be summarized as follows:

- M31 has at least 12 satellites lying within a projected radius of 200 kpc. The bulk of these systems, the low-luminosity dwarf spheroidals, are

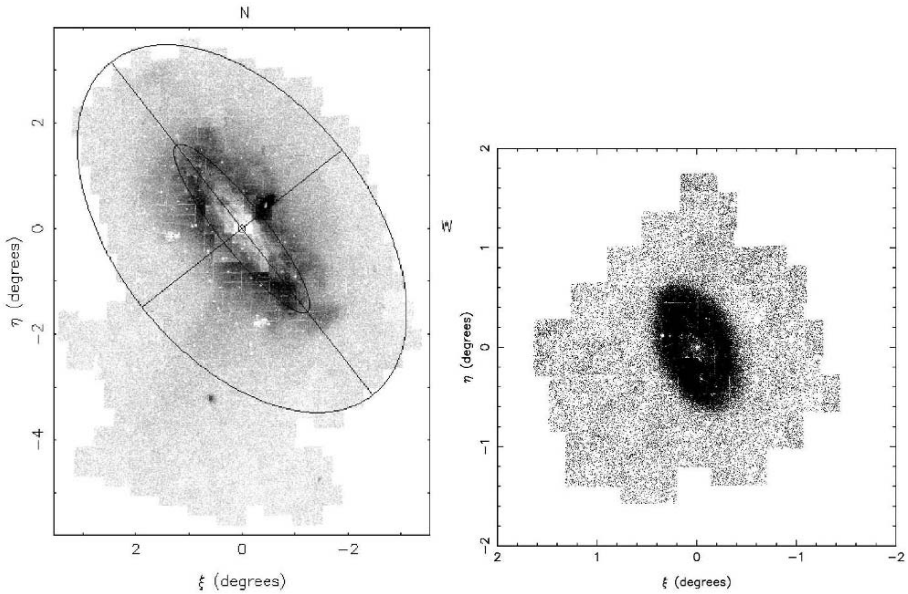

Figure 1. INT/WFC RGB star count maps of M31 (left panel) and M33 (right panel).

unlikely to be associated with the stellar overdensities since their RGB stars are much bluer than those of the substructure (Ferguson et al. 2002).

- The combination of line-of-sight distances and radial velocities for stars at various locations along the giant stellar stream constrains the progenitor orbit (e.g., McConnachie et al. 2003, Ibata et al. 2004). Currently-favoured orbits do not connect the more luminous inner satellites (e.g., M32, NGC 205) to the stream in any simple way however this finding leaves some remarkable coincidences (e.g., the projected alignment on the sky, similar metallicities) yet unexplained.

- Deep HST/ACS CMDs reaching well below the horizontal branch reveal different morphologies between most substructures in the outskirts of M31 (Ferguson et al. 2005, see Figure 2). These variations reflect differences in the mean age and/or metallicity of the constituent stellar populations. Analysis is underway to determine whether multiple satellite accretions are required, or whether consistency can be attained with a single object which has experienced bursts of star formation as it has orbited M31. The giant stream is linked to another stellar overdensity, the NE shelf, on the basis of nearly identical CMD morphologies and

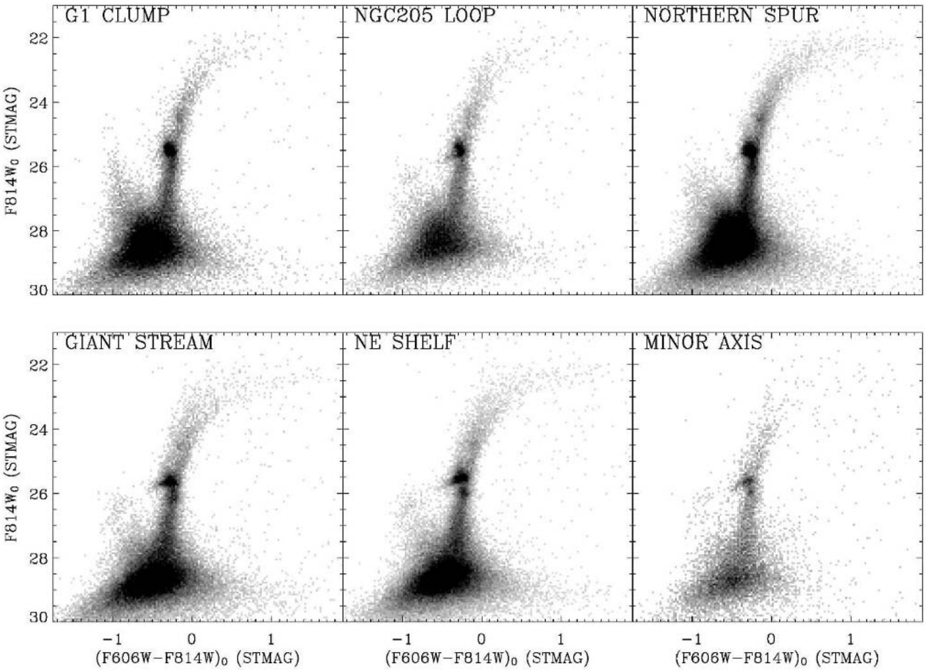

Figure 2. HST/ACS Hess diagrams of six halo fields in M31. Clear differences are apparent between most CMDs, indicating genuine stellar population variations between the substructures.

RGB luminosity functions; indeed, this coupling seems likely in view of progenitor orbit calculations (e.g., Ibata et al. 2004).

Smooth Structure: The INT/WFC survey provides the first opportunity to investigate the smooth underlying structure of M31 to unprecedented surface brightnesses. We have used the dataset to map the minor axis profile from the innermost regions to $\gtrsim$ 55 kpc (Irwin et al. 2005). Figure 3 shows how the combination of inner diffuse light photometry and outer star count data can be used to trace the effective *i*-band surface brightness profile to $\sim$ 30 magnitudes per square arcsec. The profile shows an unexpected flattening (relative to the inner $R^{1/4}$ decline) at large radius, consistent with the presence of an additional shallow power-law stellar component (index ≈ -2.3) in these parts. This component may extend out as far as 150 kpc (Guhathakurta, this conference). Taken together with our knowledge of the Milky Way halo, this finding supports the ubiquitous presence of power-law stellar halos around bright disk galaxies (see also Zibetti et al. 2004, Zibetti & Ferguson 2004).

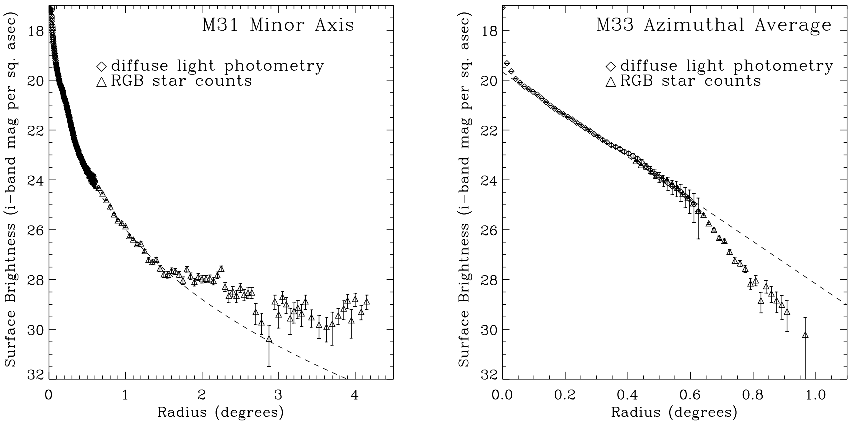

Figure 3. Effective *i*-band surface brightness profiles for M31 (left) and M33 (right). The inner points are derived from surface photometry and the outer ones from RGB star counts. Overplotted are a de Vaucouleurs $R^{1/4}$ law with $r_e = 0.1$ degrees (left panel) and an exponential profile with $r_0 = 0.1$ degrees (right panel).

The kinematics of M31's outer regions are being probed with Keck DEIMOS spectroscopy (e.g., Ibata et al. 2005). Two surprising results have emerged from our program so far. Firstly, there is a high degree of rotational support at large radius, extending well beyond the extent of M31's bright optical disk. Secondly, the overall coherence of this kinematic component is in striking contrast to its clumpy substructured appearance in the star count maps. Further work is underway to understand the nature and origin of this rotating component.

Results for M33

The right-hand panel of Figure 1 shows the RGB map of the low mass system, M33. Although it has the same limiting absolute depth as the M31 map, the stellar density distribution is extremely smooth and regular (Ferguson et al. 2006, in preparation). To a limiting depth of $\sim$ 30 magnitudes per square arcsec (readily visible by eye here), the outer regions of M33 display no evidence for stellar substructure (c.f. the simulations of Bullock & Johnston 2005). Equally surprising, our analysis of the isophote shape as a function of radius indicates no evidence for any twisting or asymmetries. M33 appears to be a galaxy which has evolved in relative isolation.

The radial *i*-band profile of M33 has been quantified via azimuthally-averaged photometry in elliptical annuli of fixed PA and inclination (Figure 3). The inner parts of the profile are constructed from diffuse light photometry, whereas the outer regions are derived from RGB star counts. The luminosity profile displays an exponential decline out to ~ 8 kpc (roughly 4.5 scalelengths) beyond which it significantly steepens. This behaviour is reminiscent of the "disk truncations" first pointed out by van der Kruit in the 80's, but until now not seen directly with resolved star counts. The steep outer component dominates the M33 radial light profile out to at least 14 kpc and limits the contribution of any shallow power-law stellar halo component in M33 to be no more than a few percent of the disk luminosity (Ferguson et al. 2006, in preparation).

3. Future Work

Quantitative study of the faint outskirts of galaxies provides important insight into the galaxy assembly process. The outskirts of our nearest spiral galaxies, M31 and M33, exhibit intriguing differences in their large-scale structure and stellar content. While M31 appears to have formed in the expected hierarchical fashion, M33 shows no obvious signatures of recent accretions. Observations of the outer regions of additional galaxies are required to determine which of these behaviours is most typical of the general disk population.

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