Age and metallicity gradients support hierarchical formation for M87

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ABSTRACT
In order to probe the inside-out formation of the most massive galaxies in the Universe, we have explored the radial (0.1 ≲ R ≲ 8 kpc) variation of the spectral energy distribution of M87 from UV to IR. For this purpose, we have combined high-resolution data in 16 different bands. Our analysis indicate that the age of the stellar population of M87 remains almost unchanged with radius. However, the metallicity ([Z/H]) profile presents three different zones: the innermost kpc shows a plateau with supersolar metallicity, followed by a decline in metallicity down to 5 kpc and another plateau afterwards. The size of the inner plateau is similar to the expected size (Rγ) of an object with the predicted mass of M87 at z = 2. The global [Z/H] gradient is −0.26 ± 0.10, similar to those found in other nearby massive ellipticals. The observed change in the stellar population of M87 is consistent with a rapid formation of the central part (R ≲ 5 kpc) of this galaxy followed by the accretion of the outer regions through the infall of more metal-poor material.

Key words: techniques: high angular resolution – galaxies: evolution – galaxies: formation – galaxies: individual: M87 – galaxies: photometry.

1 INTRODUCTION

Massive early-type galaxies are now widely believed to have been assembled hierarchically through repeated mergers which provide a relatively constant flow of accreted mass over a long time. The innermost regions of massive galaxies appear to have formed the majority of their stars at high redshift and on short time-scales (e.g. Thomas et al. 2005) whereas their outer parts are likely assembled as a consequence of multiple major and minor merging (e.g. Trujillo, Ferreras & de La Rosa 2011). This two-phase formation picture (e.g. Naab, Johansson & Ostriker 2009) agrees with the observed size evolution of the massive galaxies. At z ∼ 1 (2), massive early-type galaxies (M∗ ∼ 1011 M⊙) were a factor of 2 (4) smaller than present-day equal mass objects, having an average effective radii of only ∼1 kpc at z ∼ 2 (e.g. Daddi et al. 2005; Trujillo et al. 2006; Buitrago et al. 2008).

The merger, star formation and chemical enrichment history of massive galaxies are imprinted in their kinematics and chemical abundances. Consequently, measurements of these quantities on today’s massive galaxies should constrain their evolution and formation. Different formation scenarios predict different chemical enrichments for the massive galaxies. For instance, the classical model of monolithic collapse predicts that the inflowing gas is chemically enriched by evolving stars and contributes with metal-rich fuel for star formation. This inflowing gas gives rise to high metallicities in the galaxy centre and to significant logarithmic metallicity gradients that can be steeper than −1.0 and correlate strongly with galaxy mass (Eggen, Lynden-Bell & Sandage 1962; Larson 1974; Carlb erg 1984). However, revised monolithic models predict shallower metallicity gradients of −0.3 to −0.5 for a few massive galaxies (e.g. Chiosi & Carraro 2002; Pipino, D’Ercole & Matteucci 2008; Pipino et al. 2010; Merlin et al. 2012). On the other hand, a hierarchical formation scenario, with major mergers, is expected to dilute the metallicity gradient (Kobayashi 2004), reaching values of −0.2.

Many observational probes of stellar populations have been carried out for nearby early-type galaxies. Colours are one of the easiest observables for extragalactic systems. For instance, it has been known than the centres of low-redshift ellipticals are redder that their outskirts (e.g. Franx & Illingworth 1990; Peletier, Va lentijn & Jameson 1990). These colour gradients are generally attributed to gradients in metallicity although a small contribution due to age gradients is expected (e.g. Spolaor et al. 2010). Works as Ogando et al. (2005), Spolaor et al. (2010), Kuntschner et al. (2010) and La Barbera et al. (2010) show that logarithmic
metallicity gradients in early-type galaxies are about −0.2 to
−0.3 dex. In addition, Sánchez-Blázquez, Gorgas & Cardiel (2006),
Kuntschner et al. (2010) and Loubser & Sánchez-Blázquez (2012)
found age gradients compatible with zero. However, pieces of evi-
dence for a positive age gradient are also reported (e.g. Baes et al.
2007; La Barbera et al. 2010). There are a few but increasing num-
ber of studies exploring age and metallicity gradients in nearby
massive galaxies up to several effective radii of radial distance
(Coccato, Gerhard & Arnaboldi 2010; Roediger et al. 2011; Tal &
van Dokkum 2011; Greene et al. 2012; La Barbera et al. 2012).
These studies also agree on a metallicity decrease of the stellar
populations of massive galaxies towards the outer regions as well
as a non-negligible contribution of younger stars (La Barbera et al.
2012). As an example, Coccato et al. (2010) studied one of the
brightest galaxies in the centre of the Coma Cluster, NGC 4889.
They found pieces of evidence in its metallicity profile that point
out to hierarchical formation. Two different gradients can be seen
for \(R \lesssim 1.2 R_e\) and \(R \gtrsim 1.2 R_e\). Furthermore, the abundance of \([\alpha/Fe]\)
remains flat down to 1.2\(R_e\) but decreases outwards. These pieces of
evidence suggest that the outer parts of that galaxy were formed by
accretion of low-mass systems, i.e. satellite galaxies.

In this paper, we concentrate our analysis on M87. M87 is an
interesting target to explore the formation of massive galaxies.
Located at the centre of the Virgo cluster, this object is probably one
of the oldest massive galaxies in the Universe (Kuntschner et al.
2010). In this sense, its innermost region was most likely formed
very early-on, and consequently, its stellar population should re-
flect the evolutionary path followed by this galaxy. Davies, Sadler
& Peletier (1993) provide absorption-line strengths for the centre
of this galaxy reaching as far as 50 arcsec (~4 kpc). They found a
negative gradient in Mg\(^{2+}\) and a positive gradient in H\(^\alpha\). However,
the detected emission in H\(^\alpha\) could produce a dilution on this ab-
sorption line. As Mg\(^{2+}\) can be understood as a direct measurement
from 40 to 500 arcsec. To sum up, all these pieces of evidence point
out to a negative gradient in metallicity although the age gradient is
much more difficult to determine.

In this work, we take a step forward and explore with unprece-
dented resolution (~0.3 arcsec) the variation of the spectral energy
distributions (SEDs) of M87 from 0.1 to ~8 kpc using 16 different
bands from the UV to the IR. The large wavelength range provided
is crucial to obtain accurate estimates of age and metallicity (Anders
et al. 2004).

The vicinity of M87 and the high spatial resolution (HR) of
this work allow us to explore for the first time the substructure of
the age and metallicity profiles. Well-differentiated regions in the
profiles could be an indication of different epochs of formation
of this galaxy. Our paper will focus on this.

The structure of this paper is as follows. A description of the
data and the photometry is presented in Section 2. In Section 3,
the colour (Section 3.1), age and metallicity (Section 3.2) gradients are
derived and discussed. We discuss our results in Section 4. Finally,
a summary is presented in Section 5. The distance adopted for M87
is \(D = 16.1\) Mpc (Blakeslee et al. 2001, i.e. at the distance of
the galaxy, 1 arcsec = 78 pc). The photometry is given in the AB
system unless indicated otherwise.

## 2 DATA

### 2.1 High-resolution data

The analysis conducted in this paper is based on multiwavelength
coverage of the galaxy, the same as used in Montes et al. (2014) for
the analysis of the globular cluster population of the central region
of M87. A brief description of the data is presented here. Table 1
provides a description of the main characteristics of the data set.
The near-infrared (NIR) data consist on HR images in the \(J\) and
\(K_s\) bands acquired with the Very Large Telescope (VLT) using the
Nasmyth Adaptive Optics System plus the Near-Infrared Imager
and Spectrograph (NAOS + CONICA, NaCo, 0.0271 arcsec pixel).
These data were produced by the European Southern Observatory
(ESO, 2010). The inner half square arcminute of M87 was observed in \(J\) and
\(K_s\). The bright nucleus was used as reference for the adaptive
optics. The achieved resolution was 0.27 arcsec (\(J\)) and 0.19 arcsec
(\(K_s\)) measured as the full width at half-maximum (FWHM) of the

| Table 1. Set of filters used in this study of M87 with HR. |
|----------------------------------------------------------|
| Filter | \(\lambda\) (Å) | \(\Delta\lambda\) (Å) | Instrument | Pixel scale (arcsec pixel\(^{-1}\)) | Exp. time (s) | Date | Program |
|--------|----------|----------------|----------|----------------|--------------|------|------|
| F25SRF2 | 1456.6 | 120.8 | STIS@HST | 0.025 | 3526 | 17/05/1999 | 8140 |
| F25SRF2 | 1456.6 | 120.8 | STIS@HST | 0.025 | 2680 | 14/02/2002 | 8643 |
| F25Q7TZ | 2355.3 | 419.8 | STIS@HST | 0.025 | 2372 | 17/05/1999 | 8140 |
| F336W | 3359.5 | 204.5 | WFPC2@HST | 0.046/0.1 | 28800 | 25/12/2000 | 8587 |
| F410M | 4092.7 | 93.8 | WFPC2@HST | 0.046/0.1 | 19200 | 07/02/2001 | 8587 |
| F467M | 4670.2 | 75.3 | WFPC2@HST | 0.046/0.1 | 7200 | 28/12/2000 | 8587 |
| F475W | 4745.3 | 420.1 | ACS/WFC@HST | 0.05 | 750 | 19/01/2003 | 9401 |
| F547M | 5483.9 | 205.5 | WFPC2@HST | 0.046/0.1 | 7200 | 10/02/2001 | 8587 |
| F555W | 5442.9 | 522.2 | WFPC2@HST | 0.046/0.1 | 2430 | 03/02/1995 | 5477 |
| F606W | 5919.4 | 672.3 | ACS/WFC@HST | 0.05 | 28500 | 24/12/2005 | 10543 |
| F658N | 6590.8 | 29.4 | WFPC2@HST | 0.046/0.1 | 13900 | 09/05/1996 | 6296 |
| F702W | 6917.1 | 586.7 | WFPC2@HST | 0.046/0.1 | 280 | 23/01/1995 | 5476 |
| F814W | 8059.9 | 653.0 | ACS/WFC@HST | 0.05 | 7200 | 24/1/2005 | 10543 |
| F850LP | 9036.4 | 527.2 | ACS/WFC@HST | 0.05 | 1120 | 19/01/2003 | 9401 |
| J | 12650.0 | 2500.0 | NACO@VLT | 0.027 | 784 | 23/01/2006 | 076.B - 0493(A) |
| F160W | 16506.0 | 1177.3 | NICMOS2@HST | 0.075 | 32 | 20/11/1997 | 7171 |
| K_s | 21800.0 | 3500.0 | NACO@VLT | 0.027 | 300 | 23/01/2006 | 076.B - 0493(A) |
most compact source in each image. The NaCo data reduction was performed using the ECLIPSE package provided by ESO. Photometric calibration of the images make use of standard stars taken along with the science frames. An image taken with NICMOS camera 2 using the filter F160W was also added from the Hubble Space Telescope (HST) archive. Its field of view (FOV) is smaller (19.2 arcsec × 19.2 arcsec), so the photometry provided by this filter is limited to R < 10 arcsec. This NIR data set was complemented with HST archival data covering the UV–optical range. The spatial resolution achieved is ~0.15 arcsec for the Advanced Camera for Surveys (ACS) and ~0.22 arcsec for the Wide Field Planetary Camera 2 (WFPC2).

Space Telescope Image Spectrograph (STIS) far-UV Multi-Anode Microchannel Array (MAMA; F25SFR2) and near UV MAMA (F25QTZ) images of the central region of M87 were also extracted from the archive although the images only overlap with half of the NaCo J-band FOV. The spatial resolution is 0.13 arcsec. The HST images were combined using MULTIDRIZZLE (Fruchter & Hook 2002) to achieve the nominal resolution of each camera. MULTIDRIZZLE combines the aligned individual exposures, rejects outliers and removes the geometric distortions.

### 2.2 Photometric profiles

#### 2.2.1 High-resolution profiles of the centre of M87

The HR surface brightness profiles of the centre of M87 in all filters were obtained using a custom-made task developed in IDL. The active nucleus and jet of M87 were identified and masked by eye while the detection of the globular clusters was made using SEXTRACTOR (Bertin & Arnouts 1996) and they were also masked. The central region of M87 is circular symmetric (Cohen 1986), so the photometry was extracted using circular annuli at different radial distances. To unify the effects of the resolution in the different images, we take three times the FWHM of the worst spatially resolved image (J) as the width of the rings for the photometry, i.e. ~1 arcsec. To avoid contamination due to the point spread function (PSF) wings of the nuclear point source, the inner 1 arcsec was masked in all images. For each annulus, the surface brightness was obtained averaging the pixel values.

The prominent jet of M87 may have effects in the profiles of the galaxy. To test this possible source of contamination, we derived the surface brightness profiles at both sides around the nucleus: the right-hand side, from the nucleus to the west, and the left-hand side, from the nucleus to the east. The profiles of the right- and left-hand sides present the same properties within errors and the symmetry of the integrated properties of the galaxy are not affected by the presence of the extended component associated with the jet.

Our HR photometry is given in Table A1 and the profiles presented in Fig. 1.

#### 2.2.2 Wide-field profiles

To explore the stellar populations down to M87’s effective radii (R_e = 106.2 arcsec; Falcoon-Barroso et al. 2011), the HR data described above was complemented with 2MASS1 (Jarrett et al. 2003), SDSS griz (Chen et al. 2010) and GALEX (Gil de Paz et al. 2007) surface brightness profiles collected from the literature. Typical spatial resolutions are: ~3 arcsec for 2MASS (Skrutskie et al. 2006), ~1.5 arcsec for SDSS (York et al. 2000), ~4.5–5 arcsec for GALEX (Gil de Paz et al. 2007). The exposure times of the images are: 7.8 s for 2MASS, 55 s for SDSS and 1585 s for GALEX. In addition, we have downloaded the u-band image from the SDSS archive to complement the profiles provided by Chen et al. (2010).

We also present a brief description of the derivation of the surface brightness profiles of this wide-field data set. This is important to ensure that these profiles are consistent with our HR profiles. The 2MASS profiles (Jarrett et al. 2003) were derived using an almost circular annulus of axis ratio of 0.99. Likewise, the GALEX mean surface brightness were derived within elliptical (ε = 0.2) annuli, as described in Gil de Paz et al. (2007). Chen et al. (2010) used the IRAF task ELLIPSE to derive the SDSS griz profiles, with variable ellipticity reaching a maximum of 0.13 for R > R_e, while for u we used circular annuli. The ellipticity values used to derive these profiles are very close to the circular apertures we used for the inner regions except in the case of the GALEX photometry. In any case, GALEX data will not be used to derive the main conclusions of this work as we will explain later on. The global extension of the radial profiles from the literature are 240, 403 and 331 arcsec, respectively. These profiles were used only up to ~100 arcsec for reasons explained in the following sections. SDSS and GALEX photometry were kindly provided by the authors.

#### 2.2.3 HR versus wide-field photometry

The HR photometry, in Section 2.2.1, describes the very centre of the galaxy (R < 1 kpc). The FOV of the cameras used to explore the inner region of M87 is entirely dominated by the flux of the galaxy as it is observing its inner regions. This results in an impossibility to obtain a proper sky background for these images. Therefore, the outer shape of the surface brightness profiles of the HR is compromised. To surpass this problem, we made use of wide-field photometry from the literature to determine down to which distance the radial profiles of the HR images are reliable. This is illustrated in Fig. 1, where the surface brightness profiles

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1 http://irsa.ipac.caltech.edu/cgi-bin/2MASS/LGA/nph-lga?objstr=m87

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Figure 1. Surface brightness profiles of the multiwavelength data set for M87 up to R_e. The vertical dashed line marks the position of the R_e. Different vertical shifts to the profiles were applied for visualization. Filled circles correspond to HR photometry while open circles depict wide-field profiles from the literature.
are shown. The HR profiles are plotted down to the radial distances where they are reliable. Filled circles correspond to HR photometry while open circles depict wide-field profiles from the literature. These profiles indicate which filter was used at a certain radius. To show the agreement of the HR and the outer region photometry, the profiles shown in Fig. 1 are shifted vertically for visualization purposes. As seen in Fig. 1, the HR profiles in the optical bands reach down to 10 arcsec. For STIS F25Q, the distance reduces to 5.5 arcsec. Outwards, GALEX, SSDS and 2MASS photometry were used down to M87’s $R_e$.

To avoid zero-point biases among the different data, we decided to rely on our analysis on the ground-based photometry and shift the HST profiles. In order to estimate the offsets between HR and wide-field profiles, we have compared the profiles at ~10 arcsec, to minimize the contribution of the PSF of the ground-based telescopes and the sky background oversubtraction in the HST bands. The offsets were calculated as the difference between the HST filters and the corresponding (or the nearest) ground-based filter. We provided the offsets and the root mean square (rms) between HR and wide-field profiles in a common overlapping region (from 5 to 10 arcsec) in Table B1 in Appendix B. In this overlapping region, the HR and wide-field data were used jointly to build and analyse the SEDs, i.e. when estimating the $\hat{\chi}^2$. This common HR and wide-field region is depicted by the superposition of open circles to the (smaller) filled, see Fig. 1.

The photometry was corrected for Galactic reddening using the maps of Schlegel, Finkbeiner & Davis (1998) ($E(B-V) = 0.02$) and the Cardelli, Clayton & Mathis (1989) extinction law. The presence of almost no internal dust in this galaxy, as shown in Baes et al. (2010), indicates that internal dust extinction should not affect the results presented here.

### 2.2.4 Photometric uncertainty estimation

Obtaining a realistic error estimate of our photometry is crucial in order to constrain properly the age and metallicity of the stellar populations. As mentioned before, in the innermost region of M87 we have derived the photometric profiles using circular annuli at different radial distances, averaging the fluxes within the annuli. The nominal photometric uncertainty obtained in such way is extremely low (<0.0003 mag) and does not reflect the real precision that can be expected. The two main sources of error are the uncertainty in the photometric zero-point and the photometrical uncertainties. Consequently, to get a much better estimation of the photometric errors, for each band we have fitted the radial profiles with a Sérsic function (Sérsic 1968) to determine the rms of our profile data points in relation to the Sérsic fit. The Sérsic function is a three-parameter law that is known to model very accurately the surface brightness profile of elliptical galaxies. For instance, it is known that the surface brightness profile of M87 was reported to follow an $R^{1.4}$ law (de Vaucouleurs & Nieto 1978). Hence, we have fitted the Sérsic model to our data and estimated its scatter around the fit for each band. This scatter or deviation of the Sérsic profile should be a good indication of the real photometric error in each band. The residuals

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2 It is worth noting that our intention with these Sérsic fitting is not obtaining an estimation of the structural parameters of M87 in different bands. The spatial range of our observations will not allow us to do that properly. Our goal is to have an independent photometric way of measuring the level of oscillation of our photometric data in relation to a smooth surface brightness distribution.

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### 3 THE INNER ~8 KPC OF M87

We recall that the aim of this paper is to characterize the stellar population of the inner 8 kpc of M87 using unprecedented HR SED data for its most inner regions from UV to IR. Accessing a large wavelength range yields to more reliable estimates of age and metallicity, even for older ages (Anders et al. 2004). A first inspection of the radial profiles in all bands shows a smooth behaviour. Consequently, no drastic changes are expected in the stellar population properties but a mild increase or decrease variation. We have checked visually that the presence of a disc ($R \approx 1$ arcsec) and extended filaments (reaching ~10 arcsec) of ionized gas in the $H\alpha + [N\,\text{II}]$ (F658N) image (Ford et al. 1994; Pogge et al. 2000) do not modify the profiles of the adjacent bands, e.g. $F606W$, $F702W$ (see Fig. 1).

#### 3.1 Colour gradients

Radial colour gradients can provide valuable constraints in the formation processes of ellipticals. While the NIR wavelength range depends mainly on the red giant branch, the optical regime depends on stars near the main sequence turn-off point being both metallicity and age sensitive. By using the combination of optical–IR colours, we have therefore a better chance to break the age–metallicity degeneracy inherent in optical colours alone (e.g. Kissler-Patig, Brodie & Minniti 2002). Optical–IR colours together with optical colours can separate the effects of metallicity and age (e.g. Peletier et al. 1990).
The four panels in Fig. 2 show IR, optical and combinations of optical–IR and UV–optical colours. $r - K_s$, $g - z$ and $FUV - g$ correspond to $F606W - K_s$, $F475W - F850LP$ and $F25SFR2 - F475W$ for the HST imaging of the central parts of the galaxy. The ACS filter $F475W$ ($F850LP$) is analogous to SDSS $g$ ($z$), so the comparison with the outer region of the galaxy is straightforward. A vertical shift to the $r - K_s$, $FUV - g$ and $J - K_s$ has to be applied to account for the difference among the filters: $F606W$ and $r$, $NaCo$ $J$ and 2MASS $J$ and STIS $F25SFR2$ and GALEX FUV. We have overplotted the data from Peletier (1989) for comparison. The observed colours agree with a mild decrease on the properties of the stellar population of the galaxy down to $R_e$. The decrement observed in all the colour profiles, except the UV colour, is in agreement with the broad-band optical and NIR colours seen in Peletier (1989), although in 2MASS $J - K_s$ (purple triangles) the decrease seems less pronounced in our data. Regarding the UV colour, the FUV depends mainly on hot HB stars while the optical is dominated by main sequence and giant stars (Dorman, O’Connell & Rood 1995). Thus, $FUV - g$ is a measure of the UV excess and, consequently, of the fraction of the stellar population that appears in the form of hot HB stars. It is seen that $FUV - g$ is bluer in the central parts of the galaxy, thus the UV excess is more intense, as expected in Dorman et al. (1995), and then becomes more and more faint with radius. Ohl et al. (1998) found that the $FUV - B$ colour profile is flat out to 20 arcsec and then the colour becomes redder with increasing radial distance. The contribution of the nucleus and jet is ruled out, as they only contribute about 17 per cent of the light within 20 arcsec. This result is in agreement with our $FUV - g$ colour.

In the inner $\sim 10$ arcsec, the colour profiles present an almost flat slope compared to the wide-field imaging, except in the case of $J - K_s$, and only at larger distances the colours begin to drop. Further pieces of evidence of flat IR colour profiles in the inner regions of M87 down to 5 arcsec are found in Corbin, O’Neil & Rieke (2002). It is worth noting that the $g - z$ colour shows an abrupt increase with radius for $R > 50$ arcsec not observed in any other colours in Fig. 2, probably due to an incorrect sky background estimation or PSF issues (e.g. Tal & van Dokkum 2011). This is also observed in the $g - r$ colour. Regarding $J - K_s$, the higher errors and dispersion are produced by the low-exposure times of 2MASS data. To estimate at which radius the 2MASS photometry is reliable, we have compared our $K_s$-band profile with the deeper $K$-band profile kindly provided by R. Läsker (private communication; Läsker, Ferriere & van de Ven 2014). This comparison shows that both profiles are compatible in the central parts but at distances farther than 50 arcsec the 2MASS $K_s$ profile becomes clearly underestimated. The increase in $g - z$ and the departure of the shape of 2MASS profiles beyond M87’s $R_e$ forced us to set the limit of our analysis to $\sim 100$ arcsec. In any case, the conclusions of this work do not rely on our observations for $R > 50$ arcsec (at those distances, we have used other data from the literature).

The colour gradients seem to correlate well among them. This indicates that both optical and optical–IR radial colour gradients are likely caused by an identical physical process. As the optical–IR traces metallicity, we can therefore expect that changes in these colours indicate changes in metallicity. Consequently, the metallicity gradient is very likely the main cause for the colour gradients in the other bands as well. In the following sections, we expand on this possibility.

### 3.2 Age and metallicity gradients

Taking advantage on the large wavelength range of our data set, we fitted single stellar population (SSP) models to explore whether it is possible to detect stellar population gradients in the inner 8 kpc of M87. SSP models are the most simple description we can make of our data. Note that this could be a rough assumption at large radii because we are considering a two-phase formation scenario (see the Introduction) and at large radii we expect the accretion of a variety of low-mass galaxies. We use the same approach as in Montes et al. (2014) to determine age and metallicity of the inner 3 square kpc M87 globular cluster population. We describe our approach in the following subsections.

#### 3.2.1 Methodology

An SSP is defined as a single generation of coeval stars characterized by the same parameters, the most relevant being the metallicity, age and initial mass function (IMF). The observed SEDs are compared with some model SSPs to obtain information of the stellar populations of M87. Since our data are integrated luminosities, we convolved the theoretical SED spectra with the filter response of our photometric filters to retrieve synthetic photometry for comparison. The computed magnitude, in the AB system, for the $i$th filter is

$$m_{AB}^i = -2.5 \log \left( \int_s F_\nu \phi_i(\nu) d\nu \right) + 8.906,$$

where $F_\nu$ is the theoretical SSP SED expressed in Jy, which is a function of metallicity, age and luminosity, and $\phi_i$ is the response curve of the $i$th filter. Given the wide wavelength coverage of M87 to find the most suitable SSP model, a reduced-$\chi^2$ minimization approach is applied:

$$\chi^2 = \frac{1}{N - n - 1} \sum_{i=1}^{15} \frac{(m_{obs,i} - m_{mod,i})^2}{\sigma_i^2},$$

where $m_{mod,i}$ depend on age, metallicity and luminosity, $N$ is the number of photometric filters, $n$ is the number of fitted parameters.
and σ, are the observational errors in the photometry of each band. As the parameters to fit are three: age, metallicity and luminosity, the number of spectral bands required for the fit are at least five.

To illustrate the reliability of our age and metallicity estimations, we followed the standard procedure to estimate the 68 and 95 per cent confidence regions. For each solution, we have calculated the value of the χ² for each of our models (given by equation 2). After finding the minimum and taking into account the degrees of freedom (N − n − 1), we have searched for all the solutions in the age and metallicity maps which are at a given distance of the minimum χ² reduced value, corresponding to the 68 and 95 per cent of probability as given by a chi-squared distribution table. The areas dictated by these limits represent our confidence interval solutions. Note that the degrees of freedom (N − n − 1) vary with radius.

The models used here are Bruzual & Charlot (2003, hereafter BC03) models. The BC03 SSP models contain 221 spectra describing the spectral evolution of SSPs from 0.1 Myr to 20 Gyr for six different metallicities: Z = 0.0001, 0.0004, 0.004, 0.008, 0.02 (Z⊙), 0.05 for two possible IMFs, Chabrier (Chabrier 2003) and Salpeter (Salpeter 1955). These models cover a range of wavelengths from 91 Å to 160 μm. As the age–metallicity grid is irregular, the metallicity vector was rebinned. The grid was expanded with 200 metallicities linearly interpolating the original SSPs. The maximum age of the BC03 is 20 Gyr, in excess with the current estimate of the age of the universe 13.8 Gyr (for a flat universe with H₀ = 67.3 km s⁻¹ Mpc⁻¹, Ωₘ = 0.315, Ωₐ = 0.685; Planck Collaboration et al. 2013). Therefore, we restrict the available ages of the models to the maximum age of ~14 Gyr. We use the Salpeter IMF unless indicated otherwise. BC03 models provide Chabrier and Salpeter IMFs, but using a Salpeter IMF seems a reasonable choice taking into account the recent studies favouring this kind of IMF for the most massive galaxies in the universe (e.g. Cenarro et al. 2003; van Dokkum & Conroy 2010; Ferreras et al. 2013). The treatment of the TP-AGB stars in the new models (Charlot & Bruzual, private communication) tend to overestimate the contribution of these stars in the NIR (e.g. Zibetti et al. 2013). Nevertheless, we have confirmed that the same results presented below are obtained using the Charlot & Bruzual (private communication) models. This is discussed in more detail in Appendix C.

M87 is known to have a UV upturn for both globular clusters (Sohn et al. 2006) and the galaxy itself (Gil de Paz et al. 2007). This UV upturn is thought to be consequence of the presence of low-mass helium-burning stars, the so-called extreme horizontal branch (O’Connell 1999). The SSPs of BC03 do not include these hot horizontal branch stars; therefore, it is not expected an agreement of the models with the observations in this particular wavelength range. For this reason, we exclude the UV data points from our fits.

In Fig. 3, the best model fits are shown for four SEDs at different radial distances: 0.5 kpc, 1 kpc (Rₑ/8), 4 kpc and 8 kpc (Rₑ). The insets show the contours of the 68 and the 95 per cent of probability. We can see the shift of the contours towards low metallicity as radial distance increases. For the fit at R ~ 6 kpc, it is seen the effect of the underestimation of the u and 2MASS bands (lower limits).

### 3.2.2 Age and metallicity radial profiles

In Fig. 4, the age and metallicity radial profiles of M87 obtained by fitting the models are shown. The grey polygon represent the 68 per cent confidence region obtained from the fits to the radial SEDs (see Section 3.2.1). To illustrate the quality of the fits over the radial range, we show the minimum χ² as a function of radius in Fig. C1 in Appendix C. In Fig. 4, we have overplotted other data obtained from the literature. Purple stars are data from Davies et al. (1993) from absorption-line strength of Mg II transformed to Z using the relationship provided in Casuso et al. (1996). Red squares represent the data obtained with SAURON for the central region of M87 (Kuntschner et al. 2010). The red square in the age (left-hand plot) represents the age profile derived from the SAURON data, which does not vary down to Rₑ, and, for simplicity, is represented as a single point at R = 50 arcsec. Information at higher radial distances, obtained from the literature, was added to have an overall picture of the whole galaxy. Green circles show the values of age and metallicity derived by Liu et al. (2005). The literature data are taken from several sources and different stellar population models or relationships (PEGASE models from Fioc & Rocca-Volmerange 1997, 1999 for Liu et al. 2005; Schiavon 2007 models for Kuntschner et al. 2010; Casuso et al. 1996 relationship for Davies et al. 1993; BC03 for this work). As the comparison among these different models is not straightforward, we do not consider a direct quantitative comparison in this work. In any case, trends and gradients can be compared qualitatively regardless of the absolute value.

Although the optical+NIR photometry allows us to reasonably disentangle age and metallicity (see Anders et al. 2004), we are not able to constrain both metallicity and [α/Fe] separately, and our metallicity profiles can indeed be affected by radial changes of
[α/Fe]. However, it is worth noting that in Kuntschner et al. (2010) the values of [α/Fe] are 0.41 ± 0.05 and 0.44 ± 0.05 for apertures of radii R/8 and R, respectively, indicating almost no change within errors and supporting our interpretation that the results reflect an [Fe/H] gradient.

As seen in Fig. 4, the age radial profile is compatible with no age variation down to M87’s R (∼8 kpc), although in the inner 20 arcsec the area of the polygon is wide enough to contain ages down to 3 Gyr due to age–metallicity degeneracy. Kuntschner et al. (2010) data (represented by a red square, shifted to 14 Gyr) also agree with no age variation for M87 at these radii. Despite the large errors in our results, we can rule out young ages for large radii (where our photometrical errors are smaller) as the polygon tends to get narrower outwards, due to the smaller errors of SDSS photometry.

The metallicity profile presents a plateau for the inner 1 kpc, also observed in the flattening of the colour profiles (see Section 3.1). Still, super solar metallicity values are expected for the central 1 kpc while towards larger radii the metallicity seems to decrease, i.e. metallicity descend below solar abundance. Davies et al. (1993) studied out to 50 arcsec from the centre of M87 using absorption-line strengths in spectra (purple stars). Although our plateau could be argued to be a consequence of reaching the maximum metallicity provided in BC03 (see below), it is also observed in their data, as well as the decrease of the metallicity with radius. This strongly suggests that the inner plateau in the metallicity is real.

Kuntschner et al. (2010) using SAURON measured the properties of M87 using integral field spectroscopy (red squares). Their metallicity profile surprisingly resembles our profile too, although Kuntschner et al. (2010) absolute values in the central parts are lower. It also reproduces the plateau at R < 10 arcsec. Their estimated ages (∼17 Gyr) are rescaled according to the maximum age set in Section 3.2.1: 14 Gyr. Note that the Hβ line-strengths are significantly and systematically weaker than the stellar population model predictions (see Kuntschner et al. 2010) causing that the derived ages to saturate at the maximum allowed age of the models (∼17 Gyr). Therefore, we have to be cautious deriving conclusions using this profile. Assuming that no changes are made by the determination of ages, we can say there is an agreement between the metallicity profiles.

The gradient of the entire profile, calculated as a linear fit of the metallicity [Z/H] versus log R is −0.26 ± 0.10 (−0.25 ± 0.09 for a Chabrier IMF). The Mg2 data obtained by Davies et al. (1993) also show a gradient in metallicity compatible with our results (−0.21 ± 0.01). They also find a slightly positive slope for the Hβ profile.

Furthermore, we have also explored the metallicity profile imposing an age constraint, from 10 to 14 Gyr. It seems reasonable to assume old ages for the bulk of stars of the galaxy as seen in previous studies (e.g. Liu et al. 2005; Kuntschner et al. 2010). The results are presented in Fig. C2. The main difference compared to Fig. 4 is that the width of the allowed metallicity solutions has decreased in the range from 10 to 20 arcsec. Consequently, this result supports the idea that the plateau is a real characteristic of the metallicity profile of M87 and not an artefact due to limitations of the models. In this case, the gradient is −0.27 ± 0.08.

Our results are complemented with photometric derived ages and metallicities from Liu et al. (2005) up to 5R_e. Their ages are in agreement with our results in the overlapping region, as well as with our metallicities. The gradient in metallicity of Liu et al. (2005) is −0.080 ± 0.006, shallower than what it is found here. However, there is a hint in our data of a change in the slope of the profile towards 60 arcsec (∼5 kpc) to a much shallower gradient, as observed in Liu et al. (2005). This change in the slope may be originated by the evolution of the galaxy as we will discuss below. However, note that this change in our metallicity profile coincides with the change of behaviour in the y − z colour (while the increase in the minimum 2 in Fig. C1 is due to the underestimation of the u and IR photometry), therefore the conclusions of our work are based on Liu et al. (2005) results.
4 DISCUSSION

Using HR photometry combined with wide-field literature data, we have derived ages and metallicities for the inner $R_e$ of M87 using SED fitting. We found that changes in metallicity can explain why colours become bluer towards the outer parts of the galaxy. The metallicity profile decreases with radius while ages are constant down to M87’s $R_e$. The metallicity radial profile of M87 presents three different zones: in the innermost kpc a plateau with supersolar metallicity, a decline in metallicity down to $\sim$5 kpc which is followed by an almost flat region with near solar metallicity. The shape of the metallicity profile is independent of the IMF used, Salpeter or Chabrier, as shown in Appendix C. Down to the $R_e$ of M87, the age of the stellar population is old ($>$10 Gyr) and the lack of an age gradient is compatible with a rapid episode of star formation in the past.

4.1 Comparison with previous studies

As mentioned before, our age and metallicity estimates are in agreement with previous determinations of these values by Kuntschner et al. (2010) and Liu et al. (2005). In addition, studies of globular clusters in M87 (e.g. Cohen, Blakeslee & Ryzhov 1998; Jordán et al. 2002) and their link to the galaxy itself (Kundu et al. 1999; Harris 2009) also support old ages for the bulk of stars of the galaxy, similar to what we find in this work. Our metallicities are supersolar and show evidence for a gradient towards the outer parts of the galaxy as expected from its colour profiles (Section 3.1, and Peletier et al. 1990). This is also observed in Davies et al. (1993), Liu et al. (2005) and in Kuntschner et al. (2010).

The age of the stellar population of M87 shows no variation in agreement with the lack of gradient found in massive ellipticals in, for example, Sánchez-Blázquez et al. (2006, 2007), Spolaor et al. (2008, 2010), Kuntschner et al. (2010) and Loubser & Sánchez-Blázquez (2012). It is worth noting however that, Davies et al. (1993) find a slightly positive Hβ gradient, but possibly related to contamination from Hβ emission observed in this galaxy. Conversely, Liu et al. (2005) found a mild decrease in age for the outer parts of the galaxy ($R \gtrsim R_e/2$) compatible with some galaxies in Greene et al. (2012) but contrary to the results found in Sánchez-Blázquez et al. (2007) and La Barbera et al. (2010, 2012) where null or positive age gradients are observed in early-type galaxies.

Our global metallicity gradient is $-0.26 \pm 0.10$. Similarly, Davies et al. (1993) found a metallicity gradient of $-0.21 \pm 0.01$ using absorption-line measurements of Mg_2 of the central part of M87 up to $\sim$50 arcsec. As we show now, gradients obtained in other galaxies are similar. The mean metallicity gradient of Kuntschner et al. (2010) sample of old galaxies ($>$8 Gyr) is $-0.25 \pm 0.11$. For Loubser & Sánchez-Blázquez (2012) sample of bright cluster galaxies, the metallicity gradient is $-0.29 \pm 0.06$ and for galaxies in the Coma cluster of Sánchez-Blázquez et al. (2006) is $-0.33 \pm 0.16$. However, for $R > R_e$ the gradient turns into $-0.080 \pm 0.006$ for M87 (Liu et al. 2005), compatible with the gradients of low-mass early-type galaxies (Spolaor et al. 2009).

In relation to the different gradients observed in the metallicity profile, NGC 4889, one of the two central bright cluster galaxies of the Coma cluster show comparable gradients to M87’s (Coccato et al. 2010). Two different metallicity gradients are observed for the inner part ($R \lesssim 1.2R_e; -0.35 \pm 0.02$) and outer part ($R \gtrsim 1.2R_e; -0.1 \pm 0.2$). Moreover, Baes et al. (2007) find a also a break in the slopes of the metallicity gradients, getting shallower at larger radii. A similar change in gradient for a radius $\sim R_e$ is observed in our results. This potentially indicates that different mechanisms formed the central parts of the galaxy and the outer regions.

Summarizing, the results found in our work are similar to those found by other authors in M87 and in other massive early-type galaxies. It is worth noting that the results for M87 might be generalized only to the case of galaxies being the central objects in dark matter haloes, and not massive galaxies as a whole, as central galaxies are observed to have different properties than satellites (e.g. Pasquale et al. 2010).

4.2 How can M87’s age and metallicity profiles help us to understand its formation?

According to the current scenario of galaxy formation and evolution, massive galaxies were assembled in two different phases (e.g. Naab et al. 2009). In the first phase, the innermost regions formed the majority of their stars at high redshift and on short time-scales (e.g. Thomas et al. 2005). During this dissipative ‘monolithic collapse’, stars were efficiently created while the gas sank to the centre of the forming galaxy. As a consequence of this process, a negative radial metallicity gradient was created with the central stars being more metal rich than the stars in the outskirts. For example, Larson (1974) estimated a metallicity gradient of $\sim$0.35, $\sim$0.5 for Carlberg (1984) and $\sim$1.0 in Kobayashi (2004). However, the rapid formation of the galaxy produced almost no noticeable variation in age.

In the second phase of the galaxy formation, there is a size growth of the galaxies driven by the accretion of low-mass satellites (e.g. Kaviraj et al. 2009). These satellites, mostly depleted of gas, end located in the outskirts of these galaxies (e.g. Khochar & Silk 2006). For this reason, one would expect a significant change in the stellar properties with radius as the stars of these merged satellites are mainly located in the periphery of the main galaxy due to their higher angular momentum. These stars should be relatively evolved and no star formation is expected to occur if mergers are dry. Consequently, the new accreted stars are not expected to produce significant age variations in the galaxy. As the stars of these low-mass satellites will be metal poor (as indicated by observations, e.g. Spolaor et al. 2009), the radial metallicity gradient is predicted to change due to the contribution of metal-poor stars from the shredded satellites (Naab et al. 2009). For instance, one could expect a steepening of the metallicity gradient in the outskirts. In other words, we expect a steep negative radial gradient in the inner region of the galaxy while in the outer parts a change of gradient is suggested. On what follows, we discuss how our results fit in this picture.

One of the most intriguing results that we have found in this paper is the presence of a plateau in the colour profiles and in the metallicity gradient of M87 at $R \lesssim 1$ kpc. This flattening in the metallicity profile is not expected in the models of a dissipative ‘monolithic collapse’. Is this plateau a real property of the metallicity profile? As shown in Fig. 4, Davies et al. (1993) and Kuntschner et al. (2010) found the same behaviour using ground-based data affected by seeing up to 3 and 1 arcsec, respectively. Our HR results, show that the metallicity flattening is not caused by the blurring effect of their seeing. Intriguingly, this inner plateau is not a unique feature of M87. In fact, this kind of behaviour is also observed in Sánchez-Blázquez et al. (2007), where a similar flattening for the inner $\sim$9 arcsec ($\sim$2.5 kpc) is present in the metallicity profile of the field massive galaxy NGC 1600.

How can we explain this metallicity plateau ($\sim$1 kpc) in the context of massive galaxy formation? The time-scales for dissipative collapse are of $<0.5$–$1$ Gyr (Pipino et al. 2008). To explore the feasibility of these short time-scales for the formation of the
innermost region of M87, we have estimated the mass enclosed by
the plateau using equation 15 in Trujillo, Graham & Caon (2001).
Almost 10 per cent of the mass of M87 is within ~1 kpc. That is ~7 × 10^{10} M_{\odot}, assuming that the total stellar mass of M87 is 6.8 ± 1.1 × 10^{11} M_{\odot} (taken from Forte, Vega & Faifer 2012). So, the star formation rate within ~1 kpc should have been >70–140 M_{\odot} yr^{-1}. Star formation rates as high as ~3000 M_{\odot} yr^{-1} have been found in a massive starbursts galaxies at z ~ 6 (Riechers et al. 2013). Consequently, a rapid monolithic collapse looks like a very plausible scenario. New evidence in the recently discovered relic galaxy NGC 1277 (Trujillo et al. 2014) also support this picture.

Moreover, the size of this plateau can provide clues about the size evolution of M87. It is widely known that high-redshift massive galaxies were smaller in size than their present-day massive counterparts (e.g. Daddi et al. 2005; Trujillo et al. 2006; Buitrago et al. 2008). Possibly, this evolution in size has left a signature on the properties of the stellar populations of M87. For this reason, we have calculated the R_e that a galaxy like M87 would have had at z = 2. Using the following equation for size evolution (in Trujillo et al. 2011):

\[ \log R_f = \log R_i + \Delta \log R_{M,\text{final}} + C \log \left(\frac{M_f}{M_i}\right), \]

where R_i and M_i are the radius and the mass at z = 0, and R_f and M_f are the radius and the mass at a given z. \( \Delta \log R_{M,\text{final}} \) accounts for the variation of the radius at a fixed mass, while the term C log \( \left(\frac{M_f}{M_i}\right) \) reflects the change in radius due to the variation of the mass as a consequence of the accretion of satellite galaxies. Many of the previous parameters are fixed by the observations. For instance, we know that galaxies have doubled their mass since z = 2 (van Dokkum et al. 2010), C = 0.56 from Shen et al. (2003) and the evolution in radius at a fixed stellar mass is described by \( R_e = R_e(1 + z)^{\beta} \). The \( \beta \) parameter ranges from ~0.75 to ~1.62 (see Oser et al. 2012, and references therein). We assume that R_e is the observed R_e of M87 at z = 0 (106.2 arcsec; Falcón-Barroso et al. 2011). The above values provide us with a region of potential values for the size (R_e) of M87 at z = 2. We obtain that M87 R_e at z = 2 should have been between 0.94 to 2.5 kpc in agreement with the position of the turning point of the plateau at ~1 kpc, given that the formation of this flattening was occurred very early-on. This region is shaded in light blue in Fig. 4. As discussed in Falcón-Barroso et al. (2011), the value of the R_e of M87 is uncertain. According to the size distribution of galaxies in Shen et al. (2003), we expect a higher R_e (~10 kpc). Therefore, the values obtained for the size of M87 at z ~ 2 could range between 1 and 3 kpc, still compatible with our results. This matches the picture that this flattening of the metallicity provides a signature of the size of the protogalaxy at z = 2, after its quick formation.

Concerning the rest of the galaxy, beyond the inner plateau there is a zone of declining metallicity observed from ~1 to ~5 kpc (see Fig. 4). Although the global gradient is ~0.26 ± 0.10, the local gradient for this region, between 1 and 5 kpc, is steeper: ~0.4 ± 0.2. This steep metallicity gradient down to R_e is reminiscent of the predictions of the dissipative quasi-monolithic collapse mentioned before (e.g. Larson 1974; Carlbreg 1984; Kobayashi 2004; Pipino et al. 2008). The slopes range between ~1 and ~0.35 for different models, in agreement with the gradient found in M87. While this dissipative process tend to create metallicity gradients, mergers between galaxies destroy these gradients (e.g. White 1980; Kobayashi 2004). Our derived metallicity gradient is compatible with the ~0.3 for galaxies built in a dissipative collapse. Consequently, the observed [Z/H] gradient is probably the consequence of the dissipative formation of this zone of the galaxy. In short, the inner 5 kpc of M87 seems to have formed through a dissipative collapse, with the innermost 1 kpc having formed in an extremely short timescale as suggested by the plateau in its metallicity gradient.

Outwards, at ~5 kpc, there is a change in the metallicity gradient that becomes flat at these distances. This evidence of a change of slope supports the scenario, as discussed above, where the centre of the galaxy formed via a rapid dissipative process whereas the rest of the galaxy was built via accretion of low-mass satellites. If these low-mass systems had been accreted in a more massive galaxy, different gradients are a natural outcome as the stars tend to populate the outer parts of the galaxy as seen in, for example, Coccato et al. (2010). This flattening suggests that most of the mass that built the outskirts of the galaxy came from satellites of similar metallicity (subsolar). Moreover, this gradient turning point denotes where the influence of the massive protogalaxy ends (i.e. at 2 ~ 3 R_e at z = 2).

This behaviour of the metallicity gradient is consistent with recent studies (e.g. Daddi et al. 2005; Trujillo et al. 2006; Trujillo et al. 2011) where early-type galaxies have sizes a factor of 4 larger than their counterparts at z ~ 2. The central stellar mass density of the massive galaxies at high-z do not differ much from the central density of nearby galaxies (Hopkins et al. 2009). Consequently, the majority of the evolution has taken place in their outer regions. The high dispersion in gradients for high-mass galaxies observed in Spanelor et al. (2009) also points to minor mergers as a mechanism for the build-up of the galaxy.

In summary, the metallicity profile presents three different zones that correspond to two separate mechanisms for the formation of the galaxy. The inner parts of the galaxy, \( R < 5 \) kpc, are likely formed as a result of a dissipative event in the past. They have formed very rapidly, especially the very central ~1 kpc which seems to be the consequence of a very intense burst of star formation. Oppositely, the outer galaxy, \( R > 5 \) kpc may be the result of the accretion of low-mass galaxies.

5 SUMMARY AND CONCLUSIONS

Using HR imaging from HST and adaptive optics from NaCo at VLT, we derived radial SEDs for the central ~1 kpc of M87. This data set was complemented with wide-field imaging from GALEX, SDSS and 2MASS to reach up to M87’s R_e (~8 kpc). Constructing colours from this data set, radial changes in the stellar populations are seen. Studying this in more detail through SED fitting, we found that radial variations trace changes in metallicity (Section 3.2). Adding data from the literature up to 5R_e, three different behaviours for the metallicity profile are observed: a central flattening or plateau at \( R < 1 \) kpc, a decline in metallicity down to \( R_e \) and a change in the metallicity gradient for \( R > R_e \). The central metallicity gradient agrees with previous estimates of M87 with absorption-line strengths. The metallicity structure of M87 is consistent with the current scenario of galaxy formation where the central part of the galaxy had formed first and the outer part was accreted via dry minor merging.

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REFERENCES

Anders P., Bissantz N., Fritze-v. Alvensleben U., de Grijs R., 2004, MNRAS, 347, 196
Baes M., de Zeeuw P., 2010, A&A, 518, L53
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Blakeslee J. P., Lucey J. R., Barris B. J., Hudson M. J., Tonry J. L., 2001, MNRAS, 327, 1004
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000 (BC03)
Buitrago F., Trujillo I., Conselice C. J., Bouwens R. J., Dickinson M., Yan H., 2008, ApJ, 687, L61
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Carlberg R. G., 1984, ApJ, 286, 416
Cassu E., Vazdekis A., Peletier R. F., Beckman J. E., 1996, ApJ, 458, 533
Cenarro A. J., Gorgas J., Vazdekis A., Cardiel N., Peletier R. F., 2003, MNRAS, 339, L12
Chabrier G., 2003, ApJ, 586, L133
Chen C.-W., Côté P., West A. A., Peng E. W., Ferrarese L., 2010, ApJS, 191, 1
Chiosi C., Carraro G., 2002, MNRAS, 335, 335
Coccato L., Gerhard O., Arnaboldi M., 2010, MNRAS, 407, L26
Coleman J. G., 1986, AJ, 92, 1039
Cohen J. G., Blakeslee J. P., Ryzhov A., 1998, ApJ, 496, 808
Corbin M. R., O’Neil E., Rieke M. J., 2002, AJ, 124, 183
Daddi E. et al., 2005, ApJ, 626, 680
Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS, 262, 650
de Vaucouleurs G., Nieto J.-L., 1978, ApJ, 220, 449
Dorman B., Ferreras I., de la Rosa I. G., Vazdekis A., de Carvalho R. R., Falcón-Barroso J., Ricciardelli E., 2013, MNRAS, 429, L15
Fioc M., Rocca-Volmerange B., 1997, A&A, 326, 950
Fioc M., Rocca-Volmerange B., 1999, preprint (astro-ph/9912179)
Ford H. C. et al., 1994, ApJ, 435, L27
Forte J. C., Vega E. I., Faifer F., 2012, MNRAS, 421, 635
Franx M., Illingworth G., 1990, ApJ, 359, L41
Fruchter A. S., Hook R. N., 2002, PASP, 114, 144
Gallazzi A., Charlot S., Pierini D., Pasquali A., 2013, MNRAS, 439, L15
Gallazzi A., Charlot S., Pierini D., Pasquali A., 2013, MNRAS, 439, L15
Greene J. E., Murphy M. J., Comerford J. M., Gebhardt K., Adams J. J., 2012, ApJ, 750, 32
Greene J. E., Murphy M. J., Comerford J. M., Gebhardt K., Adams J. J., 2012, ApJ, 750, 32
Harris W. E., 2009, ApJ, 703, 939
Hopkins P. F., Bundy K., Murray N., Quataert E., Lauer T. R., Ma C.-P., Harris W. E., 2009, ApJ, 703, 939
Huchra J. P., 2002, A&AS, 117, 393
Izotov I. Y., Thuan T. X., 1999, ApJ, 514, 103
Johansson P. H., Ostriker J. P., West M. J., Marzke R. O., 2002, ApJ, 576, L113
Kobayashi C., Mori M., Kodama T., 2008, ApJ, 676, 15
Kuntschner H. et al., 2010, MNRAS, 408, 1996
La Barbera F., Ferreras I., de la Rosa I. G., Vazdekis A., de Carvalho R. R., Falcón-Barroso J., Ricciardelli E., 2013, MNRAS, 429, L15
La Barbera F., Ferreras I., de la Rosa I. G., Vazdekis A., de Carvalho R. R., Falcón-Barroso J., Ricciardelli E., 2013, MNRAS, 429, L15
Laird R. B., 1974, MNRAS, 166, 585
Lisker R., Ferrarese L., van de Ven G., 2014, ApJ, 780, 69
Liu Y., Zhou X., Ma J., Wu H., Yang Y., Li J., Chen J., 2005, ApJ, 129, 2628
Lopes P. A. A., 2010, AJ, 140, 1528
van Dokkum P. G. et al., 2010, ApJ, 709, 1018
van Dokkum P. G., Conroy C., 2010, Nature, 468, 940
van Dokkum P. G., Conroy C., 2010, ApJ, 709, 1018
White S. D. M., 1980, MNRAS, 191, 1 p
York D. G. et al., 2000, AJ, 120, 1579
Zibetti S., Gallazzi A., Charlot S., Pierini D., Pasquali A., 2013, MNRAS, 428, 1479

APPENDIX A: THE RADIAL PROFILES OF THE CENTRE OF M87

Here, we present the photometric data derived for the centre of M87 using HR imaging. The photometric errors are derived from the residuals to Sérsic fits for HR and wide-field profiles in the overlapping region.

APPENDIX B: SÉRSIC FITS RESIDUALS AND HR/WIDE-FIELD OFFSETS

To illustrate how the errors have been estimated, we provide the residuals of the profiles to the corresponding Sérsic fits for HR and wide-field data in Fig. B1. In Table B1, we also reported the shifts and the rms between HR and wide-field profiles in the overlapping region.

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Table A1. Data for the inner 19 arcsec of M87.

| Radius (arcsec) | FUV STIS | NUV STIS | F336W STIS | F410M STIS | F467M STIS | F475W STIS | F555W STIS | F547M STIS | F606W STIS | F658N STIS | F702W STIS | F814W STIS | F850LP STIS | J NaCo STIS | F160W STIS | Ks STIS |
|----------------|----------|----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|----------|--------|
| 1.5            | 21.93    | 21.66    | 19.76      | 18.50      | 17.67      | 17.63      | 17.15      | 17.03      | 16.85      | 16.45      | 16.18      | 15.97      | 15.61      | 15.33      | 15.54    |
| 2.5            | 22.15    | 21.96    | 19.94      | 18.64      | 17.81      | 17.77      | 17.30      | 17.17      | 17.00      | 16.67      | 16.64      | 16.33      | 16.11      | 15.74      | 15.48    |
| 3.5            | 22.22    | 22.16    | 20.07      | 18.76      | 17.93      | 17.89      | 17.41      | 17.29      | 17.13      | 16.86      | 16.76      | 16.45      | 16.24      | 15.86      | 15.61    |
| 4.5            | 22.47    | 22.34    | 20.19      | 18.87      | 18.05      | 18.00      | 17.53      | 17.40      | 17.25      | 17.00      | 16.88      | 16.57      | 16.35      | 15.97      | 15.72    |
| 5.5            | 22.60    | 22.53    | 20.31      | 18.98      | 18.16      | 18.12      | 17.65      | 17.52      | 17.37      | 17.12      | 17.00      | 16.69      | 16.48      | 16.08      | 15.84    |
| 6.5            | 22.75    | –        | 20.43      | 19.10      | 18.29      | 18.24      | 17.77      | 17.64      | 17.49      | 17.25      | 17.12      | 16.81      | 16.60      | 16.20      | 15.96    |
| 7.5            | 22.89    | 20.55    | 19.23      | 18.41      | 18.37      | 17.89      | 17.77      | 17.62      | 17.37      | 17.25      | 16.94      | 16.72      | 16.31      | 16.08      | 16.30    |
| 8.5            | 22.99    | 20.68    | 19.35      | 18.54      | 18.49      | 18.01      | 17.89      | 17.74      | 17.50      | 17.37      | 17.07      | 16.85      | 16.42      | 16.20      | 16.43    |
| 9.5            | 23.14    | 20.80    | 19.47      | 18.66      | 18.61      | 18.13      | 18.02      | 17.86      | 17.62      | 17.49      | 17.19      | 16.97      | 16.52      | 16.32      | 16.55    |
| 10.5           | 23.25    | 20.93    | 19.59      | 18.78      | 18.73      | 18.25      | 18.14      | 17.98      | 17.75      | 17.62      | 17.31      | 17.09      | –          | –          | –        |
| 11.5           | 23.36    | 21.05    | 19.70      | 18.90      | 18.84      | 18.37      | 18.26      | 18.10      | 17.86      | 17.74      | 17.43      | 17.21      | –          | –          | –        |
| 12.5           | 23.44    | 21.17    | 19.81      | 19.02      | 18.95      | 18.48      | 18.38      | 18.21      | 17.97      | 17.85      | 17.54      | 17.32      | –          | –          | –        |
| 13.5           | 23.54    | 21.29    | 19.92      | 19.13      | 19.06      | 18.59      | 18.49      | 18.32      | 18.08      | 17.96      | 17.65      | 17.43      | –          | –          | –        |
| 14.5           | 23.62    | 21.40    | 20.02      | 19.14      | 18.69      | 18.59      | 18.42      | 18.19      | 18.07      | 17.75      | 17.53      | –          | –          | –          | –        |
| 15.5           | 23.71    | 21.50    | 20.11      | 19.35      | 19.25      | 18.79      | 18.69      | 18.52      | 18.30      | 18.17      | 17.85      | 17.63      | –          | –          | –        |
| 16.5           | 23.78    | 21.57    | 20.21      | 19.43      | 19.35      | 18.89      | 18.78      | 18.61      | 18.40      | 18.27      | 17.94      | 17.73      | –          | –          | –        |
| 17.5           | 23.85    | 21.64    | 20.30      | 19.51      | 19.43      | 18.99      | 18.87      | 18.70      | 18.49      | 18.37      | 18.04      | 17.82      | –          | –          | –        |

Figure B1. Residuals of the observed profiles after subtracting their corresponding Sérsic fits. The filled circles indicate HR profiles while the open circles depict the wide-field data.

APPENDIX C: AGE AND METALLICITY RADIAL PROFILES FOR DIFFERENT CONSTRAINTS

Here, we present the results of the fits to the radial SEDs of M87, following Section 3.2. Fig. C1 shows the minimum $\tilde{\chi}^2$ as a function of radius corresponding to Fig. 4. When the model is a good representation of the data and the errors are properly estimated, the

Figure C1. Minimum $\tilde{\chi}^2$ as a function of radius. It is clearly seen the effect of the incorrect sky subtraction for $u$ and 2MASS photometry at $R > 40$ arcsec.

Table B1. Offset and rms between HR and wide-field profiles.

| Filter       | Shift (mag arcsec$^{-2}$) | rms |
|--------------|---------------------------|-----|
| FUV STIS     | -0.21                     | 0.096 |
| NUV STIS     | 0.50                      |      |
| F336W STIS   | -0.25                     | 0.050 |
| F410M STIS   | -0.02                     | 0.020 |
| F467M STIS   | -0.02                     | 0.010 |
| F475W STIS   | -0.04                     | 0.006 |
| F555W STIS   | -0.10                     | 0.010 |
| F547M STIS   | -0.40                     | 0.030 |
| F606W STIS   | -0.11                     | 0.007 |
| F658N STIS   | -0.15                     | 0.014 |
| F702W STIS   | -0.10                     | 0.009 |
| F814W STIS   | -0.10                     | 0.015 |
| F850LP STIS  | 0.08                      | 0.014 |
| J NaCo       | 0.01                      | 0.005 |
| F160W STIS   | 0.01                      | 0.010 |
| K NaCo       | 0.00                      | 0.010 |
Figure C2. The same as in Fig. 4 but using the BC03 SSP models with ages constrained from 10 to 14 Gyr. The gradient is $-0.27 \pm 0.08$.

Figure C3. The same as in Fig. 4 but using the BC03 SSP model with a Chabrier (2003) IMF. The gradient is $-0.25 \pm 0.09$.

Figure C4. The same as in Fig. 4 but using the Charlot & Bruzual (in preparation) models. The gradient in this case is $-0.29 \pm 0.09$. 
expected values of $\chi^2$ should be around 1. For $R \gtrsim 40$ arcsec, the increase in the value of the $\chi^2$ is due to the effect of the sky over-subtraction in the 2MASS and $u$ profiles. For this reason, the values are marked as upper limits.

We have also tested different SSPs constraints and models to check the reliability of our results. First, we imposed an age constraint: from 10 to 14 Gyr. It seems reasonable to assume an old age for the bulk of stars of the galaxy given the results of previous studies (e.g. Liu et al. 2005; Kuntschner et al. 2010). The results are presented in Fig. C2. The uncertainty on the metallicity profile has decreased in the inner 20 arcsec, not reaching the highest metallicity available for the models. Consequently, this result supports the idea that the plateau at $R < 1$ kpc is a real characteristic of the metallicity profile of M87 and not an artefact due to the limitations of the models. We also present the results of using BC03 models with a Chabrier (2003) in Fig. C3 and Charlot & Bruzual (private communication) in Fig. C4. The gradients are $-0.27 \pm 0.08$, $-0.25 \pm 0.09$ and $-0.29 \pm 0.09$, respectively.