The stellar population content of the thick disc and halo of the Milky Way analogue NGC 891

M. Rejkuba, M. Mouhcine and R. Ibata

1 ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany
2 Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD
3 Observatoire Astronomique de Strasbourg (UMR 7550), 11 rue de l’Université, 67000 Strasbourg, France

Accepted 2009 March 20. Received 2009 March 19; in original form 2009 February 27

ABSTRACT

We present deep VI images obtained with the Advanced Camera for Surveys on board the Hubble Space Telescope, covering three fields in the north-east side of the edge-on disc galaxy NGC 891. The observed fields span a wide range of galactocentric distances along the eastern minor axis, extending from the plane of the disc to 12 kpc, and out to ~25 kpc along the major axis. The photometry of individual stars reaches ~2.5 mag below the tip of the red giant branch. We use the astrophotometric catalogue to probe the stellar content and metallicity distribution across the thick disc and spheroid of NGC 891.

The colour–magnitude diagrams of thick disc and spheroid population are dominated by old red giant branch stars with a wide range of metallicities, from the sparsely populated metal-poor tail at [Fe/H] ~ −2.4 dex, up to about half-solar metallicity. The peak of the metallicity distribution function of the thick disc is at −0.9 dex. The inner parts of the thick disc, within ~14 kpc along the major axis show no vertical colour/metallicity gradient. In the outer parts, a mild vertical gradient of Δ(V − I)/Δ|Z| = 0.1 ± 0.05 kpc−1 or less than 0.1 dex kpc−1 is detected, with bluer colours or more metal-poor stars at larger distances from the plane. This gradient is, however, accounted for by the mixing with the metal-poor halo stars. No metallicity gradient along the major axis is present for thick-disc stars, but strong variations of about 0.35 dex around the mean of [Fe/H] = −1.13 dex are found. The properties of the asymmetric metallicity distribution functions of the thick-disc stars show no significant changes in both the radial and the vertical directions. The stellar populations situated within the solar-cylinder-like distances show strikingly different properties from those of the Galaxy populating similar distances. This suggests that the accretion histories of both galaxies have been different.

The spheroid population, composed of the inner spheroid and the halo, shows remarkably uniform stellar population properties. The median metallicity of the halo stellar population shows a shallow gradient from about −1.15 dex in the inner parts to −1.27 dex at 24 kpc distance from the centre, corresponding to ~13r_eff. Similar to the thick-disc stars, large variations around the mean relation are present.

Key words: galaxies: formation – galaxies: haloes – galaxies: individual: NGC 891 – galaxies: stellar content.

1 INTRODUCTION

The study of nearby spiral galaxies can provide an ‘external view’ of galaxies similar to the Milky Way (MW), and constrain the formation of spiral galaxy haloes. The last decade has witnessed a spectacular increase in the discoveries of stellar streams and accretion events in the MW and Andromeda (e.g. Ibata, Gilmore & Irwin 1994; Helmi et al. 1999; Ibata et al. 2001; Ferguson et al. 2002; Ibata et al. 2003; Yanny et al. 2003; Martin et al. 2004), showing that at least part of the stellar haloes, and perhaps even discs, of these galaxies are assembled from disrupted dwarf galaxies. However, the question whether the stellar haloes in galaxies are built entirely through the multiple hierarchical merging processes (a la Searle & Zinn 1978) or rather have the majority of their mass assembled in an early dissipative collapse (Eggen, Lynden-Bell & Sandage 1962) is still open (for the MW halo, see the recent review by Helmi 2008). The thick discs in spiral galaxies, while observationally well...
established in most galaxies (Gilmore & Reid 1983; Dalcanton & Bernstein 2002; Mould 2005; Seth, Dalcanton & de Jong 2005b), still need to be characterized better. Through the observations of resolved stellar populations, it is possible to determine the average metallicity, metallicity distribution, radial profile and the amount of substructure. These observables provide empirical constraints to the thick disc and halo formation models.

In contrast, the unambiguous detection of stellar haloes in galaxies beyond the Local Group is very challenging. The expected low metallicity and the low surface brightness make the surface photometry very challenging (Morrison et al. 1997; de Jong 2008). Extremely deep observations, and the technique of stacking of huge number of similar edge on galaxies, produced the detection of faint red haloes in distant galaxies (Zibetti & Ferguson 2004; Zibetti, White & Brinkmann 2004). However, the study of metallicity distributions of stars in individual galaxy haloes is only possible through resolved stellar photometry, which is limited by current telescopes and instruments to about 10–12 Mpc. The emerging picture is that the inner regions of haloes are relatively metal-rich with extended tails to lower metallicity (Durrell, Harris & Pritchet 2001, 2004; Mouhcine et al. 2005; Mouhcine 2006; Mouhcine, Rejkuba & Ibata 2007, hereafter Paper I). Selecting stars at very large distances, and ensuring that they show halo-like kinematic signature, the metal-poor population, similar to the dominant component of the MW halo, was detected in M31 (Chapman et al. 2006; Kalirai et al. 2006). The halo of the MW has been shown to comprise two different stellar components that exhibit different chemical compositions, spatial distributions and kinematics. This comparison between the two massive spirals of the Local Group shows the need for larger samples, and more detailed comparison with other spiral galaxies with similar structure and mass as massive galaxies in the Local Group, before general conclusions can be drawn about the formation and evolution of spiral galaxy haloes.

Edge-on galaxies are the ideal targets, as this configuration permits a clear distinction between the halo, disc and bulge, and allows for efficient search and characterization of stellar substructures. With its high inclination (89.8 ± 0.5; Kregel & van der Kruit 2005), NGC 891 is the ideal target for the study of vertical structure and stellar populations above the plane of the disc. At a distance of 9.7 Mpc (Paper I), it is the closest edge-on spiral galaxy with morphological type, disc structure and mass similar to that of the MW (van der Kruit 1984; Garcia-Burillo et al. 1992). However, it has been acknowledged in numerous studies that it has much higher vertical extent of neutral and ionized gas structure (Garcia-Burillo et al. 1992; Scoville et al. 1993; Kamphuis et al. 2007), with a huge neutral H I halo surrounding it (Oosterloo, Fraternali & Sancisi 2007; Sancisi et al. 2008).

Seth, Dalcanton & de Jong (2005a) used the Advanced Camera for Surveys (ACS) on board Hubble Space Telescope (HST) to resolve the stars in a field centred on the thin disc of NGC 891. However, the crowded inner regions observed, and the shallow images did not allow them to study the stellar population properties of the observed field in more detail. The deeper ACS images (one of the three fields presented in this work) allowed Tikhonov & Galazutdinova (2005) to resolve red giant branch (RGB) stars, determine the distance from the luminosity of the RGB tip and discuss the RGB and asymptotic giant branch (AGB) stellar distribution along the minor axis.

In a series of papers, we study in detail the structure, metallicity distribution and stellar populations of NGC 891 using archival observations of three HST/ACS fields. In the first paper (Paper I), we investigated the metallicity distribution of the stellar halo of NGC 891. The results of that study revealed a surprisingly high average metallicity of [Fe/H] ∼ −0.9 dex at 9.5 kpc above the galaxy disc. This is ∼0.5 dex more metal-rich than the MW halo (e.g. Carollo et al. 2007; Ivezic et al. 2008). Ibata, Mouhcine & Rejkuba (2009, hereafter Paper III) investigated the structure of the halo and the disc of this galaxy. Using star counts which cover much larger area than in the work of Tikhonov & Galazutdinova (2005), we detected the thick disc with vertical scaleheight of $h_z = 1.44 ± 0.03$ kpc and radial scalelength of $h_R = 4.8 ± 0.1$ kpc. Moreover, in the stellar spheroid, which is well fitted with a de Vaucouleurs like profile out to the edge of our survey at $r \sim 25$ kpc, significant small-scale variations in the median colour and density are detected over the halo area. Harris et al. (2009, Paper IV) investigated the globular cluster population in the observed fields.

In this paper, we present in detail the complete data set and data reduction, the photometric catalogue and completeness simulations. The colour–magnitude diagrams and metallicity distribution of stars are used to investigate the stellar content of the thick disc and halo of NGC 891.

2 DATA AND PHOTOMETRY

Observations of three fields (H1, H2 and H3) along the eastern edge of NGC 891 (Fig. 1) have been taken in 2003 February with the wide field camera (WFC) of ACS as part of program GO-9414. The field of view of the ACS WFC is 202 arcsec$^2$ and the pixel size is 0.05 arcsec. At the distance of NGC 891 (9.7 Mpc), the field of view covers 90 kpc$^2$, and the pixels are 2.4 pc in size.

Each field was observed with nine F606W exposures and nine F814W exposures. These HST filters, similar to ground-based V and I, bands, are often used in studies of resolved stellar populations in the haloes of galaxies, where most of the sources are expected to be red giants, because of the match in the sensitivity of the filter–detector response and the emission of the sources. The observing strategy was such that for each field three sets of three

![Figure 1. HST/ACS fields H1, H2 and H3 overlayed on Digitized Sky Survey image of NGC 891. The scale bar of 2 arcmin corresponds to a physical scale of 5.7 kpc.](Image)
exposures per filter were taken. These three triplets were dithered with subpixel shifts between them. Each triplet of images was taken to ensure cosmic ray rejection through the CR-split observing strategy with exposure times tuned to fit the three exposures within one orbit. The summary of the observations, with the coordinates of the centre of the pointings, exposure times and observing dates are given in Table 1. The total integration time per filter per field is 7710 s.

We used the flat-fielded (\_ff), cosmic ray rejected (\_crj), and drizzled (\_drz) images produced by the ‘on-the-fly’ reduction pipeline of the European Southern Observatory/Space Telescope-European Coordinating Facility (ST-ECF) archive. The drizzled images obtained from the archive had combinations of only three CR-split exposures for each dither position. Therefore to make the deepest possible stack for each field, using the full 7710-s exposures we run the Multidrizzle (Koekemoer et al. 2002) task within the STSDAS package in Pyraf to combine the nine images taken for each filter, separately for the three fields and two filters. In Fig. 2, we show the combined deep image of the H1 field.

## 2.1 Photometry

Due to large geometrical distortions of the ACS field of view, the pixel size varies across the field resulting in incorrect photometry for point sources in flat-fielded (\_ff) images. The DRIZLE and Multidrizzle packages have been developed to correct these distortions. However, the photometry done on the \_drz images is non-optimal because the stars in different parts of the field of view are resampled in a different way by the drizzling process. Moreover, the signal in the adjacent pixels is correlated. Therefore following the recommendations of Anderson (2006) and the DOLPHOT/ACS user’s guide (Dolphin 2005), we decided to run the point spread function (PSF) fitting on the images that were not corrected for distortion. To obtain correct flux measurements for point sources, these images need to be multiplied by a pixel area map (PAM) prior to PSF fitting. PAM files are available for all the filters from the Space Telescope Science Institute (STScI) website.

PSF fitting photometry of all the stellar objects in the images was run with the DOLPHOT photometric package, which is an extension of HSTPHOT (Dolphin 2000), and contains the specialised ACS module tailored for accurate PSF photometry of ACS images. It contains image preparation and processing routines that should be run prior to the DOLPHOT PSF fitting program in the following order. The first step is running the ACSMASK program in order to mask out all the pixels flagged as bad from the data quality extension of the images, and to multiply the images with PAM files and so obtain geometrically corrected images in units of electrons. The next step of data preparation is sky measurement using the CALCSKY routine. Finally, the alignment between the reference image and the input images is calculated using ACSFITDISTORT program. The

| Field name          | RA       | Dec.       | Date     | Filter   | Exposure time (s) |
|---------------------|----------|------------|----------|----------|------------------|
| NGC 891-HALO1       | 02:22:42.70 | +42:19:42.0 | 2003-02-19 | F606W  | 3 × 824          |
| NGC 891-HALO1-Off1  | 02:22:42.74 | +42:19:42.4 | 2003-02-20 | F606W  | 3 × 873          |
| NGC 891-HALO1-Off2  | 02:22:42.74 | +42:19:42.4 | 2003-02-20 | F606W  | 3 × 873          |
| NGC 891-HALO2       | 02:22:49.70 | +42:22:49.0 | 2003-02-17 | F606W  | 3 × 873          |
| NGC 891-HALO2-Off1  | 02:22:49.74 | +42:22:49.0 | 2003-02-17 | F606W  | 3 × 873          |
| NGC 891-HALO2-Off2  | 02:22:49.74 | +42:22:49.6 | 2003-02-17 | F606W  | 3 × 873          |
| NGC 891-HALO2       | 02:22:49.70 | +42:22:49.0 | 2003-02-16 | F814W  | 3 × 824          |
| NGC 891-HALO2-Off1  | 02:22:49.74 | +42:22:49.0 | 2003-02-16 | F814W  | 3 × 873          |
| NGC 891-HALO2-Off2  | 02:22:49.74 | +42:22:49.9 | 2003-02-16 | F814W  | 3 × 873          |
| NGC 891-HALO3       | 02:22:56.60 | +42:25:54.7 | 2003-02-17 | F606W  | 3 × 824          |
| NGC 891-HALO3-Off1  | 02:22:56.64 | +42:25:54.7 | 2003-02-17 | F606W  | 3 × 873          |
| NGC 891-HALO3-Off2  | 02:22:56.64 | +42:25:55.1 | 2003-02-17 | F606W  | 3 × 873          |
| NGC 891-HALO3       | 02:22:56.60 | +42:25:54.7 | 2003-02-17 | F814W  | 3 × 824          |
| NGC 891-HALO3-Off1  | 02:22:56.64 | +42:25:54.7 | 2003-02-17 | F814W  | 3 × 873          |
| NGC 891-HALO3-Off2  | 02:22:56.64 | +42:25:55.1 | 2003-02-17 | F814W  | 3 × 873          |
PSF fitting program DOLPHOT is run with the USEACS flag set to 1 and the parameter file with the recommended values for the PSF radius, aperture size, sky region and threshold for detections. The PSF fitting is run simultaneously on the set of input images, where the coordinates for the fitting objects are derived from the reference image. All the parameters for the fitting, as well as the list of input images are passed through a configuration file.

Given the small overlap between the three fields, we run the photometry separately for each of the three fields. The stars detected in common in the overlap regions were used to verify the accuracy of the photometry (see below).

We have made several runs of DOLPHOT photometry: the first run used as the reference image one of the _crj images provided by the pipeline, which is the combination of only three out of nine exposures for a given field, and as input data all the available _crj images. The second run was done using as the reference again single _crj image, but with _flt images in input, where each _flt image was an average of three CR-split exposures taken at the same offset position and with the same filter. Finally, in the last run we used for the reference the deepest exposure, which we created ourselves using the MULTIDRIZZLE task within PYRAF. It consisted of the combination of all the nine exposures taken with the F814W filter into a single deep image per field.

The difference between the first two photometry runs allows one to evaluate how successful DOLPHOT is in rejecting the numerous cosmic rays when using _flt images in input which are not cosmic ray cleaned. The last run was then used to obtain the deepest photometry. The photometry from all these runs provides the same results for the bright part of the stellar populations present in the images. We note that the photometry used in our first analysis of the halo metallicity distribution in NGC 891 (Paper I) was based on _crj reference images. Here, we present the results obtained using the deepest multidrizzled images as reference image.

The output of DOLPHOT contains the instrumental magnitudes as well as transformed, calibrated magnitudes for all the fitted objects. The transformations have been made using calibrations from Sirianni et al. (2005) and include aperture corrections, as well as Charge Transfer Efficiency (CTE) loss corrections following Riess (2003). For each object, the global solution is listed first, and then the photometry results are given for each of the input images. Here, we use the global, combined photometry. Together with the magnitudes and the associated errors, DOLPHOT provides also a range of quality flags: \( \chi \), signal-to-noise ratio (S/N), sharpness, roundness, crowding, ellipticity and object type. These flags were used to select the bona fide stellar objects. Our selection criteria were the following: (1) object type 1 or 2, corresponding to a stellar (point source) object; (2) \( \chi < 3 \); (3) sharpness between \(-0.5\) and 0.5; (4) crowding parameter smaller than 0.35 and (5) detection in both \( V \) and \( I \) bands with global photometric errors smaller than 0.5 mag.

Applying these selection criteria, the photometric catalogues contain 149 076 stars in H1, 138 133 stars in H2 and 106 647 stars in the H3 field.

In Fig. 3, the photometric quality parameters for the H3 sources are shown: magnitude error (\( \sigma \)), sharpness and \( \chi \) of the PSF fit, as a function of magnitude. Magnitude error values (\( \sigma \)) in Fig. 3 are DOLPHOT values multiplied by 1.6 to account for the fact that the photometry was run combined averages of three _flt images, while DOLPHOT computed the photometric errors based on the noise characteristics of the raw ACS images. Although in principle this correction factor should have been \( \sqrt{3} \), we adopted the value of 1.6 based on the comparison of the photometry in the overlapping regions between fields (see Section 2.2 for details). There are several parallel sequences in the magnitude-error plots. The larger errors at a given magnitude are assigned to stars that are not detected in all the _flt images, but only in a subset of them. The sharpness parameter for a perfect star has value of zero, it is negative for sharper, more spiky objects, possibly contaminated by some remaining cosmic rays, or bad pixels, and has positive values for more extended objects. The \( \chi \) parameter is a measure of how well the model PSF matches the light distribution of the star. The crowding parameter measures the change in brightness for the star if the neighbours are not subtracted, and is expressed in magnitudes. It is an indicator of how much blending there is due to overlapping PSF wings of neighbouring stars.

The final photometric catalogue contains all the stars detected in the three fields. The H2 field overlaps with both H1 and H3 in its corners. To make the final catalogue, we derived RA and Dec. coordinates for all the stars using PYRAF task XYTOSKY. The relative accuracy of the astrometry was checked by overplotting the photometric catalogue over the _drz images. Several bright stars were identified in common between the two independent catalogues in overlap regions, and these stars were used to compute the initial shifts between H1 and H3, with respect to H2 field. Based on coordinates and \( V \) magnitude matches of all the stars, these shifts were refined iteratively, and the stars detected independently in two fields in the overlap regions were found. There are 13 054 and 4534 detections in H1–H2 and H2–H3 overlap regions, respectively. Fig. 4 shows the distribution of differences in RA and Dec. between the stars found in the overlap regions. The differences in magnitudes for these stars are shown in Fig. 5. There is no systematic offset between H2 and H1/H3 detections for stars above the 50 per cent completeness limits. In the final catalogue, we use the average magnitude measured independently on two different sets of images for these matched stars.

Our final photometric catalogue contains 377 320 stars detected in both F606W and F814W images in the three fields. The first five lines of the catalogue are given in Table 2. The full catalogue is available in the electronic version. The columns of the catalogue are: (1) ID number; (2) and (3) RA and Dec. in degrees; (4)–(7) calibrated and transformed, calibrated magnitudes for all the fitted objects. These flags were used to select the bona fide stellar objects. Our selection criteria were the following: (1) object type 1 or 2, corresponding to a stellar (point source) object; (2) \( \chi < 3 \); (3) sharpness between \(-0.5\) and 0.5; (4) crowding parameter smaller than 0.35 and (5) detection in both \( V \) and \( I \) bands with global photometric errors smaller than 0.5 mag.

Applying these selection criteria, the photometric catalogues contain 149 076 stars in H1, 138 133 stars in H2 and 106 647 stars in the H3 field.

In Fig. 3, the photometric quality parameters for the H3 sources are shown: magnitude error (\( \sigma \)), sharpness and \( \chi \) of the PSF fit, as a function of magnitude. Magnitude error values (\( \sigma \)) in Fig. 3 are DOLPHOT values multiplied by 1.6 to account for the fact that the photometry was run combined averages of three _flt images, while DOLPHOT computed the photometric errors based on the noise characteristics of the raw ACS images. Although in principle this correction factor should have been \( \sqrt{3} \), we adopted the value of 1.6 based on the comparison of the photometry in the overlapping regions between fields (see Section 2.2 for details). There are several parallel sequences in the magnitude-error plots. The larger errors at a given magnitude are assigned to stars that are not detected in all the _flt images, but only in a subset of them. The sharpness parameter for a perfect star has value of zero, it is negative for sharper, more spiky objects, possibly contaminated by some remaining cosmic rays, or bad pixels, and has positive values for more extended objects. The \( \chi \) parameter is a measure of how well the model PSF matches the light distribution of the star. The crowding parameter measures the change in brightness for the star if the neighbours are not subtracted, and is expressed in magnitudes. It is an indicator of how much blending there is due to overlapping PSF wings of neighbouring stars.

The final photometric catalogue contains all the stars detected in the three fields. The H2 field overlaps with both H1 and H3 in its corners. To make the final catalogue, we derived RA and Dec. coordinates for all the stars using PYRAF task XYTOSKY. The relative accuracy of the astrometry was checked by overplotting the photometric catalogue over the _drz images. Several bright stars were identified in common between the two independent catalogues in overlap regions, and these stars were used to compute the initial shifts between H1 and H3, with respect to H2 field. Based on coordinates and \( V \) magnitude matches of all the stars, these shifts were refined iteratively, and the stars detected independently in two fields in the overlap regions were found. There are 13 054 and 4534 detections in H1–H2 and H2–H3 overlap regions, respectively. Fig. 4 shows the distribution of differences in RA and Dec. between the stars found in the overlap regions. The differences in magnitudes for these stars are shown in Fig. 5. There is no systematic offset between H2 and H1/H3 detections for stars above the 50 per cent completeness limits. In the final catalogue, we use the average magnitude measured independently on two different sets of images for these matched stars.
Stellar population content of NGC 891

2.2 Error analysis and completeness

Completeness simulations were run for all three observed fields. Artificial star lists with at least 100,000 stars per field were created using ACSFAKELIST program within DOLPHOT, and then DOLPHOT was run using the FAKESTARS parameter in the configuration file equal to the artificial star list. As DOLPHOT adds one fake star to the image at the time and then remeasures its photometry, there is no danger of creating ‘overcrowded’ image by adding too many stars with overlapping PSF wings. In the output file of the completeness photometry run all the stars, including those that were added to the images but not detected, are listed. Therefore it is easy to compute the completeness ratio: the number of detected divided by the number of added fake stars. The criteria to detect stars were set equal to those for selection of ‘good’ stars in the original photometry runs, by selecting only stars that satisfy all the χ, sharpness, crowding and magnitude error cuts.

Table 2. Astrophotometric catalogue. This is a sample of the full catalogue, which is available in the online version of the article (see the Supporting Information).

| ID | RA   | Dec. | V (mag) | I (mag) | σ_V | σ_I | χ   | S/N | Sharp | Round | Crowd | typ | f   | vflag | iflag |
|----|------|------|---------|---------|-----|-----|-----|-----|-------|-------|-------|-----|-----|------|-------|
| 1  | 35.646270 | 42.308975 | 21.212 | 19.155 | 0.002 | 0.003 | 1.89 | 1385.3 | 0.017 | 0.027 | 0.061 | 1 | 1 | 4 | 2 |
| 2  | 35.671210 | 42.308643 | 21.086 | 19.522 | 0.002 | 0.002 | 1.93 | 1371.3 | 0.045 | 0.007 | 0.025 | 1 | 1 | 4 | 6 |
| 3  | 35.654569 | 42.308503 | 21.011 | 19.595 | 0.002 | 0.002 | 1.28 | 1362.0 | 0.009 | 0.010 | 0.019 | 1 | 1 | 6 | 4 |
| 4  | 35.664751 | 42.336123 | 21.482 | 19.298 | 0.002 | 0.003 | 1.41 | 1404.6 | 0.015 | 0.013 | 0.002 | 1 | 1 | 4 | 4 |
| 5  | 35.675835 | 42.303078 | 20.990 | 19.766 | 0.002 | 0.002 | 1.83 | 1358.2 | 0.050 | 0.041 | 0.001 | 1 | 1 | 4 | 4 |

We have defined the following coordinate system with respect to the major and minor axis of the galaxy: the centre of NGC 891 was taken to lie at RA = 02°22′33.4′′, Dec. = 42°20′57″ (J2000.0) and the position angle of the major axis was PA = 22°. In this coordinate system, positive X is located north-east of the centre of NGC 891, and negative Z is to the east. The ACS images cover ∼12 kpc perpendicular to the disc and ∼25 kpc along the major axis.

Given the large gradient in stellar density across the observed fields, we investigated the dependence of completeness and magnitude measurement errors as a function of distance from the plane and stellar density. In Fig. 6, we show the distribution of all the observed stars colour-coded according to the number density of RGB stars [ρ = N(RGB)/kpc²]. We use here the interpolated density profiles derived in Paper III. Solid black lines delimit

![Figure 6. Distribution of the observed stars in the three ACS fields are plotted in the coordinate system of NGC 891. Different colours denote regions of different density of RGB stars according to interpolated observed density profile (Paper III). The number of RGB giants per square kiloparsec in these regions are as follows: region 1 (blue) N(RGB)/kpc² > 1200; region 2 (cyan) 1200 > N(RGB)/kpc² > 450; region 3 (green) 450 > N(RGB)/kpc² > 140; region 4 (yellow) 140 > N(RGB)/kpc² > 44; region 5 (red) 44 > N(RGB)/kpc². The black lines indicate the limits of the regions and are used to select the same regions (in X–Z space) from the completeness simulations. An additional black line overplotted on region 2 (cyan) indicates the limit of the stellar density of ∼650 N(RGB)/kpc².](https://example.com/figure6.png)
five regions that have the following range of RGB star densities: region 1 (blue) $\rho > 1200$; region 2 (cyan) $1200 > \rho > 450$; region 3 (green) $450 > \rho > 140$; region 4 (yellow) $140 > \rho > 44$ and region 5 (red) $44 > \rho$. These same regions, selected based on $X, Z$ galactocentric coordinates were used to derive completeness and magnitude error dependence on magnitude in Figs 7 and 8.

By comparing directly the errors from DOLPHOT and from magnitude differences in the overlap regions, it is possible to verify the photometric errors computed by DOLPHOT. The overlap region between the H2 and H3 fields coincides with region 4 (RGB number density between 44 and 140 stars), while the overlap between H2 and H1 has most of its stars within region 3, and some in region 2. The ratio between DOLPHOT errors and the average scatter of the magnitude differences as a function of magnitude is computed using the following expression:

$$\text{ratio} = \frac{\text{mag}_{\text{H2}} - \text{mag}_{\text{H3}}}{\sqrt{\sigma_{\text{H2}}^2 + \sigma_{\text{H3}}^2}},$$

(1)

where $\sigma_{\text{H2}}$ and $\sigma_{\text{H3}}$ are the photometric errors for stars obtained from DOLPHOT in the corresponding field. This ratio indicates that DOLPHOT underestimates the errors by as much as a factor of 1.6. This factor is consistent with the expected factor of $\sqrt{3} = 1.7$, which is due to the fact that the input images are averages of three flt frames, while DOLPHOT computed the magnitude errors using the noise characteristics of raw images. All the uncertainties in Table 2 incorporate this factor of 1.6, and are adopted in Paper III and in all subsequent analysis in this contribution.

The dependence of the photometric error measurements on magnitude for each region is given in Fig. 7. The solid lines are the analytic fits to the data using the following function:

$$\text{error}_i = c_1 \exp(c_2 (\text{mag} + c_3)).$$

(2)

The values of the coefficients of the fits are given in Table 3. The photometric measurements have large errors and show severe blending in region 1. Therefore, we will not consider this region further in the stellar populations analysis. Region 2, which corresponds approximately to 2–4 kpc above the plane and therefore is strongly dominated by thick-disc stars (Paper III), has slightly larger errors than outer regions, but blending does not affect the ~1–1.5 mag below the RGB tip.

The analytic fits to the photometry errors derived from the completeness simulations for $450 > \rho > 140$ and $140 > \rho > 44$ fit well the errors derived from the overlap regions H1–H2 and H2–H3, respectively, provided that the noise characteristics of the input images are properly taken into account. This is a nice consistency check that the artificial star simulations are providing a reliable estimate of photometric errors.

The completeness as a function of magnitude can be fairly well fitted using the following analytical function (Fleming et al. 1995):

$$f = \frac{1}{2} \left[ 1 - \frac{\alpha (m - m_o)}{\sqrt{1 + \alpha^2 (m - m_o)^2}} \right].$$

(3)

The values of the fitted coefficients are given in Table 4. We also derived the completeness relations as function of distance from the galaxy plane, selecting stars only based on Z coordinates. The values of fitted coefficients are given in Table 4 as well. The plot and the tabulated values show that the region within ~2 kpc of the galaxy plane is too crowded to yield accurate photometry even at the level of the RGB tip. The area between 2 and 4 kpc from the plane has 50 per cent incompleteness at an I-band magnitude of 27.27, while above 4 kpc above the disc the radial dependence of incompleteness and magnitude errors is much weaker.

In spite of the relatively low Galactic latitude of the observed fields ($b = -17^\circ$), the contamination from the MW stars is negligible due to the small size of the ACS field. For example, according to the Besançon model of the Galaxy (Robin et al. 2003), less than

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Average error as a function of magnitude and stellar density in the field based on completeness simulations. The errors are shown separately for each region (see Fig. 6) selected according to the density of RGB giants observed across the field. Solid lines are the fits of the analytic function given in equation (2). The coefficients of the fits are given in Table 3.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Completeness for F606W (upper panel) and F814W (lower panel) bands as a function of magnitude. Different symbols are used to plot completeness functions for different regions according to the density of RGB stars (see Fig. 6), and the selected ranges are given in the diagrams. The lines are fitted analytical functions of the form equation (3) (Fleming et al. 1995). The coefficients of the fits are given in Table 4.
170 Galactic stars are expected within the three ACS fields within the magnitude range $24 < F814W < 28.5$. This implies that the contamination from foreground stars is $\lesssim 0.05$ per cent. Most of the background sources are resolved due to the high resolution of the ACS images.

### 3 RESULTS

In our analysis, we use the distance to NGC 891 of 9.73 Mpc (Paper I), corresponding to a distance modulus of $(m - M)_0 = 29.94$ mag. The foreground reddening, obtained from Schlegel, Finkbeiner & Davis (1998) maps is $E(B - V) = 0.065$. This corresponds to $A_V = 0.22$ and $A_I = 0.13$ mag.

In addition to the foreground extinction, the inner regions of NGC 891 suffer from dust extinction, which is readily visible in optical images covering the plane of the disc. Some amount of extinction is expected to be present also above the disc plane, given the extended distribution of the ionized gas, as well as the detected vertical distribution of molecular and H\textsc{i} gas (Scoville et al. 1993; Kamphuis et al. 2007; Oosterloo et al. 2007). To correct for internal extinction within NGC 891, we proceed in the same way as in Paper III: we compute the extra reddening $E(B - V)$ from the local value of the H\textsc{i} column density using the high-resolution deep H\textsc{i} map of Oosterloo et al. (2007) and assuming the conversion between H\textsc{i} column density and $E(B - V)$ derived for the MW by Rachford et al. (2009). Then, half of this additional $E(B - V)$ is added to the foreground MW reddening value. In assigning only half of the extra-extinction derived from the H\textsc{i} map, we assume that approximately half of the gas (and dust) is in front and half behind the observed stars in NGC 891.

The impact of the absorption correction uncertainty is minimized in the following by investigating primarily the areas beyond 2 kpc above the disc plane, where most of the dust and gas is located. The derived metallicity and colour gradients are consistent within the 2σ error bars if the additional extinction contribution is varied by about a factor of 2. If less extinction is assumed the gradient is steeper, while it flattens if extinction is higher than assumed. This is primarily due to the change in colour/metallicity in the inner 2.5–3 kpc.

After applying this extinction correction to our photometry, we investigate first the stellar population content at the distance corresponding to the solar circle. After that, we discuss the metallicity distributions of the thick disc, the inner spheroid and the halo of NGC 891. To minimize the photometric errors and crowding, we limit our analysis to stars located in regions with stellar density lower than 650 $N$(RGB)/kpc$^2$.

### 3.1 Metallicity distribution function

Both stellar evolution models and globular cluster observations show that colours of red giant stars are much more sensitive to metallicity than age, provide thus an excellent way to estimate the metallicity distribution of a stellar population. This approach has been widely used in the literature (e.g. Harris, Harris & Poole 1999; Saviane et al. 2000; Zoccali et al. 2003; Mouhcine et al. 2005; Rejkuba et al. 2005), and is calibrated using Galactic globular clusters, and stellar evolutionary tracks. Its drawback is that one cannot separate stars belonging to the early-AGB (E-AGB) evolutionary phase, which are located along the RGB, with colours bluer with respect to the first ascent giants of the same age. In a composite stellar population, with a range of metallicities, the E-AGB stars of a metal-rich population may overlap in colour with metal-poor RGB stars. However, the lifetime of AGB stars is significantly shorter, and one expects only one E-AGB star for 40 RGB stars in an old population (e.g. Renzini 1998). Moreover, at the blue edge, E-AGB stars belonging to the metal-poor population are excluded because they are bluer than the most metal-poor evolutionary track. An additional complication is due to a possible mix of ages in our fields. In the interpolation, we assume a single old age for all the stars, which may introduce a bias of up to 0.1 dex, if the age is 4-Gyr younger (Rejkuba et al. 2005). From comparison with simulated CMDs, and from the absence of blue plume stars and a large fraction of thermally pulsing AGB (TP-AGB) stars, the fractions of stars younger than ~6 Gyr are expected to be small in both the thick disc and the halo of NGC 891.

Metallicities for each star were derived by interpolating between the set of α-enhanced RGB tracks for stars with 0.8 M\odot (VandenBerg, Bergbusch & Dowler 2006). For more details, we refer to Mouhcine et al. (2005) and Paper I. We note here that only stars with colours corresponding to the metallicity range between $\text{[Fe/H]} = -2.314$ and $-0.397$, that satisfy our selection criteria, and have $F$-band magnitudes brighter than 26.5 mag (to avoid as much as possible completeness corrections), have been used to construct the metallicity distribution functions (MDFs). From the comparison of the observed CMDs with the stellar evolutionary isochrones, it is clear that there are almost no stars with metallicity above $Z = 0.008$ isochrone (see below), which corresponds to $\text{[Fe/H]} = -0.38$. Therefore, we expect that this choice of tracks used for interpolation, and the fact that we do not extrapolate beyond the validity of the models, does not affect the metal-rich end of our MDF.

### 3.2 Solar-cylinder-like populations

Fig. 9 shows the MDFs of stars selected at 8 ± 1 kpc distance along the major axis and at two different heights above the plane of the galaxy: at 3–4 kpc (left-hand panel) and 5–7 kpc (right-hand panel). The histograms are normalized, extinction-corrected stellar MDFs in the $(X,Z)$ regions indicated in each panel. Both distributions have a prominent relatively metal-rich peak with a median of $\text{[Fe/H]} \sim -1.0$ dex and a sparsely populated metal-poor tail. The properties of metallicity distributions are quantified using the widely used Kaye’s Mixture Model (KMM) statistical test (Ashman, Bird & Zepf 1994 and references therein). The KMM test uses the maximum likelihood technique to test if a distribution is better modelled.
as a sum of two Gaussians than as a single Gaussian (the null hypothesis). (Ashman et al. 1994) have cautioned that the output likelihood in the case where the two populations have different dispersions is difficult to interpret, so we have assumed that both populations have similar dispersions. The solid line shows the best double-Gaussian distribution fit, which is preferred to a single-Gaussian distribution based on the KMM statistics. Indicated are the parameters of the best-fitting models as assigned by the KMM test for the two components, referred to as the metal-poor and the metal-rich component and shown by the dashed lines.

The distribution functions shown in Fig. 9 are significantly different from those of the MW stars at similar locations. Ivezić et al. (2008) have shown for stars with 7 kpc < R < 9 kpc that the metal-rich components, with ⟨[Fe/H]⟩ ~ −0.7, dominate only at relatively small vertical distances from the plane, i.e. |Z| < 2 kpc. For higher vertical distances, i.e. |Z| ≥ 5 kpc, the fraction of stars belonging to the metal-rich component is vanishingly small, and are completely outnumbered by stars with ⟨[Fe/H]⟩ ~ −1.5. NGC 891 stars at similar distances along the minor and the major axes exhibit a different behaviour. The properties of the metal-rich and the metal-poor components of the stellar MDF do not change significantly as a function of the vertical distance from the galactic plane. Metal-rich stars are still present in abundance at a vertical distance beyond 5 kpc, in stark contrast with the stellar content of the Galaxy at similar distances.

The lower panels of Fig. 9 show the residuals from the double-Gaussian fits of the observed metallicity distributions. No systematic deviations are notable. The difference between the observed MDF of the MW stars at the solar cylinder and the double-Gaussian fit shows the presence of an additional population of intermediate metallicity stars, i.e. [Fe/H] ~ −1.0 dex, a reminiscent of the so-called metal-weak thick disc (Morrison, Flynn & Freeman 1990). The metal-rich peak of the MDF of the MW stars within the solar cylinder is best fitted by a double-Gaussian model up to |Z| ~ 4 kpc. For NGC 891, however, the metal-rich peak of stars at the solar-cylinder-like locations is satisfactorily modelled as a single component, indicating the absence of a distinct stellar population with intermediate metallicities within |Z| ~ 3–6 kpc.

The observed differences could be due to that thick-disc stars, which should be the dominant contributors at Z = 3–4 kpc, are still present beyond 5 kpc (see fig. 7b of Paper III). In addition, the stellar halo of NGC 891 has a higher mean metallicity than that of the MW at comparable radial and vertical distances (Paper I and also Section 3.4). All this points towards the presence of a mix of populations that could be due to more massive accretion events than is typical in the Galaxy at the solar neighbourhood. While this may sound like a far-fetched conclusion, the occurrence of recent accretion events is supported by the detection of significant small-scale substructures across the thick disc and spheroid of NGC 891 (Paper III).

3.3 Thick-disc stellar population

The structural analysis presented in Paper III has shown that a thick-disc component is present in NGC 891, with stellar densities well fitted by exponential profiles both vertically, with a scaleheight of h_Z = 1.44 ± 0.03 kpc, and radially with a scalelength of h_R = 4.8 ± 0.1 kpc. The presence of an inner stellar spheroid, combined with large stellar densities, causing large photometric uncertainties, incompleteness and significant blending (density region 1 with \rho > 1200 stars extends almost up to 4 kpc above the plane along the minor axis) prevent the detection of the thick-disc population within the inner ~5–6 kpc. To investigate the properties of the thick-disc stellar content, as free as possible from the bulge and halo stars, we select stars with −4 < Z < −1 kpc, and |X| > 7 kpc (Paper III; in particular see their figs 4 and 7). As already mentioned, to minimize the photometric errors and crowding we limit our analysis to stars located in regions with stellar density lower than 650 \rho(N(RGB))/kpc^2.

The colour–magnitude diagram of selected thick-disc stars is shown in Fig. 10. The most prominent feature is the well-populated RGB, with stars covering a wide range of colours. In the area of the diagram where blue plume stars, belonging to the young main sequence, and blue supergiant stars are expected to be located, there are only a handful of stars, which could be either scattered there by the combination of photometric errors and blending or misidentified background or foreground sources. Overplotted on the CMD are Teramo stellar evolutionary isochrones for a 10-Gyr old stellar population with the range of metallicities Z = 0.0001, 0.0003, 0.0006, 0.001, 0.002, 0.004, 0.008, 0.01. While the incompleteness prevents the detection of stars with metallicities...
higher than half-solar, only very few, if any, are expected, given that the density of stars decreases strongly between the $Z = 0.004$ and 0.008 isochrones. The right-hand panel of Fig. 10 shows the MDF of all thick-disc stars with $I$-band magnitudes brighter than 26.5 mag. The peak of the stellar metallicity distribution of the thick-disc stars is around $-0.9$ dex, with a mean metallicity of $-1.09$ dex and 1σ scatter of 0.34 dex. The median of the stellar metallicities of the thick disc is $[\text{Fe/H}] = -1.01$ dex, slightly lower than that measured for the MW thick disc of $-0.8$ dex for stars at comparable vertical distances above the galaxy plane (Gilmore, Wyse & Jones 1995; Ivezić et al. 2008). It is worth mentioning that thick-disc stars selected here are distributed over a wide range of radial distances, i.e. $7 \lesssim R/kpc \lesssim 22$, while the samples of the Galaxy thick-disc stars are restricted generally to the solar neighbourhood.

The spatial variation of the properties of thick-disc stars holds important clues on the formation mechanism(s) of this disc component. The size of the sample of thick-disc stars selected here is large enough to permit a study of the vertical and radial variation of their properties. The left-hand panel of Fig. 11 shows the variation of the median colour of thick-disc stars with $M_I = -3.5 \pm 0.1$ mag, i.e. $(V-I)_{0.3} - 3.5$ a powerful metallicity indicator for old stellar populations, along the vertical direction. The dashed line shows a linear fit to the data where only solid dots ($Z \leq 2$ kpc) are used in the fit. Despite our efforts to correct for incompleteness due to crowding and large extinction in the inner parts, we have chosen to exclude stars in those regions for the sake of obtaining clear conclusions. The right-hand panel of Fig. 11 shows the variation of the median metallicity along the vertical direction. A strong vertical gradient of the median colour and metallicity of thick-disc stars is present. The detected vertical gradient could be genuine, or alternatively, given the wide range of radial distances covered by stars in the thick-disc sample, could be due to a mix of different populations with radially varying contributions. The inspection of the vertical stellar density profiles indicates that the contribution of halo stars to the overall populations with $|Z| < 4$ kpc, estimated from the extrapolation of the star count profiles stars with $|Z| > 6$ kpc, changes as one moves...
and 16 and 18 kpc (bottom panel). In each panel, we indicate the slope and the normalization of the linear fit to the data, restricted to the solid dots. The results of this exercise are given in a tabular format in Table 5 reporting the mean, median and rms dispersion of the $(V - I)_0$ and [Fe/H] distributions at a range of distances along the minor axis (Z range) and major axis (X range). The thick-disc stars with $X \lesssim 11$ kpc, where the contamination from halo stars is expected to be small, do not show vertical variations of their median metallicities and colours. This is similar to what is observed for the Galactic thick-disc stars at similar radial distances and heights from the Galactic plane (Ivezic et al. 2008). For thick-disc stars well away from the minor axis, i.e. $X \gtrsim 14$ kpc, marginally significant mild vertical gradients are present however. The outer spheroid stellar populations shift the average colour of stars close to the edge of the thick disc outside 14 kpc towards bluer values, lowering therefore the median metallicities.

Fig. 13 shows the variation of the median colour (left-hand panel) and median metallicity (right-hand panel) of thick-disc stars along the radial direction, for those with $-3.5 < Z_0/kpc < -2.5$. The dashed lines show the linear fits to the data. No radial metallicity gradient is detected for thick-disc stars. However, the median metallicities/colours are found to vary significantly within the narrow bin of vertical distances. The mean thick-disc colour for the vertically selected stars is $(V - I)_{0,-3.5} = 1.65$, with 1σ scatter around the mean of 0.13 mag. The dispersion around the mean metallicity is approximately 0.35 dex, and does not vary much as one moves along the major axis.

Fig. 14 shows the normalized, extinction-corrected, MDF histograms for thick-disc RGB stars, and selected to lie at radial distances $9 < X < 11$ kpc (left-hand column), $14 < X < 16$ kpc (central panel). The a and b values indicated in each panel are the coefficients of the linear least-squares fit.

### Table 5. Statistics (number of stars $N$, mean, 1σ dispersion and median values) of the colour and metallicity distributions of thick-disc stars in different bins along the minor (Z) and major (X) axis.

| $Z$ range (kpc) | $X$ range (kpc) | $N_{(V-I)}$ | $(V-I)_{0,-3.5}$ mean mag | $\sigma_{(V-I)}$ | $(V-I)_{0,-3.5}$ median mag | $N_{[Fe/H]}$ | [Fe/H] mean dex | $\sigma_{[Fe/H]}$ | [Fe/H] median dex |
|-----------------|-----------------|-------------|---------------------------|-----------------|-----------------------------|-------------|----------------|----------------|----------------|
| $-1 > Z > -4$   | $7 < X < 9$     | 311         | 1.59                      | 0.30            | 1.57                        | 552         | $-1.17$        | 0.35            | $-1.11$         |
| $-1 > Z > -4$   | $9 < X < 11$    | 356         | 1.61                      | 0.31            | 1.59                        | 625         | $-1.19$        | 0.38            | $-1.11$         |
| $-1 > Z > -4$   | $14 < X < 16$   | 478         | 1.67                      | 0.33            | 1.66                        | 944         | $-1.05$        | 0.30            | $-0.99$         |
| $-1 > Z > -4$   | $16 < X < 18$   | 320         | 1.66                      | 0.32            | 1.62                        | 654         | $-1.04$        | 0.31            | $-0.96$         |
| $-1 > Z > -4$   | $18 < X < 20$   | 138         | 1.71                      | 0.30            | 1.67                        | 297         | $-1.05$        | 0.32            | $-0.99$         |
| $-1 > Z > -4$   | $20 < X < 25$   | 38          | 1.58                      | 0.27            | 1.58                        | 67          | $-1.19$        | 0.39            | $-1.15$         |
| $-1.6 > Z > -2.4$| $7 < X < 9$     | 0           | —                         | —               | —                           | 0           | —              | —               | —               |
| $-1.6 > Z > -2.4$| $9 < X < 11$    | 65          | 1.55                      | 0.32            | 1.53                        | 82          | $-1.28$        | 0.44            | $-1.15$         |
| $-1.6 > Z > -2.4$| $14 < X < 16$   | 175         | 1.68                      | 0.31            | 1.68                        | 343         | $-1.02$        | 0.28            | $-0.97$         |
| $-1.6 > Z > -2.4$| $16 < X < 18$   | 96          | 1.70                      | 0.34            | 1.69                        | 212         | $-1.01$        | 0.27            | $-0.93$         |
| $-1.6 > Z > -2.4$| $18 < X < 20$   | 55          | 1.73                      | 0.29            | 1.72                        | 105         | $-1.05$        | 0.30            | $-0.99$         |
| $-1.6 > Z > -2.4$| $20 < X < 25$   | 6           | 1.51                      | 0.20            | 1.61                        | 6           | $-0.86$        | 0.23            | $-0.81$         |
| $-2.4 > Z > -3.2$| $7 < X < 9$     | 120         | 1.61                      | 0.30            | 1.59                        | 214         | $-1.15$        | 0.33            | $-1.12$         |
| $-2.4 > Z > -3.2$| $9 < X < 11$    | 187         | 1.62                      | 0.32            | 1.60                        | 335         | $-1.20$        | 0.39            | $-1.11$         |
| $-2.4 > Z > -3.2$| $14 < X < 16$   | 75          | 1.71                      | 0.31            | 1.71                        | 145         | $-1.02$        | 0.28            | $-0.95$         |
| $-2.4 > Z > -3.2$| $16 < X < 18$   | 53          | 1.65                      | 0.28            | 1.60                        | 84          | $-1.06$        | 0.34            | $-0.96$         |
| $-2.4 > Z > -3.2$| $18 < X < 20$   | 24          | 1.71                      | 0.25            | 1.69                        | 57          | $-1.13$        | 0.36            | $-1.06$         |
| $-2.4 > Z > -3.2$| $20 < X < 25$   | 14          | 1.58                      | 0.38            | 1.58                        | 26          | $-1.23$        | 0.42            | $-1.15$         |
| $-3.2 > Z > -4.0$| $7 < X < 9$     | 191         | 1.58                      | 0.30            | 1.55                        | 338         | $-1.18$        | 0.36            | $-1.11$         |
| $-3.2 > Z > -4.0$| $9 < X < 11$    | 104         | 1.62                      | 0.29            | 1.60                        | 208         | $-1.15$        | 0.33            | $-1.09$         |
| $-3.2 > Z > -4.0$| $14 < X < 16$   | 47          | 1.69                      | 0.40            | 1.65                        | 100         | $-1.13$        | 0.35            | $-1.05$         |
| $-3.2 > Z > -4.0$| $16 < X < 18$   | 24          | 1.53                      | 0.34            | 1.49                        | 67          | $-1.13$        | 0.37            | $-1.04$         |
| $-3.2 > Z > -4.0$| $18 < X < 20$   | 22          | 1.52                      | 0.21            | 1.55                        | 43          | $-1.06$        | 0.32            | $-0.97$         |
| $-3.2 > Z > -4.0$| $20 < X < 25$   | 18          | 1.60                      | 0.20            | 1.61                        | 35          | $-1.22$        | 0.37            | $-1.20$         |
Figure 13. Median colour (left-hand panel) and median metallicity (right-hand panel) of the thick-disc stars as a function of the major axis distance. Only the thick-disc stars between 2.5 and 3.5 kpc above the plane are selected in this plot.

Figure 14. Normalized MDFs of thick-disc RGB stars selected to lie at different heights above the plane (upper row: $-2.4 < Z < -1.6$ kpc, middle row: $-3.2 < Z < -2.4$ kpc and bottom row: $-4.0 < Z < -3.2$ kpc), and at different distances along the major axis (left-hand column: $9 < X < 11$ kpc, middle column: $14 < X < 16$ kpc and right-hand column: $16 < X < 18$ kpc). The mean [Fe/H] and $1\sigma$ dispersion around the mean are indicated in each panel together with the number of stars in each region. The vertical dotted lines indicate the median [Fe/H].

3.4 The stellar population of the spheroid

The analysis of the star counts around NGC 891 has shown the presence, in addition to the thick disc, of a spheroidal component with a de Vaucouleurs like profile from $r \sim 0.5$ kpc to the edge of the survey at $r \sim 25$ kpc. This morphological component consists of an inner spheroid, prominent between $-4 \lesssim X \lesssim 6$ kpc and $-5 \lesssim Z \lesssim -2$ kpc and the halo (see fig. 3 of Paper III).
two-dimensional fit of the star number count distribution indicates that the spheroid becomes more flattened with distance, changing from $q = 0.73 \pm 0.01$ in the inner parts to $q = 0.50 \pm 0.03$ in the outermost halo region probed. To sample the stellar populations of the inner spheroid, we select stars with $-6 < X < 6$ kpc and $-5 < Z < -2$ kpc. To avoid contamination from the inner spheroid and/or the thick-disc, halo stars are selected as those with $|Z| > 6$ kpc and $X > 6$ kpc. As in the case of the thick-disc stellar population analysis, we restrict the sample to stellar density regions with less than 650 RGB stars per kpc$^2$.

The colour–magnitude diagrams of both inner spheroid and the halo are shown in the left-hand panels of Figs 15 and 16, respectively. The CMDs of both components look strikingly similar and, as for the thick disc, dominated by old stars, with RGB stars covering a wide range of colours, indicative of a mixture of low-to-intermediate metallicities. The MDFs of selected stars in each component are shown in the right-hand panels of Figs 15 and 16, respectively. The average metallicity of stars of the inner spheroid is $-1.15$ dex, with a spread of 0.35 dex and a median of $-1.08$ dex. For the halo, the average $[\text{Fe/H}]$ is $-1.20$ dex, 1σ spread 0.34 dex and the median $-1.15$ dex. The stellar populations dominating the two components of the spheroid surrounding the galaxy seem to be almost identical. This was remarked by Paper III, who found that inner spheroid and halo share similar colour and structure properties. Here, we repeat their caveat: the inner most parts of the ‘bulge’ inside the $\sim 2$ kpc radius are almost impossible to probe with resolved stellar populations, while integrated light suffers from substantial extinction from the dust in the disc.

To investigate the spatial variations of stellar metallicity, we compute the median colour $(V-I)_{0.5}$ and the median metallicity in elliptical rings, where we use different axis ratios for the inner spheroid and the halo. Fig. 17 shows the evolution of the median colour and metallicity as a function of minor axis distance. A modest metallicity gradient, i.e. $\sim 0.02$ dex kpc$^{-1}$, is present at about $3\sigma$ level. The scatter around the mean-metallicity–distance relation is substantial however. The 1σ dispersion around the median metallicity is remarkably constant across the outer spheroid with $\sigma \approx 0.35$ dex. The presence of small-scale chemical substructures is evident from the large scatter around the mean relation.

Fig. 18 shows the spatial variation of the normalized, extinction-corrected stellar metallicity distributions of the inner spheroid (left-hand panels) and the halo (right-hand panels). Stars have been...
selected in elliptical rings with the minor axis distances \((b)\) indicated in each panel. The properties of the stellar content of the inner spheroid appear to be remarkably invariant over an extended range of distances along the minor axis. Beside the mild metallicity gradient, with average metallicity decreasing from about \(-1.15\) to \(-1.27\) dex from the innermost regions to the outskirts (Fig. 17), the properties of the stellar halo metallicity distribution appear to be the same over the surveyed area. No evidence that the contribution of the metal-poor peak of the stellar halo MDF increases at larger distances is present. No second stellar halo component is present in the halo of NGC 891, at least within the range of distance probed by our survey.
4 DISCUSSION

Stars brighter than the RGB tip can either be foreground contaminants, or old and metal-rich ([Fe/H] \(\geq -0.6\) dex) TP-AGB stars, or intermediate-age TP-AGB, or blends of RGB tip stars. In the most inner fields, i.e. \(Z < 2\) kpc, most of bright stars are expected to be blends. While some blends are expected to be present in the fields with stellar density larger than \(N(RGB) / kpc^2 \geq 650\), the blends of two RGB tip stars that would mimic a bright AGB star are expected to be negligible in the regions with lower densities: at the distance of NGC 891, 1 kpc subdents about 420 pixels, and there is only one bright red giant within 1 mag of the RGB tip for every 120 fainter RGB stars in an old stellar population with solar metallicity (Renzini 1998). Judging by the lack of stars with metallicities above approximately half solar in the probed field, the bulk of stars above the RGB tip are probable intermediate-age AGB stars. To investigate whether an age gradient is present across the thick disc and halo, we plot the ratio between AGB and RGB stars in Fig. 19. Filled (red) dots show this ratio along the minor axis, while the (green) triangles are used to plot the ratio at \(X = 17\) kpc from the centre. In both cases, the number ratio of AGB and RGB stars is computed for the same range of distances above the disc (\(|Z| = 10.5, 7.5, 5\) and 3 kpc). AGB stars are selected between 0.2 and 1.0 mag brighter than the RGB tip, while the RGB stars are selected between the RGB tip and 0.5 mag fainter than the RGB tip. The number ratio is fairly constant with radius and perpendicular to the disc plane. Accounting for the Poissonian errors (1σ error bars are plotted), the ratio remains constant at \(\sim 0.13\) across the surveyed thick disc and halo areas. This is strikingly similar to the measured ratios for three small edge-on galaxies and is consistent with an old stellar population (Mould 2005). No significant bias is expected then when converting RGB photometry into metallicity.

Stars populating the halo and thick disc of NGC 891 are found to be predominantly old, similar to what is well established for the MW halo (e.g. Ryan & Norris 1991) and the thick disc (Gilmore & Reid 1983; Bensby, Feltzing & Lundström 2003; Fuhrmann 2004). The vertical variations of the shape of the metallicity distributions of stars located at solar neighbourhood like distances, where it is well determined in the case of the MW, are significantly different in both galaxies however. This indicates that the mix of stellar populations that have been assembled to form the outskirts of the thick discs of both galaxies is different. Probably more massive or later accretions happened in NGC 891. A metal-poor thick disc and halo might be present but with a more extended component dominating the probed regions, or alternatively a large accretion (unidentified given the restricted extent of the area surveyed here) has polluted the stellar populations within the few kpc above the disc of NGC 891. A survey delivering a panoramic view of the outskirts of NGC 891 is needed. Whatever the exact driver(s) of the observed different vertical structures of the MW and NGC 891, it is safe to conclude that the accretion histories of both galaxies have been substantially different.

The scaleheights of the MW thin and thick discs are \(\sim 300\) and \(\sim 900\) pc, respectively (Jurić et al. 2008), and essentially all the stars within the \(|Z| > 1.5\) kpc above the plane belong to the thick disc. NGC 891 has a larger thick disc, with a scaleheight of \(1.44 \pm 0.03\) kpc and the scalelength of \(4.8 \pm 0.1\) kpc (Paper III). The thin and the thick discs of NGC 891 have similar radial scalelengths, with \(h_R(\text{thick}) = 4.8 \pm 0.1\) kpc, and \(h_R(\text{thin}) = 4.19 \pm 0.01\) kpc. The structure of the thick disc appears to be similar at different distances above the plane. What can this similarity tell us about the formation of the thick disc of NGC 891? The metallicity distributions of the Galactic thin and thick discs overlap (Freeman & Bland-Hawthorn 2002 and reference therein). It is still debated whether the thick-disc metallicity distribution extends up to solar values, or at most to [Fe/H] \(\sim 0.2\) dex (Bensby et al. 2007; Fuhrmann 2008). However, there is a discontinuity in the \(\alpha\)-element abundances between the thin and thick disc in the MW, which points to a disjoint formation histories for the two discs. The metallicity distribution of the thick disc of NGC 891 does not seem to extend to such high metallicity. However, our conclusion is limited due to possible bias in the inner regions due to blending. Observationally challenging spectroscopy of the low surface brightness regions of the NGC 891 thick disc is therefore needed to measure the \(\alpha\)-element abundances.

The very high stellar density and the presence of significant amounts of dust in the plane of the galaxy, prevent the analysis of the thin-disc population in similar detail as is feasible for the thick disc and halo. The colour composite of our ACS images (Fig. 2 in this paper and fig. 3 of Paper III) shows the presence of blue, young stars and H \(\alpha\) regions in the thin disc. Clearly, the star formation is still on-going in the thin disc. The question is whether the thick disc may have formed from migrated thin-disc stars, dispersed to higher orbits by some heating mechanism (Norris 1987). The similar sizes of the thin and thick disc support the stellar diffusion formation scenario. This scenario is, however, not supported by the observed lack of vertical metallicity/colour gradient of thick-disc stars. This is consistent with the finding of Dalcanton & Bernstein (2002) and Yoachim & Dalcanton (2005) who have found that the scalelengths of thin and thick discs (derived from fitting of vertical surface brightness profiles) are not correlated.

Alternative scenarios for the thick-disc formation include a slow pressure-supported collapse, violent chemical heating of the early thin disc by satellite accretion or violent relaxation of the galactic potential, direct accretion of thick-disc material and the rapid dissipational collapse (e.g Gilmore et al. 1995). In the slow dissipative disc formation scenario, disc settling on time-scales longer than chemical enrichment time-scale would give rise to metallicity gradients of about 2 dex kpc\(^{-1}\) (e.g. Burkert, Truran & Hensler 1992), which are much stronger than we observe in NGC 891. Furthermore, in that scenario the vertical gradient is expected to be present also in the inner regions, in contradiction with the observed properties.

![Figure 19. Ratio of AGB versus RGB stars as a function of distance from the plane (Z), and for two different distances along the disc direction, at X = 17 ± 5 kpc (green triangles) and X = 0 ± 5 kpc (red dots).](https://academic.oup.com/mnras/article-abstract/396/3/1231/988963)
Our finding of no vertical gradient in the inner thick-disc regions, and no radial colour gradient, combined with the evidences of inhomogeneities seems to point to a combination of possible rapid dissipational collapse or fast assembly of few gas-rich satellites at high redshift (z ∼ 1.5–2; Broek et al. 2004, 2005). Although the data point to a merger/accretion origin for the thick disc, it is difficult to disentangle models in which thick-disc stars are accreted from those in which the stars form in situ further off the mid-plane during gas-rich mergers (Brook et al. 2004). Stars that formed in subhaloes before being accreted are likely to have different properties than those that formed from accreted gas. Presumably, one could use detailed stellar kinematics, age and abundance information to distinguish between the two scenarios.

The stellar halo of NGC 891 shows a shallow metallicity gradient, i.e. ∼0.02 dex kpc⁻¹, with stars getting less chemically enriched in the outer regions. This is similar to what is found in the inner halo of M31 (Durrell et al. 2001), and in the outskirts of the giant elliptical NGC 5128 (Rejkuba et al. 2005). However, at distances larger than ∼12r_eff from the centres of M31 and giant elliptical galaxy NGC 3379, the metal-poor halo was detected (Chapman et al. 2006; Kalirai et al. 2006; Harris et al. 2007). For NGC 891, the 12r_eff corresponds to about 21.5 kpc. The metal-poor halo, similar to those found in the MW and outer regions of M31, is then either missing, or we do not detect it at 13r_eff due to higher flattening of the halo and a more extended and/or less populated metal-poor component. This points again towards the need for a panoramic coverage of the outskirts of this analogue of the MW to map the shape and the properties of its stellar halo.

5 SUMMARY AND CONCLUSIONS

We have derived an astrophotometric catalogue of 377 320 stars detected in both F606W and F814W filters in three HST ACS fields in the north-eastern quadrant of NGC 891. A detailed description of the data reductions, completeness simulations and photometric error analysis is presented. The final photometry is calibrated on to the ground-based V Johnson–Cousins system.

The colour–magnitude diagrams are morphologically dominated by RGB stars, with no significant number of stars brighter than the classic old tip of the RGB. The number ratio of AGB stars to RGB stars, with no significant number of stars brighter than the classic old tip of the RGB. The number ratio of AGB stars to RGB stars is indicative of predominantly old stellar populations, and is roughly constant across the thick disc and the halo. The metallicity gradient of the thick-disc population perpendicular to the plane of the galaxy is mild, amounting to Δ[Fe/H]/Δ[Z] = 0.05 ± 0.01 kpc⁻¹, with bluer colours (lower metallicity) at higher distances from the plane. This is, however, fully dominated by the gradient in the outer regions of the thick disc, at distances larger than about 14 kpc from the centre along the major axis. The inner thick-disc metallicity distribution is consistent with no gradient, similar to what is observed for MW thick-disc stars (Gilmore et al. 1995), and suspected for other spiral galaxies from their vertical colour gradients. In the radial direction, data are consistent with no colour gradient, but with strong variations 1σ = 0.13 mag around the mean colour of (V − I)ₜₜₜₜ = 1.65. The overall metallicity distribution of the thick-disc stars peaks around [Fe/H] = −0.9 dex has the mean of [Fe/H] = −1.1 dex with a 1σ scatter of 0.34 dex. The MDFs of thick-disc stars do not show any significant variation in either the vertical direction or along the major axis.

A difference between the MW and NGC 891 is provided by the significantly different vertical variations of stellar metallicity distributions at solar-circle-like locations. In NGC 891, there is a lack of a significant metal-poor component at high distances above the plane, i.e. Z ≳ 3 kpc, that could be compared to the metal-poor MW halo. As concluded in Paper I for regions at Z ≳ 10 kpc, the extraplanar stellar populations at lower heights from the disc of NGC 891 are more chemically enriched than those at similar locations in the MW. The presence of a significant scatter of thick-disc stellar metallicities along the vertical and the radial directions might indicate that the observed difference could be due to a large accretion that has affected the properties of stars over the entire surveyed area.

A metallicity gradient is detected for the spheroid changing from [Fe/H] = −1.15 dex in the inner regions to −1.27 dex in the outermost halo regions, with a large scatter around the mean metallicities of ∼0.35 dex throughout. The inner spheroid and the halo component up to about 12r_eff shows remarkable similarity in structure and stellar populations, with quite high average metallicity for the halo.

ACKNOWLEDGMENTS

This work was based on observations with the NASA/ESA HST, obtained at the STScI, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. We thank Andy Dolphin for suggestions regarding DOLPHOT data reduction package and Tom Oosterloo for providing his high-resolution deep H I map of the galaxy.

REFERENCES

Anderson J., 2006, in Koekemoer A. M., Goudfrooij P., Dressel L. L., eds, The 2005 HST Calibration Workshop: Hubble After the Transition to Two-Gyro Mode Empirical PSFs and Distortion in the WFC Camera, NASA, Greenbelt, MD, p. 11
Ashman K. M., Bird C. M., Zept S. E., 1994, AJ, 108, 2348
Bensby T., Feltzing S., Lundström I., 2003, A&A, 410, 527
Bensby T., Zenn A. R., Oey M. S., Feltzing S., 2007, ApJ, 663, L13
Brook C. B., Kawata D., Gibson B. K., Freeman K. C., 2004, ApJ, 612, 894
Brook C. B., Gibson B. K., Martel H., Kawata D., 2005, ApJ, 630, 298
Burkert A., Truran J. W., Hensler G., 1992, ApJ, 391, 651
Carollo et al. 2007., Nat, 450, 1020
Chapman S. C., Ibata R., Lewis G. F., Ferguson A. M. N., Irwin M., Macconnachie A., Tanvir N., 2006, ApJ, 653, 255
Dalcanton J. J., Bernstein R. A., 2002, AJ, 124, 1328
de Jong R. S., 2008, MNRAS, 388, 1521
Dolphin A. E., 2000, PASP, 112, 1383
Dolphin A. E., 2005, DOLPHOT User’s Guide (http://purcell.as.arizona.edu/dolphot/dolphot.ps.gz)
Durrell P. R., Harris W. E., Pritchet C. J., 2001, AJ, 121, 2557
Durrell P. R., Harris W. E., Pritchet C. J., 2004, AJ, 128, 260
Eggen O. J., Lynden-Bell D., Sandage A. R., 1962, ApJ, 136, 748
Ferguson A. M. N., Irwin M. J., Ibata R. A., Lewis G. F., Tanvir N. R., 2002, AJ, 124, 1452
Fleming D. E. B., Harris W. E., Pritchet C. J., Hanes D. A., 1995, AJ, 109, 1044
Freeman K., Bland-Hawthorn J., 2002, ARA&A, 40, 487
Fuhrmann K., 2004, Astron. Nachr., 325, 3
Fuhrmann K., 2008, MNRAS, 384, 173
García-Burillo S., Guelin M., Cernicharo J., Dahlem M., 1992, A&A, 266, 21
Gilmore G., Reid N., 1983, MNRAS, 202, 1025
Gilmore G., Wyse R. F. G., Jones J. B., 1995, AJ, 109, 1095
Harris G. L. H., Harris W. E., Poole G. B., 1999, AJ, 117, 855
Harris W. E., Harris G. L. H., Layden A. C., Wehner E. M. H., 2007, ApJ, 666, 903
Harris W. E., Mouhcine M., Rejkuba M., Ibata R., 2009, MNRAS, 395, 436
Helmi A., 2008, A&A, 15, 145

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 396, 1231–1246
Helmi A., White S. D. M., de Zeeuw P. T., Zhao H., 1999, Nat, 402, 53
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nat, 370, 194
Ibata R., Irwin M., Lewis G., Ferguson A. M. N., Tanvir N., 2001, Nat, 412, 49
Ibata R. A., Irwin M. J., Lewis G. F., Ferguson A. M. N., Tanvir N., 2003, MNRAS, 340, L21
Ibata R., Mouhcine M., Rejkuba M., 2009, MNRAS, 395, 126 (Paper III)
Ivezić Ž. et al., 2008, ApJ, 684, 287
Jurić M. et al., 2008, ApJ, 673, 864
Kalirai J. S. et al., 2006, ApJ, 648, 389
Kamphuis P., Holwerda B. W., Allen R. J., Peletier R. F., van der Kruit P. C., 2007, A&A, 471, L1
Koekemoer A. M., Fruchter A. S., Hook R. N., Hack W., 2002, in Arribas S., Koekemoer A., Whitmore B., eds, The 2002 HST Calibration Workshop: MultiDrizzle: An Integrated Pyraf Script for Registering, Cleaning and Combining Images. Space Telescope Sci. Inst., Baltimore, MD, p. 337
Kregel M., van der Kruit P. C., 2005, MNRAS, 358, 481
Martin N. F., Ibata R. A., Bellazzini M., Irwin M. J., Lewis G. F., Dehnen W., 2004, MNRAS, 348, 12
Morrison H. L., Flynn C., Freeman K. C., 1990, AJ, 100, 1191
Morrison H. L., Miller E. D., Harding P., Stinebring D. R., Boroson T. A., 1997, AJ, 113, 2061
Mouhcine M., 2006, ApJ, 652, 277
Mouhcine M., Rich R. M., Ferguson H. C., Brown T. M., Smith T. E., 2005, ApJ, 633, 828
Mouhcine M., Rejkuba M., Ibata R., 2007, MNRAS, 381, 873 (Paper I)
Mould J., 2005, AJ, 129, 698
Norris J., 1987, ApJ, 314, 357
Oosterloo T., Fraternali F., Sancisi R., 2007, AJ, 134, 1019
Pietrinferni A., Cassisi S., Salaris M., Castelli F., 2004, ApJ, 612, 168
Rachford B. L. et al., 2009, ApJS, 180, 125
Rejkuba M., Greggio L., Harris W. E., Harris G. L. H., Peng E. W., 2005, ApJ, 631, 262
Renzini A., 1998, AJ, 115, 2459
Riess A., 2003, ACS ISR 2003-09
Robin A. C., Reylé C., Derrière S., Picaud S., 2003, A&A, 409, 523
Ryan S. G., Norris J. E., 1991, AJ, 101, 1835
Sancisi R., Fraternali F., Oosterloo T., van der Hulst T., 2008, A&A, 15, 189
Saviane I., Rosenberg A., Piotto G., Aparicio A., 2000, A&A, 355, 966
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Scoville N. Z., Thakkar D., Carlstrom J. E., Sargent A. I., 1993, ApJ, 404, L59
Searle L., Zinn R., 1978, ApJ, 225, 357
Seth A. C., Dalcanton J. J., de Jong R. S., 2005a, AJ, 129, 1331
Seth A. C., Dalcanton J. J., de Jong R. S., 2005b, AJ, 130, 1574
Sirianni M. et al., 2005, PASP, 117, 1049
Tikhonov N. A., Galazutdinova O. A., 2005, Astrophys., 48, 221
van der Kruit P. C., 1984, A&A, 140, 470
VandenBerg D. A., Bergbusch P. A., Dowler P. D., 2006, ApJS, 162, 375
Yanny B. et al., 2003, ApJ, 588, 824
Yoachim P., Dalcanton J. J., 2005, ApJ, 624, 701
Zibetti S., Ferguson A. M. N., 2004, MNRAS, 352, L6
Zibetti S., White S. D. M., Brinkmann J., 2004, MNRAS, 347, 556
Zoccali M. et al., 2003, A&A, 399, 931

SUPPORTING INFORMATION
Additional Supporting Information may be found in the online version of this article.

Table 2. Astrophotometric catalogue.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting material supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TeX/LaTeX file prepared by the author.