Distinct core and halo stellar populations and the formation history of the bright Coma cluster early-type galaxy NGC 4889

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ABSTRACT

We study the stellar population far into the halo of one of the two brightest galaxies in the Coma cluster, NGC 4889, based on deep medium resolution spectroscopy with FOCAS at the Subaru 8.2m telescope. We fit single stellar population models to the measured line-strength (Lick) indices (Hβ, Mg b, [MgFe]' and <Fe>). Combining with literature data, we construct radial profiles of metallicity, [α/Fe] element abundance ratio and age for NGC 4889, from the center out to ~ 60 kpc (~ 4 R_e). We find evidence for different chemical and star formation histories for stars inside and outside 1.2 R_e = 18 kpc radius. The inner regions are characterized by a steep [Z/H] gradient and high [α/Fe] at ~2.5 times solar value. In the halo, between 18 and 60 kpc, the [Z/H] is near-solar with a shallow gradient, while [α/Fe] shows a strong negative gradient, reaching solar values at 60 kpc. We interpret these data in terms of different formation histories for both components. The data for the inner galaxy are consistent with a rapid, quasi-monolithic, dissipative merger origin at early redshifts, followed by one or at most a few dry mergers. Those for the halo argue for later accretion of stars from old systems with more extended star formation histories. The half-light radius of the inner component alone is estimated as ~ 6 kpc, suggesting a significantly smaller size of this galaxy in the past. This may be the local stellar population signature of the size evolution found for early-type galaxies from high-redshift observations.

Key words: galaxies: halos — galaxies: individual (NGC 4889) — galaxies: abundances — galaxies: elliptical and lenticular, cD — galaxies: formation

1 INTRODUCTION

Brightest cluster galaxies (BCGs) are the largest and most luminous galaxies located in galaxy clusters. The merger, star formation and chemical enrichment history of these galaxies are imprinted in their kinematics and chemical abundances. Spatially extended measurements for such quantities can therefore constrain their evolution and formation, believed to be closely related to the formation of the cluster (e.g., [Dubinski]1998) and the presence of the diffuse intracluster light (e.g., [Napolitano]2003, [Murante]2007).

In the cold dark matter-based scenario, early-type galaxies (ETGs) form via merging of subclumps with various masses. According to [Kobayashi]2004, their merging histories can vary between spherical infall of gas-rich subunits at high redshift, and a sequence of merging events at different epochs and masses. Galaxies of the former assembly history are created via a process that is similar to the classical monolithic collapse. This dissipative process gives rise to high metallicity in the galaxy center, and to significant logarithmic metallicity ([Z/H]) gradients that can be steeper than ~0.5 and correlate strongly with galaxy mass (e.g., [Chiosi & Carraro]2002, [Kobayashi]2004, [Pipino]2008). Gas-rich binary mergers, on the other hand, produce only shallow gradients (~0.1) with weak mass dependence ([Bekki & Shioya]1999). Merging events that take place after most of the stars are in place reduce, but do not erase completely the pre-existing gradients, because of the way in which stars of different metallicities are redistributed in both energy and radius ([White]1980, [di Matteo]2009). In case of a later gas rich merger with a central starburst, a metallicity gradient can form again, but is confined to the central regions after a few Gyrs ([Hopkins]2009).

Stellar population studies in ETGs based on spectral indices show metallicities higher than solar in their nuclei, negative logarithmic metallicity ([Z/H]) gradients ranging from ~0.16 to ~0.30, and nearly constant [α/Fe] element abundances with radius (e.g., [Kobayashi & Arimoto]1999, [Sánchez-Blázquez]2006, [Reda]2007, [Annibali]2007). For BCGs, several studies provide information on the chemical abundances reaching up to ~20 kpc radius ([Carter]1999, [Brough]2007, [Loubser]2009). No significant gradients of [α/Fe] are observed, as in the case of normal early-type galaxies, while the range of [Z/H] gradi-
ents is somewhat wider, with values from \(-0.20\) down to \(-0.58\). Stellar ages are determined to be mostly old, \(>8\) Gyr.

In this paper we analyse Lick absorption line indices from deep spectra for NGC 4889, one of the two central BCGs in the Coma cluster (see, e.g. [Gerhard et al. 2007]), reaching unprecedented radii of \(\sim 60\) kpc (\(\sim 4R_e\)) in its outer halo (Section 2). We then derive age, \([Z/H]\) and \([\alpha/Fe]\) radial distributions using single stellar population models (Section 3). Finally, we discuss the implication of these stellar populations properties for the formation history of the core and halo of this galaxy (Section 4).

2 LINE-STRENGTH INDEX PROFILES FOR NGC 4889

Combining new data for the outer halo of NGC 4889 with literature data we first construct radial Lick index profiles extending from the center to \(\sim 60\) kpc radius (\(\sim 4R_e\)); see Figure 1.

The outer halo measurements are taken from [Coccato et al. 2010, paper I]. These data cover the radius range \(\sim 7\) kpc to 60 kpc and are based on 8 hr (run 1, PA=81°7, \(\sigma_{\text{inst}}=76\) km s\(^{-1}\)) and 5.5 hr (run 2, PA=8°3, \(\sigma_{\text{inst}}=96\) km s\(^{-1}\)) exposures, long-slit spectra obtained with FOCAS@ Subaru on Mauna Kea. Typical signal to noise ratios range from \(\sim60\) to \(\sim10\) for the innermost and outermost spectra, respectively.

The data analysis is described in Paper I and includes wavelength- and flux-calibration, convolution to the spectral resolution of the Lick system, correction for line-of-sight velocity broadening and correction for the offset to the Lick system. The sky background is evaluated from both offset sky exposures and dark regions in the scientific frames, using the former to identify regions of the slit in the latter that are free from stellar light continuum. Then we used the sky spectra from these regions (\(\sim5/6\) from the galaxy center in run 1, and \(\sim2/9\) in run 2); they have the same continuum as in the offset sky, and ensure the best removal of the variable sky emission lines. After sky subtraction, residual unresolved emission lines are still present in the Mg bandpass (run 2) and H\(\beta\) blue pseudo continuum (run 1). They are possibly caused by internal reflection in the spectrograph and are removed via a Gaussian fit (Paper I). Scattered light is measured in regions of the CCDs not illuminated by the slit. It amounts to \(\sim4.5\) ADUs (\(\sim20\%\) of sky), also in the offset sky images, and is nearly uniform across the detectors in both runs; it is subtracted off the science frames together with the sky background.

On the final spectra, H\(\beta\), M\(g_1\), M\(g_2\), M\(gh\), Fe5270 and Fe5335 line-strength indices are measured (see [Worthey et al. 1994]), from which we determine \(\langle\text{Fe}\rangle = (\text{Fe5270} + \text{Fe5335})/2\) and \([\text{Fe}]=\sqrt{\text{Mg}b_{0.72} \cdot \text{Fe5270} + 0.28 \cdot \text{Fe5335}}\). Their errors are determined by Monte Carlo simulations which accounted also for the errors in the radial velocities. Special care is taken to quantify possible systematic errors caused by sky subtraction. Residual contributions of up to \(\pm2\%\) of the subtracted sky spectrum are added to the galaxy spectrum. Larger residuals are excluded because they would produce detectable line features in the spectra (see Paper I).

New index values are then determined for these new spectra. The systematic deviations of the new values are found to be no larger than the error bars, except for M\(g_2\), which we therefore do not use to derive stellar population parameters.

For the inner regions of NGC 4889, we use spatially resolved Lick index measurements along the major axis from

![Figure 1. Lick absorption line indices for NGC 4889 as projected onto the galaxy major axis. Diamonds: data from Mehler et al. (2000), Corsini et al. (2008), averaged in radial bins. Here the second panel gives unprimed [MgFe], and H\(\beta\) values are shown without (blue) and with offset correction (black); see text. Filled circles: outer halo data from Paper I, also averaged in radial bins. Second panel gives primed [MgFe]; see Table I. Squares and crosses: measurements before averaging (dark and light green are from both sides of major axis spectrum), red and pink from both sides of minor axis spectrum). Stars: Central aperture measurements, from Jørgensen (1999, red), Moore et al. (2002, magenta), Sánchez-Blázquez et al. (2006, green), Loubser et al. (2009, blue).](image)
Stellar populations and formation history of the BCG NGC 4889

3 SINGLE STELLAR POPULATION (SSP) PARAMETERS: [Z/H], [α/Fe] AND AGE

In all bins of the radial average profiles in Fig. 1 we determine luminosity-weighted metallicity [Z/H], [α/Fe] abundance ratio, and population age from fitting single stellar population models of Thomas et al. (2003) to the line-strength indices Hβ, Mgb, <Fe> and [MgFe]' or [MgFe]. Their grid of models covers age values from 0.1 to 15 Gyr, [Z/H] from $-3.0$ to 0.3. For one of the central data points and a few error bars we had to extrapolate to metallicities up to 0.9. For each radial bin, we determine the best fit model from the measured Hβ, Mgb [MgFe]' and <Fe> values by minimizing $\chi^2$. Errors for [Z/H], [α/Fe] and ages are computed by means of Monte Carlo simulations. The results are shown in Figure 2 and are listed in Table 1. Logarithmic gradients of the SSP parameters are determined from standard linear regression fits in log-log-diagrams. For given parameter $P$ (denoting either [Z/H], [α/Fe], or log$_{10}$[age/Gyr]), its logarithmic gradient $\Delta P$ is defined through $P(R) - P(R_e) = \Delta P \cdot \log_{10}(R/R_e)$. The derived stellar population gradients are shown in Fig. 2.

3.1 Results

Over the entire radial range from the centre to 60 kpc, the metallicity and [α/Fe] profiles in Fig. 3 can no longer be described as single power-laws. Rather, they show a “break” at $\sim$ 18 kpc ($\sim 1.2 \, R_e$): in the inner regions, the logarithmic [Z/H] gradient is negative and steep: $\Delta [Z/H] = -0.35 \pm 0.02 \, (-0.49 \pm 0.03)$ using the corrected (uncorrected) inner Hβ data, with metallicity that decreases from $\sim 5$ times solar in the centre to $\sim 0.8$ solar at 18 kpc. The [α/Fe] abundance ratio in the inner $1.2R_e$ is nearly constant at a value of 0.37, i.e., $\sim 2.5$ times solar. By contrast, in the halo outside $\sim 1.2 \, R_e$, the logarithmic [Z/H] gradient flattens, $\Delta [Z/H] = -0.1 \pm 0.2$, and the [α/Fe] profile shows a steep negative gradient, $\Delta [\alpha/Fe] = -0.68 \pm 0.23$, reaching solar values at $\sim 60$ kpc. No peculiar features corresponding to this “break” are seen in the surface brightness profile.

The robustness of the “break” in the abundance profiles to possible systematic errors caused by sky subtraction has been quantified as follows. New SSP models are computed using Lick indices derived from spectra including up to ±2% residual sky contribution (Section 2). The corresponding range of SSP parameters is shown by the yellow regions in Fig. 2 and approximately corresponds to the detection limit 8% of the subtracted sky spectrum would be required to remove also the “break” in [α/Fe] (green lines in Fig. 2).

The inferred SSP ages show an almost bimodal pattern. The halo of NGC 4889 at radii $> 18$ kpc is uniformly old, with SSP ages ranging between 10 and 13 Gyr. Younger ages are determined for the inner regions of NGC 4889: using the original Hβ values results in average SSP ages between 2 and 8 Gyr, with the lowest values inferred in the central kpc. With the offset correction to the average literature Hβ scale, average ages in the inner regions increase to 8 Gyr, but some of the aperture data still imply quite young ages ($\sim 3$ Gyr; Fig. 2).

Young inferred SSP ages for BCG centers are not uncommon (Fisher et al. 1995, Pipino et al. 2009). However, such young SSP ages, if real for NGC 4889 and not caused by the heterogeneous nature of the inner measurements, do not necessarily indicate that the main bulk of stars are young but can also be due to a contamination of a small percentage of young stars. In fact, a component with age 1 Gyr and 10% mass fraction can bring the inferred SSP age of an otherwise old population down to $\sim 3$ Gyr (Trager et al. 2000, Table 8), similar to the lowest central values in NGC 4889. Conversely, the inferred SSP [Z/H] and [α/Fe] of a composite stellar population follow approximately its V-band luminosity weighted values (Serra & Trager 2007), i.e., are only moderately sensitive to the [Z/H] of a minor young component (correspondingly less than the difference between the black and blue points in the top panel of Fig. 2). Thus the steep [Z/H] gradient and high [α/Fe] characterize the dominant stellar population in the inner half of NGC 4889.

4 DISCUSSION

From measurements at large radii combined with previous literature data, we find evidence for distinct stellar populations in the inner half and outer halo of the nearby BCG NGC 4889. These point to a rapid formation process for the core and a more extended accretion phase building the halo, as we now discuss.

Within $\sim 1.2R_e = 18$ kpc, all [α/Fe] measurements give high values, implying a flat profile at $\sim 2.5$ times solar abundance ratio. This implies rapid conversion of the gas into stars. Using a formula derived by Thomas et al. (2003) from simple chemical evolution models would predict that most of the stars within 18 kpc radius were formed in less than 0.1 Gyr. This is about one dynamical time at 18 kpc. However, given the current uncertainties about SNIa progenitors and delay time distributions (e.g. Pritchet et al. 2009), this timescale of 0.1 Gyr is not very secure. At the same time, the combined measurements support a steep inner [Z/H] gradient (at least $\Delta [Z/H] \sim -0.3$ dex), while the published SSP age values inside 18 kpc show considerable scatter, including both old (10-13 Gyr) and intermediate age (3-6 Gyr) values. These data are consistent with a superposition of a dominant old population with a minor, younger component (see previous section).

The rapid formation and steep [Z/H] gradient of the stars in the inner half of NGC 4889 are reminiscent of predictions of a quasi-monolithic dissipative collapse model, in which stars form in a rapid burst progressing from the outside in, while the gas collapsing to the center is continuously enriched (Carlberg 1984, Arimoto & Yoshii 1987, Thomas et al. 1999). In this process, logarithmic gradients of $\sim -0.5$ can be reached. The chemical properties of the inner NGC 4889 population are consistent with a scenario in which a dominant, old population formed rapidly at high redshift in quasi-monolithic, dissipative merger collapse, as described by Kobayashi (2004) in the context of hierarchical models. Subsequently, several of such units could have been involved in one or at most a few dry mergers, such that the original steep [Z/H] gradients are only partially erased - a major dry merger between two...
ellipticals with identical gradients already reduces the gradient by a factor 0.6 (di Matteo et al. 2005) - and such that at most a small fraction of more iron-enriched stars is added to the stellar population.

By contrast, the halo of NGC 4889 at radii larger than 1.2R_e = 18 kpc is characterized by near-solar metallicities with shallow gradient, a steep [α/Fe] gradient reaching solar values at 60 kpc radius, and old ages (9-13 Gyr, possibly decreasing towards the outermost radii). The old ages and lower but still enhanced [α/Fe] gradient reaching solar values at 60 kpc radius, with effective radius evolving as R_e ∝ (1 + z)^-1.3. Scaling the present R_e of NGC 4889 with this relation would predict R_e ∝ 6.2 kpc at z = 1. An estimate for the size of the inner [α/Fe]-enhanced population in this galaxy is the radius enclosing half of the current luminosity within 18 kpc, obtained by truncating the surface brightness profile (Thomas et al. 2007) at that radius; this is also ∼ 6 kpc. The consistency of these numbers suggests that we may have found local stellar population signatures of the observed ETG size evolution.

In general, BCG galaxies have a range of [Z/H] gradients and [α/Fe] (see Introduction), thought to arise from the relative influence of the early collapse component and subsequent mergers (Kobayashi 2004; De Lucia & Blaizot 2007). In NGC 4889, a relatively large (∼50%) fraction of the galaxy light appears to have been involved in the early collapse. Because of the steep [Z/H] gradient and high [α/Fe] this galaxy may be a particularly good case for distinguishing the different core and halo populations. It will be important to obtain similarly extended [α/Fe] and [Z/H] profiles for a larger sample of bright ETGs and to connect their analysis with the properties of the high-redshift ETG population.

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Figure 2. Single stellar population parameters and their gradients in NGC 4889. Diamonds show values derived from the data of Mehltet al. (2000), Corsini et al. (2008), averaged in radial bins, without (blue) and with offset correction (black); see Fig. 1. Filled circles show halo values derived from the data of Paper I also averaged in radial bins; see Table 1. Stars show values derived from the aperture measurements given in Fig. 1. The dashed lines show the logarithmic gradients in [Z/H], [α/Fe], and age fitted to these data (in two radial ranges for the first two), with numerical values given on the figure. The shaded yellow regions indicate the range of SSP parameters that would result if systematic residual effects in the sky subtraction at the level of ±2% were present. The green lines correspond to (unrealistic) ±8% residuals (see Section 3.1 and paper I).
### Table 1. Line strength indices and stellar population parameters for NGC 4889, averaged in radial bins.

| $R$ (kpc) | Hβ (Å) | Mgβ (Å) | [MgFe] (Å) | $<\text{Fe}>$ (Å) | Age [Gyr] | [Z/H] | [$\alpha$/Fe] | GAL/BKG | $\Delta R$ [arcsec] |
|-----------|---------|---------|------------|-----------------|-----------|-------|----------------|---------|------------------|
| 0.14      | 1.64±0.15 | 5.46±0.17 | 4.19±0.11 | 3.22±0.13 | 5.04±2.0 | 0.63±0.17 | 0.30±0.06 | –       | –                |
| 0.43      | 1.61±0.16 | 5.35±0.17 | 4.05±0.11 | 3.07±0.13 | 7.83±4.0 | 0.50±0.10 | 0.32±0.06 | –       | –                |
| 0.84      | 1.57±0.05 | 5.46±0.08 | 4.07±0.06 | 3.03±0.08 | 8.61±4.0 | 0.50±0.07 | 0.34±0.02 | –       | –                |
| 1.73      | 1.55±0.06 | 5.54±0.08 | 4.02±0.06 | 2.92±0.08 | 9.41±4.0 | 0.47±0.03 | 0.38±0.02 | –       | –                |
| 3.67      | 1.66±0.12 | 5.36±0.11 | 3.77±0.07 | 2.65±0.08 | 8.61±4.0 | 0.40±0.13 | 0.44±0.04 | –       | –                |
| 8.74      | 1.67±0.27 | 4.66±0.30 | 3.69±0.15 | 2.91±0.14 | 8.21±4.0 | 0.33±0.23 | 0.22±0.08 | –       | –                |

Notes: Upper part of the table based on data from [Mehlert et al. 2000; Corsini et al. 2008]; lower part based on data from Paper I. Values for literature data refer to the case in which the Mehlert et al. Hβ values are offset-corrected by 0.32 Å, and provide [MgFe] rather than [MgFe]’ (see Section 2 for details). Col. 1: Mean distance of the radial bins from the galaxy center, projected along the major axis. Cols. 2-5: average values for indices and errors in the bins. Cols. 6-8: values are offset-corrected by 0.32 Å, and provide [MgFe] rather than [MgFe]’ (see Section 2 for details). Col. 9: ratio between counts from galaxy and background (both sky and scattered light), collected from all pieces of the slit that contribute to that bin. These counts are obtained in the wavelength range 5000 Å – 5150 Å, which is free from intense spectral lines, and therefore representative of the galaxy and background continuum. Col. 10: total radial extent covered by the bin. The number of slit portions (data points in Fig. 1) used for this bin is given in parentheses.