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Stellar Substructure in the Halos of the Milky Way and M31

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Abstract. Dedicated wide-field surveys have uncovered a variety of debris features and stellar streams in the halos of the Milky Way and M31. I briefly compare these perspectives and discuss how observations of the peripheral regions of M31 can help shape our current understanding of the Milky Way. Much complexity resides in the outer halos of both systems in terms of overlapping structures, and I conclude by briefly highlighting some ongoing work to characterise a narrow tidal stream in the vicinity of the ultra-faint satellite Segue 1.

Keywords. Galaxy: halo, Galaxy: formation, Galaxy: evolution, galaxies: individual (M31)

1. Introduction

Over the last 15 years, the stellar halos of the Milky Way (MW) and M31 have been explored in superb detail with a variety of wide-field photometric and spectroscopic surveys. In the Milky Way, major advances in characterising the structure and substructure of the halo have been made by the Sloan Digital Sky Survey (SDSS) and the Pan-STARRS PS1 3π Survey, as well as smaller area surveys such as the Dark Energy Survey (e.g., Belokurov *et al.* 2006, Schlaufman et al. 2009, Bernard *et al.* 2016, Balbinot *et al.* 2016). In M31, the Isaac Newton Wide Field Camera Survey, followed by the Pan-Andromeda Archaeological Survey (PAndAS), have revealed fascinating complexity in the stellar density distribution at very large radius (e.g., Ferguson *et al.* 2002, Ibata *et al.* 2014), while the SPLASH survey has detailed the rich kinematical structure that is also present (e.g. Gilbert *et al.* 2014). Recent reviews of the substructures in the halos of these two galaxies can be found in Grillmair and Carlin (2016) and Ferguson and Mackey (2016).

The properties of stellar halos, including their substructures, reflect the accretion histories of their host galaxies (e.g. Johnston et al. 2008) and it is of obvious interest to compare and contrast the halos of the MW and M31. Indeed, these roughly L_* spirals are similar in terms of many of their global properties and it is natural to expect that they have experienced comparable amounts of accretion. Although our views of their stellar halos are completely unrivaled by those of any other galaxy, these views are nonetheless somewhat limited and each is subject to different completeness issues and biases. For example, while deep photometry reaching to old main sequence turn-off (MSTO) stars is possible over enormous areas in the MW sky, M31 is sufficiently distant that equivalent wide-field studies can only probe the much more luminous – but rarer – red giant branch (RGB) populations. As a result, only the brightest substructures can be detected in the M31 halo (i.e. those features with considerable populations of RGB stars), with the myriad of MW streams detected through modest overdensities of MSTO stars being well out of reach. In addition, it is possible to trace substructure in the MW halo through a variety of stellar tracers (e.g. MSTO stars, RR Lyrae, M-giants), providing sensitivity to disrupted progenitors of varying age and metallicity. In M31, only RGB stars can be

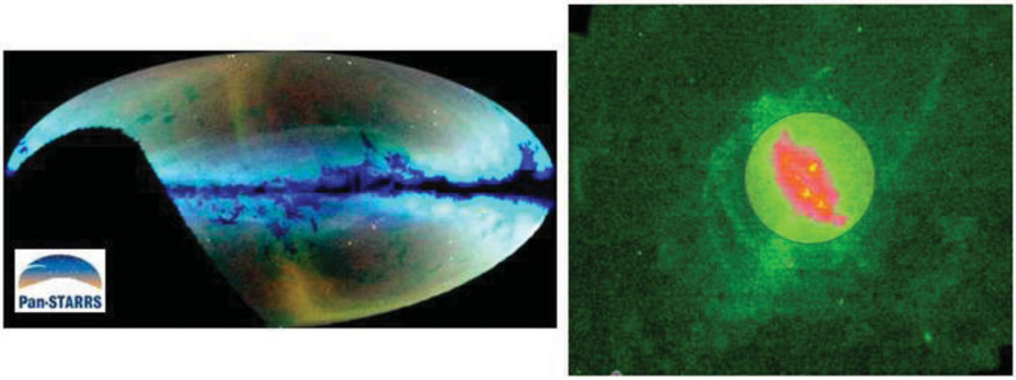

Figure 1. Views of the stellar distribution in the MW halo (left) from MSTO stars detected in the PS1 survey (Bernard *et al.* 2016, see https://www.oca.eu/fr/ebernard/452-streams) and from RGB stars in the M31 halo (right) from PAndAS (McConnachie *et al.* 2009). The circle superposed on M31 indicates a projected radius of 40 kpc, the approximate distance limit of MW MSTO stars in the PS1 survey.

used trace halo substructures at present, although on the assumption of a fixed age these populations can be examined in different metallicity slices (e.g. Ibata *et al.* 2014).

In some ways, however, M31 provides an optimal view. Our external vantage point facilitates a global view of the halo and this means it is much easier to distinguish and characterise stellar substructures, as well as develop an understanding of how different features relate to each other. For example, Fig. 1 shows that several streams in the M31 halo actually overlap each other, at least in projection, and that much of the low latitude substructure appears to be connected to the outer disc. This birds-eye view also means that the stellar halo can be mapped out to large projected radii with relative ease since, to first order, the stars at any radius lie at the same effective distance from us.

I briefly discuss some insights gained from studies of halo substructure in M31 and consider how these might help inform and contextualise our understanding of the MW.

2. Lessons from the M31 Halo

2.1. *Our current view of the MW halo is strongly biased to small radii*

The PAndAS+SPLASH surveys have detected M31 halo stars out to radii of at least 150 kpc (e.g. Ibata *et al.* 2014, Gilbert *et al.* 2012), and discovered some M31 globular clusters (GCs) with 3D galactocentric distances of $\sim$ 200 kpc (Mackey *et al.* 2010a). Importantly, PAndAS has provided a contiguous view of the M31 halo out to these distances. This can be contrasted with the situation in the MW, where most of the information is limited to the northern hemisphere and to radial distances within $30-40$ kpc from the Sun, which is the reach of SDSS and PS1 for detecting MSTO stars (see Fig. 1). Although some detections of far outer halo MW substructure have been made (e.g. Sesar *et al.* 2007), a panoramic view of these peripheral regions awaits the LSST.

The different volumes probed by current MW and M31 halo studies mean that some important measurements are not (yet) directly comparable. For example, Deason *et al.* (2011) use blue straggler stars to estimate that $\sim 5-20\%$ of the MW halo resides in substructure, while Ibata et al. (2014) estimate that, summing over all metallicities, more than 70% of the M31 halo in the (projected) radial range $27-150$ kpc is in substructure.

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It remains unclear if these numbers reflect genuine differences in the two halos, or merely the fact that the amount of substructure is a strongly increasing function of radius.

2.2. *Much low latitude substructure in the MW may be heated disc*

As seen in Fig. 1, the appearance of the inner halo (R< 40 kpc) of M31 is that of a flattened ellipsoid, on top of which relatively bright tidal features can be seen (e.g., streams, clumps, spurs, shelves). Most prominent of these is the giant stellar stream (GSS), which can be traced in the south-west quadrant of the galaxy to almost 100 kpc. Dedicated studies have been carried out to characterise the properties of M31's inner halo tidal features, including the GSS, and shed light on their origins. For example, Bernard *et al.* (2015) present detailed star formation and chemical enrichment histories for 14 substructure fields derived from deep HST colour-magnitude diagrams, finding that the material can be classified into two main types. The first category consists of stellar populations that strongly resemble those of the GSS, where almost all the stellar mass was formed 6–10 Gyr ago and with a broad range of metallicities reaching up to solar; these substructures are presumably composed of material stripped off the GSS progenitor on various pericentric passages. On the other hand, the remaining fields show evidence for continuous star formation until recently, with a young mean age and a much milder chemical evolution. Combined with the strong rotation seen in many of these fields (Ibata *et al.* 2005), the most obvious interpretation of this material is that it has been formed in and subsequently kicked out of the disc. This demonstrates the important contribution that heated disc stars can make to inner halo substructure and may be of relevance for the interpretation of similar – albeit much harder to study – low-latitude substructures in the MW, such as the Monoceros Ring and the Triangulum-Andromeda stellar clouds (e.g. Price-Whelan *et al.* 2015).

2.3. *The last significant accretions in the MW and M31 were similar*

There are several indications that M31 may have accreted more stellar mass over its history than the MW has, and that this mass may have been accreted over a more prolonged period. This evidence includes M31's more luminous stellar halo, the unbroken radial density profile of its halo and the fact that it has roughly 3 times more GCs than the MW (e.g. Ibata *et al.* 2014, Deason *et al.* 2013, Huxor *et al.* 2014). But although their past histories may have been different, there is a tantalising similarity between the properties of the Sagittarius dwarf – the last significant accretion event experienced by the Milky Way – and those inferred for the GSS progenitor – the last significant accretion event experienced by M31. Specifically, both are early-type galaxies with estimated initial stellar masses in the range $0.5 - 1 \times 10^9$ $M_\odot$ (Bernard *et al.* 2015). Nonetheless, their orbits and accretion times were rather different. Sagittarius has been on a near-polar orbit for several Gyr while the GSS progenitor appears to have plunged towards the center of M31 on a highly-radial orbit within the last Gyr (e.g. Ibata *et al.* 2004).

2.4. *Complexity and complicity at large radius*

A striking feature of the M31 outer halo is the (projected) spatial and velocity coincidence of GCs and tidal streams, most naturally interpreted as evidence that GCs are being accreted along with their now-disrupted host galaxies (Mackey *et al.* 2010b, Veljanoski et al. 2014, Mackey *et al.* 2014). Evidence is beginning to emerge that such correlations might also exist in the MW halo (e.g. Carballo-Bello et al. 2017). Bernard *et al.* (2016) have recently discussed the existence of a narrow tidal stream which projects in front of the enigmatic ultra-faint MW satellite, Segue 1 (Fig. 2). This feature extends over $\sim 24°$ and, although the distance uncertainties are significant, it appears to lie only a few kpc

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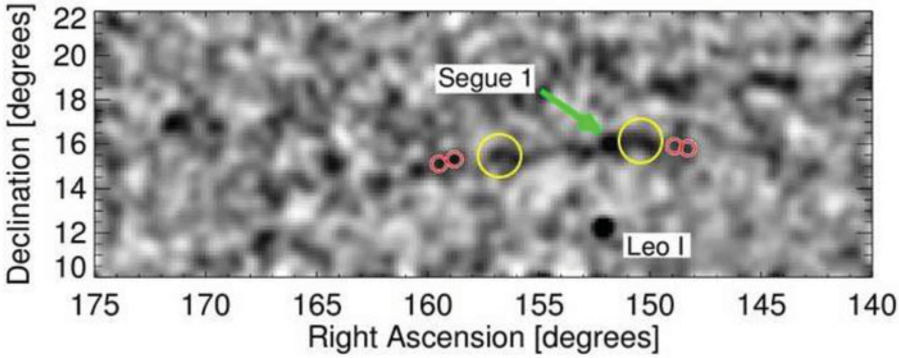

Figure 2. A smoothed matched-filter map of the region around Segue 1 from the PS1 3π survey. A narrow tidal stream can be seen projecting in front of this system. Spectroscopic fields observed with the AAT and WHT are indicated by large and small circles respectively.

closer than Segue 1, which is at a heliocentric distance of 23 kpc. We have recently used the AAT+AAOmega/2dF and the WHT+WYFFOS/AF2 to obtain spectroscopy for stars at various positions along this stream. Our preliminary results indicate that, in addition to the expected Galactic components at low velocities, there are stars with radial velocities in the range 200–300 km s^{-1} at various positions along this stream. Given the systemic velocity of Segue 1 (V_{helio} = 208.5 km s^{-1}) and the very high mass-to-light ratio of $\sim$ 3400 inferred for this system (Simon *et al.* 2011), the issue of contamination by the foreground stream may need to be carefully re-assessed.

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