Deep Studies of the Resolved Stellar Populations in the Outskirts of M31

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Abstract. We discuss the first results from ongoing studies of the resolved stellar populations in the outskirts of our nearest large neighbour, M31. Deep HST/WFPC2 archival observations are used to construct colour-magnitude diagrams which reach well below the horizontal branch at selected locations in the outer disk and halo, while a panoramic ground-based imaging survey maps spatial density variations through resolved star counts to a projected radius of $\sim 50$ kpc.

1. Introduction

The fossil record of star formation and galaxy evolution is imprinted on the spatial distribution, ages and metallicities of galactic stellar populations. Surprisingly little is known about the old and intermediate-age stellar populations in massive galaxies outside our own Milky Way. Located at $\sim 780$ kpc, M31 provides our best opportunity to explore the stellar populations across the face of a large disk galaxy. Furthermore, its favourable inclination means that the disk and halo components at large radii can be easily distinguished and independently studied.

Most previous studies of M31 have either been based on observations of single fields (eg. Holland et al 1996, Durrell et al 2001) or on large-area surveys limited to the bright disk (eg. Walterbos & Kennicutt 1988). It is generally thought that M31 resembles the Milky Way in many ways, although it is somewhat larger, more luminous and has a denser stellar halo (see Freeman 1999 for a review). The disparity between the mean metallicity of M31’s field halo and that of the Milky Way ($\approx$ factor of 10 lower) was first recognized by Mould & Kristian (1986) but remains to this day poorly understood.

2. Probing M31 with Deep HST/WFPC2 Pointings

We searched the HST archive for all deep (T $> 4000$ s) WFPC2 pointings towards M31 in the F555W and F814W filters. We focus here on those fields which sample the disk and halo at large radius ($R_{deproj} \gtrsim 20$ kpc).
Figure 1. CMDs of the M31 outer disk field (30 kpc or 5 disk scalelengths). (Left) the dashed line indicates the 75% completeness level. (Right) GC fiducials are overlaid corresponding to NGC 6397 ([Fe/H] = −1.9), 47 Tuc ([Fe/H] = −0.7) and NGC 6553 ([Fe/H] = −0.3). Also indicated is the mean V magnitude of the blue horizontal branch detected in M31 halo by Holland et al (1996).

Figure 1 shows the WFPC2 CMD of a field at ∼30 kpc (or 5 disk scale lengths) along the major axis. Based on extrapolation of the structural parameters of Walterbos & Kennicutt (1988), we expect 95% of the stars in this field to belong to the disk. The prominence and morphology of the red giant branch (RGB) and red clump (RC) indicate an old-to-intermediate age, fairly metal-rich population. Comparison of the outer disk RGB with globular cluster fiducials indicates a mean metallicity comparable to 47 Tuc ([Fe/H] = −0.7). The significant width of the RGB exceeds that of photometric errors, and is most easily explained by an intrinsic dispersion (∼2 dex) in the metallicity of the stellar population. While these properties have been noted before for the M31 halo (eg. Holland et al 1996), we find here that they also characterise the outer disk. See Ferguson & Johnson (2001) for details.

The RC properties, when coupled with the mean metallicity from the RGB colour, suggest a mean age for the population of ∼8 Gyr (Cole 1999, Girardi & Salaris 2001). This is also consistent with the apparent lack of asymptotic giant branch stars above the tip of the RGB (I∼20.5), which would represent young-to-intermediate age (2–6 Gyr) shell He-burning stars. Finally, we note the marginal detection of horizontal feature in the CMD connecting the blue plume at V∼25 to the RC. While this could represent the subgiant branch of a ∼1 Gyr population, it is more likely to be an old (≥10 Gyr), metal-poor ([Fe/H]∼−1.7) horizontal branch (see Figure 1).

Figure 2 shows CMDs for a representative halo-dominated field and a field in which disk and halo are expected to contribute in roughly equal amounts. Apart from stellar density (which reflects both intrinsic variations as well how much of the WF area was useable in our analysis), the dominant stellar population in these fields appears strikingly similar (and indeed, both resemble the outer disk CMD in Figure 1). The
homogeneity of halo and outer disk populations was first remarked upon by Morris et al (1994) from shallow ground-based data, but we show here the similarity holds to well below the horizontal branch.

![CMDs for a halo-dominated field (left) and a field which is expected to contain equal numbers of disk and halo stars (right). Both fields sample roughly the same halo radius (10.5 kpc) but the disk contribution is greater in the latter.](image)

### 3. Probing M31 with Panoramic Ground-based Imagery

While providing detailed information on the stellar populations, the HST pointings tell us nothing about the large-scale structure of M31 (WFPC2 FOV $\sim 0.3$ kpc$^2$). We have therefore embarked upon a ground-based, moderate-depth panoramic imaging survey of the outskirts of M31 with the INT Wide Field Camera. To date, 58 contiguous fields (0.3 $\square$ per pointing) have been observed in the SE half of the galaxy, mapping out to a projected radius of $\sim 50$ kpc.

An exciting first result has been the discovery of a giant stream of stars (overdensity a factor of 2) in the halo of M31 near the southern minor axis (Ibata et al 2001). The stream extends beyond the limit of our imagery, or $\sim 40$ kpc at this position angle, and has an average V-band surface brightness of $\sim 30$ mag/$\square''$. If an old coeval population is assumed, the excess stream population is found to be of similar or slightly higher metallicity than the M31 field halo and outer disk.

The stream appears to lie along a line which connects M32 and NGC 205, the two dwarf elliptical companions of M31. Both these satellites display rather odd properties for their morphological class – including young and/or intermediate-age stars and in the case of NGC 205, cold gas – and both exhibit distorted isophotes in the outer regions, suggestive of tidal distortion and possibly disruption. The similarity between the metallicities of these dwarfs and that of the stream suggests that one or both of them may be the origin of the feature.
4. Discussion

We are exploring the stellar populations in the outskirts of M31 using deep HST archival pointings in combination with a ground-based panoramic imaging survey. We summarise our first results as follows:

♣ the disk of M31 appears to have a significant mean age ($\gtrsim 8$ Gyr). For current cosmologies, this lookback time corresponds to a redshift of $\simeq 1$ by which about half the stellar disk was in place at 30 kpc. This may be problematic for theories which invoke delayed disk formation as a way to circumvent the angular momentum problem seen in numerical simulations of galaxy formation (eg. Weil et al 1998). Equally puzzling is our finding that the dominant populations in the outer disk and halo are remarkably similar, suggesting these components have experienced similar formation epochs and evolutionary histories.

♣ the discovery of a giant stellar stream in the outer halo of M31 attests to the fact that the hierarchical process of galaxy formation continues to the present-day and that at least some fraction of the M31 field halo has not formed in-situ, but has been accreted from lower mass objects. Could this interaction have polluted the outer regions of M31 to such an extent that it explains that apparent uniformity of the stellar populations in these parts? Future observations will help us assess this possibility more thoroughly.

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