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Unravelling the histories of M31 and M33

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Abstract. Our Local Group neighbours, M31 and M33, can be studied in far greater detail than any of their more distant disc galaxy counterparts. Wide-field surveys are mapping their outer structures to faint surface brightness levels, while deep colour-magnitude diagrams are placing high-precision constraints on their star formation and chemical enrichment histories. I review some recent results and discuss how representative these might be of the disc galaxy population as a whole.

Key words. galaxies: Local Group – galaxies: formation – galaxies: evolution– galaxies: structure – galaxies: stellar content

1. Introduction

Disc galaxies account for a sizeable fraction of the stellar mass in the universe yet the details of their formation and evolution remain poorly constrained. In particular, numerical simulations of disc galaxy formation within a cosmological framework cannot uniquely predict the baryonic properties of the resultant system, even when the halo assembly history is fully specified (e.g. Scannapieco et al. 2012). Different implementations of gas cooling, star formation and stellar feedback can all drastically affect the size, mass, morphology and star formation history of the simulated disc, making it difficult to identify generic predictions.

The challenges associated with *ab initio* modelling of cosmological disc formation have made the need for high precision observational constraints on their histories especially pressing. Such data can enable robust discrimination between the myriad of competing baryonic physics prescriptions, leading to the exclusion of models which blatantly fail to match the data and the refinement of those which show some degree of success. Attention thus far has largely focused on comparing the global properties of simulated and real galaxies, such as the Tully-Fisher and mass-size relations (e.g. McCarthy et al. 2012). While this is obviously important, the internal properties of galaxies provide more stringent tests since these typically show greater sensitivity to the input physics. Key issues include the importance of *in situ* star formation versus accretion in building disc galaxies, the epoch at which significant disc star formation first occurred, the radial star formation and chemical enrichment histories of discs, and the role of internal processes (e.g. radial migration) in shaping the structure and content of the disc at later times.

From an observational standpoint, our large Local Group neighbours, M31 and M33, arguably provide the best current laboratories for addressing these and other issues. Our external vantage point enables spatially-resolved properties to be studied far more easily in these systems than in the Milky Way, where stellar

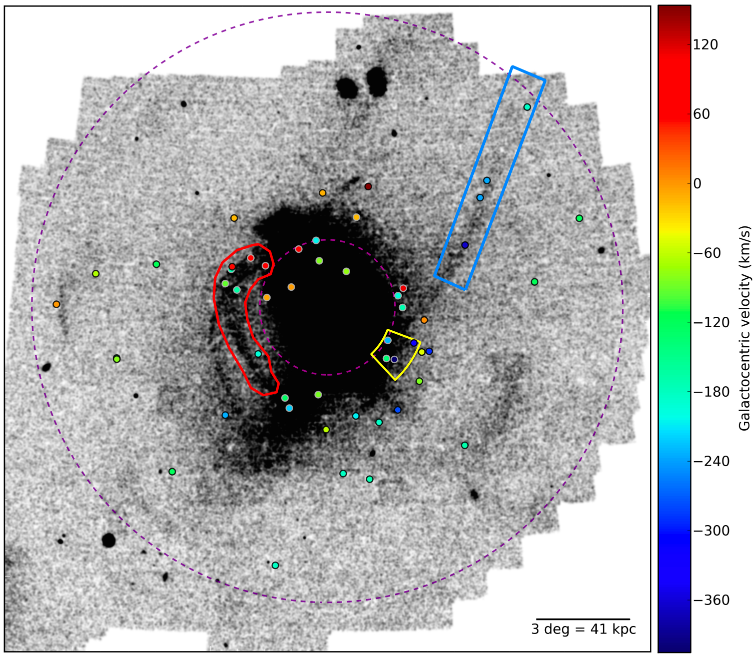

Fig. 1. The metal-poor RGB stellar density map of M31 from PAndAS. The dashed circles correspond to projected radii of 30 and 130 kpc. The positions of some newly-discovered halo GCs are indicated with dots, the colours of which reflect their Galactocentric radial velocities in km s^{-1} (see colour bar). For reference, the Galactocentric velocity of M31 is -109 ± 4 km s^{-1}.

distances are very poorly known beyond the immediate solar neighbourhood. Additionally, their proximity means that their stellar populations can be partially resolved into individual stars enabling the construction of colour-magnitude diagrams (CMDs) that offer superior insight into age and metallicity compared to integrated light analyses. I highlight here a few recent results regarding the assembly history of these systems.

2. Substructure in the outer regions of M31 and M33

Building on earlier surveys (e.g. Ferguson et al. 2002), the Pan-Andromeda Archaeological Survey (PAndAS) has mapped individual red giant branch (RGB) stars over ≈ 400 square degrees around M31 and M33 using CFHT/MegaCam (McConnachie et al. 2009). Figure 1 shows a portion of the metal-poor RGB stellar density map, centred on M31. The faintest features visible by eye on this map have surface brightnesses of ≈ 31 mag arcsec^{-2}. In addition to revealing a copious amount of stellar debris in the outer disc and extended halo, PAndAS has also uncovered over 90 new halo globular clusters (GCs) (Huxor et al. 2005, 2008, 2011; Veljanoski et al. 2013a). The halo GC system extends to at least 200 kpc in galactocentric radius (Mackey et al. 2010a), making it significantly more numerous and extended than that of the Milky Way. M33 also possesses substructure at large radius (McConnachie et al. 2010; Cockcroft et al. 2013), as well as its own retinue of halo GCs (Huxor et al. 2009; Cockcroft et al. 2011).

The mere existence of low surface brightness tidal debris provides support for the hierarchical picture of galaxy assembly in which accretions and mergers play a role in the evolution of galaxies (e.g. Cooper et al. 2010). However, confirming this model at the most basic level is just the first step in developing a

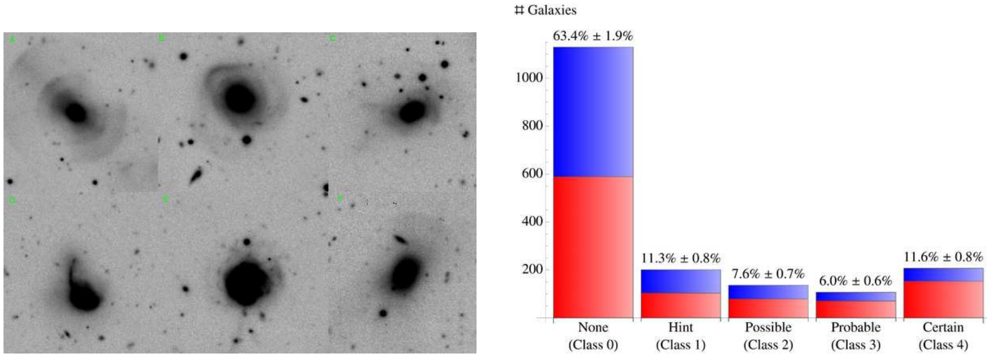

Fig. 2. (Left) Examples of the six different categories of tidal disturbances classified by Atkinson et al. (2013). Clockwise from top-left: shells, streams, diffuse envelope, fans, linear feature and arm. (Right) Distribution of detection classes within the CFHTLS-Wide sample. Each histogram bin is labeled by its fractional contribution to the total galaxy population, and divided into red sequence and blue cloud populations.

detailed picture of galaxy formation. For example, how many accretions has M31 experienced and what was the nature of the accreted system(s)? The halo GCs may provide important insight into these questions. Of particular interest is the apparent spatial correlation between halo GCs and underlying stellar substructure seen in Figure 1. Using an earlier version of the PAndAS map, Mackey et al. (2010b) demonstrated that this behaviour is highly significant and argued that this reflected a genuine physical association, with the inference being that most of the GCs beyond $\gtrsim$ 30 kpc have been accreted along with their satellite hosts. Veljanoski et al. (2013b) (see also this volume) have recently confirmed this conclusion through the measurement of coherent velocities amongst GCs that lie on discrete substructures. Since no galaxies fainter than $M_V \sim -12.5$ are known to host GCs (see Veljanoski et al. 2013a), this places a lower limit on the luminosity of the accreted system(s) responsible for producing the halo debris. Furthermore, GCs will prove valuable in orbit reconstruction of the accreted satellite(s) and thus in answering questions about the number of accretions and the shape of M31's dark halo. This will be achieved through modelling their line-of-sight distances (which we are currently obtaining with the Hubble Space Telescope (HST)) in combination with their radial velocities and projected positions on the sky.

2.1. Is the substructure observed typical?

It is prudent to ask whether the observed level of substructure in M31 and M33 is typical for galaxies of similar mass and morphological type. Surprisingly, rather little is known about the statistics of faint tidal debris for the galaxy population as a whole. While complex stellar structures are seen in the outer regions of both spiral and elliptical galaxies (e.g. Martínez-Delgado et al. 2010), studies tend to target systems that have long been known or suspected to harbour peculiarities. Furthermore, some galaxies have been surveyed to very faint depths and failed to reveal any signatures of bright tidal debris whatsoever (e.g. Barker et al. 2012).

In order to better assess the frequency of faint tidal debris around galaxies, we have visually-examined 1800 luminous galaxies in the "Wide" portion of the Canada-France-Hawaii Legacy Survey, one of the most sensitive large multi-band datasets in existence. The galaxies have been selected to have redshifts in the range $0.04 < z < 0.2$, and stellar masses of

$\sim 3\times10^{9-11}$ $M_{\odot}$. For reference, the stellar mass of M31 is 1.6×10^{11} $M_{\odot}$ (Barmby et al. 2006) and of M33 is $3-6\times10^{9}$ $M_{\odot}$ (Corbelli 2003).

We have classified tidal features according to their morphology, using the categories illustrated in the left panel of Figure 2. We find that around 12% of the sample show clear evidence for tidal features at the highest confidence level (Class 4), which increases to 18% if systems are included which exhibit convincing albeit weaker structures. Thus, fewer than one in five M31/M33-like systems exhibit substructure in the CFHTLS-Wide. However, the detectability of debris is a strong function of rest-frame colour, with red galaxies (like M31) almost twice as likely to show features than blue galaxies (see right panel of Figure 2).

The surface brightness limit of the Atkinson et al. (2013) sample is $g_{AB}\sim 27.7$ mag arcsec^{-2}, which is several magnitudes brighter than the effective limit of our PAndAS survey. Indeed, when viewed at the depth of the CFHTLS-Wide survey, probably only the giant stellar stream of M31 would be (marginally) visible and nothing in M33. This suggests that the amount of substructure in Local Group galaxies is not in stark contrast to that observed for general field galaxy population, at least when considered at comparable surface brightnesses. Clearly more interesting limits will come from repeating the analysis of Atkinson et al. (2013) on the deeper large survey datasets that are now emerging.

3. The star formation histories of the M31 and M33 outer discs

The complexity in the outskirts of M31 and M33 means that caution is required when interpreting small field-of-view studies of these parts. While it was once assumed that observing a field at $\gtrsim$ 20 kpc from the centre of a large galaxy would provide a clean probe of it's spheroid populations, it is now clear that such a field could in fact sample any number of stellar components in addition to or even instead of the halo – for e.g. the thick disc, the extended thin disc and/or tidal debris streams. This problem is particularly acute in the case of HST studies where the field-of-view ($\approx 3'$ on a side) is tiny compared to the $\gtrsim$ 1 degree extents of M31 and M33. Thus, while deep HST CMDs allow exquisite star formation history (SFH) reconstructions for M31 and M33, an understanding of their global structure is essential for the interpretation of these small field-of-view datasets.

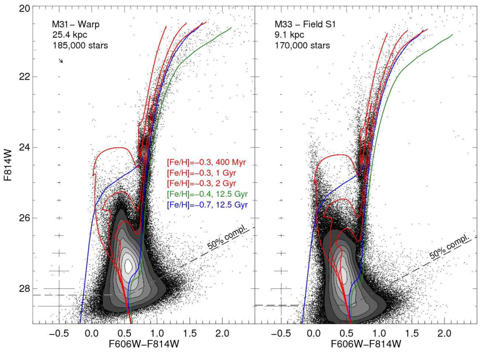

Fig. 3. CMDs for the M31 warp field (left) and the M33 outer disc (right). Selected isochrones and a zero age horizontal branch from the BaSTI library are shown. The projected radial distances of each field, along with the total number of stars, are listed in the upper left of each panel

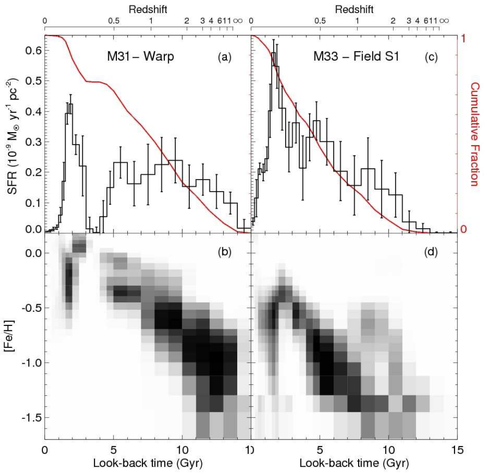

Fig. 4. The best-fit SFH solutions (top) and corresponding AMRs (bottom) for the M31 warp (left) and M33 outer disc (right) fields. The cumulative mass fraction is shown in red.

Exploiting our wide-field survey work for this purpose, we carefully selected positions in the outer discs of M31 and M33 to target with the *Advanced Camera for Surveys* on board HST (Barker et al. 2011; Bernard et al. 2012). In M31, we selected a field lying in the stellar warp while a field just inside the disc truncation was chosen in M33. Figure 3 shows the resultant CMDs which reach the old main sequence turn-offs ($\sim$ 12.5 Gyr) with high precision and can be used to extract the outer disc SFHs back to early epochs (see Figure 4, and Bernard et al. (2012) for a full discussion of the methods). The derived behaviours are rich and complex. M31 is found to have experienced roughly constant SF until about 4.5 Gyr ago, after which there was a lull in activity for $\sim$1.5 Gyr followed by a strong recent burst. In M33, a strong burst also occurred $\sim$ 2 Gyr ago, but prior to this the SF rate showed a steady rise towards recent epochs. The onset of SF was also delayed in M33 relative to M31 and the stellar mass built up more gradually in this lower mass system. While 50% of the mass in the M31 outer disc field was in place 7.5 Gyr ago, this did not occur until 4.5 Gyr ago for M33. The simultaneous bursts of star formation $\sim$ 2 Gyr ago are accompanied by apparent declines in metallicity, which could be a signature of the inflow of metal-poor gas (Bernard et al. 2012). Intriguingly, this timescale corresponds to the last close passage of M31 and M33 as predicted by N-body models (McConnachie et al. 2009), and gas inflow may have been triggered by this event (see the simulations of Rupke et al. 2010). The complex behaviour of the SFHs and the smoothly-increasing age-metallicity relation (AMRs) over most of cosmic time suggest that the stellar populations observed in these remote fields mostly formed *in situ* instead of having migrated from smaller radii. Indeed, it has been argued that smooth SFHs and flat AMRs are expected if radial migration is an efficient process within discs (Roškar et al. 2008). Furthermore, the moderate metallicity of the oldest stars in both discs ([Fe/H]≈ -1.3) suggests the outer discs formed from pre-enriched material. Additional observations are being obtained with HST to study how these properties vary with radius in M31.

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