The stellar halo of the edge-on galaxy NGC 891

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Abstract
Using the Advanced Camera for Surveys on board the Hubble Space Telescope, we have resolved individual red giant branch stars in the outskirts of the edge-on galaxy NGC 891, down to ~2 mag fainter than the tip of the red giant branch. The data set allows investigation of the stellar populations in the outer regions of analogues galaxies to the Milky Way. We discuss the properties of the stellar populations located at ~10 kpc above the galaxy disc. We find that these extraplanar stellar populations exhibit a broad red giant branch star colour distribution, suggestive of a large spread in heavy element abundance. The mean stellar metallicity at this height from the galaxy disc, derived using the mean colours of red giant branch stars, is [Fe/H] ≈ −0.9, a full ~0.5 dex more metal rich than the mean metallicity of the non-rotationally supported stars in the inner haloes of the Galaxy and Andromeda. This suggests that metal-poor stars are not the dominant stellar component in the outskirts of massive spiral galaxies.

Key words: galaxies: formation – galaxies: haloes – galaxies: individual: NGC 891 – galaxies: metal-poor stellar components of galaxies. Therefore, their properties are clues to the understanding of how galaxies have assembled their mass, and constrain the early phases of galaxy formation. One of the fundamental tenets of the popular cold dark matter paradigm is that dark matter haloes form hierarchically, via a series of mergers with smaller haloes. This gives rise to the natural expectation that the outer regions of galaxies are formed from disrupted, accreted small galaxies (e.g. Johnston, Sigurdsson & Hernquist 1999; Bullock & Johnston 2005). The discovery of stellar streams and substructures in the outer regions of both the Galaxy (Ibata, Gilmore & Irwin 1994; Ivezić et al. 2000; Yanny et al. 2000; Dohn-Palmer et al. 2001; Ibata et al. 2001a) and M31 (Ibata et al. 2001b; Ferguson et al. 2002; Kalirai et al. 2006a) supports the scenario that at least a fraction of the stellar populations in the outskirts of galaxies are assembled through accretion of smaller protogalactic structures.

Few constraints currently exist on the nature and the origin of the stellar haloes of galaxies. Much of what we know about such early populations comes from studies of the stellar halo of the Milky Way (e.g. Eggen, Lynden-Bell & Sandage 1962; Searle & Zinn 1978; Carney et al. 1996; Chiba & Beers 2000), M31 (e.g. Pritchet & van den Bergh 1988; Holland, Fahman & Richer 1996; Reitzel & Guhathakurta 2002; Durrell, Harris & Pritchet 2004; Ibata et al. 2005) and NGC 5128 (e.g. Harris & Harris 2001; Rejkuba et al. 2005). The main conclusion drawn from the comparison between the Milky Way and M31 halo star properties is that the Galaxy halo may not be typical, suggesting that the haloes of spiral galaxies are quite diverse. Mouhcine et al. (2005a,b) used Hubble Space Telescope (HST) observations to derive photometric metallicities of red giant branch (RGB) stars in halo fields at projected distances of 2–13 kpc in a sample of highly inclined spiral galaxies beyond the Local Group. The Milky Way halo stars at similar distances above the Galactic disc are found to be underabundant with respect to halo stars of galaxies with comparable luminosities, in agreement with earlier measurements in M31. Kinematically selected pressure-supported stars in M31, both in the inner halo, i.e. in the 10–20 kpc range (Chapman et al. 2006), and the outer halo, i.e. in the 60–160 kpc range (Kalirai et al. 2006b), are found, however, to be significantly more metal poor compared to the mean metallicities of the stellar populations of galaxies of similar luminosities. Interestingly, kinematically selected halo stars in M31 have similar metallicities to the non-rotating halo stars in the Galaxy (Chiba & Beers 2000, Morrison et al. 2003). In order to gain insight into the properties and the origin of the diffuse stellar content of the outskirts of galaxies, and the dominant stellar population components, we are conducting a study of NGC 891, a prime Milky Way analogue (e.g. van der Kruit 1984; Rupen 1991) using deep optical HST/Advanced Camera for Surveys (HST/ACS) imaging. Using photometry of resolved giant stars in the outskirts of NGC 891, we obtain the RGB locus, and hence an inference on the metallicity of the stellar populations in the outer regions. This galaxy is a nearby large, highly inclined Sb-type.
spherical. Its high inclination (with an inclination angle of 89°), relative proximity ($D \sim 10$ Mpc), and the wealth of available data make it an ideal candidate to search for, and to characterize the properties of the stellar populations in the outskirts of galaxies. Its inclination and its small bulge component minimize contamination by stars belonging to other galaxy components. By virtue of the large radial coverage of the observed fields, it is possible to characterize the properties of stars well above the galaxy disc, and well away from the galaxy bulge, and thereby to sample genuine stellar halo objects. Here, we report the first results from the survey and establish the predominance of intermediate-metal-rich stars at $\sim 10$ kpc above the disc of this Milky Way twin. Analysis of the spatial distribution of extraplanar stellar populations, the bi-dimensional distribution, search for substructures, the metallicity distribution functions and globular cluster properties over the entire surveyed area will be published in forthcoming papers. The layout of this paper is as follows: in Section 2, we present briefly our data set, in Section 3, we present the colour–magnitude diagrams (CMDs) and the properties of the selected fields. The implications of our finding are discussed in Section 4. Finally, in Section 5 the results and the implications of this work are summarized.

2 DATA

To study the stellar populations in the outskirts of NGC 891, we analysed archival images obtained with the HST/ACS (GO-9414; PI: R. de Grijs). The locations of the observed halo fields, superimposed on the Digitized Sky Survey image of NGC 891, are shown in Fig. 1. For each field, the ACS observations consist of three full-orbit integrations in F606W (broad V) and F814W (I), each split into three exposures to allow easier rejection of cosmic rays. The observations were obtained with the ACS Wide Field Channel. The total exposure time was chosen to detect stars with roughly solar metallicity one magnitude fainter than the tip of the RGB at the distance of NGC 891. The observations and the reduction techniques applied to HST/ACS data will be described elsewhere. We therefore only briefly summarize this information here.

We performed point spread function (PSF) photometry with the DOLPHOT photometry package (Dolphin 2000), adapted for the ACS images. For each field, photometry was done simultaneously on all the flat-fielded and cosmic ray cleaned images from the Space Telescope Science Institute archive, relative to a reference image. The DOLPHOT software accounts for the hot pixel and cosmic ray masking information provided with each flat-fielded image, fits the sky locally around each detected source, and provides magnitudes corrected for charge-transfer efficiency effects on the calibrated scale of Sirianni et al. (2005). For each detected object, a variety of quality information is listed including the object type, the quality of the PSF fit, sharpness, defined as the difference between the square of the width of the object and the square of the width of the PSF, and roundness of the object, and a parameter which describes how much brighter an object would have been had neighbouring objects not been fit simultaneously. We used this information to select only stars with high-quality measurements. We have chosen as stars with valid photometry those with global sharpness parameters lower than 0.5 in each filter, and the crowding parameters lower than 0.3. In addition, we restricted the maximum allowed absolute value of the roundness parameter to 1.2, and of $\chi^2$ to 3.

As a focus of this paper is to derive the abundance distributions from a star-by-star analysis, sources of contamination and errors must be understood and controlled. One of the factors that could influence the colour width of the RGB, and thus affect the measurement of the stellar metallicities, is the photometric errors and incompleteness. The photometric errors may introduce a broadening of the RGB sequence that may be interpreted as indicative of a physical metallicity distribution function. Photometric incompleteness may mask the presence of red/metal-rich stellar populations. In order to assess these effects, we carried out artificial star experiments, evaluating the photometric scatter and completeness as a function of magnitude and colour. In each simulation, stars were added to the original images, with input colours and magnitudes following RGB sequences spanning a range of metallicities. The locations of stars in each frame were chosen randomly, so that over different experiments the added stars were uniformly distributed over the whole frame. The images were then reduced by following the same procedure used for the original frames.

The evolution of the photometric errors, quantified as difference between the input and the output magnitude of the artificial stars, for both V and I band as a function of the apparent magnitude is shown in Fig. 2. The vertical dashed lines indicate the magnitudes of the 50 per cent completeness limits for $(V - I) \lesssim 1.3 (I \sim 27.4)$, $(V - I) \sim 2(I \sim 27.3)$ and $(V - I) \sim 2.6 (I \sim 26.8)$. The upper panels show that the mean magnitude difference is consistent with zero for magnitudes brighter than the 50 per cent incompleteness limits for different colours. As shown in the lower right panel, the mean scatter, a measure of the photometric error, is smaller than $\sim 0.1$ for all the magnitudes brighter than the 50 per cent incompleteness level at different colours.

Contamination by foreground and/or background stars may be important. To estimate Galactic foreground contamination, we used the Besançon group model of stellar population synthesis of the Galaxy available through the Web1 (Robin et al. 2003), simulating the total number and optical photometry of foreground stars. The

Figure 1. HST/ACS footprint of the observations overlayed on the Digitized Sky Survey image of NGC 891. The scale bar of 2 arcmin shown in the lower left corner corresponds to a physical scale of 5.8 kpc.

1 http://bison.obs-besancon.fr/modele/.
To lie at RA galaxy’s major and minor axes, we have taken the centre of NGC 891 relative to the centre of NGC 891, and coordinates aligned with the ∼0.2 arcsec. In the HDF-S, there are 22 such sources. Some of these in three different fields located, respectively, at (X, Z) ≈ (8, 9.5) and (X, Z) ≈ (17, 9.5) kpc. Each of the selected fields covers a range of ∼5 kpc along the major axis.

3 COLOUR–MAGNITUDE DIAGRAMS AND METALLICITIES

Fig. 3 shows the reddening-corrected CMDs of the three selected extraplanar fields. No significant internal extinction is expected to affect the stellar populations well above the galaxy disc, as these regions are most likely dust free. The 50 per cent detection completeness levels are shown as dash–dotted lines. The foreground reddening towards the halo fields was estimated using the all-sky map of Schlegel, Finkbeiner & Davis (1998). We have neglected the effect of any possible differential reddening across our fields and along the line of sight. Indeed, the differential reddening due to the Galactic foreground across the ACS fields is likely to be small. As demonstrated extensively in the literature, the tip of the RGB is a useful distance indicator (Lee, Freedman & Madore 1993). The I-band luminosity function can be used to identify the magnitude level of the tip of the RGB, and thus the distance modulus to our sample galaxies. We use the edge-detection algorithm, that is, the tip of the RGB discontinuity causes a peak in the first derivative of the luminosity function, to estimate the tip of the RGB luminosity function for NGC 891. We derive that the tip of the RGB is located at I = 25.84 ± 0.04 mag. Following the procedure described in Mouchine et al. (2005c), we find a distance modulus (m − M)0 = 29.94 ± 0.04 (random) ± 0.16 (systematic) in excellent agreement with distance measurements from the literature (Tkitchonov & Galaxutdinova 2005).

To provide a first indication of the range of metallicities across the RGB, we overplot in Fig. 3 the loci of the observed RGB sequences for standard Milky Way globular clusters of different metallicities which encompass the majority of RGB stars in the observed fields. These lines are for the observed RGB sequences of M 15, NGC 1851 and 47 Tuc from Da Costa & Armandroff (1990).

Figure 3. CMDs of the selected fields. Each of the selected fields covers a range of ∼5 kpc along the major axis. Overplotted are galactic globular cluster fiducials; from the left- to the right-hand side these are: M 15 ([Fe/H] = −2.2), NGC 1851 ([Fe/H] = −1.2) and 47 Tuc ([Fe/H] = −0.7). The dash–dotted lines show the 50 per cent detection completeness levels.

model predicts ∼20 stars in the magnitude range of I = 24.5–27 over the entire ACS field. This is negligible compared to the total number of objects in our photometric catalogue. A few faint background galaxies may have been misclassified as stars. An upper limit to the contamination can be estimated from the Hubble Deep Fields (HDFs) (catalogues described in Casertano et al. 2000), which have the same area as the fields we have observed. In the HDF-N, we find 10 sources with magnitudes 23 < F814W < 26 and FWHM < 0.2 arcsec. In the HDF-S, there are 22 such sources. Some of these are Galactic foreground stars. Thus, the level of compact-source contamination is also entirely negligible.

To define right ascension (RA) and declination (Dec.) offsets relative to the centre of NGC 891, and coordinates aligned with the galaxy’s major and minor axes, we have taken the centre of NGC 891 to lie at RA = 02h22m33s, Dec. = 42°20’57” (J2000.0), and have adopted a position angle for the major axis of PA = 22°. With this choice of coordinates, positive X is located north-east of the centre of NGC 891 and positive Z lies to the east. The ACS images cover ∼12 kpc perpendicular to the disc, and ∼25 kpc along the major axis. In the Milky Way, the halo begins to dominate the disc at a radius well inside 10 kpc (e.g. Majewski 1993). To investigate the properties of the stellar populations at a comparable height above the disc of a galaxy with similar properties to those of the Milky Way, we select here stars located at perpendicular distances to the disc of NGC 891 within the range 10 ± 1.5 kpc. Contamination from other galactic components is expected to be negligible at this height from the disc of NGC 891 (Ibata et al., in preparation). Given the orientation of the ACS fields, stars at this height are distributed in three different fields located, respectively, at (X, Z) ≈ (−1.5, 9.5), (X, Z) ≈ (8, 9.5) and (X, Z) ≈ (17, 9.5) kpc. Each of the selected fields covers a range of ∼5 kpc along the major axis.
The most prominent features in the CMDs are the well-populated red giant branches. The overall CMD morphologies of the extraplanar stellar populations are similar, showing an old RGB population that ends abruptly at the tip of the sequence. However, clear differences are present between extraplanar stellar populations distributed along the major axis, at 10 kpc above the galactic disc. From the comparison in Fig. 3, it is clear that the three fields contain a metal-poor stellar component extending down to [Fe/H] ~ −2; however, the contribution of stars with intermediate metallicities decreases from the innermost to the outermost fields. When analysing a CMD of RGB stars, the standard assumption which is used in the absence of other constraints is that the stellar populations are as old as Milky Way globular clusters. For an old simple stellar population, redder stars are generally more metal rich than bluer ones, and the width of the RGB at a given luminosity is an indicator of the spread in the stellar metallicity. The CMDs contain no indication of significant young- or intermediate-age stellar populations in the extraplanar regions of NGC 891. There are few stars in the region where one may expect to see early-type stars; in addition, above the first-ascent giant stars there are a negligible number of stars that may be identified as bright asymptotic giant branch stars, associated with intermediate-age populations. The predicted number of foreground Galactic stars in the range of \( I = 25–25.8 \), where intermediate-age stars are expected to be at the distance of NGC 891, within the selected area is of \( 5–8 \). Galaxy counts from Smail et al. (1995) suggest that there should be 30–50 galaxies in this brightness range, consistent with the detected number of sources in the selected fields, that is, 20–40. While we cannot rule out an age spread in these galaxies, the colour spread observed in the data is due primarily to a spread in metallicity. Theoretical isochrones show that metallicity has a much larger effect than age on RGB colour. For example, at \( M_I = −3 \) on the RGB, a 0.2 mag shift in \((V − I)\)0 to the blue can be achieved by a relatively large decrease in age from 13 to 6 Gyr or a relatively small decrease in [Fe/H] from −1 to −1.2. In the following analysis, we assume that the extraplanar stellar populations have a fixed age similar to globular clusters. Mean metallicities will be slightly higher if the ages are lower.

The left-hand panels of Fig. 4 show the normalized foreground reddening-corrected colour distributions of RGB stars within the magnitude range \( M_I = −3.5 ± 0.1 \) ranked as a function of the radial distance, along with Gaussian functions with the mean and dispersion of the stars composing the colour distribution functions shown as a dashed line, and the mean shown as a vertical dotted line. At the brightest magnitudes of the CMDs, a weakly populated sequence is visible around colour \((V − I)\)0 ~ 0.7. To avoid biasing the colour distributions, stars bluer than this limit were excluded. Considering the colour distribution of giant stars alone, two properties emerge. The mean colour and the colour distribution of the extraplanar stellar populations at \( ~10 \) kpc above the disc tend to get, respectively, bluer and narrower as a function of distance along the major axis. The innermost field is dominated by a broader colour distribution function that extends to blue stars while still containing a red stellar component. Although the outermost field is not as well populated as the other two fields, it is clearly dominated by a large number of metal-poor stars.

Once the stellar photometry is extinction- and distance-corrected, we can estimate the mean metal abundances via a comparison with the fiducial globular cluster giant branches. Lee et al. (1993) have provided a calibration of the colour versus [Fe/H] relation based on the mean \((V − I)_0\) colour of the RGB at a luminosity of \( M_I = −3.5 \) for the full abundance range of the calibration clusters, that is, M15 ([Fe/H] = −2.2), NGC 6397 ([Fe/H] = −1.91), M2 ([Fe/H] = −1.58), NGC 6752 ([Fe/H] = −1.54), NGC 1851 ([Fe/H] = −1.29) and 47 Tuc ([Fe/H] = −0.71). Adopting \( M_I = −3.5 \) mag as a reference for the abundance determination increases the sensitivity to the abundance, minimizes the influence of early-asymptotic giant branch stars, and also reduces the effect of photometric errors in most cases. We fit a Gaussian to the histogram of the colours of stars within \( M_I = −3.5 ± 0.1 \), and used its mean to estimate \((V − I)_0\). To determine the uncertainties, we carry out a bootstrap resampling procedure. For each simulated sample, the histogram of stellar colours within \( M_I = −3.5 ± 0.1 \) is fitted by a Gaussian. The mean colour is then used to estimate the mean stellar metallicity using the colour versus metallicity relation of Lee et al. (1993). We then fit a Gaussian to the final distribution of stellar metallicities for the simulated samples, and use its dispersion as the best estimate of the uncertainty of the mean stellar metallicity. We have repeated the same procedure using the median value for the simulated samples instead of the peak of the Gaussian, or using a mean value of simulated samples means, and the differences never exceed 0.02 dex. For the \( (X, Z) \approx (−1.5, 9.5) \) kpc field, we find [Fe/H] = −0.82 ± 0.06, for the \( (X, Z) \approx (8, 9.5) \) kpc field, we find [Fe/H] = −1.03 ± 0.07 and for the outermost field \( (X, Z) \approx (17.9, 5) \) kpc, we find [Fe/H] = −1.34 ± 0.15. Directly comparing the observed extraplanar fields shows a metallicity gradient at \( ~10 \) kpc above the disc of the NGC 891 of decreasing...
metallicity as a function of the distance along the major axis. The mean metallicities change by \(~0.5\) dex over the radial \(~18\) kpc covered by the survey.

By assuming an age of a stellar population, it is possible to convert the observed stellar photometry to metallicity on a star-by-star basis. To do so, we superimpose a fiducial grid of RGB tracks on the CMDs, and interpolate between them to derive a metallicity estimate (e.g. Holland et al. 1996; Harris, Harris & Poole 1999). Such a procedure relies implicitly on the assumption that all of the halo stellar population has a globular cluster-like age. The shape of the metallicity distribution will change only slightly if the age distribution is narrow. The random errors in the colour measurements are significantly smaller than the observed colour spread at the bright RGB end, and used to derive the metallicity distribution function.

To generate the metallicity distribution function, we use VandenBerg et al. (2000) models of \(\alpha\)-enhanced red giant tracks for \(0.8-M_\odot\) stars and covering the abundance range in metallicity from \([\text{Fe/H}] = -2.314\) to \(-0.397\), approximately in steps of \(0.1\) dex (see Harris & Harris 2000; Mouhcine et al. 2005b, for more details on the interpolation procedure and the calibration of the track grid). All the models we used assume that the stars are \(\alpha\)-enhanced, i.e. \([\text{Fe/H}] = 0.3\), to take account of recent results on the abundance analysis of Galactic halo stars (e.g. McWilliam 1997; Gratton et al. 2000), and in the globular clusters of nearby early-type galaxies (Larsen et al. 2002). The grid has been compared and well calibrated against the observed loci of standard globular cluster fiducial sequences (Harris & Harris 2000; Bergbusch & VandenBerg 2004; VandenBerg et al. 2006). We use only stars in the brightest \(1.3\) mag of the RGB, where the photometric errors are smallest, that is, lower than \(~0.1\) for all magnitudes brighter than \(I \sim 27.3\) (see the lower right panel of Fig. 2), and where the colour difference caused by metallicity variations is largest. For the purpose of deriving the metallicity distribution functions for stellar haloes, the completeness effects may be large for extremely red and bright giant stars at the upper right corner of a CMD near the completeness cut-off determined by the \(V\) filter; those stars are likely to have solar or super-solar abundances. For all the observed fields, the \(50\) per cent completeness limits fall well below the brightest end of the RGB (see Fig. 3) to allow accurate measurements of the metallicity distribution functions and to ensure that we are not missing metal-rich stars. It is unlikely that the shape of the constructed metallicity distribution functions at the metal-rich end will be biased.

The resultant normalized metallicity distribution functions of the selected extraplanar fields are shown in the right-hand panels of Fig. 4 ranked as a function of the distance along the major axis. The metallicity distribution functions for all the selected extraplanar fields show similar features, that is, a prominent metal-rich peak, a metal-poor tail and a sharp metal-rich end. The cut-off at the high-metallicity end appears to be real instead of an effect of the photometric incompleteness or another observational artefact.

The most straightforward chemical evolution model to compare the data with is the so-called simple chemical evolution model (Pagel & Patchett 1975). This chemical evolution model considers the closed box evolution of a homogeneous proto-galactic gas cloud having initial abundance \(Z_0\). By considering the instantaneous recycling approximation, and assuming a complete and homogeneous ejecta mixing, the stellar metallicity distribution follows the simple law:

\[
f(z) = \left(\frac{1}{y}\right) \exp\left[-\frac{z - Z_0}{y}\right], \tag{1}
\]

where \(y\) is the stellar yield, defined as the ratio of the mass of new metals ejected to the mass locked into long-lived stars and remnants. If metals are lost from the system by gas outflow, assuming that the gas-loss rate is proportional to the star formation rate, the functional form of the metallicity distribution is unchanged, but the true yield is reduced to the effective yield \(y_{\text{eff}} = y/(1 + c)\), where \(c\) is a parameter related to the gas-loss rate. The yield and the mean abundance \((z)\) are related via: \(y = (z) - Z_0\), where \(Z_0\) is the initial metallicity. Predictions of the simple chemical evolution model for a range of effective yields, chosen to produce acceptable fits to the metallicity distribution functions of each field and indicated in each panel, are overplotted on the top of the observed metallicity distribution functions. We have assumed that the initial star formation event has consumed a primordial heavy element-free gas, that is, \(Z_0 = 0\). The photometric uncertainties for the stars considered here are small, and the models have not been smoothed. It should be noted that by comparing the observed metallicity distribution to the simple chemical model predictions, we implicitly assume that galaxies are built up within a single potential well.

The overall shape for the metallicity distribution functions of the observed extraplanar fields is similar, they are characterized by prominent peaks at the metal-rich end with extended metal-poor tails. The position of the dominant peak moves to lower metallicities as we move from the innermost to the outermost field, confirming the presence of a metallicity gradient along the major axis well above the disc of the galaxy. The simple chemical model reproduces the general shape of the estimated metallicity distribution function. The number of observed stars at the low metallicity end continues to rise as the metallicity decreases as required by the model.

Despite the success of the simple chemical model to reproduce, in broad terms, the metallicity distributions, there are, however, notable deviations, especially for the innermost fields. The simple model predicts that the subsolar regime \((Z < 0.5 Z_\odot)\) is more populated than what is observed, deviating from the exponential-decay condition. On the other hand, the number of stars in the intermediate-metallicity regime \((Z \sim 0.1–0.2 Z_\odot)\) is underestimated by the simple chemical evolution models. It is quite striking that these discrepancies tend to get weaker when going from the innermost to the outermost field. The sharper observed cut-off at the metal-rich end compared to the simple chemical evolution model predictions, and the excess of stars in the intermediate-metallicity regime, which are pronounced features of the metallicity distribution function of the innermost field, is absent in that of the outermost field. This confirms that the extraplanar stellar populations are different over the radial extent probed.

4 IMPLICATIONS

Based on the colours of RGB stars at projected distances of \(2–13\) kpc along the minor axis of a sample of eight nearby highly inclined spiral galaxies, Mouhcine et al. (2005b) found evidence for a correlation between stellar halo metallicity and parent galaxy luminosity. Specifically, they found that more luminous galaxies possessed a more metal-rich halo, with a higher metallicity spread. Strikingly, the mean metallicity of the kinematically selected pressure-supported halo stars within \(~10\) kpc above the disc of the Milky Way (Laird et al. 1988; Ryan & Norris 1991; Chiba & Beers 2000) is lower than what is predicted by the halo metallicity versus luminosity relation for a luminosity similar to that of the Galaxy. Morrison et al. (2003) have measured metallicities of Milky Way halo red giant stars located at distances between \(15\) and \(83\) kpc from the Galactic Centre, and found that the mean metallicity of this
sample is comparable to what is found in the inner halo, indicating that the pressure-supported halo shows little or no metallicity gradient. Equally striking, Chapman et al. (2006) have reported that the pressure-supported halo stars within 10–30 kpc above the disc of M 31 are metal poor with a comparable metallicity to what is found in the Milky Way halo. In contrast, Kalirai et al. (2006b) have found that a kinematically selected sample of M 31 stars within the radial range 10–20 kpc along the minor axis has an average metallicity [Fe/H] ~ −0.5, for [α/Fe] = 0.0, significantly higher than what was reported in Chapman et al. (2006). However, Ibata et al. (2007) showed that at a projected radius from R ~ 10 to ~20 kpc on the minor axis of M 31, the dominant component is an extended rotating disc-like component with an approximately exponential profile (Ibata et al. 2005). Thus, the finding of a metal-rich ‘spheroid’ in this region reported by Kalirai et al. (2006b) is open to some doubt: it is likely due to a combination of pollution from the ‘extended disc’ as well as the metal-rich ‘Giant stream’ (which models show wraps around the galaxy, contaminating inner minor axis fields; Ibata et al. 2004; Fardal et al. 2007). It also should be noted that it is extremely difficult to assess the properties of the inner stellar halo of M 31 by observing on the minor axis, as all galactic stellar components have the same mean velocity and so their velocity distributions overlap. Metallicities of halo stars in the 60–160 kpc range along the minor axis (Kalirai et al. 2006b) are found to be comparable to those measured for stars in the inner halo by Chapman et al. (2006), suggesting that the pressure-supported halo of M 31 shows little or no radial metallicity gradient.

Fig. 5 shows the variation of halo star mean metallicity as a function of galaxy absolute V-band magnitude (the right-hand panel) and galaxy circular velocity (the left-hand panel). The mean photometric metallicity of the stellar populations at ~10 kpc above the disc of NGC 891, i.e. [Fe/H] = −0.94 ± 0.06, shown as an open pentagon, is estimated from the colour (V − I)0.94 of the combined CMDs of the three extraplanar fields. Field circles represent HST/Wide Field Planetary Camera 2 (WFPC2) data from Mouchine et al. (2005b), and open stars show the metallicities of the outskirts of the Local Group spiral galaxies. M 31 and M 33 are shown twice in the figure: the higher metallicities for both galaxies correspond to the photometric estimates, i.e. from Durrell et al. (2004) for a field at R ~ 30 kpc along M 31 minor axis, and from Brooks, Wilson & Harris (2004) for a field at ~10 kpc from the centre of M 33 along the minor axis, the lower ones represent the metallicities of the kinematically selected pressure-supported halo stars (Chapman et al. 2006; Kalirai et al. 2006b; McConnachie et al. 2006). We note that the absolute luminosity of NGC 891 is corrected for foreground reddening, but not for internal reddening. The extraplanar stellar populations at ~10 kpc above the disc of NGC 891, where the contamination from metal-rich stars belonging to other galactic components is expected to be negligible, are clearly dominated by intermediate-metallicity stars, suggesting that a trend between the mean metallicity of the outskirts of galaxies and parent galaxy properties is indeed present.

The correlation between galaxy luminosity/circular velocity and stellar halo metallicity suggests that the pressure-supported metal-poor stellar populations observed in Local Group spirals might not be the dominant component in the outskirts of massive galaxies, at least in the inner ~10 kpc. The implications for galaxy formation are profound: within the hierarchical galaxy formation framework, moderately metal-rich stellar outskirts suggest an origin involving the disruption of chemically evolved accreted fragments, which in turn has implications on the mass function of the objects accreted to form the stellar halo.

A way to reconcile the apparent small dependence of the mean metallicity of kinematically selected halo stars on galaxy luminosity, and also the observed relation between mean photometric metallicity and galaxy luminosity is to assume the presence of multiple stellar populations in the outskirts of galaxies. It is possible that the less massive galaxies generally have haloes dominated by debris of disrupted small satellites, which would be likely of lower metallicity. The more massive galaxies might have, in addition to this universal metal-poor pressure-supported halo, a second population with stellar metallicities and mass fraction increasing with the parent galaxy mass.

Chemo-dynamical models of hierarchically formed galaxies by Renda et al. (2005) suggest that galaxies with metal-rich stellar haloes at the present epoch have longer assembly histories, whereas
galaxies with a more metal-poor stellar halo experienced shorter assembly. The metal-rich component in the outskirts of galaxies may be accreted over a longer assembly time-scale than the metal-poor pressure-supported component. The simulations of Bullock & Johnston (2005) suggest that the most massive merging events occur early on ($t_{\text{lookback}} \gtrsim 8$ Gyr) and form the inner stellar halo ($R \lesssim 20$ kpc), whereas the recently accreted satellites form structures in the outer halo (Bullock & Johnston 2005). In contrast with the Milky Way, many simulated stellar haloes contain old metal-rich stellar populations (Renda et al. 2005; Font et al. 2006). The similarity between the metallicities of the pressure-supported stellar halo of M 33 (McConnachie et al. 2006) and its photometric halo (Brooks et al. 2004) supports this scenario. This is also consistent with the most up to date scenario for the formation of halo globular clusters in spiral galaxies (Goudfrooij et al. 2003; Chandar, Whitmore & Lee 2004). Unfortunately, the galaxies for which stellar haloes were studied both photometrically and spectroscopically up to now are grouped into two clumps. The properties of stellar haloes of intermediate-mass galaxies, that is, $V_\text{c} \sim 150$ km s$^{-1}$ ($M_\odot \sim -20$), are not known yet, so we cannot draw a firm conclusion about the connection between stellar populations in the outskirts and their parent galaxies.

5 SUMMARY AND CONCLUSIONS

We present the results from a deep HST/ACS imaging survey of extraplanar stellar populations of the edge-on galaxy NGC 891, a prime analogue of the Milky Way. We have found that the stellar populations at $\sim 10$ kpc above the galaxy disc are dominated by old RGB stars, with broad colour distributions. No significant number of stars brighter than the old tip of the red giant branch are found. This is consistent with the conventional interpretation of galaxy outskirts being composed primarily by an old stellar population. The morphologies of the CMDs demonstrate that the stellar populations at this height from the galaxy disc are diverse. The mean colour of RGBs at $\sim 10$ kpc above the galaxy disc gets bluer, the colour distribution gets narrower and the departure of observed metallicity distributions from the predictions of the simple chemical models gets weaker with increasing distance along the major axis. RGB CMDs of stellar populations at $\sim 10$ kpc perpendicular to the disc of NGC 891 are dominated by intermediate-metallicity stars, that is, [Fe/H] $\sim -0.9$. This contrasts with the low metallicities of non-rotating stars in the inner haloes of the Milky Way and M 31, suggesting that the outskirts of massive galaxies are not dominated by metal-poor pressure-supported stellar populations.

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