On the stellar populations in NGC 185 and NGC 205, and the nuclear star cluster in NGC 205 from *Hubble Space Telescope* observations

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ABSTRACT

We present the first detailed analysis of resolved stellar populations in the dwarf galaxies NGC 185 and NGC 205 based on archival V- and I-band WFPC2 pointings.

For NGC 185 we deduce from the brightest main sequence and blue loop stars that star formation was probably still active about $4 \times 10^8$ yr ago; and have three key abundance-related results: (1) We identify ancient stars with $[\text{Fe/H}] \lesssim -1.5$ dex by a well-defined horizontal branch (HB). (2) We find a prominent clump/bump-like feature along the red giant branch/faint asymptotic giant branch (RGB/faint AGB) with the same mean V-band magnitude as in the HB, within uncertainties (i.e., $\Delta V(\text{Bump} - \text{HB}) = 0$); from a comparison with theory, the implication is that ancient stars have $[\text{Fe/H}] \sim -1.5$ dex, with a higher abundance level for intermediate-age stars. (3) From colour information we infer that median $[\text{Fe/H}] > -1.11 \pm 0.08$ dex for ancient stars (assuming $E(\text{B-V}) = 0.18$ mag).

For NGC 205, we record a new distance modulus, $(m-M)_0 = 24.76 \pm 0.1$ mag, taking $E(\text{B-V}) = 0.11$ mag, based on the red giant branch (RGB) tip magnitude method in I-band. We find that stars were probably still forming less than $3 \times 10^8$ yr ago in NGC 205, which is compatible with star formation triggered by an interaction with M31. Three key abundance-related results for NGC 205 are: (1) The red giant/faint-asymptotic giant branch is significantly skewed to redder values than that of a control field in the outskirts of M31; it probably results from a relatively narrow metallicity and or age range for a significant fraction of the dwarf’s stars. (2) From a comparison with models, the most metal-rich RGB stars reach to $[\text{Fe/H}] \gtrsim -0.7$ dex ($\gtrsim 0.2 Z_\odot$). (3) For ancient stars we infer from colour information that median $[\text{Fe/H}] > -1.06 \pm 0.04$ dex (for $E(\text{B-V}) = -1.11 \pm 0.08$ dex).
0.11 mag). We briefly compare the stellar populations of NGC 205, NGC 185 and NGC 147.

Finally, we study several V- and R-band structural properties of the nuclear star cluster in NGC 205 for the first time: The apparent V-/R-band effective radii indicate a blue excess in the cluster’s outer region. In terms of size, the cluster is like a typical galactic globular cluster or a nuclear cluster in a nearby late-type spiral galaxy; but it is quite bright \(10^6 L_{\odot} \), unlike an ancient globular cluster, and by matching with models, the blue colour hints that its stellar population is young, up to a few times \(10^8\) yr old.

Subject headings: galaxies: dwarf – galaxies: evolution – galaxies: individual (NGC 185, NGC 205, NGC 147) - galaxies: photometry – Local Group

1. Introduction

Successive merging and accretion of many comparatively small stellar systems like dwarf galaxies, as well as intergalactic gas, is an important part of the theoretical framework in which large (disk) galaxies are predicted to have formed (e.g., White & Rees 1978; Steinmetz & Muller 1995). Significantly, studies of resolved stars in dwarf companions ultimately allow one to explore two paired issues, namely giant galaxy assembly as well as the star formation history of dwarfs, which describes the gradual conversion of gas into stars, followed by the expulsion of remaining gas by stellar winds and the resultant heating and cooling of the interstellar medium.

Since Baade (1944a, 1944b) first succeeded in resolving the brightest stars of several dwarf elliptical (dE) satellites of the giant spiral galaxy Andromeda, those galaxies have been regarded as simple, old stellar systems, with a stellar content resembling that of Galactic globular clusters (Population II). From the mid-1990s onward however the impressive improvement in the quality of colour-magnitude diagrams (CMDs) for nearby dE galaxies provided by the HST has revealed that those “simple” galaxies often display varied, and in some cases, complex star formation histories (SFHs) (Da Costa 1998; Mateo 1998). However, it remains unclear whether the Andromeda dE companions (NGC 205, NGC 147 and NGC

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\(^1\)Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.
185) have had significant star formation episodes since the primeval event (see Da Costa 1998 for a recent review).

The existence of a dozen luminous blue stars (Baade 1944a) and other Population I features (dust clouds, HI gas, SN remnant) at the centre of NGC 185 has been an intriguing feature of this galaxy for several decades because such galaxy building blocks had been alleged to have been depleted at earlier formation epochs in elliptical galaxies. This recent star formation epoch is confined to its central $150 \times 90$ pc, where the youngest, 100 Myr old, population is found (Hodge 1963; Lee, Freedman & Madore 1993; Martinez-Delgado, Aparicio & Gallart 1999, hereafter MD99). In NGC 147 however, there are no signs of recent star formation (in the past 1 Gyr) or gas at its centre (Han et al. 1997; Young & Lo 1997; Sage, Welch & Mitchell 1998). Thus, this difference between NGC 185 and NGC 147 is intriguing because otherwise they are similar in many of their properties (e.g. type, mass, size). Similarly, NGC 205 has been regarded as an unusual dE galaxy – it has gas (Johnson & Gottesman 1983; Young & Lo 1997) and a young central stellar population (Baade 1944b; Lee 1996), and many of the brightest objects have recently been resolved into groups of UV-bright stars (Cappellari et al. 1999). So, why do the recent (< 1 Gyr) SFHs of Andromeda’s dE companions differ?

A natural way to probe this issue is to search for an intermediate-age (1-10 Gyr) population in these galaxies. The first evidence of such a population in these galaxies was the presence of stars above the tip of the red giant branch (TRGB) in CMDs from ground-based observations of their inner regions (NGC 205: Lee 1996; NGC 185: Lee et al. 1993, Martinez-Delgado & Aparicio 1998, hereafter MDA98; and NGC 147: Davidge 1994) and have been interpreted as intermediate-age AGB stars by several authors (Davidge 1994; Lee et al. 1993; Lee 1996). However, ground-based observations can lead to severe central crowding, making RGB stars appear brighter than they are, mimicking an intermediate-age AGB population (Martinez-Delgado & Aparicio 1997).

Two other paired issues are the origin and possible stripping of the gas from which young stars are born in such galaxies. One could view the concentration of young stars lying in the central part of NGC 185 and NGC 205 as a hint that new stars could originate from material ejected by dying stars and that this process would only be efficient enough at the center of the galaxies. This would suggest an internal origin for the gas in these systems, as was argued by Faber & Gallagher (1976). However, Young & Lo (1997) find different scenarios for the three Andromeda dE satellites: no gas in NGC 147 ($M_{\text{HI}}/L_V \lesssim 4 \times 10^{-5} M_\odot/L_\odot$); gas with a different angular momentum per unit mass to the stars in $^2$MH/L data is taken from from Grebel, Gallagher & Harbeck (2003; their Table 1)
NGC 205 ($M_{HI}/L_V \sim 1 \times 10^{-3} M_\odot/L_\odot$); and gas kinematically compatible with that of the stellar component in NGC 185 ($M_{HI}/L_V \sim 1 \times 10^{-3} M_\odot/L_\odot$). Although several theories (e.g. external origin: Knapp et al. 1985; ram-pressure stripping: Lin & Faber 1983; or different initial conditions – (e.g., gas number density and gas mass): Hensler & Burkert 1989) have been proposed to explain this puzzling situation in dwarf galaxies, the exact origin of the current inner region differences remains a mystery.

In the present paper, we draw on a new colour magnitude diagram–based analysis of resolved stellar populations in NGC 205 and NGC 185 to take a new look at their ages and abundances. We re-analyze NGC 147 data for comparative purposes.

The layout of the present paper is as follows. The data and data reduction are described in Sec. 2. Extinction is assessed briefly in Sec. 3 and an overview of the stellar content based on an inspection of our colour magnitude diagrams is given in Sec. 4. We infer the distance modulus and [Fe/H] in Sec. 5. Abundance distributions are probed in Sec. 6, and we make a comparison with previous studies and a control field in Sec. 7. In Sec. 8, we briefly discuss the possible nature of the red clump/bump feature in NGC 185. Results concerning young-to-intermediate–age stars are reported in Sec. 9. In addition, as NGC 205 offers an opportunity to study a bona fide nucleated dwarf satellite in our neighbourhood we report several newly studied properties of its central compact star cluster and comment briefly on NGC 205 in the context of tidal stripping (Sec. 10). Finally, we discuss briefly the nature of NGC 205 in Sec. 11 and summarize our main conclusions in Sec. 12.

### 2. Data and data reduction

In the present study of NGC 185 and NGC 205 (and NGC 147), calibrated science- and data-quality images have been retrieved from the Space Telescope Science Institute HST data archive. I (F814W)- and V (F555W)-band frames from selected HST/WFPC2 pointings has been examined. For our study of the nuclear star cluster in NGC 205 we retrieved V(F555W)- and R (F675W)-band frames. Source information is given in Table 1; and relative positions of WFPC2 footprints can be seen in Fig. 12.1.

For the data reduction, the following strategy has been applied. Photometry of the stars was determined using the HSTphot (Dolphin 2000a) point spread function (PSF)-fitting photometry package which is designed for optimal reduction and analysis of WFPC2 data. Stellar magnitudes are calibrated by HSTphot using the charge transfer efficiency and zero point magnitude corrections derived by Dolphin (2000b) and are transformed into the V- and I-band passes. Lastly, artificial star tests identical to those described in Butler,
Martinez-Delgado & Brandner (2004) have been performed using HSTphot.

Fig. 2 plots the completeness function against magnitude for each pointing: The completeness functions are the number of artificial stars recovered divided by the number of input stars. A completeness plateau generally occurs for the brightest stars because their signal-to-noise is sufficiently high and crowding affects these stars equally. A completeness of 100% is typically not reached because of bad pixels\(^3\). In those frames containing one or more prominent star clusters, an over-detection of bright stars at bright magnitudes occurs due to the so-called bin-shifting effect – some faint artificial stars have blended with stars from the star cluster(s), and have been detected as brighter stars.

For the final photometry list used in this study, objects have been selected if flagged as valid stars for both band-passes and have \(S/N > 5\); \(\chi^2 < 7\); \(-0.5 < \text{sharpness} < 0.5\); and \(\sigma_{V,I} < 0.25\, \text{mag}\). The number of stars in each field after selection is given in Table 1.

### 3. Extinction

Knowledge of the extinction towards stars is a basic necessity for determining their distances, masses, chemical compositions and ages. For an upper limit on the extinction from M31’s dust clouds in front of NGC 205, plus foreground extinction due to the Galaxy, we recall that extinction in several outer disk fields in M31 has been estimated to be of the order of \(E(B-V) = 0.13\, \text{mag}\) (e.g., Hodge & Lee 1988; Bellazzini et al. 2003 / BCF03) with a dispersion in their values of about 25%. For an estimate of the foreground extinction alone, towards M31/NGC 205, we adopt \(E(B-V) = 0.086\, \text{mag}\) from the Schlegel, Finkbeiner & Davis (1998; SF98) dust maps.\(^4\) As NGC 205 is behind M31 (e.g. Sec. 5.2) with a projected location at the far outer edge of M31, one might presume \(E(B-V) < 0.13\, \text{mag}\), i.e., smaller than values measured using outer disk stars of M31. As a reasonable compromise, we adopt the average of extinction data for the M31 outer disk and the SFD98 value, namely \(E(B-V) = 0.11\, \text{mag}\), and assume the Galactic reddening law with \(A_V = 3.1 \times E(B-V)\) and \(A_I/A_V = 0.48\) (Cardelli, Clayton & Mathias 1989).

A further issue is the internal extinction in NGC 205. About a dozen dust patches in the

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\(^3\)The number of pixels deemed to be bad in the unvignetted portion of each chip/frame is of the order of 1% (includes cosmic ray events; also includes columns and pixels flagged as bad in the STScI data quality file).

\(^4\)M31 has strong far-IR emission in its spiral arms, which could potentially contaminate a dust map, but it was excised before SFD98 generated their final dust map.
central 1-2' have been catalogued, the largest of which points toward differential extinction values of up to about 0.4 mag in V-band (Hodge 1973). Those patches occupy about 5% of the F4 field, and their effect on results in the present paper is minor as determined by repeated tests in which photometry from 5% of each field was dimmed, conservatively, by 0.3 mag – the resulting systematic change in RGB/faint-AGB colours is up to 0.02 mag or 0.01 mag in distance modulus with a negligible change in [Fe/H]. However, there remains the possibility of systematic errors with a similar order of magnitude due to a larger area being affected by a smaller level of extinction (e.g. 0.05 mag).

For NGC 185 and NGC 147, foreground extinction estimates from SFD98 are E(B-V) = 0.184 mag and 0.173 mag respectively. However, NGC 185 and NGC 147 are located closer to the galactic plane (b ≈ -14.5°) than NGC 205 (b ≈ -21°), and so, it is important to be aware of the possibility of significant inaccuracy in SFD98 extinction estimates towards low galactic latitudes that has yet to be established (for |b| < 10° at least; see SFD98). It is however rather encouraging that the above-mentioned extinction estimate from SFD98 for NGC 185 is in very good agreement with the result of a direct measurement of the stellar colour excess, i.e. E(B-V) = 0.19±0.03 mag (Lee et al. 1993). Extinction data from SFD98 is given for each galaxy in Table 2.

4. Stellar content from colour-magnitude diagrams

Figs. 3 and 4 show the (I, V-I) CMD at each pointing in NGC 185 and NGC 205 respectively. They display the brightest 5-6 mag of the RGB/faint-AGB sequence and give information on the stellar content therein.

In NGC 185, the fields in general look very similar. The most prominent feature is the RGB-like structure, the upper two magnitudes of which is very similar to that found by MDA98 in a low spatial resolution study of NGC 185. This structure is typical of a galaxy that clearly comprises a mixed stellar population: It is the locus of old and intermediate-age RGB stars, as well as faint AGB stars. There is a prominent red clump-like feature at a similar V-band magnitude to the red-end of the horizontal branch (HB) described below; and we discuss the clump later in Sec. 8. A significant number of bright red stars occur above the I-band discontinuity that marks the top of the RGB: They could be intermediate-age AGB stars covering a moderate range of ages and metallicities, and are discussed further in Sec. 9. There is clear evidence for blue and red horizontal branch (HB) stars at 0.2 < V-I (mag) < 0.6, characteristic of an ancient population of metal poor stars with [Fe/H] < -1.5 dex. This is the first direct evidence for such a population in this galaxy (also see Geisler et al. 1999). There are stars surrounding the HB at V-I < 0.5 mag, for example, that could
comprise main sequence stars, blue loop stars as well as a foreground population of stars; and those will be discussed further using isochrones in Sec. 9.\textsuperscript{5}

In NGC 205, somewhat like NGC 185, there is a prominent sequence of RGB/faint-AGB stars, similar to that presented by Lee (1996). That upper sequence does not appear to have a homogeneous colour distribution at a given I-band magnitude, which we detail in Sec. 6. We fail to detect evidence for, or against, a HB in the central region due to the magnitude limit of the photometry. However, there is an increased density of stars at about I = 24.5-25.5, V-I \lesssim 0.6 \text{ mag}, the location where a HB might be expected in outer fields (F2 and F1), because crowding-noise is less there, but contamination from the stars in M31’s halo is more likely, as detailed later below. There is also a scatter of stars redward of the RGB/faint-AGB (V-I \gtrsim 3); they could be very metal-rich stars that belong to M31 and are briefly mentioned later in Sec. 7. Lastly, the NGC 205 CMDs contain several bright, blue stars (at I \lesssim 23, (V-I) < 1) that are probably mostly main sequence and blue loop stars; they are examined further in Sec. 9.

For an analysis of how much the NGC 205 CMDs are contaminated by M31 stars, we used a B-band isopleth map of NGC 205 (with an elliptically averaged surface brightness profile of M31 subtracted; Fig. 9 of Ferguson et al. 2002) and minor axis surface brightness data for M31 from Walterbos & Kennicutt (1988; WK88). It follows that 16-40\% of the brightest stars (probably field stars, upper MS/blue loop stars and upper AGB/RGB stars) across the F1 field belong to M31. Adopting that level of contamination, we would implicitly assume the same age and chemical composition for NGC 205 and the halo of M31, and we therefore made a different check: Applying our selection criteria, detailed in Sec. 2, to photometry from Bellazzini et al. (2003) for a nearby field\textsuperscript{6} (G58), we found 1193 stars at I < 22.5 \text{ mag}. Scaling that number for NGC 205, where the M31 halo is approximately 1.5 \text{ mag arcsec}^{-2} \text{ fainter}, the estimated contamination is in good agreement with the previous estimate of 16-40\%; and can be applied for AGB/RGB stars at I < 22.5 \text{ mag}. Changing now to the F2 field, the contamination level should be below 1\%, which is negligible, and even less for the remaining fields which are closer to the nucleus of NGC 205. Additional evidence that contamination from M31 stars decreases towards NGC 205 comes from the blue plume or upper main sequence population in M31: I.e., compare the blue plume in fields G58, G64 and G108 from BCF03. We note that about half a dozen bright, blue stars occur at V-I < 1 \text{ mag} and 20 < I (\text{mag}) < 21 in each NGC 205 field – they may well be foreground stars, even

\textsuperscript{5}It is however interesting to compare the observed morphology with the prediction of MD99 (their Fig. 16), which is similar

\textsuperscript{6}G58 is 11.2′ distant from NGC 205 and lies between NGC 205 and M31.
though inspection of nearby (control) fields, G58 and G64 (see Fig. 5 & 6 in BCF03), argues for a negligible surface density of foreground stars. Alternately, they might be members of NGC 205, but that interpretation is disfavoured in Sec. 9.

For NGC 185 and NGC 147, the surface density of (unobscured) field stars (and point-like field galaxies) along the line of sight is taken to be 65±8 and 70±8 stars respectively per WFPC2 pointing at $I \lesssim 22.2$ mag and dominated by stars redder than about R-I =0.4 mag (Battinelli & Demers 2004a, 2004b). Their surface density is such that they are unlikely to have a significant effect on our distance/abundance measurements later. As we consider the population of MS and blue-loop stars later, we note that some contamination by field stars at R-I < 0.4 mag is possible, but the level should be negligible (<< few percent of the field surface densities given above) on average based on an inspection of the CMDs from the Battinelli & Demers wide-field study. The number of contaminating field galaxies was estimated to be 23±5 per WFPC2 pointing at $20 < I (\text{mag}) < 22$ from the Medium Deep Survey (Griffiths et al. 1994), which is an unlikely source of significant contamination that was not assessed by the artificial star tests.

5. Median abundances and distances

In the absence of star-to-star abundance information from spectroscopic measurements, popular ways to measure distances and to infer [Fe/H] values for ancient stars in Local Group galaxies have included the RGB method, the horizontal branch (HB) V-band magnitude, RR Lyrae stars, and the turn-off magnitude of main sequence stars. We consider the first two of these. Such diagnostic tools have, necessarily, been calibrated using ancient stellar populations (galactic globular clusters; GGCs); and are thus best applied to a single stellar population of similar ancient age (e.g. 13 Gyr). Clearly, our photometry does not sample such simple stellar populations but for NGC 185 and NGC 147 there is evidence that their stellar populations are mostly ancient, with a small intermediate-age component – see MD99 (NGC 185) and Han et al. (1997; NGC 147). For NGC 205 however we are less certain because of the possibility of a significant fraction of intermediate-age stars.

On the reliability of the absolute magnitude-abundance relation for the HB, on which the HB method relies, we recall the relation is controversial in the literature (e.g. see Caputo 1997, and references therein) due to the dependence of $M_V$(RR Lyrae) on the composition and evolutionary phase of the variable star. That leads to a possible range in [Fe/H] of the order of 0.2 dex for a given absolute V-band magnitude. Despite this caveat, there is an advantage to using both the HB magnitude method together with the RGB method, namely that in stellar systems dominated by ancient stars with similar abundance levels, one
would expect an agreement, within uncertainties, between the two methods. Based upon
the hypothesis that the RGB is dominated by ancient stars with similar abundance levels to
those of the HB stars, we will make a comparison of the inferred abundance estimates.

5.1. Lower $[\text{Fe/H}]$ limits

In the present paper, when we refer to stellar abundance (or metallicity), we are referring
to $[\text{Fe/H}]$ as inferred from the colour $((V-I)_0)$ at a certain absolute I-band magnitude for
ancient stellar populations. In this way, we are making an inference of the metallicity of
ancient RGB stars, using an approach that can be applied to other stellar systems. A key
concern however is the so-called age-metallicity degeneracy in stellar populations comprising
ancient and intermediate-age stars. The trouble is that evolved (i.e., post-main sequence)
stars that are between about one and a few times $10^9$ yr old evolve along the blue side of
the RGB causing the inferred median (or mean) colour to be bluer than that of the ancient
RGB stars. We use the median colour as opposed to the mean value as the median is
a more reliable tracer of the predominant colour when the colour distribution is skewed
– otherwise the median and mean values are identical. However, whichever of these two
statistics is used, an inferred (mean/median) $[\text{Fe/H}]$ value will under-estimate the actual
$[\text{Fe/H}]$ of ancient RGB stars, and so our photometric abundance is taken as a lower limit
as is done implicitly in other studies that determine photometric abundances (see Grebel,
Gallagher & Harbeck 2003). Photometric abundances are useful because they are available
for a wide range of systems, thereby allowing them to be compared. For example, see Grebel,
Gallagher & Harbeck 2003, their section 2.1, for a useful comparison of nearby dwarf galaxy
properties.

5.2. Applied methods and results

For the RGB-tip indicator of distance and $[\text{Fe/H}]$, one requires a knowledge of the
tip I-band magnitude of the RGB, $I_{\text{TRGB}}$, and its uncertainty. In the case of NGC 205,
we estimated $I_{\text{TRGB}}$ by applying a slightly modified version of the edge-detection method
described by Sakai et al. (1996). I.e., we evaluated the edge-detection response at fine
intervals ($<10^{-3}$ mag) followed by smoothing using a 0.05 mag-wide moving-average window
and recorded the peak response in a restricted magnitude range ($I<21$ mag). That was
repeated a few hundred times in a bootstrap way\(^7\) to measure the average tip magnitude and its uncertainty. For the inner two fields combined, we found \(I_{\text{TRGB}} = 20.85 \pm 0.1\) mag where the uncertainty includes a conservative error to account for the probable slight bias introduced by the smoothing process. For NGC 185 and NGC 147, we could not accurately identify the RGB tip magnitude using the edge-detection approach using individual fields as there are too few stars, making the RGB tip poorly defined. Using the ensemble data for NGC 185, but restricting the edge detection to \(I < 20.5\), we find \(I_{\text{TRGB}} = 20.4 \pm 0.1\) mag which is close to the value from Nowotny et al. (2003; NK03) – one obtains \(I_{\text{TRGB}} = 20.31\) mag for NGC 185 from their data. However, as their detection criterion is much better, owing to significantly more stars, we adopt their value, which agrees with previous estimates in the literature (Lee et al. 1993; MDA98; NGC 185). For NGC 147, we deduce that there are too few stars at \(I < 21\) mag to allow an accurate measurement using the edge detection method; and so, we adopt \(I_{\text{TRGB}} = 20.70\) mag taken from the NK03 – incidentally, that \(I_{\text{TRGB}}\) value is in good agreement with the estimate by Han et al. (1997) that was based on visual inspection of the I-band luminosity, using the same WFPC2 dataset retrieved for the present paper. The (median) colour of the RGB/faint-AGB sequence at \(M_{I,-3.5}\) could then be measured. Derived (median) \((V-I)_{\text{TRGB,0}}\) data as well as the inferred \([\text{Fe/H}]\) and distance modulus values, using the RGB-[\text{Fe/H}] relation (Lee et al. 1993; see below), and the RGB magnitude and colour ranges detailed below are given in Table 3.

For the (V,(HB)) method of \([\text{Fe/H}]\) and distance estimation, the relevant relations are (a) the \(M_V-[\text{Fe/H}]\) relation for the HB at the location of the RR Lyrae star instability strip, i.e., \(M_V = 0.17[\text{Fe/H}] + 0.82\) (Lee et al. 1993) and (b) the empirical calibration relating the de-reddened RGB V-I colour at \(M_{I,0} = -3.5\) mag ((V-I)\(_{0,-3.5}\)) to \([\text{Fe/H}]\) i.e., \([\text{Fe/H}] = -12.64 + 12.61 (V-I)_{0,-3.5} - 3.33 (V-I)^2_{0,-3.5}\) (Lee et al. 1993); the relation is valid for \(-2.2<[\text{Fe/H}]<-0.7\) dex. We recall that \((m-M)_0 = I_{\text{TRGB}} + BC_I - M_{\text{bol,TRGB}} - A_I\), where \(BC_I\) is the bolometric correction to the I-band magnitude, and \(M_{\text{bol,TRGB}}\) is the bolometric magnitude of the RGB tip magnitude. Following Da Costa & Armandroff (1990), we take \(BC_I = 0.881 - 0.243 (V-I)_{\text{TRGB}}\) and \(M_{\text{bol,TRGB}} = -0.19[\text{Fe/H}] - 3.81\). We obtained median RGB colours and uncertainty values using the previously mentioned bootstrap approach in the \(M_I\) range -3.3 to -3.7 mag ((V-I)\(_{0,-3.5}\)) and -4.1 to -3.95 mag ((V-I)\(_{\text{TRGB}}\))). Similarly, we measured the HB V-band magnitude and its uncertainty for stars at \(24.5 < V(\text{mag}) < 25.7\) and \(0.2 < V-I\) (mag) < 0.7. We then solved for the distance modulus and \([\text{Fe/H}]\) in an iterative way that is approximately self-consistent because both relations used are calibrated

\(^7\)85\% of the stars are selected randomly and the median value taken. This is repeated a few hundred times, followed by a gaussian fit to the resulting distribution of values. The peak of the fit is taken as the average median value while its standard deviation is taken as the uncertainty.
against ancient simple stellar populations (galactic globular clusters) – the systematic error arising from the [Fe/H] matching tolerance is ±0.025 dex. In order to estimate the (random) uncertainty in the derived [Fe/H] value, the iterative procedure was re-run using $V(HB) + \sigma_{V(HB)}$ and again using $V(HB) - \sigma_{V(HB)}$. The final [Fe/H] value, the derived distance modulus, the $V(HB)$ magnitude and their uncertainties are given in Table 4 for NGC 185 and NGC 147. Such measurements for the F1 field in NGC 205 are precluded by a poorly defined HB.

Comparing our distance (and [Fe/H]) data from the two methods we applied, there is a good agreement for NGC 185. As we adopted the TRGB I-band magnitude data from NK03, it is not surprising that the derived distance modulus is in excellent agreement with their value, 24.04 mag, also determined using colour information. Our [Fe/H] lower limit for NGC 185, -1.11±0.08 dex, derived using the $V(HB)$ method (Table 4), is consistent with that from MDA98, as well as their report of an outward radial decrease in [Fe/H]; but is insufficient to confirm it. However, there is a marked discrepancy between the NK03 finding of -0.89 dex for NGC 185 and our value that can be explained by a mis-match between the foreground extinction adopted by NK03 ($A_V=0.48$ mag) and our value ($A_V=0.57$ mag, from SFD98): That extinction difference causes their value to be systematically more metal-rich than our finding, by about 0.2 dex.

For NGC 147 the $V(HB)$ method provides a distance modulus estimate that is markedly bigger by 0.1 mag than the value from the RGB method which relies on the TRGB magnitude from NK03 and is significantly different to their high signal-to-noise estimate of 24.44 mag based on the RGB tip magnitude method; and could be hinting that the dominant population on the RGB/faint-AGB is not ancient and / or is more metal-rich than the HB stars. As expected, our [Fe/H] data from the RGB method is in fine agreement with that of Han et al. (1997) and agrees well with the finding of NK03 (-1.11 dex) and Mould, Kristian & Da Costa (1983), each of whom also used colour information.

Our distance modulus calculation for NGC 205 leads to $(m-M)_0=24.76±0.1$ mag (for $E(B-V)=0.11$ mag) which would place NGC 205 farther behind M31 than previously estimated in the literature, e.g. Grebel et al. (2003) and references therein. Lastly, our inferred [Fe/H] lower limit is -1.06±0.04 dex from the RGB method, which is markedly more metal-poor than the Mould, Kristian & Da Costa (1984) inference that was based on RGB colour information from seeing-limited data ([Fe/H] > -0.85±0.2 dex). Just like the discrepancy we found for NGC 185 between our [Fe/H] value NK03 result, mentioned above, a probable cause is a systematic under-estimation of foreground extinction by about ($A_V=0.1$ mag by Mould et al. (they assumed $A_V=0.23$ mag).

Lastly, it is worth remembering that if future reddening maps with higher spatial resolu-
tion than that of the SFD98 maps (6.1 arcmin) find that SFD98 underestimates extinction at our WFPC2 pointings (FoV~2.5 arcmin), our inferred photometric abundance data should be shifted to lower abundances values (e.g., using the Lee et al. 1993 [Fe/H]_{pho}–RGB relation).

6. Abundance distributions from colour information

In the previous section, one of the relations we used to infer abundances is the often employed empirical RGB-[Fe/H] relation that is calibrated using ancient RGB stars, to infer a photometric abundance for the stars in each field. In the present section, we examine the distribution of abundances in each field, and in order to be able to check the effect of a wide age range in a homogeneous way, we use model RGB-[Fe/H] relations by employing a code to generate synthetic CMDs. As one does not know the actual age distribution of the stars, we adopt a single, mid-range age (10 Gyr), as Worthey et al. (2004) did, and an adequately wide abundance range 0.0001 \leq Z \leq 0.009 (~-2.3 to -0.30 dex) – spreading age uniformly in a wide range (e.g. 5-15 Gyr) causes the inferred abundance distribution to widen by about \pm 0.2 dex, as expected (see Worthey 1994; his Table 6). Incidentally, that age dependence is why the abundances derived later using the synthetic 10 Gyr models (see Table 6) produce [Fe/H] values that are systematically more metal-rich by about 0.1 dex than the mean data derived in Sec. 5 using GGC stars that are a few times 10^9 yr older (see Tables 3 and 4).

The basic idea here is to assign an abundance value to measured giant star colours from a synthetic CMD (10 Gyr, with random Z values from 0.0001 to 0.009) in which realistic photometric scatter is added – giant stars were selected such that -3.9 < M_I (mag) < -3.3 and 0.7 <(V-I)_0 (mag) < 4. Only distributions for two fields in each galaxy are plotted for the sake of clarity (see Fig. 7), but for all fields we give in Table 6 the number of stars per distribution as well as (a) the fraction of stars that are old and metal-poor and or young and metal-rich ([Fe/H]< -1.4 dex) and (b) the fraction that is metal-rich (-1.4 <[Fe/H]< -0.2 dex); the abundance separation at -1.4 dex is an ad hoc value roughly mid-way in the range -0.5 to -2.5 dex.

For a check of the dependence of the inferred metal-rich tail in NGC 205 on a significant

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8Using software from G. Bertelli, and based on a library of stellar evolution tracks (Bertelli et al. 1994). It has been used in numerous studies in the literature, including Butler, Martinez-Delgado & Brandner (2004).

9Taking [Fe/H] = Log(Z/Z_{\odot}) where Z_{\odot} = 0.018.

10That implicitly assumes that metal-richness is higher on average at successive epochs of star formation.
error in extinction (20%, for instance), owing to its proximity to M31, we made a visual inspection of the distribution of stars in the \((M_{\text{K}}, V-K)_0\) CMD, shown in Fig. 8, where the \(K'\)-band photometry is from Davidge (2003). That photometry came from observations under 0.7arcsec seeing at \(r < 1.33'\) (e.g., see his Fig. 8); \(K'\)-band completeness is above 75\% at \(K' \lesssim 18.2\) mag and \(\sigma_{K'} < 0.35\) mag\(^{11}\). Accordingly, with the help of the wide dereddened colour baseline \((V-K)_0\), it follows from visual inspection that even with the sizeable hypothetical extinction error, the metal-rich component of the RGB is probably at least as rich as -0.7 dex.

Another issue is whether there are radial changes in the shapes of inferred distributions, for which one can make use of the skewness parameter listed in Table 6. There is no clear evidence for NGC 185, but NGC 205 becomes systematically redder towards its inner regions. That finding is unlikely to be affected by strong differential extinction, which affects only a small fraction (~5\%) of the central field; but there remains the possibility of a smaller levels of differential extinction (e.g. 0.05 mag) over a wider area. Lastly however, as abundance levels could be higher at successive epochs of star formation there remains the possibility of a correlated spatial variation in stellar ages that might act together to give an RGB/faint-AGB colour roughly independent of position.

On the issue of metal-poor stars, it is hard to make a firm statement regarding the accuracy of a metal-poor tail reaching to \([\text{Fe/H}] < -1.5\) dex without spectroscopic information and or evidence for a HB, simply because stellar ages are unknown. For NGC 185 however we know that at least some of the stars in the metal-poor tail should be ancient because of the presence of a HB reaching to colours as blue as \(V-I \sim 0.1 - 0.2\) mag.

Another issue is the similarity of the distributions. In the case of NGC 205, we determined whether the shape of the control field and NGC 205 distributions differ. We did this by determining the mean skewness and its uncertainty based on the bootstrap approach described earlier in Sec. 5.2 – the derived data is given in Table 6. Based on an application of the Student’s T-statistic to the bootstrap samples, we find that the skewness in the control field (G58) differs significantly from that in any of the NGC 205 fields. As the skewness in NGC 205 is unlikely to be the result of significant contamination from M31 (see Sec. 4), we infer that the RGB/faint-AGB sequence in NGC 205 is significantly redder than that in the control field (G58). The RGB/faint-AGB sequence in NGC 205 is also skewed to redder colours than the sequence in NGC 147 or NGC 185. An exact interpretation for the RGB/faint-AGB sequence NGC 205 is out of reach without modeling using data with a much fainter magnitude limit, but the skewness data hints that a significant fraction of the

\(^{11}\)That data is useful in our study at \(M_{\text{K}} \lesssim -6\) mag only, due to a substantial increase in K-band incompleteness at fainter magnitudes.
RGB/faint-AGB stars occur in a relatively narrow age and or abundance interval compared to the control field.

Finally, we note that skewness varies markedly with radial position in NGC 205, in the sense that the inner region stars are generally redder than the outer region stars; and it is unlikely to be fully attributeable to contamination from M31.

7. Abundances: Comparison with previous studies and a control field

From the poorly defined red-end of the bright AGB, we infer $Z \sim 0.1 Z_\odot$ at $(V-I)_0 \sim 3.5$ mag, with higher abundances likely for redder colours based on synthetic CMDs. For a comparison, the work of Gallagher, Hunter & Mould (1984) suggests that the abundances of the most metal-rich stars in NGC 185 may be less than $1/3$ solar (i.e., $Z \lesssim 1/3 Z_\odot = 0.006$) based on the $N_{\text{II}}/S_{\text{II}}$ ratio for one planetary emission nebula near the centre of NGC 185. Similarly, the mean oxygen abundance $(12 + \log (O/H) = 8.2)$ from several planetary nebulae (PNe) (Richer & Mc Call 1995) is consistent with a system whose most metal-rich stars have about one third of the solar abundance. Consequently, there is rough agreement with our CMD-based finding.

In NGC 205, the reddest pair of AGB stars reach to $(V-I)_0 \sim 4.3$ mag corresponding to $Z \sim 0.0065$, about one third of the solar value. Consequently, abundances in NGC 205 appear to reach to richer values than in NGC 185, a fact that is supported by the richer mean oxygen abundance for NGC 205 $(12 + \log (O/H) = 8.6$; Richer & Mc Call 1995).

Further on the subject of metal-rich stars, there are some very red stars $(V-I \gtrsim 3)$ below the I-band RGB tip magnitude in NGC 185 and NGC 205. Whether those stars belong to NGC 205 is unclear, but such stars occur in M31 fields. For example, BCF03 found them in WFPC2 photometry of M31 halo fields and noted that such stars would be highly metal-rich, if they are members of M31. Examination of such stars with high abundance levels is largely precluded by incompleteness and model uncertainties.

8. Age and abundance clues: the red bump and HB in NGC 185

Stellar evolution theory predicts that the luminosity of the RGB and AGB bumps in the colour magnitude plane depends on stellar abundance and age. Such theory also predicts a red HB in intermediate-age -to–ancient stars. In the present section we consider the red bump/clump (RC) and the prominent HB in NGC 185.
For the mean RC magnitude in each band-pass, we fitted a Gaussian function to the RC a few hundred times in a bootstrap way (see Sec. 5.2) at V-I = 1-1.6 mag, binned at 0.05 mag intervals. The mean V(RC), I(RC) and associated standard errors are 25.28 ± 0.02 mag and 24.20 ± 0.01 mag respectively. Consequently, we find that there is no V-band offset between the clump and the HB that we determined at 0.2 < V-I (mag) < 0.7, within uncertainties – the offset is 0.01 ± 0.15 mag.

It is unclear whether the RC actually comprises RGB / faint-AGB stars, a red HB, or both. However, we may examine the implications of the third option using the model \( \Delta V_{\text{Bump}} \) diagram from Alves & Sarajedini (1999) (their Fig. 6). Consequently, based on visual inspection of their Fig. 6 we infer that [Fe/H] would be about -1.5 dex at \( \Delta V(\text{Bump-HB}) = 0 \) for ancient stars, with a higher abundance level for intermediate-age stars, regardless of whether the V-band magnitude of the red HB is the same for all ages or one considers the theoretical age-dependence adopted by Alves & Sarajedini (1999).

9. Young and intermediate-age stars

Fig 5 and Fig 6 show the (V, V-I) CMDs for NGC 205 and NGC 185 respectively, in which an arbitrary selection of stellar isochrones from Bertelli et al. (1994) covering young and old ages are overlaid as a visual guide.

The presence of the brightest stars at V-I \( \lesssim 0.5 \) mag in the NGC 205 CMD is curious as one might not suspect a foreground population because of the negligible surface density of such young blue stars in the nearby (control) fields G58 and G64 (see Fig. 5 & 6 of B03). On the other hand they occur in each field with no significant radial trend in the dwarf galaxy. Additionally, from a visual inspection there is an (apparent) paucity of blue stars, e.g., V-I <0.5 mag, at V \( \sim 21.5-23 \) mag that is hard to explain by a conspiracy of incompleteness functions, and is inconsistent with a main sequence/blue loop population. We take the opinion that the bright, blue stars are not the upper part of a main sequence/blue loop stellar population, but rather that they are probably foreground stars.

For the fainter, blue stars at (V \( \lesssim 23, \) V-I \( \lesssim 0.5 \) mag) in NGC 205, which are probably dominated by main sequence and blue loop stars, we made a visual comparison with several sets of isochrones, and deduce that star formation was probably still active about 1-3 \( \times 10^8 \) yr ago. That finding fits broadly with the discovery that many of the objects identified as bright

\(^{12}\)It is recognised that more empirical data from AGB populations is required to place the diagram on a firm footing, but the theoretical plane is nevertheless taken here to provide clues on abundances and ages.
stars by Hodge (1973) are in fact clusters of bright UV sources, two of which have stellar ages of $0.5 \times 10^8$ and $10^8$ yr respectively (Cappellari et al. 1999). This confirms earlier reports of recent episodes of star formation in the nuclear region, based on IUE\(^{13}\) observations with a $10'' \times 20''$ aperture (Wilcots et al. 1990). Furthermore, complementary information comes from near-IR studies of AGB peak brightness and J-K colours of the blue AGB sequence that find there are AGB stars near the centre of NGC 205 that formed less than $10^8$ yr ago (Davidge 2003; his Fig 5). Lastly, we note that with an orbital period of $10^8$ yr (Cepa & Beckman 1988), it is possible that a past disk crossing triggered the recent star formation activity.

In the case of NGC 185, there are about two dozen blue stars (V-I $\lesssim 1$ mag) at V $\sim 20.5$-23 mag in the ensemble CMD presented in Fig 6. A comparison with models (see Sec. 4) indicates that the bulk of them are probably foreground stars owing to NGC 185's low galactic latitude, but some red supergiants from NGC 185 may be present as noted by Nowothny et al. (2003) and Martinez-Delgado & Aparicio (1998). Another point against them as members of NGC 185 is that a significant number of fainter stars would be needed if the stars were actually MS and blue loop stars. However, the presence of a significant population of faint blue stars at V $\geq 24$ mag (excluding the HB of ancient stars at V $\sim 25$-25.5 mag) argues for a real population of MS and blue loop stars. Guided by the isochrones in Fig 6, one infers that star formation was probably still active about $4 \times 10^8$ yr ago.

We have not tried to derive the star formation history of the faint blue stars at V $\geq 24$ mag due to significant incompleteness at such faint magnitudes. However, although we detect the faint population of blue stars at V $\geq 24.5$ mag based on visual inspection of the ensemble (V, V-I) CMD, the model produced by MD99 (their Fig. 16), based on a synthetic CMD analysis, appears to be markedly fainter. Thus, the mean SFR density for the last $10^9$ yr is probably above the MD99 estimate, i.e., $> 2.6 \times 10^{-9} M_{\odot} \text{yr}^{-1} \text{pc}^{-2}$ at $r < 2'$.

Next, we probe whether the mean age of young AGB stars varies radially with respect to older stars. For that reason we list in Table 5 the star counts and count ratios for bright, young AGB stars (I $< I_{\text{TRGB}}$) and stars on the upper RGB/faint-AGB sequence, defined in colour–magnitude space by boxes A and B respectively in Fig. 3 for NGC 185; we shifted the boxes appropriately for NGC 205 and NGC 147 with regard to distance and extinction differences. For NGC 205, it follows that a real increase occurs in the mean ages of bright, young AGB stars with respect to older stars towards the nuclear region, even if a conservative contamination level of 40% in the F1 field is included. Simulating conservative systematic errors of 50% in E(V-I) and / or 0.1 mag, for example, in the distance modulus causes a shift

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of a few percent in bright, young AGB star counts, but the conclusion remains unchanged.

In the NGC 185 (and NGC 147) data, we find no statistically significant field-to-field changes in the mean ages of bright, young AGB stars with respect to older stars. Due to a relatively short crossing time in and between the WFPC2 fields, the AGB and older stars could be well-mixed (e.g. conservatively, take an rms velocity of $1 \text{ km s}^{-1}$), a case that would be compatible with the apparent absence of field-to-field variations.

9.1. Do the intermediate-age populations in NGC 185, 205 and 147 differ?

We can make a stab at answering the question using Table 5 which lists the number of AGB stars that are relatively young (i.e., are above the RGB I-band tip magnitude in (I,V-I) CMDs), normalised by the number of fainter (and mostly older) stars, selected from suitable colour magnitude boxes (see Fig. 3). In fact, we are using (i) the fact that the brightness of a young AGB star of a given chemical composition is a function of its age, meaning that brighter AGB stars are younger and (ii) and that the population of ancient stars, which is probably significant, is fainter than the RGB I-band tip magnitude. We assume that there is a negligible contamination from (a) RGB stars near the RGB tip magnitude that might arise due to photometric scatter and (b) the number of Mira variable stars occurring near the tip of the RGB that are in their bright state. As the fractional contributions of faint-AGB and RGB stars is unknown, we consider the available low time resolution (wide-age bins) information offered by our star count data. Consequently, we infer that the contribution of stars that formed in the past several $10^{9}$ yr is significantly greater in NGC 205 than in NGC 185 or NGC 147. For NGC 147 the contribution is significantly greater than that in NGC 185.

10. On the nuclear star cluster in NGC 205

NGC 205 offers an opportunity to study a bona fide nucleated dwarf satellite in our neighbourhood. We perform a detailed assessment of a number of the nuclear cluster (NC) properties, namely colour, size and intensity.

10.1. Profiling method

For a determination of an NC's structural properties there are a number of useful studies to refer to. For example, see Böker et al. 2004 and references therein (also see Walcher et al.
We fitted a separate analytical profile to the NC and to the underlying galaxy surface brightness profile that we model as a Sérsic profile; such a profile is regarded as plausible based on galaxy morphology studies and has the form $I_{gal}(r) = I_0^{gal} \exp \left(\frac{(r/r_0)^{1/n}}{n}\right)$, where a Sérsic index $n = 1$ represents an exponential profile and $n = 4$ is a de Vaucouleurs law. As the radial coverage of the central WFPC2 field makes an accurate fit to the galaxy’s profile hard, we fitted the Sérsic profile to the R-band surface brightness profile from Peletier (1993) by trial and error at $r = 20''$ to $250''$. For the V-band data, that Peletier profile was simply shifted to match the V-band WFPC2/PC1 data at $r = 9''$. At such distances from the NC, the light contribution from the NC is negligible, as is the effect of the HST WFPC2 PSF on the fitting.

To model the intrinsic cluster profile, we used the nuker-law profile (Lauer et al. 1995) that is implemented in GALFIT (Peng et al. 2002). The ‘best’ model parameters are those that minimize the deviation from the data in a $\chi^2$ sense, and is determined by minimizing residuals between the model and the original image. We note that the nuker model is a fine choice for the present study as it provides the best fit to the cluster data in a reduced-$\chi^2$ sense, so that reliable magnitudes and colours may be derived. We used GALFIT in a circular aperture ($r < 4''$), centred on the NC, that is dominated by emission from the NC; the underlying galaxy profile had been subtracted beforehand. Significantly, the GALFIT software takes the input instrumental PSF into account by convolving the analytical cluster profile with it. We made a PSF for each band-pass using isolated stars, modeled by a Moffat function with power index of 2.5. A technical point is that the width of a WFPC2 stellar PSF for a given filter depends on the spectral type(s) of the reference stars; however, as the cluster is well-resolved a mismatch between the spectral energy distribution of the PSF and the NC has a negligible effect on the derived intrinsic profile of the cluster. Circular symmetry was not assumed during cluster profile fitting which resulted in a minor-to-major axis ratio of about 0.92, similar to $q=0.90 \pm 0.05$ from Capellari et al. (1999), $q = 0.89$ measured by Heath Jones et al. (1996) using PC1/F555W data, all based on data of comparable angular resolution that resolve the NC well. The actual R-band profile, the fitted and derived intrinsic profiles as well as the Peletier (1993) profile are included in Fig. 9.

### 10.2. Effective radius and intensity

In order to quantify the cluster size, we used the so-called effective radius, $r_e$, the radius of an area that contains half of the cluster light in projection (see Carlson & Holtzman 2001); and deduced it for each band-pass from the derived intrinsic profile of the NC.

To check how much the measured $r_e$ (and intensity) depends upon small errors in the
wings of the fitted NC profile, we masked 15% of the PC1 pixels, randomly selected, and fitted the mucker profile. After repeating this several times, we determined the mean and standard deviation for each of the affected parameters ($M_{V/R}^C$, $r_{e,V/R}$, $\log I_{e,V/R}$) (see Table 7).

Taking the derived (dereddened) colour and size at face value, we conclude that the NC’s blue and red stellar components have similar compactness, as judged by the FWHM\(^{14}\) parameter, but there is an excess of blue light with respect to red in the cluster’s outer region – the measured NC’s (apparent) effective radius is smaller by a factor of 2.4 in R-band than in V-band. Some tentative supporting evidence for a blue excess comes from Cappellari et al. (1999) who noted that the NC looks more elongated in the UV than at longer wavelengths (e.g. V-band). However, caution is needed regarding our interpretation because the possibility of significant differential extinction, on a length-scale similar to the cluster size, remains.

We find that like the NCs in late-type spirals, which have $10^6$-$10^8 L_\odot$ (deduced from Böker et al. 2002), and unlike GGCs, the NC in NGC 205 is quite bright, with $10^6 L_\odot$, R $(10^{0.4(M_\odot,R-M^{C,R}_0)})$ where $M_\odot,R = 4.31$ mag and $M^{C,R}_0$ is given in Table 7.

Lastly, it is worth bearing mind that the NC may be a multi-component population, as suggested by the (apparent) blue excess in its outer region, possibly a merged pair of globular clusters (but also read the Walcher et al. (2005) discourse on possible NC formation scenerios). In that case the youngest/bluest component would probably be younger than the mean age derived from the integrated V-R colour (see the next section), and could therefore be less than a few times $10^8$ yr old.

\subsection{10.3. Mean age}

Clues regarding mean age can be drawn from the NC’s colour. Mean age can also be estimated from the clusters luminosity and mass-to-light ratio; however both of these require a mass estimate, whose significance would be uncertain.

The NC in NGC 205 is bluer than catalogued Milky Way globular clusters (Harris 1996), whose bluest clusters reach to V-R $\sim 0.4$ mag. Consequently, the NC’s colour hints that the NC is not ancient, a supposition that is supported by spectra from Da Costa & Mould (1988), especially strong hydrogen lines, that are similar to those seen in the spectra of young globular clusters in the Magellanic Clouds.

\footnote{The azimuthally-averaged FWHM are 0.276±0.007\arcsec (R) and 0.258±0.007\arcsec (V).}
A further way to get a handle on the mean NC age is through a comparison of the cluster colour with model predictions, again for a single burst of star formation. Based on models of an instantaneous burst of star formation that produces a $10^6 \text{M}_\odot$ stellar cluster\footnote{Taking an IMF slope of 2.35 or 3.3; a lower mass cutoff of 1 $\text{M}_\odot$; an upper mass cutoff of 30 or 100 $\text{M}_\odot$; and $Z = 0.001 - 0.040 \text{dex}$}, a (dereddened) V-R index above 0.3 mag would only be expected for an approximately 0.5 Gyr-old cluster progressing to values as blue at (V-R)$_0 \sim 0.1$ mag at younger ages for a wide abundance range, $0.04 \leq Z \leq 0.001$, (Leitherer et al. 1999). Consequently, taking the measured mean colour at face value and assuming a single epoch of star formation, one would argue for a young system up to a few times $10^8 \text{yr}$ old.

10.4. Discussion – Cluster size

Two key issues will be examined briefly here. They are: (a) Is it significant that the NC in NGC 205 is two-to-three times smaller than those in the Virgo sample of Geha, Guhathakurta & van der Marel (2002)?, and (b) Are typical galactic globular clusters akin to NCs?

On the first question, it is interesting that the NC in six bright dE galaxies in the Virgo cluster examined by Geha et al. have V-band effective radii of 8-13 pc, larger than the NC in NGC 205 ($r_e, V \sim 4$ pc). However, they sampled the bright end of the dE luminosity function. Consequently, future studies extending to the NCs of fainter Virgo dEs should aim to state whether or not the observed sizes are ubiquitous in the Virgo cluster.

On the link, if any, between nuclear star clusters and galactic globular clusters, which are non-central objects, it is of at least academic interest to make a brief comparison. We note that the median $r_e$ of GGCs is almost 3 pc, with the bulk of them below 10 pc (see Böker et al. 2004; Fig. 4). So, although similar to some GGCs in terms of size, GGCs are ancient unlike the NC in NGC 205 which may be up to a few times $10^8 \text{yr}$ old as surmised in the previous sub-section. Consequently, the fact that the average size of the NC in NGC 205 ($\sim 3$ pc) happens to be compatible with a massive GGC might be hinting that NC size is not strongly age dependent.
11. Has NGC 205 experienced tidal stripping?

That NGC 205 may have experienced interactions with M31 has been suggested in the literature (e.g., velocity dispersion: Bender, Paquest & Nieto 1991; twisted outer isophotes: Choi, Guhathakurta & Johnston 2002). Interactions can cause tidal stripping of stellar matter that could produce stellar sub-structure in so-called streams. The most prominent sub-structure around M31 belongs to its giant stellar stream (Ibata et al. 2001; Ferguson et al. 2002). Recent kinematical evidence plus modeling suggests that it probably does not include NGC 205 (Ibata et al. 2004). Our distance modulus measurement for NGC 205, \((m-M)_0 = 24.76 \pm 0.1\) mag (when E(B-V) = 0.11 mag), would support that result by placing NGC 205 at \(d \sim 890\) kpc, putting it farther behind M31 than previously estimated.

12. Conclusions

We presented the first detailed study of NGC 205 and NGC 185 using WFPC2 data. Our key results are:

**NGC 185**

- There is an ancient stellar sub-population in NGC 185 with \([\text{Fe/H}] \lesssim -1.5\) dex, based on the presence of a well-defined horizontal branch.
- We inferred the median \([\text{Fe/H}]\) of ancient stars (>10 Gyr) in NGC 185 from colour information to be \(>-1.11 \pm 0.08\) dex, assuming \(\text{E(B-V)} = 0.184\) mag.
- In NGC 185, we found no V-band offset between the red bump/clump and the HB V-band magnitude. From a comparison with theory, that finding suggests that ancient stars have \([\text{Fe/H}] \sim -1.5\) dex, with a higher abundance level for intermediate-age stars (1-10 Gyr).
- We find that star formation was probably still active about \(4 \times 10^8\) yr ago.

**NGC 205**

- Whether there is a horizontal branch in NGC 205 is still an open question as the photometry’s limiting magnitude is insufficient to detect central HB stars if they are present.
• We determined that the RGB/faint-AGB at each pointing in NGC 205 is significantly skewed to redder colours than that of our control field. That is probably the result of a narrower range in stellar abundances and or age for a significant fraction of the stars in NGC 205 than in the control field located on the outskirts of M31.

• We inferred the median $[\text{Fe/H}]$ of ancient stars in NGC 205 from colour information to be $>-1.06\pm0.04$ dex, assuming $E(B-V) = 0.11$ mag.

• Our analysis indicates that star formation activity in NGC 205 was probably still active less than $3\times10^8$ yr ago. Such recent star formation activity could have been triggered by an interaction with M31.

• We derived a new distance estimate using the RGB I-band tip magnitude method, obtaining $(m-M)_0 = 24.76\pm0.1$ mag, adopting $E(B-V) = 0.11$ mag.

• Several properties of the nuclear star cluster in NGC 205 have been examined: In terms of size and intensity, it is like a galactic globular cluster or a nuclear cluster in a late-type spiral galaxy; but from a comparison with models, the blue colour hints that its stellar population is young, up a few times $10^8$ yr old. The (apparent) V-/R-band effective radii indicates an excess of blue light with respect to red light in the cluster’s outer region.

Like the NCs in late-type spirals, which have $10^6$-$10^8 L_{\odot}$ (deduced from Böker et al. 2002), and unlike GGCs, the NC in NGC 205 is quite bright, with $10^6 L_{\odot}$. 

12.1. Conclusion – a brief comparison of NGCs 205, 185 & 147

In the introductory section we raised key questions about the similarities and differences between the three M31 dwarf companions. Although an investigation of whether the galaxies had significant star formation episodes since the primeval occurrence is precluded by the low temporal resolution afforded by our CMDs and also by the bright limiting magnitude of our CMDs, we can compare the galaxies in other ways, namely via the abundances of certain sub-populations; the most recent epoch of star formation; and the contribution of intermediate-age stars to the total population.

NGCs 205, 185 and 147 do not show marked differences in their inferred median photometric abundances (from colour information) for ancient stars, which correspond to intermediate or richer values ($[\text{Fe/H}] > -1.1$ dex). However, both NGC 147 and NGC 185 have a sub-population of ancient stars with $[\text{Fe/H}] \lesssim -1.5$ dex, based on the presence of a HB in each of them. The difference between these $[\text{Fe/H}]$ estimates (i.e., from the RGB colour and HB
methods) could be explained if each contains an ancient and or intermediate-age population of predominantly metal-rich stars with $[\text{Fe/H}] \gtrsim -1.5$ dex. Alternatively, the discrepancy may be resolved to some extent if extinction has been under-estimated. For example, based on the RGB colour–$[\text{Fe/H}]$ relation from Lee et al. (1993), an under-estimation of our NGC 185 E(B-V) data by 0.04 mag, for example, leads to a more metal-rich abundance ($[\text{Fe/H}]$) by about 0.2 dex. Accordingly, we conclude that the ancient stellar populations of the three galaxies appear to have broadly similar $[\text{Fe/H}]$ values; but these need to be scrutinized by detailed future star formation history analyses and spectroscopy-based studies.

On the issue of the most recent epoch of star formation activity, NGC 185 and NGC 147 differ markedly, in the sense that star formation occurred more recently in NGC 185 ($\sim 4 \times 10^8$ yr ago) than in NGC 147 ($\gtrsim 1$ Gyr ago; Han et al. 1997). This is a restatement of the known crisis in explaining the differences in the NGC 147/NGC 185 pair (Mateo 1998). For example, if gas origin in dwarf galaxies is largely internal (via dying stars), and they are still capable of gas accumulation at the present epoch, there is the suggestion (Mateo 1998; his Sec. 4) from the lack of gas and recent star formation activity that NGC 147 has avoided accumulating gas since the last star formation episode(s).

For the intermediate-age population we probed whether their contribution varied significantly among the three galaxies. We inferred from an AGB–RGB star count analysis that the contribution from stars that formed in the past several $10^9$ yr is significantly greater in NGC 205 than in NGC 185 or NGC 147. For NGC 147 the contribution is significantly greater than that in NGC 185. As NGC 147 and NGC 185 are similar in terms of mass and size, an implication is that NGC 147 has had a markedly higher star formation rate at intermediate-age epochs, compared to that at older epochs, than in NGC 185.

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Fig. 1.— False optical colour mosaic image of NGC 205 (left; Credit: R. Gendler (2002), 0.32 m telescope, F/6). I-band image of NGC 185 (right; Nowothny et al. 2003). Locations of the archival pointings are indicated with full or partial WFPC2 footprints.
## Table 1. Source information

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<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>NGC 185</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>F4</td>
<td>1.6</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2800</td>
<td>22857</td>
</tr>
<tr>
<td>F3</td>
<td>2.1</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2800</td>
<td>22833</td>
</tr>
<tr>
<td>F2</td>
<td>3.3</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2800</td>
<td>20747</td>
</tr>
<tr>
<td>F1</td>
<td>4.1</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2800</td>
<td>16899</td>
</tr>
<tr>
<td>NGC 205</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>F4</td>
<td>0.3</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2700</td>
<td>8957</td>
</tr>
<tr>
<td>F3</td>
<td>0.8</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2700</td>
<td>15718</td>
</tr>
<tr>
<td>F2</td>
<td>2.6</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2700</td>
<td>24073</td>
</tr>
<tr>
<td>F1</td>
<td>8.1</td>
<td>V/I</td>
<td>2/3</td>
<td>1300/2700</td>
<td>19053</td>
</tr>
<tr>
<td>NGC 205</td>
<td>0.5</td>
<td>V/R</td>
<td>4/3</td>
<td>400/50</td>
<td>-</td>
</tr>
</tbody>
</table>

(0) Galaxy name; (1) Angular separation of the field taken from MAST, the multi-mission archive at STScI, from the galaxy's center to the coordinates listed in the data pointings table (nominally the middle of the field of view); (3) & (4) selected filters and frame integration time; (5) Number of stars detected; '-' Means that stellar photometry was not performed.
Fig. 2.— $V_-$- and I-band fractional completeness as a function of magnitude for WFPC-2 $V_-$- and I-band PC1 (solid), WF2 (dotted), WF3 (dashed) and WF4 (dot-dashed) frames at each pointing in NGC 205 (left) and NGC 185 (right) as determined by artificial star tests. See the text in Sec. 2 for further explanations.
Fig. 3.— I, V-I CMDs for NGC 185. (Median) error bars in magnitude and colour, taken at $V - I = 1$ mag, are included. Box boundaries used for star counts given in Table 5 are shown for the field F4; I-band box boundaries are $M_I = -5.0, -4.06, and -2.0$ mag. For further explanations see the text in Sec. 2.
Fig. 4. — As Fig. 3, except for NGC 205.
Table 2. Adopted extinction values and galactic coordinates

<table>
<thead>
<tr>
<th>Object</th>
<th>$A_V$ (mag)</th>
<th>$A_I$ (mag)</th>
<th>$l$ (deg)$^a$</th>
<th>$b$ (deg)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 185</td>
<td>0.570</td>
<td>0.273</td>
<td>120.79</td>
<td>-14.48</td>
</tr>
<tr>
<td>NGC 205</td>
<td>0.34$^b$</td>
<td>0.16$^b$</td>
<td>120.72</td>
<td>-21.14</td>
</tr>
<tr>
<td>NGC 147</td>
<td>0.535</td>
<td>0.257</td>
<td>119.82</td>
<td>-14.25</td>
</tr>
</tbody>
</table>

Extinction values from Schlegel, Finkbeiner & Davis (1998); $^a$: Galactic coordinates are from the Simbad database; $^b$: (see Sec. 3 for further explanations).
Table 3. Derived and inferred data from the RGB method for each galaxy

<table>
<thead>
<tr>
<th>NGC</th>
<th>Angular Separation (arc min)</th>
<th>(V-I)\textsubscript{TRGB,0} ± r (mag)</th>
<th>(m-M)\textsubscript{0} ± r (mag)</th>
<th>[Fe/H] ± r (dex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>4.1</td>
<td>1.72±0.01</td>
<td>24.10±0.04</td>
<td>-1.12±0.08</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>1.79±0.02</td>
<td>24.06±0.04</td>
<td>-1.20±0.06</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>1.74±0.04</td>
<td>24.09±0.04</td>
<td>-1.11±0.05</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>1.99±0.01</td>
<td>24.06±0.03</td>
<td>-1.00±0.04</td>
</tr>
<tr>
<td></td>
<td>Mean*</td>
<td>1.81±0.12</td>
<td>24.08±0.02</td>
<td>-1.11±0.08</td>
</tr>
<tr>
<td>205</td>
<td>8.1</td>
<td>1.82±0.03</td>
<td>24.77±0.03</td>
<td>-1.04±0.03</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>1.86±0.03</td>
<td>24.76±0.03</td>
<td>-1.05±0.03</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>1.89±0.02</td>
<td>24.76±0.03</td>
<td>-1.03±0.03</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1.90±0.10</td>
<td>24.74±0.05</td>
<td>-1.11±0.03</td>
</tr>
<tr>
<td></td>
<td>Mean*</td>
<td>1.87±0.04</td>
<td>24.76±0.01</td>
<td>-1.06±0.04</td>
</tr>
<tr>
<td>147</td>
<td>3.0</td>
<td>1.85±0.03</td>
<td>24.47±0.03</td>
<td>-1.12±0.04</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>1.82±0.06</td>
<td>24.48±0.05</td>
<td>-1.14±0.08</td>
</tr>
<tr>
<td></td>
<td>Mean*</td>
<td>1.84±0.2</td>
<td>24.48±0.01</td>
<td>-1.13±0.01</td>
</tr>
</tbody>
</table>

Columns: As for Table 4, except for (2) Dereddened median colour of the RGB/faint AGB sequence at the absolute I-band tip magnitude of the RGB (3) Derived dereddened distance modulus; * Mean (and standard deviation) of all values; Error values (r) are uncertainties in V-\textsubscript{TRGB,0}, or the effect of the error in V-\textsubscript{TRGB,0} and I\textsubscript{TRGB} ((m-M)\textsubscript{0}) (\textsubscript{3.5} ([Fe/H]), or the effect of the error in V-\textsubscript{TRGB,0} and I\textsubscript{TRGB} ((m-M)\textsubscript{0}).
Table 4. Derived and inferred data from the V(HB) method for each galaxy

<table>
<thead>
<tr>
<th>NGC</th>
<th>Angular Separation (arc min)</th>
<th>V(HB) ± r (mag)</th>
<th>(m-M)_0 ± r (mag)</th>
<th>[Fe/H] ± r (dex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>4.1</td>
<td>25.33±0.01</td>
<td>24.18 ± 0.00</td>
<td>-1.39 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>25.24±0.02</td>
<td>24.04 ± 0.02</td>
<td>-1.14 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>25.24±0.01</td>
<td>24.02 ± 0.00</td>
<td>-1.02 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>25.33±0.01</td>
<td>24.11 ± 0.02</td>
<td>-1.04 ± 0.05</td>
</tr>
<tr>
<td>Mean*</td>
<td>25.29±0.05</td>
<td>24.09 ± 0.07</td>
<td>-1.15± 0.17</td>
<td></td>
</tr>
<tr>
<td>147</td>
<td>3.0</td>
<td>25.57±0.02</td>
<td>24.40±0.02</td>
<td>-1.10± 0.03</td>
</tr>
<tr>
<td>0.2</td>
<td>-</td>
<td>24.38±0.01</td>
<td>0.98± 0.02</td>
<td></td>
</tr>
<tr>
<td>Mean*</td>
<td>-</td>
<td>24.38± 0.01</td>
<td>-1.04± 0.08</td>
<td></td>
</tr>
</tbody>
</table>

Columns: (0) Galaxy ID; (1) Angular separation of the field from the galaxy’s centre; (2) Measured median horizontal branch V-band magnitude; (3) derived dereddened distance modulus; (4) Inferred lower limit for the logarithm of the iron-to-hydrogen abundance relative to the solar value, for ancient RGB stars. * Mean (and standard deviation) of all values; Error values (r) are uncertainties in V(HB), or indicate the effect of that error on (m-M)_0 or [Fe/H]. The systematic error estimate for [Fe/H] is 0.025 dex; it is half of the tolerance used to end the iterative search for [Fe/H] and (m-M)_0. Formally, the corresponding systematic error in (m-M)_0, determined by applying M_V = 0.17[Fe/H] + 0.82 from Lee et al. (1993) is 0.005 mag. -: Means the HB is poorly defined; *: Adopted the V(HB) value from the outer WFPC2 field in NGC 147.
Fig. 5.— $V$, $V$-I CMD for NGC 205 with a set of isochrones overlaid. Stellar mass at the bright-end of the tracks is 6.3, 3.6, 2.8, 2.3, and 0.92 $M_\odot$ respectively, in order of increasing isochrone age. The main sequence (MS) and blue-loop region (BL) of the isochrones are marked. See Sec. 9 for further explanations.
Fig. 6.— Ensemble V, V-I CMD for NGC 185 with a set of isochrones overlaid. The mass at the bright-end of the isochrone tracks is 20.3, 3.0, 2.17, and 0.87 M\(_\odot\) respectively, in order of increasing isochrone age. As explained in the text in Sec. 9, the stars at V ~ 20.5-23 mag be field stars.
Fig. 7.— Abundance distributions for NGC 205 (top), NGC 185 (middle), NGC 147 (bottom) derived by matching colours of bright giants with isochrones of 10 Gyr old stars. Star count error is $\pm \sqrt{N}$. We determined the uncertainty in each median [Fe/H] value using the bootstrap technique outlined in Sec. 5, which turns out to be negligible. See Sec. 6 for further explanations.
Fig. 8.— NGC 205: $M_K$, $(V-K)_0$ and $M_I$, $(V-I)_0$ CMDs for the inner-most pointing using $(m-M)_0 = 24.76$ mag and $E(V-I) = 0.18$ mag. Stars brighter than the RGB tip magnitude in I-band (dots/tiny squares) are separated from fainter stars (open squares) for the purpose of presentation. Globular cluster fiducial ridgelines (solid) and stellar evolution tracks for the adopted $Z = 0.001$ and 0.004 Padova models (dashed) are overlaid. Globular cluster [Fe/H] data is on the Caretta & Gratton (1997) scale and is listed in Table 1 of Ferraro et al. (1999). The [Fe/H] – Z relation used is $[\text{Fe/H}] = 1.024 \log Z + 1.739$, valid for 10 to 15.8 Gyr-old stars and -2. < $[\text{Fe/H}]$ (dex) < -0.5 (Bertelli et al. 1994; their Eqn. 11). See Sec. 6 for further details.
Table 5. Star counts and count ratios for bright AGB and RGB/faint-AGB stars. See Sec. 6 for further details.

<table>
<thead>
<tr>
<th>NGC/region</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>185 A</td>
<td>15±4</td>
<td>24±5</td>
<td>47±7</td>
<td>47±7</td>
</tr>
<tr>
<td>185 B</td>
<td>1105±33</td>
<td>1668±41</td>
<td>2193±47</td>
<td>2409±49</td>
</tr>
<tr>
<td>185 A/B (185)</td>
<td>0.013(4)</td>
<td>0.015(3)</td>
<td>0.021(4)</td>
<td>0.020(3)</td>
</tr>
<tr>
<td>205 A</td>
<td>72±8</td>
<td>224±15</td>
<td>272±16</td>
<td>219±15</td>
</tr>
<tr>
<td>205 B</td>
<td>1706±41</td>
<td>3554±60</td>
<td>3122±56</td>
<td>2034±45</td>
</tr>
<tr>
<td>205 A/B (205)</td>
<td>0.042(6)</td>
<td>0.063(5)</td>
<td>0.087(7)</td>
<td>0.11(1)</td>
</tr>
<tr>
<td>147 A</td>
<td>69±8</td>
<td>175±13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>147 B</td>
<td>1890±43</td>
<td>7122±84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>147 A/B (147)</td>
<td>0.037(5)</td>
<td>0.025(2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A: bright young AGB, B: upper RGB/faint-AGB. The star counts (N) and ratios (corrected for a mean incompleteness of about 5% at I ≲ 23 mag). Star count error is ±\sqrt{N}. The error in the last digit of each A/B value is given in parentheses. Box boundaries are defined in Fig. 3.
### Table 6. Key abundance distribution quantities

<table>
<thead>
<tr>
<th>Object/parameter</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 185</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta r$ ($'$)</td>
<td>4.1</td>
<td>3.3</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>No. of stars</td>
<td>254</td>
<td>398</td>
<td>691</td>
<td>740</td>
</tr>
<tr>
<td>[Fe/H] (dex)</td>
<td>-0.96</td>
<td>-0.98</td>
<td>-0.93</td>
<td>-0.86</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.70±0.01</td>
<td>-0.57±0.12</td>
<td>-0.76±0.058</td>
<td>-0.98±0.11</td>
</tr>
<tr>
<td>$F_{MP}$</td>
<td>0.12±0.03</td>
<td>0.15±0.03</td>
<td>0.11±0.02</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>$F_{MR}$</td>
<td>0.88±0.11</td>
<td>0.85±0.09</td>
<td>0.89±0.07</td>
<td>0.93±0.07</td>
</tr>
<tr>
<td>NGC 205</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta r$ ($'$)</td>
<td>8.1</td>
<td>2.6</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>No. of stars</td>
<td>386</td>
<td>950</td>
<td>814</td>
<td>585</td>
</tr>
<tr>
<td>[Fe/H] (dex)</td>
<td>-0.96</td>
<td>-0.91</td>
<td>-0.89</td>
<td>-0.88</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.74±0.01</td>
<td>-0.85±0.01</td>
<td>-1.16±0.12</td>
<td>-1.13±0.09</td>
</tr>
<tr>
<td>$F_{MP}$</td>
<td>0.16±0.03</td>
<td>0.16±0.02</td>
<td>0.13±0.02</td>
<td>0.14±0.02</td>
</tr>
<tr>
<td>$F_{MR}$</td>
<td>0.84±0.08</td>
<td>0.84±0.06</td>
<td>0.87±0.06</td>
<td>0.86±0.07</td>
</tr>
<tr>
<td>NGC205/G58$^a$</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta r$ ($'$)</td>
<td>11.2$^b$</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No. of stars</td>
<td>63</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[Fe/H] (dex)</td>
<td>-0.94</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.62±0.19</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$F_{MP}$</td>
<td>0.08±0.047</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$F_{MR}$</td>
<td>0.92±0.24</td>
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<td>-</td>
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<tr>
<td>NGC 147</td>
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<td></td>
</tr>
<tr>
<td>$\Delta r$ ($'$)</td>
<td>3.0</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
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<td>No. of stars</td>
<td>399</td>
<td>1410</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[Fe/H] (dex)</td>
<td>-0.91</td>
<td>-0.84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.56±0.15</td>
<td>-0.96±0.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$F_{MP}$</td>
<td>0.06±0.01</td>
<td>0.07±0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$F_{MR}$</td>
<td>0.94±0.1</td>
<td>0.93±0.05</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$ means no WFPC2 data available. The [Fe/H] data refer to median values. $F_{MP}$ and $F_{MR}$ refer to the fraction of stars that are metal-poor or young ([Fe/H]< -1.4 dex) and the fraction that are metal-rich (-1.4 <[Fe/H]< -0.2 dex). $^b$ We applied our photometry selection criteria to photometry from BCF03. Angular separation from the centre of NGC 205. Star count error is $\pm \sqrt{N}$. For each histogram, skewness is defined here as $1/N \sum_{j=0}^{N-1} ((x_j - \bar{x})/\sigma)^3$, where $x$ is the abundance data, and $\sigma$ is its standard deviation.
Fig. 9.— Left: R-band image of the central region of NGC 205. Right: radial surface brightness plot of WFPC2 R-band data and derived surface brightness profiles.
Table 7. Summary of derived nuclear cluster properties

<table>
<thead>
<tr>
<th>NGC</th>
<th>d</th>
<th>Disk $\mu_0^V$</th>
<th>Disk $\mu_0^R$</th>
<th>$m_C^V$</th>
<th>$m_C^R$</th>
<th>$M_{V,0}^C$</th>
<th>$M_{R,0}^C$</th>
<th>$r_{e,V}/r_{e,R}$</th>
<th>$r_{e,V}/r_{e,R}$</th>
<th>$\log I_{e,V}/\log I_{e,R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Mpc)</td>
<td>(mag arcsec$^{-2}$)</td>
<td>(mag arcsec$^{-2}$)</td>
<td>(mag)</td>
<td>(mag)</td>
<td>(mag)</td>
<td>(mag)</td>
<td>(arcsec)</td>
<td>(pc)</td>
<td>($L_\odot$ pc$^{-2}$)</td>
</tr>
<tr>
<td>205</td>
<td>0.89</td>
<td>19.22</td>
<td>18.82</td>
<td>14.49</td>
<td>14.32</td>
<td>-10.59</td>
<td>-10.69</td>
<td>0.95/0.43</td>
<td>4.3/1.9</td>
<td>4.23/4.64</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td></td>
<td></td>
<td>(0.04)</td>
<td>(0.01)</td>
<td>(0.13)</td>
<td>(0.07)</td>
<td>(0.02)/(0.03)</td>
<td>(0.2)/(0.25)</td>
<td>(0.01)/(0.05)</td>
</tr>
</tbody>
</table>

Notes: Col. (2): Adopted galaxy distance (see Sec. 5). Col. (3) and (4): Observed (not inclination-corrected) peak surface brightness of the galaxy disk underlying the NC. Col. (5) and (6): Apparent $V$- and $I$-band magnitude of NC. Cols. (7) and (8): Absolute magnitudes of the NC corrected for foreground reddening. Uncertainties are given in parentheses and arise from fitting errors, a distance uncertainty of 0.05 mag and an adopted 10% error in foreground extinction. Col. (9) Angular effective R-band radius and uncertainty as discussed in Sec. 10. Col. (10): Effective R-band radius in parsecs. Col. (11): Logarithm of effective R-band intensity of the NC, $\log I_{e,R} = 0.4(M_{R,0}^C - M_{V,0}^C) - \log(2\pi r_{e,R}^2)$, and $\log I_{e,V} = 0.4(M_{V,0}^C - M_{V,0}^C) - \log(2\pi r_{e,V}^2)$ with $r_e$ in parsecs.