THE STELLAR POPULATIONS OF M31 HALO SUBSTRUCTURE

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ABSTRACT

We present the first results from our survey of stellar substructure in the outskirts of M31 using the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope. We discuss the stellar populations associated with five prominent stellar overdensities discovered during the course of our panoramic ground-based imaging survey with the Isaac Newton Telescope Wide-Field Camera (INT WFC); a sixth pointing targets a region of ‘clean’ halo. The colour-magnitude diagrams (CMDs), which contain between \(\approx\)10,000–90,000 stars and reach four magnitudes below the horizontal branch, reveal clear variations in morphology between most fields, indicating that the age and/or metallicity mix of stars is not constant at large radius. This directly confirms the existence of large-scale population inhomogeneities within the halo of M31 and lends further support to the notion that M31 has formed, at least in part, through satellite accretions. We find a striking similarity between the populations of the giant stellar stream and those of another overdensity, the NE shelf, which lies north-east of the galaxy center. If these overdensities are associated with the same population, then the difference in their red clump magnitudes implies the NE shelf lies in front of the stream by several tens of kpc, in good agreement with recent orbit calculations for the stream progenitor.

Subject headings: galaxies: formation – galaxies: evolution – galaxies: structure – galaxies: halos – galaxies: stellar content

1. INTRODUCTION

The INT WFC survey of M31 has led to the discovery of significant stellar substructure in the halo and outer disk of our nearest giant neighbour (Ibata et al. 2001). Ferguson et al. 2002, McConnachie et al. 2003, 2004, Irwin et al. 2005. At the present time, the survey consists of more than 40 square degrees of V- and i-band imaging to a depth sufficient to resolve stars to \(\approx\)3 magnitudes below the tip of the red giant branch (RGB).

Few constraints currently exist on the nature and origin of the stellar substructure in M31. Within the popular \(\Lambda\)CDM model for galaxy formation, substructure is expected in the outer regions of galaxies as they continue to grow from the accretion and tidal disruption of satellite companions. Recent calculations suggest that massive disk galaxies, like the Milky Way and M31, could have cannibalised \(\sim\)100 dwarf galaxy-like systems over their lifetimes (Bullock & Johnston 2004). Since these accreted satellites are likely to have experienced a range of stellar populations, one expects their tidal debris to be distinct in terms of stellar populations. If this picture is correct, then the spatial substructure in M31 should be accompanied by stellar population inhomogeneities.

In order to gain insight into the origin of the M31 halo substructure, we are conducting a detailed study of the associated stellar populations using the HST/ACS. Our INT WFC survey indicated intriguing variations in the mean RGB colour across the halo, which could reflect changes in metallicity and/or age. HST is required to confirm these variations and, via detection of fainter and more evolved populations such as the red clump and horizontal branch, provide constraints on their nature. In this Letter, we present the first results from our HST/ACS survey which establish clear differences, as well as some similarities, between the populations in various substructures.

2. OBSERVATIONS

Observations at six locations in the outskirts of M31 were obtained during Cycle 11 with the Wide Field Camera of the ACS as part of GO\#9458. Our fields sample the five most prominent stellar overdensities in the maps of Ferguson et al. (2002) as well as a region of apparently ‘clean’ halo (Minor Axis) situated 20 kpc along the southern minor axis (see Figure 1). The main characteristics of the stellar overdensities can be summarized as follows:

Giant Stream - a stellar stream, with a well-defined eastern edge, which can be traced in projection to \(\sim\)70 kpc from the center of the galaxy towards the
between multiple sub-exposures to facilitate warm pixel within a single visit. Integer pixel dithers were executed filter (broad V) and two orbits in the F814W filter (I), all major axis.

plume of stars which sits just above the north-eastern 2004); (Reitzel, Guhathakurta, & Rich 2004; Ferguson et al. expected, radial velocity data have now ruled this out initially a connection between the two was sus-

While the geometry is very suggestive of a connection along the south-western major axis, in close proxim-

diameter N31) as mapped with the INT WFC. Overlaid are the locations of the HST/ACS pointings presented here (red) and the deep HST/ACS halo pointing of Brown et al. (2003) (cyan).

south-east 2001, McConnachie et al. 2003). Radial velocity data have ruled out a simple connection to the dwarf elliptical companions M32 and NGC 205 (Ibata et al. 2004; Font et al. 2004);

NE Shelf - a large overdensity north-east of the galaxy centre which also exhibits a sharp outer boundary; NGC 205 Loop - a small (~ 15 kpc) loop of stars which appears, in projection, to emanate from NGC 205. While the geometry is very suggestive of a connection between the two, extant stellar kinematical data still leave open other possibilities (McConnachie et al. 2003); G1 Clump - a stellar overdensity which sits 30 kpc along the south-western major axis, in close proximity to the anomalous globular cluster G1. Although initially a connection between the two was sus-

Northern Spur - first hinted at by Walterbos & Kennicutt 1988), this is an extended plume of stars which sits just above the north-eastern major axis.

Each field was observed for one orbit in the F606W filter (broad V) and two orbits in the F814W filter (I), all within a single visit. Integer pixel dithers were executed between multiple sub-exposures to facilitate warm pixel and cosmic-ray rejection. Given the low stellar density in the outer halo, two separate pointings were obtained in each of the three outermost fields (Minor Axis, NE Shelf and Giant Stream) in order to ensure sufficient statistics on the upper RGB and horizontal branch.

Images were first processed through the ACS pipeline and those in a given passband were combined using the Multidrizzle task (Koekemoer, Fruchter, Hook, & Hack 2002) within PyRAF. We used the default mode of Multidrizzle which calculates the offsets between dithered exposures using the information in the image header world coordinate system. The final drizzle was conducted using the Lanczos3 kernel with pixfrac and scale set to unity.

Photometry was subsequently obtained using the IRAF implementation of DAOPHOT (Stetson 1987). The stellar density in our fields is low enough to allow precise results from aperture photometry alone. PSF-fitting photometry was also carried out to compare with the aperture photometry and to measure how accurately individual sources could be modelled by a stellar PSF. For this purpose, a spatially non-varying PSF was built using ~ 150 bright stars in each of the nine ACS pointings. Sources were retained in our final photometry list if their magnitude errors, sharpnesses and chi values all lay within 3-sigma of the average value at their magnitude. Aperture corrections were derived from several tens of bright stars in each combined frame and our photometry was placed on the STPMAG system using the latest ze-


density of the CMD makes it difficult to discern values of (B−V) = 0.06−0.09, (B−V) = 0.07 for all fields and values of the selective extinction coefficient in the F606W and F814W passbands from Sirianni et al. 2004). The final CMDs contain between 10,000 stars (the Minor Axis field) and 90,000 stars (the Northern Spur field) and extend to four magnitudes below the horizontal branch (see Figure 2). Artificial star tests indicate 75% completeness to F814W0 = 28.5 in fields of average stellar density. Details of our analysis will be presented in a forthcoming paper.

3. RESULTS

3.1. The CMD Morphologies

Figure 2 shows Hess diagrams for the six halo fields targetted in our survey. In all cases, a broad RGB and a prominent red clump are evident, consistent with the findings of earlier HST studies of the M31 halo (e.g. Holland, Fahlman, & Richer 1996; Bellazzini et al. 2003). However, on closer inspection, noticeable differences can be seen in the morphol-

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Fig. 2.— Hess diagrams of six halo fields in M31 shown with a square root stretch. G1 Clump, NGC205 Loop, Northern Spur, Giant Stream and NE Shelf are regions of stellar substructure within the M31 halo, while Minor Axis was chosen to represent clean halo. Clear differences are apparent between most CMDs, indicating genuine stellar population variations within the halo substructure.

(e.g. Monaco, Ferraro, Bellazzini, & Pancino (2002)). The clarity of this feature in the shelf and stream CMDs suggests these regions contain a dominant stellar population with a small to moderate range of age and metallicity, perhaps the result of one or more bursts. Additionally, the location of the RGB bump at approximately 0.4 magnitudes fainter than the red clump in these fields supports the inference from the RGB colour that this is a relatively metal-rich population (e.g. Alves & Sarajedini (1999)).

The G1 Clump is distinct in showing clear evidence for a young population. It exhibits a well-populated upper main sequence (blue plume), with some stars as bright as F814W ≈ 24.5. Comparison to the Padova isochrones (Girardi 2004) indicates the brightest stars are consistent with a population of age of ~ 2.5 × 10^8 years (Faria et al. 2005). On the other side of the major axis, and at a slightly smaller radius, the Northern Spur shows no evidence for such a young component. Instead, this field shows a low-amplitude RGB bump at F814W ≈ 26 and another bump at ~ 24.5. Given the moderate metallicity inferred from the RGB colour, the models of Alves & Sarajedini (1999) indicate that the brighter bump is more likely to be an asymptotic giant branch (AGB) bump as opposed to a secondary RGB bump (such features are also marginally present in the G1 Clump CMD). The NGC 205 Loop is similar to the Giant Stream, NE Shelf and Minor Axis fields in having an extended blue horizontal branch, but it differs in having neither an RGB/AGB bump nor a blue plume. Finally, all three CMDs in the top panel of Figure 2 show tantalizing evidence of a bright main-sequence turn off at F814W ≈ 27.5, roughly matched by a population of ~ 2.5 × 10^9 years with [Fe/H] = −0.7 (Girardi 2004). As the Giant Stream and NE Shelf fields contain more stars than either the G1 Clump or NGC 205 Loop, the visibility of this putative turnoff is not simply dependent on total stellar density.

Although the CMD morphologies often differ, the mean colour of the (broad) RGB remains surprisingly constant. When measured in the region 27 < F814W < 26, the mean RGB colour varies by less than 0.05 magnitudes from region to region. This is comparable to the difference expected in colour between [Fe/H] = −0.4 and −0.7 stellar isochrones for a population of 14 Gyr (Girardi 2004).

3.2. Using Stellar Populations to Trace the Giant Stream
The striking resemblance between the Giant Stream and NE Shelf CMDs motivates further exploration of the relationship between these features. Figure 3 shows the F814W0 luminosity function (LF) of these populations in the vicinity of the red clump and RGB bump. We fit the LF in the red clump region with the sum of a first order polynomial and a gaussian, selecting stars with the same range of de-reddened magnitude and colour in each case. We find the peak magnitude of the red clump to differ slightly between the fields, being F814W0 = 25.67 ± 0.01 for the stream and 25.53 ± 0.01 for the shelf.

The magnitude and colour of the red clump are known to vary as a function of age and metallicity (e.g. Girardi & Salaris (2001)) but the overall similarity of the CMD morphologies suggests that population-driven differences between the stream and shelf regions are small. This is further confirmed by the nearly identical luminosity function slopes observed. In this case, a more likely cause of the offset in red clump magnitude is that the regions are located at different line-of-sight distances. The red clump magnitude difference of Δ(F814W0)stream−shelf = 0.14 ± 0.01 implies that the Giant Stream region lies beyond the NE Shelf by a factor of 1.07 ± 0.01. McConnell et al. (2003) have measured the line-of-sight distance to the stream as a function of position along it. We have interpolated their measurements to the location of our Giant Stream ACS field and find a line-of-sight distance of 830 ± 20 kpc. Combining this value with the differential distance modulus inferred from the red clump magnitudes yields a distance to the shelf of 776 ± 20 kpc.

4. DISCUSSION

Our HST/ACS survey of M31 substructure has revealed significant variations in CMD morphology at large radius, indicating that the age and/or metallicity of stars in these parts is not constant. This is the first direct evidence for large-scale population inhomogeneities in the outskirts of M31. Prior HST studies, which have inferred a uniform population, have generally been based on random pointings within the inner halo and have missed the main stellar overdensities (e.g. Bellazzini et al. (2003)).

It is tempting to interpret the observed population variations as evidence for multiple satellite accretions within the M31 halo, each having a distinct star formation and chemical evolution history. One puzzle, however, is the rather uniform mean RGB colour (though broad distribution) observed from field-to-field. If interpreted purely in terms of metallicity, the mean RGB colour suggests a variation of ≤ 0.3 dex throughout the substructure. This could suggest that much of the halo debris comes from the accretion of a single system – one which has undergone little chemical evolution during several orbits around M31 but experienced at least one burst of star formation. On the other hand, age and metallicity may be varying in tandem throughout these regions, conspiring to produce a remarkably constant mean RGB colour (for example, as seen in the Carina dwarf spheroidal galaxy (e.g. Rizzi et al. 2003)). We will evaluate these scenarios in more detail in subsequent papers where we will model the CMDs in terms of star formation and chemical evolution histories.

Previous studies of the M31 inner halo have demonstrated that ∼25-50% of the population is old and metal poor (e.g. Holland, Fahlman, & Richer (1996); Brown et al. (2003)). The presence of a blue horizontal branch in four of the six CMDs in Figure 2 suggests this smooth halo population is also present at larger radii. The Northern Spur and G1 Clump CMDs, which probe the most extreme radii in our sample, do not, however, show this feature. Assuming our Minor Axis field is representative of the smooth halo component in M31, we can ask whether we should see this component in the outermost fields studied. We find that, for both a spherical and flattened (b/a=0.6) $R^{1/4}$ distribution, the amount of smooth halo expected in the Northern Spur and G1 Clump CMDs is almost entirely negligible compared to the number of stars in the overdensity (4–10% of the detected stars). In other words, the absence of an obvious extended blue horizontal branch in these fields does not necessarily mean that the smooth halo component seen at smaller radii is not also present.

The currently-favoured orbit for the stream progenitor is highly radial and passes very close to the galaxy center before re-emerging north-east of the nucleus (Ibata et al. 2004; Font et al. 2004). Although radial velocities have not yet been published for stars in the NE Shelf region, the strong similarity between the stream and shelf CMDs found here appears to support this prediction. Furthermore, the calculations of Ibata et al. (2004) and Font et al. (2004) indicate that the shelf region probed by our ACS pointing should lie many tens of kpc in front of our stream pointing. Our differential distance estimate based on the red clump magnitude is $\approx 50 \pm 30$ kpc and is thus in encouraging agreement. Brown et al. (2003) have recently obtained a very deep CMD of the M31 halo at a location 11 kpc along the southern minor axis (see Figure 1). The data reveal the surprising discovery of a significant (30% by mass) intermediate-age (6–8 Gyr) metal-rich population – a result somewhat at odds with the traditional picture of stellar halos as old and metal-poor. The results presented in this Letter suggest caution in interpreting this finding, as well as all others that are based on observations of small single fields. The stellar populations in the outskirts of M31 exhibit large-scale variations and hence inferences about halo formation drawn from such pointings may not be representative of the entire halo. This is especially true in the case of Brown’s field, which lies in close proximity to two regions which are strongly

![Fig. 3.— F814W0 LFs in the vicinity of the red clump and RGB bump for the Giant Stream (left) and NE Shelf (right). Overlaid (dashed line) are gaussian fits to the red clump.](image-url)
contaminated by stream debris.

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