PPAK Wide field Integral Field Spectroscopy of NGC 628
III. Stellar population properties

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ABSTRACT
We present a stellar population analysis of the nearby, face-on, SA(s)c galaxy, NGC 628, which is part of the PPAK IFS Nearby Galaxies Survey (PINGS). The data cover a field of view of ~ 6 arcmin in diameter with a sampling of ~2.7 arcsec per spectrum and a wavelength range (3700-7000 Å). We apply spectral inversion methods to derive 2-dimensional maps of star formation histories and chemical enrichment. We present maps of the mean (luminosity- and mass-weighted) age and metallicity that reveal the presence of structures such as a nuclear ring, previously seen in molecular gas. The disk is dominated in mass by an old stellar component at all radii sampled by our data, while the percentage of young stars increase with radius. The mean stellar age and metallicity profiles have two well-defined regions, an inner one with flatter gradients (even slightly positive) and an external one, with a negative, steeper one, separated at ~60 arcsec. This break in the profiles is more prominent in the old stellar component. The young component shows a metallicity gradient that is very similar to that of the gas, and that is flatter in the whole disc. The agreement between the metallicity gradient of the young stars and the gas, and the recovery of the measured colours from our derived star formation histories validate the techniques to recover the age-metallicity and the star formation histories in disc galaxies from integrated spectra. We speculate about the possible origin of the break and conclude that the most likely scenario is that we are seeing, in the center of NGC 628, a dissolving bar, as predicted in some numerical simulations.

Key words: galaxies: abundances; galaxies: evolution; galaxies: formation; galaxies: spiral; galaxies: stellar content

1 INTRODUCTION
Quantifying the star formation histories of galaxies constitutes one of the major unsolved issues towards a complete understanding of galaxy formation. Although this task is difficult, analyses of stellar populations constitute a step forward toward the achievement of this goal. In the majority of cases, these studies have to be made using integrated spectra or colours, as we can only resolve stars in a limited number of galaxies. While studies of stellar populations for early-type galaxies are abundant in the literature (e.g., Trager et al. 2000; Kuntschner 2000, Thomas et al. 2005; Sánchez-Blázquez et al. 2006abc; Smith, Lucy & Hudson 2007, among many others), these studies are much more sparse for disc galaxies. Until very recently, the study of the stellar component in disk galaxies outside the local group was restricted to broadband photometric data (Bell & de Jong 2000; MacArthur et al. 2004; Pohlen & Trujillo 2006; Muñoz-Mateos et al. 2007; Roediger et al. 2012). These studies find that disc galaxies tend to be bluer in the external parts, a trend that is usually interpreted in terms of stellar population gradients as galaxies tend to be younger and more metal poor in the external parts. However, there are large discrepancies in the magnitude of the stellar population gradients as galaxies tend to be younger and more metal poor in the external parts. However, there are large discrepancies in the magnitude of the stellar population gradients derived by different authors due, partially, to the difficulty in disentangling the effects of the age, metallicity and dust extinction by using only colours. Spectroscopic studies may help to alleviate the associated degeneracies but the low surface brightness of the disc region and the nebular emission lines filling some of the most important age-diagnostic absorption features make these studies very difficult. In the last few years, however, the advent of
new techniques to separate the contributions of stellar and gaseous components (see, e.g., Sarzi et al. 2005) and large aperture telescopes have allowed the obtention of enlightening results in this field (see, e.g., Yoachim & Dalcanton 2008; MacArthur, González & Courteau 2009; Pérez et al. 2011; Sánchez-Blázquez et al. 2011).

All the studies quoted above used long-slit spectroscopy, focusing along a predefined spatial axis. Disc galaxies, however, have a complex geometry, with many structural components, such as bulges, bars, rings, etc., which makes the interpretation of the long-slit data a difficult task. Integral Field spectroscopy (IFS, hereafter) allows the study of the different galaxy components mentioned above separately. IFS data cubes provide, for each pixel of the galaxy, a spectrum from which absorption and emission lines can be extracted, allowing to decipher the star formation history and the physical properties of the interstellar medium in galaxies. Also, IFS offers a unique opportunity to improve the signal to noise ratio of the data by averaging many more spectra in the external parts of the galaxy and makes easier the masking or the extraction of the HII regions in the spatial map. In the last few years, there have been some studies of the stellar population properties of disc galaxies from IFS spectroscopy (Ganda et al. 2007; Sánchez et al. 2011; Yoachim et al. 2009, 2012), probing the potential of this technique. In fact, many ongoing and planned surveys are devoted to the observations of nearby galaxies using Integral Field Units (e.g., CALIFA (Sánchez et al. 2011); VENGA (Blanc et al. 2010); SAMI (Croom et al. 2012); MANGA (K. Bundy)).

A further complication in the study of stellar population in disc galaxies is that, surely, the stars did not form in a single burst of a given age and metallicity as usually assumed in studies of early-type galaxies. Therefore, the comparison of spectral characteristics with single stellar populations (SSP) models leads to information which is difficult to interpret. Fortunately, in the last decade there has been a tremendous improvement in the stellar population analysis techniques, associated with the release of well-calibrated stellar libraries (e.g., STELIB, LeBorgne et al. 2003; MILES, Sánchez-Blázquez et al. 2006; Indo-US (Valdes et al. 2004); CaT (Cenarro et al. 2001ab) that have allowed the construction of stellar population models that predict the whole synthetic spectrum of a population with a given age and metallicity (e.g., Vazdekis 1999; Vazdekis et al. 2003, 2010; Bruzual & Charlot 2003, Conroy et al. 2009, 2010ab; Maraston & Strömbck 2011). This has driven the development of inversion algorithms to extract information about the star formation histories and the metallicity evolution from integrated spectra (e.g., MOPED, Heavens et al. 2000, Panter et al. 2003; STARLIGHT: Cid Fernandes et al. 2005, Moutata et al. 2005; STECKMAP: Ocvirk et al. 2006ab; VESPA: Tejeiro et al. 2007; FIT3D: Sánchez et al. (2008); UlySS: Koleva et al. 2009). The combination of these two developments make the study of the stellar population properties in disc galaxies very timely.

In the present paper we derive the stellar population properties and star formation histories of NGC 628 in a 3-dimensional fashion, using several techniques. NGC 628 (M74) is an extensively studied isolated grand-design SA(s)c spiral galaxy at a distance of 9.3 Mpc in the constellation of Pisces. It does not show any evidence of having had encounters with satellites or other galaxies in the last 10⁹ yr (Kamphuis & Briggs 1992). Regarding its structure, NGC 628 shows an outer III ring at around 12 arcmin from the nucleus (Roberts 1962; Briggs et al. 1980) that seems to be due to the interaction with two large high-velocity clouds accreting onto the outer parts of the disc (Kamphuis & Briggs 1992; Lópe-Corredoira et al. 2002; Beckman et al. 2003). It also has a inner rapidly rotating disc-like structure (Baigle et al. 2006), a circumnuclear ring of star formation at ~2 kpc from the center (discovered in 12CO J=1-0 sub-mm, Wakker & Adler 1995, and 2.3 µm CO absorption, James & Seigar 1999) and a nuclear, nested bar on a ~100 pc scale (Laine et al. 2002). An oval structure has also been detected at a radii around 50” ~ 2.3 kpc (Seigar 2002). All these characteristics indicate that secular evolution processes are taking place in this galaxy (see Fathi et al. 2007).

This paper can be considered as a pilot study that allows us to explore the techniques that will be applied to the study of a larger sample of galaxies from the CALIFA survey (Sánchez et al. 2012). The study complements and expands the ones presented in Sánchez et al. (2011, paper I) and Rosales-Ortega et al. (2011, paper II) for the same galaxy. NGC 628 is the largest object within the PPAK Integral Field Spectroscopy Nearby Galaxies Survey: PINGS (Rosales-Ortega et al. 2010). PINGS IFS survey of nearby (<100 Mpc) well-resolved spiral galaxies is specially designed to obtain complete maps of the emission-line abundances, stellar populations, and reddening using an IFS mosaicking imaging, which takes advantage of what is currently one of the world’s widest field-of-view (FOV) integral field units.

Section 2 briefly describes the observations, Sec. 3 the analysis performed to derive the stellar population properties and, in Sec. 4 we present our results. Section 5 tests the robustness of the solution comparing with the analyses performed with different techniques and by different authors. In Sec. 6 we provide a brief discussion and Sec. 7 summarizes our conclusions.

2 OBSERVATIONS

The observations analysed here are part of the PPAK IFS Nearby Galaxies Survey (PINGS, Rosales-Ortega et al. 2010). The PPAK fibre bundle consists of 382 fibers of 2.7” diameter each. Of these 382 fibers, 331 are concentrated in a single hexagonal bundle covering a field-of-view of 72×63”, with a filling factor of ~65%. The sky background is sampled by 36 additional fibers in 6 bundles of 6 fibers each, distributed along a circle of ~90 arcsec from the center. Due to the large size of NGC 628 compared to the field-of-view of the instrument, a mosaicking scheme was adopted. The
central position was observed in dithering mode to gain spatial resolution, while the remaining positions were observed without dithering due to the large size of the mosaic.

The observations for this galaxy extended over a period of three years in different stages, with a total of six observing nights. The spectroscopic mosaic contains 11094 spectra covering an area of ∼44 arcmin$^2$ (see papers I and II for details), which is the largest area ever covered by an IFU mosaicking. The V300 grating was used for all the observations, covering the wavelength range ∼3700-7100Å, with a spectral resolution of FWHM ∼8Å. The seeing varied between ∼1 and ∼1.8 arcsec, and the median seeing was 1.4 arcsec. Different spectrophotometric stars were observed during the observing runs with, at least, two stars observed each night. The estimated spectrophotometric accuracy is ∼0.2 mag.

Figure 1 shows the mosaic pattern covered by the observations. The data reduction is described in Rosales-Ortega et al. (2010) and will not be repeated here. The main properties of the galaxy are shown in Table 1.

3 ANALYSIS

3.1 Emission line removal

We used a clean version of the integral field spectroscopy (IFS hereafter) mosaic of NGC 628 obtained by: 1) applying a flux threshold cut choosing only those fibers with an average flux along the whole spectral range greater than 10$^{16}$ ergs$^{-1}$ cm$^{-2}$ Å$^{-1}$ (in order to get rid of spectra for which no information could be derived); 2) removing bad fibers (due to cosmic rays and CCD cosmetic defects) and foreground stars (10 within the observed FOV of NGC 628). In total, 63% of clean fibers were preserved with respect to the original mosaic.

The first step to analyse the stellar population properties is to decouple the emission from the underlying stellar population. One of the advantages of IFS over the long slit observations is that it allows this decoupling in a spatially-resolved basis. The underlying stellar continuum was thus decoupled from the emission lines following the procedure outlined in papers I and II. First, for each fiber, the stellar population was fit by a linear combination of synthetic templates of three ages (0.09, 1.00 and 17.78 Gyr) and two metallicities (Z = 0.0004 and 0.03) from the MILES library (Vazdekis et al. 2010) using FIT3D (Sánchez et al. 2012). These templates are too simplistic to describe in detail the stellar populations in the dataset, and were merely used to get a first-order model of the stellar continuum to be subtracted from each spectrum, obtaining a pure-emission one.

Based on this residual spectrum, we obtained a model for the most prominent emission lines in the considered wavelength range, including: Hα, Hβ, Hγ, [O II] λ3727, [O III] λλ4959,5007, [N II] λλ6548,6583 and [S II] λλ6717,6731, and also for the most prominent sky residuals present in the spectrum, i.e. [O I] λ5577, and [Na I] λ5893 lines. The modeled emission lines were subtracted from the observed spectrum, obtaining an emission-free one. Finally, the data was spatially resampled to a data cube with a regular grid of 2 arcsec/spaxel, adopting a flux-conserving interpolation method, leading to a pure-continuum 3D cube.

However, the aim of this removal in papers I and II was to extract the strong emission lines from HII regions, not the diffuse component and, with this aim, a threshold in the emission line flux was imposed. In the reanalysis of the data presented here, we have also removed the fainter diffuse emission remaining in some of the spectra. To do this, we use the software GANDALF (Sarzi et al. 2005) for the stellar component are derived. The best values of velocity and $\sigma$ and the best template mix are then used as initial values for the derivation of emission lines using GANDALF. Emission line equivalent-widths, radial velocities and $\sigma$ for the gaseous component are derived in this second step. The fit allows for a low-order Legendre polynomial in order to account for small differences in the continuum shape between the pixel spectra and the templates. The best fitting template mix is determined by a $\chi^2$ minimization in pixel space. Emission line spectra at each bin were subtracted from the observed spectra for the subsequent analysis. Figure 2 shows an example of the residual emission in two of the spectra before and after removing the nebular component.

3.2 Star formation histories

The most popular approach to derive stellar population properties from integrated spectra has been to compare absorption lines –usually Lick/IDS indices– with those com-

\footnote{The use of a different code simply does not respond to any reason in particular, and this second step could have been perform also with FIT3D.}

\footnote{http://miles.iac.es}
computed with single stellar populations (SSP) of a given age and metallicity (e.g., Trager et al. 2000; Thomas et al. 2005; Sánchez-Blázquez et al. 2006abc; Kuntschner et al. 2006, among many others). Although this may not be a bad approximation for luminous, early-type galaxies, studies of resolved stellar population in nearby discs have shown that their star formation history is better represented by exponential shapes, and that enhanced star formation at later times is not uncommon (e.g., Kennicutt, Tamblyn & Congdon 1994; Huang et al. 2013). Therefore, the SSP approach is not adequate for the present study\(^4\). Furthermore, we want to study the possibility of deriving, not only mean ages and metallicities, but also the evolution of the metallicity gradient with time, for which we need to derive the whole star formation history and the evolution of the metallicity with age in all spectra.

In this paper we have chosen to perform a full spectral fitting using the code STECKMAP (STEllar Content via Maximum A Posteriori likelihood, Ocvirk et al. 2006ab\(^5\)). In STECKMAP, the reconstructions of the stellar age distribution and the age-metallicity relation are non-parametric, i.e. no specific shape is assumed. The only \textit{a priori} conditions that we use are positivity and the requirement that the solution (the variation of the flux with age and the age metallicity relation) is sufficiently smooth. The smoothness parameter can be set by generalized cross-validation according to the level of noise in the data in order to avoid over-interpretation. We use here the stellar population models MILES, spanning an age range from \(6.3 \times 10^7\) to \(1.7 \times 10^{10}\) yr, divided in 30 logarithmic age bins, and a metallicity range \([Z/H]=[-0.2, -1.3]\).

The function to minimize (the objective function) is defined as:

\[
Q_\mu = \chi^2(s(x, Z, g)) + P_\mu(x, Z, g),
\]

which is a penalised \(\chi^2\), where \(s\) is the model spectrum, \(x\) represent the flux distribution, \(Z\) the metallicity distribution and \(g\) the broadening function. The penalization \(P_\mu\) can be written as:

\[
P_\mu(x, Z, g) = \mu_x P(x) + \mu_z P(Z) + \mu_g P(g),
\]

where the function \(P\) gives high values for solutions with strong oscillations (ie., when the flux or the metallicity changes rapidly with time) and small values for smoothly varying solutions. Adding the penalization \(P\) to the objective function is exactly equivalent to injecting \textit{a priori} probability density to the solution as \(f_{\text{prior}}(x) = e^{-\mu_x P(x)}\) (see Ocvirk et al. 2006ab for more details), where \(P\) is a quadratic function of the unknown.

Choosing the right values for the smoothing parameters \(\mu_x, \mu_z\) is not a trivial problem. In principle, one could choose the values giving the smaller \(\chi^2\) in the fit, but this usually yields a wide range of smoothing parameters, spanning typically 3-4 decades, in which the fit is acceptable. In any case, the exact choice of the smoothing parameter, although affecting the detailed shape of the star formation history and the age-metallicity relation, does not impact the overall interpretation of the fit, and we have checked, via Monte Carlo simulations, that the global shape of the solution and, in particular, the average values, such as the luminosity-weighted and mass-weighted age and metallicity for the old

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**Table 1. Main properties of NGC 628.**

| Object | Type   | Distance (Mpc) | projected size (arcmin) | \(M_B\) mag | i degrees | PA degrees | \(r_{25}\) (arcmin) | \(r_d\) (arcsec) |
|--------|--------|----------------|-------------------------|--------------|-----------|------------|----------------------|-----------------|
| NGC628 | SA(s)c | 9.3           | 10.5x9.5                | -19.9        | 6         | 25         | 5.23                 | 71.8 (1)        |

\(^4\) However, for the sake of comparison with other studies we present the Lick/IDS line-strength indices maps in Appendix\(^6\).

\(^5\) http://astro.u-strasbg.fr/~ocvirk/

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**Figure 1.** \textit{B}-band Digital Sky Survey image of NGC 628. The mosaic of the PPAK pointings is shown as overlaid hexagons indicating the field-of-view of the central fiber-bundle. The numbers correspond to the identification number of each pointing. The image is \(10'\times10'\) and it is displayed in top-north, left-east standard configuration.
and young components are stable for this range of smoothing parameters. The final chosen values were $\mu_{x,y} = 1$.

Although the code allows to fit the kinematic properties of the galaxy simultaneously with its stellar content, for this work we have not fit the kinematics, and we use, instead, the values obtained with ppxf (Cappellari & Emsellem 2004) during the emission line removal. The reasons are explained in more detail in Appendix B of Sánchez-Blázquez et al. 2011. Basically, the existing degeneracy between the metallicity and the velocity dispersion (Koleva et al. 2008) biases the mean-weighted metallicity if both parameters are fitted at the same time. We have found that this degeneracy affects, mostly, values of the metallicity; in the sense that the derived mass-weighted metallicity is higher if the kinematic is not fixed. Furthermore, in this case, the program fails to recover properly the age-metallicity relation (see Sánchez-Blázquez et al. 2011). However, the biases disappear when using spectra of high signal-to-noise (> 70) Appendix A shows the comparison of the derived mean stellar population parameters with and without fixing the kinematics.

In order to deal with possible flux calibration errors, we multiply the model by a smooth non-parametric transmission curve, representing the instrumental response multiplied by the interstellar extinction. This curve has 30 nodes spread uniformly along the wavelength range, and the transmission curve is obtained by spline-interpolating between the nodes. The latter are treated as additional parameters and adjusted during the minimization procedure. This continuum matching technique is similar in essence to the multiplicative polynomial used by NBurst (Chilingarian et al. 2007); Gandalf (Cappellari & Emsellem 2004) or UlySS (Koleva et al. 2009). This decision of ignoring the continuum shape in the fit was taken to avoid biases in the derivation of star formation histories due to possible flux calibration errors, to a non-perfect extinction correction or to any other cause affecting the shape of the continuum. Appendix A shows the comparison of the mean stellar population parameters obtained without using the shape of the continuum and those obtained when we allow the continuum to be fitted. As can be seen, fitting or not the continuum have a very strong influence in the derived parameters, specially in the mean metallicities. In general, the metallicities obtained when the continuum is rectified are higher than those obtained when we fit the continuum. This is not necessarily a rule as it will depend on the particular shape of the continuum, affected by the particular data flux calibration, extinction correction, etc. However, this is only true for lower signal-to-noise data. For spectra with signal-to-noise (per angstrom) higher than 30 the values obtained are independent of our choice of using or not the continuum for our analysis. We fit the spectral range 3800-6215Å, masking the region between 5545 and 5590 Å, affected by sky-removal residuals. Figure 2 shows an example of the fit obtained with STECKMAP for the integrated spectrum of the galaxy. One of the most important problems affecting stellar population studies is the well known age-metallicity degeneracy, i.e., the colours and spectral characteristics of a given population can be mimicked with another population younger but more metal rich or older but more metal poor. To explore upon what extent we are affected by this degeneracy, we use the integrated spectrum of NGC 628 and added noise to simulate spectra of signal-to-noise 20, 40 and 70 (70 is the S/N of the original spectrum). We performed 2500 Montecarlo simulations in which each pixel was perturbed with the associated noise error, following a Gaussian distribution. For each simulation a new value of the age and metallicity was derived. The results are shown in Fig. 3. The mean values obtained and the root-mean square dispersion (RMS) are shown in Table 2.

As can be seen, as the noise increase, also the uncertainty in the parameters and, therefore, the age-metallicity degeneracy. Furthermore, there seem to be a small systematic effect in the sense that as the noise increase, the mean derived age decrease. We decided to bin our data with a minimum signal-to-noise of 40 (see Sec. 4.1) as a compromise between obtaining good quality spectra and resolve spatially the different components of the galaxy. The typical dispersion in the mean luminosity-weighted age and metallicity derived in a spectrum with this signal-to-noise is 0.05, and slightly larger for the mass-weighted means (0.08 and 0.06 for the age and metallicity values respectively).

Figure 4 shows the typical STECKMAP outputs for the integrated spectra of NGC 628. The flux and mass fraction and the derived age metallicity relation shows that the majority of the stars in this galaxy formed 13 Gyr ago and less than 10% of stars did it $\sim$ 1 Gyr ago. Note, that the maximum age of the models used here is 17.78 Gyr, i.e., exceeding the age of the Universe in the adopted cosmology. It goes beyond the scope of this paper discussing the reasons for these discrepancies and we just caution the reader that the absolute values of the old populations have to be taken as approximate values. In any case, this does not affect any of our conclusions as we will only discuss relative stellar population variations along the galactic radius and relative trends between very old and young populations.

4 RESULTS

4.1 Age and metallicity maps

In order to reach the desired signal-to-noise ratio for our analysis – to ensure an appropriate modeling of the stellar populations – we used the Voronoi tessellation algorithm of Cappellari & Copin (2003) and the PINGSof (Rosales-Ortega 2011) software to bin the data cube in regions with a minimum signal-to-noise (S/N) ratio of 40 (see Sec. 5.2), over a spectral region centered at 5400 Å with a 100 Å width. Figure 5 shows the different regions binned in our scheme of the Voronoi-tessellation algorithm.

We run STECKMAP on each of the binned spectra and obtained star formation histories and age-metallicity relations for all of them. Once we have derived star formation histories, we can obtain average values weighted by the flux or by the mass of the population. While the mean values weighted with mass are going to be biased towards the parameters of the majority of the stars, the flux-weighed values are biased to the parameters of the youngest component, as young stars are much more luminous in the wavelength range we are studying.

6 Note that this systematic effect depend on the specific dataset. In fact, the opposite trend was found in Sánchez-Blázquez et al. 2011.
Figure 3. Example of the fit (red line) obtained with STECKMAP for the integrated spectrum of the galaxy (black line). The bottom panel shows the residuals from the fit (observed-fitted). Note the scale of this panel. Hashed regions indicate the regions that were masked during the fit.

Table 2. Luminosity-weighted (LW) and mass-weighted (MW) mean values and RMS resulting of 2500 simulations where each pixel was perturbed with Gaussian noise expected for a spectrum with a signal-to-noise per angstrom of 70, 40 and 20.

| S/N | MW (log Age) | RMS | MW ([Z/H]) RMS | LW (log Age) | RMS | LW ([Z/H]) RMS |
|-----|--------------|-----|----------------|--------------|-----|----------------|
| 70  | 9.976        | 0.015 | -0.285 | 0.035 | 9.491 | 0.021 | -0.176 | 0.022 |
| 40  | 9.816        | 0.079 | -0.204 | 0.062 | 9.359 | 0.054 | -0.125 | 0.052 |
| 20  | 9.706        | 0.081 | -0.263 | 0.125 | 9.281 | 0.070 | -0.143 | 0.099 |

Figure 4. Luminosity-weighted age-metallicity relation obtained by performing 2500 Montecarlo simulations in which each pixel is perturbed with the associated noise error, following an Gaussian distribution. The histograms show the distribution of the mean age and metallicity obtained in each simulation. From left to right, test performed for spectra of signal-to-noise 20, 40 and 70.
Figure 5. Mass and flux-fractions derived with STECKMAP for the integrated spectrum of NGC 628.

Figure 7. Mean age and metallicity 2-dimensional maps weighted by the mass (MW) and by the light (LW) of the stars.

Figure 7 shows the luminosity- and mass-weighted maps of age and metallicity for NGC 628. Several things can be appreciated in these maps. The mass-weighted mean age map shows that the majority of the stars in the galaxy are old, even in the most external regions sampled by the data, while the luminosity weighted age map reveals younger population in the external parts. In the mass-weighted age map a ring of younger (with an average age of \(\sim 1.7 \text{ Gyr}\)) population is also clearly visible with yellowish colors, coincident with a young ring that has also been detected in CO (Wakker & Adler 1995).

The mass-weighted metallicity map shows that the ring and the central parts of the galaxy are more metal poor than the external parts, which is compatible with the idea that the central ring has been formed as a consequence of the inflows of gas from the external parts (e.g., Kormendy & Kennicutt 2004; Sánchez et al. 2011). In the next section, we quantify these trends.
4.2 Stellar population gradients in the disc region

To obtain radial trends of the stellar population parameters, we average the individual spectra in concentric annuli, which allows to obtain the required signal-to-noise ratio for our analysis up to \( \sim 120 \) arcsec (\( \sim 0.4 \rho_25 \) or \( \sim 5.4 \) kpc) in linear projected galactocentric radii. We obtained azimuthally averaged spectra by co-adding all the spectra within successive rings of 4 arcsec. These azimuthally averaged spectra were then analysed using the fitting procedure described above. Following Zou et al. (2011) we will consider the disc the region R\(>\)30 arcsec, while the bulge that of R\(<\)12.6 arcsec.

Figure 8 shows the mean flux fraction as a function of age and the age-metallicity relation calculated at different distances from the center of the galaxy. It can be seen that, in the center, there is a younger population (\( \sim 2 \) Gyr) that dominates the flux while its contribution gets diluted as we go to larger radii. We also see an increase in the metallicity with time, as it will be expected in a normal chemical evolution model.

To quantify these trends we show, in Figure 9, the mass and luminosity-weighted age and metallicity gradients for NGC 628.

In both, age and metallicity profiles, there seems to be change of slope at around \( \sim 60 \) and \( \sim 80 \) arcsec respectively. We will analyse the gradients inside and outside this region separately.

4.3 Age gradient

The mass-weighted age of this galaxy is old (\( \sim 10 \) Gyr) at all sampled radii, i.e., the disc is dominated in mass by old stars, even at \( \sim 2 \) scale-length. This is in agreement with Sánchez-Blázquez et al. (2011), where it was found that the mean, mass-weighted age of 4 disc galaxies was also around \( \sim 10 \) Gyr, at radii larger than 2 scale-length of the discs (see also MacArthur et al. 2009).

The luminosity-weighted mean age is biased towards the age of the youngest components, as these components are much more luminous in the wavelength range we are studying. Here, it can be seen, as we have already mentioned, that the age gradient show two different behavior.

In the inner disc the gradient is flatter (or even positive, with age increasing with radius). A minimum in the mean luminosity-weighted age can also be seen in at \( \sim 10^\circ \) (this is more readily seen in the azimuthally weighted values, where the errors are smaller), coincident with the radius of a circumnuclear star forming ring previously detected in sub-mm CO (1-0) observations (Wakker \\& Adler 1995) and infrared 2.3 \( \mu m \) CO absorption (James \\& Seigar 1999) and was also seen by Ganda et al. (2006) in their H\(\beta\) and [OIII] maps of SAURON.

In the outer disc, the luminosity-weighted age shows a clear gradient, with a variation of almost \( \sim 6 \) Gyr in 2 scale-lengths.

Previous studies of the stellar population across the radius for this galaxy include those of Natali et al.(1992) and Zou et al. (2011) –using photometry in different bands – and that of Sánchez et al.(2011), using spectroscopy. Zou et al. (2011) found, as in the present study, a different two distinct disc components, on from 30 to 60 arcsec, and the second one from 60 to 132 arcsec. At \( 1^\circ \), the age profile change slope. We also find a change of slope at a similar radius but the trends that we derive are very different in both studies. Zou et al. (2011) found that the inner region of the disc (from 30-60") have a much steeper gradient than the outer region, which is completely the opposite to what we find in the present study. Our profile, however, coincides very well with that of Sánchez et al. (2011) (see Fig. 12).

4.4 Metallicity gradient

The metallicity gradient also shows two differentiated regions, being almost flat or slightly positive in the central parts and negative outwards. The radius at which the metallicity gradient changes slope is similar to the break calculated by Scarano \\& Lépine (2013) for the gas-phase metallicity using data from Rosales-Ortega et al. (2011), and also similar to the break in the stellar metallicity found by Zou et al. (2011). In fact, qualitatively, the trends found by Zou et al. (2011) are very similar to our; in the disc region the metallicity increase with radius until \( R \sim 60^\circ \) and decrease slightly beyond. Our gradient in the internal regions is, however, much milder and the overall metallicities considerably larger than those that derived by the quoted authors and the radius at which the gradient change slope is larger. This dual behavior is, however, not reported by Sánchez et al. (2011), although their luminosity-weighted values of age and metallicity are in a very good agreement with ours (see Fig. 12).

To check the reliability of this break we compare the metallicities obtained with our methods with those obtained with a better understood and widely used method, a classical index-index diagram. Figure 10 shows the comparison of the metallicity gradient obtained with STECKMAP and the one obtained using an index-index diagram combining H\(\beta\) and [MgFe]. We are not comparing exactly the same quantity as the metallicity obtained by using an index-index diagram is a single-stellar population equivalent value, while the one obtained with STECKMAP is a luminosity-weighted
one. However, it has been shown that these two measurements give very similar values (Serra & Trager 2007). It can be seen that, although the SSP-equivalent values are noisier, the trends obtained with the two methods are very similar and, in particular, a change of slope is visible at the same radius.

The different trends in age and metallicity between this study and that of Zou et al. (2011) shows the difficulty in deriving accurate stellar population parameters using broad band colors, due to the existent degeneracies between age, metallicity and dust extinction. It is worth noticing that the broad band optical color profiles of this galaxy show, in fact, a very steep slope in the inner region of the disc while it flattens out beyond 1′. On the contrary, we obtain much flatter colors of age and metallicity in the inner regions of the disc. We prove, however, in Sec. 5.2 that we can reproduce the observed colors of this galaxy using our derived star formation histories.

4.5 Time evolution of the gradients

One of the advantages of being able to derive an age-metallicity relation is that it allows us, in principle, to obtain the time evolution of the metallicity gradient. The temporal evolution of the metallicity gradient is an issue that is not yet settled from neither, the theoretical or the observational point of view. Some chemical evolution models predict a steepening with time starting from initially inverted or flat gradients (e.g. Chiappini, Matteucci & Romano 2001) while others predict an initially negative gradient that flattens (e.g., Mollá & Díaz 2005). Recent work (Pilkington et al. 2012; Gibson et al. 2013) have showed that, in cosmological simulations, the evolution of the metallicity gradient with time depends on the details of the sub-grid physics implemented in the hydrodynamical codes of galaxy formation, in particular, on the feedback scheme. Therefore, the study of the metallicity gradient for different age populations in galaxies are key to reveal the formation processes of...
disc galaxies and better constrain the physics included in numerical simulations.

Some authors have studied this evolution in our own MW using planetary nebulae (e.g., Maciel et al. 2003; Stanghellini & Haywood 2010; Maciel & Costa 2013) also with discrepant results. A direct measurement of the evolution of the metallicity gradients can be obtained analysing the magnitude of the gas-phase metallicity gradient at high redshift (Cresci et al. 2010; Jones et al. 2010; Yuan et al. 2011; Queyrel et al. 2012). Yuan et al. (2011) found that, for at least one grand design spiral at redshift $z \sim 1.5$, the metallicity gradient is significantly steeper ($\sim -0.16$ dex/kpc) than the typical gradient encountered today. However, the difficulties in obtaining high resolution data for likely MW progenitors mean that the theoreticians have had very few constraints on their models, as different paths can lead to a similar final metallicity gradient. Figure 11 shows the spatially resolved metallicity in the HII regions of this galaxy (taken from Rosales-Ortega et al. 2011) and the stellar components younger than 2 Gyr and older than 5 Gyr. To compare the gas- and stellar metallicities we have transformed the former to the scale of the latter assuming a solar metallicity of $\text{[O/H]} = 8.7$ (Asplund et al. 2005). It can be seen that, if we restrict ourselves to the younger stars (those with ages < 2 Gyr), the gradient shows a linear behavior, decreasing slightly with radius, and it is very similar to the gradient of the ionized gas. On the contrary, the metallicity profile for the older stars have a different slope inside and outside $\sim 50-60''$. The metallicity gradient for the older populations is slightly positive in the internal zones, but it is steeper than that of the young population in the external parts.

Note that, although in Paper I and in Scarano & Lépine...
Figure 11. Mean (luminosity-weighted) metallicity considering only those populations with age younger than 2 Gyr and older than 5 Gyr. Error bars represent the RMS dispersion of the metallicity obtained in 25 simulations where each pixel of the spectrum is perturbed according to its signal-to-noise following a Gaussian distribution. The dark blue line shows the gas-phase metallicity gradient obtained by Rosales-Ortega et al. (2011) using two different calibrators, $\text{Fe}^{2+}$ and O3N2 (see the text for details). To convert the scales we have adopted a solar abundance of $12+\log(O/H)=8.7$.

Figure 13. Comparison of the R-I and B-V color gradients derived by Natali et al. (1992) (red open circles) and those derived by us from the star formation histories and age-metallicity relation (black circles).

5 COMPARISON WITH OTHER METHODS AND ROBUSTNESS OF THE SOLUTION

5.1 Comparison with Sánchez et al. 2011

Sánchez et al. (2011) presented an analysis of the stellar population properties for the same galaxy using also the same data as the one presented here. These authors used FIT3D (Sánchez et al. 2007bc). FIT3D enables linear fits of a combination of single stellar populations, and non-linear ones of emission-lines plus an underlying stellar population. It also includes the Cardelli, Clayton & Mathis (1989) attenuation law (see Sánchez et al. 2011 for details). In Sánchez et al. (2011), FIT3D was used in combination with Bruzual & Charlot (2003) models, assuming a Salpeter IMF. The comparison between their results and those of the present study are shown in Fig. [12] It is remarkable the excellent agreement between both studies, despite the differences in the code and in the stellar population models used. This agreement gives particular confidence in the results.

6 DISCUSSION

It is clear from previous studies that NGC 628 is a perfect candidate for a galaxy having experienced secular evolution. Its bulge has the characteristic of a bulge formed secularly (Kormendy & Kennicutt 2004), with a surface brightness profile showing a Sérsic index <2 (Zou et al. 2011), presence of nuclear spiral arms (Cornett et al. 1994) and a young ring structure, a nuclear velocity dispersion drop (Ganda et al. 2006). Fathi et al. (2007) found indications that the gas is falling in from the outer parts towards the central regions, where a nuclear ring has formed at the location of the inner Lindblad resonance radius of an m=2 perturbation. We have analysed the stellar population gradients in the galaxy NGC 628 and found that the stellar population gradients in the disc shows a two distinct regions, one older
and more metal rich with almost flat gradient in metallicity and slightly positive in the mean (luminosity-weighted) age and an external part with slightly decreasing gradients in both, luminosity-weighted age and metallicity. The mass-weighted age gradient is compatible with being flat in all the regions sampled by our data, indicating that this galaxy is dominated, in mass, by old stars (>9 Gyr).

6.1 The outer disc

Outside r~1′, the analysis above shows that the majority of the stars in the disc of this galaxy are old, even at ~ 2 scale-lengths of the disc, but that the proportion of young stars is higher at larger radii, i.e., the outer parts of the disk formed a larger fraction of their stars at recent times than the inner parts, consistent with the ”inside-out” growth scenario. However, even the outer regions sampled by us, contain a large percentage of old stars, reflected in an old mass-weighted mean age. Studies of stellar populations using resolved stars have found old stellar populations in the outskirts of disc galaxies (e.g., Ferguson & Johnson 2001 (M31); Davidge 2003 (NGC2403, M33); Galleti, Bellazzini & Ferraro 2004 (M33); Gogarten et al. (2010) (NGC300)). It has been suggested that these properties are not expected in CDM models (Ferguson & Johnson 2001) where the disc grows inside-out and at relatively recent epochs (z ≤ 1). However, in Sánchez-Blázquez et al. (2009), we analysed a fully cosmological, hydrodynamical disc galaxy simulation in a ΛCDM Universe finding, also, a large percentage of old stars in the outskirts.

On the other hand, numerical simulations have shown that radial migrations due to the presence of non-axisymmetric components, like bars or spiral arms, can make that an important percentage of stars currently in the outer parts of the disc may have formed closer to the center of the disc and migrated outward to their current locations. Therefore, an observed old stellar population in the outer disc may not necessarily indicate that the outer disc formed early. In the present study, we have been able to analyse, for the first time, the evolution of the stellar metallicity gradient with time from integrated spectra. In the "outer"-disc region, we have found that the metallicity gradient for the old stellar population is steeper than that of the young component. This, in principle, can be a sign that stellar migration has not been very important in the disc region of this galaxy. However, to conclude this we would need to know the original gas-phase metallicity gradient at the epoch of formation of these old stars, which could have been even steeper.

6.2 The inner disc

At radius R <~ 60′ both, the mean age and metallicity profiles, are flatter than in the external disc. In fact, the gradient is even positive for the luminosity-weighted values of age and metallicities. This is difficult to explain in an inside-out formation scenario for the disc formation and requires an explanation. The change in the slope of the gas-phase metallicity gradient has been observed before in many galaxies (e.g., Zaritsky 1992; Vila-Costas & Edmunds 1992; Martin & Roy 1995; Dutil & Roy 1999; Roy & Walsh 1997; Zahid & Bresolin 2011; Scarano & Lépine 2013) and it is usually interpreted as the result of variations of gas density, the large-scale mixing induced by a bar (Friedli & Benz 1995), or by the spiral arms. In this case, the change of slope coincide with the corotation radius of the spiral patterns (e.g., Scarano, Lépine & Marcon-Uchida 2011; Scarano & Lépine 2013). This is because the main gas flows have opposite directions inside and outside corotations. However, the above mechanism applies to young objects, such HII regions, that reveal the present value of the metallicity in the interstellar medium The fact that the break in the stellar metallicity is more pronounced in the older component points toward dynamical effects (radial migrations) as the cause for the observed dual behavior.

Flat gradients, as the ones found here in the inner disc, require strong radial mixing, which is difficult to produce with star formation histories but can be achieved in ongoing strong galaxy interactions (Rupke et al. 2010) or can be produced by secular evolution in the presence of non-axisymmetric components, like bars, oval or spiral arms. NGC 628 is classified as an unbarred galaxy and, therefore, if secular evolution has happened, one is tempted to attribute it to the presence of spiral arms. Strong resonant interaction with transient or long-lived spiral arms at the corotation radius can produce stellar wanderings of several kpc in a few hundred Myr (e.g., Sellwood & Binney 2002; Lépine, Acharova & Mishurov 2003; Roskar et al. 2008a). If the spirals are long-lived, this mechanism has been shown to
produce bimodal patterns in the metallicity gradients with breaks at the spiral corotation radius. The corotation radius for NGC 628 is located around \( \sim 7 \) kpc (Sakhibov & Smirnov 2004) which is outside the region sampled by us. Therefore, the break that we observe here is too internal to be produced by the spiral arms. However, a change on the slope of the color gradients around this radius has been reported in Natali et al. (1992).

On the other hand, despite NGC 628 is classified as an unbarred galaxy in de Vaucouleurs et al. 1991 atlas, near-infrared imaging and isophotal analysis has revealed the existence of an oval distortion with radius of \( r \sim 50'' \) (Laine et al. 2002; Seigar 2002) confirmed by the kinematical analysis by Fathi et al. (2007). These authors also conclude that this oval (a \( m=2 \) perturbation) is the most prominent in the observed velocity field. Thought ovals are rather frequent in disk galaxies, their exact nature has not yet been investigated. Kormendy (1979) hypothesized that they are products of bars decays, which is supported by some observations of galaxies with prominent rings (e.g. Sil’chenko & Afanasiev 2002). Such a scenario is also predicted by the models of Friedli & Benz (1993, 1995); Combes et al. 1990; Raha et al. 1991; Martínez-Valpuesta & Shlosman 2004. The presence of a circumnuclear ring of star formation (Wakker & Adler 1995; James & Seigar 1999) and a central \( \sigma \)-drop (Ganda et al. 2006) in NGC 628 support this hypothesis, as the large-scale oval perturbation can transport material from the outer zones to regions near the center of the galaxies (see Fathi et al. 2007 for discussion).

Our results also show that we have found that the stellar population in the region dominated by the oval distortion reveals a positive luminosity-weighted age and metallicity gradients. This has been observed in bars (Pérez, Sánchez-Blázquez & Zurita 2009) and, in fact, Moorothy & Holtzman (2006), found that the only galaxies with positive metallicity gradients in the central regions were those hosting bars. Positive stellar population gradients have also been reproduced in chemodynamical simulations of barred galaxies (Wozniak et al. 2007). Weak oval structures are not believed to have a strong influence in the redistribution of stars inside the galaxy. However, this structures could have been stronger in the past. In fact, some authors (Kormendy 1979; 1981, 1982; Combes 1996) suggest that some bars evolve into lens components. Therefore, the arguments above suggest that we could be witnessing a bar in the process of being destroyed, support coming from previous kinematical studies and from our stellar population analysis.

Understanding bar formation and evolution is crucial to understand galaxy evolution, yet a fundamental question, namely whether bars can be destroyed by internal processes, remains unanswered. From the theoretical point of view, there is currently a debate in the literature. On one hand, bars seem to be robust structures which cannot be easily destroyed by central mass concentration as the observed are not massive enough (Shen & Sellwood 2004; Athanassoula, Lambert & Dehnen 2005). On the other hand some numerical simulations predict that bars can be destroyed and reformed when disc are very gaseous, and that galaxies can have up to 3-4 generations of bars over a Hubble time (Bournaud & Combes 2002). Recent observations are consistent with the picture in which bars in early-type disc galaxies are long-lived, whereas those in late-type spirals could be dynamically young (Gadotti & de Souza 2005, 2006; Elmegreen et al. 2007; Sheth et al. 2008). However, there is no observational result to date that indicates whether bars can dissolve. In particular, we cannot tell whether an unbarred galaxy has had a bar in the past. However, ovals (or lenses) can give us some clues, as one of the proposed formation scenarios is that lenses could be the remnants of a dissolved bar. Here we show stellar population gradients that are compatible with this scenario as, otherwise, it would be difficult to obtain the change on the slope of the stellar population parameters at the radius we are observing them and the slightly positive metallicity gradient in the inner disc.

7 CONCLUSIONS

In this paper we have presented an analysis of the star formation history and metallicity evolution in a 2-dimensional fashion for the galaxy NGC 628, using data form the survey PINGS (Rosales-Ortega et al. 2010) with the main purpose of validate our techniques to derive reliable stellar population properties.

• We derive 2D-star formation histories for NGC 628 using the code STECKMAP. The analysis allows to obtain mean ages and metallicities weighted with both, luminosity and stellar mass.
• We check the robustness of the derived mean ages and metallicities to different choices of the fit. In particular, we have checked the effect of deriving simultaneously kinematics and metallicities, and also the effect or fitting or not the stellar continuum. We have found that, when the kinematics is fitted simultaneously to the derivation of star formation histories, the ages are not very affected, but the derived metallicities are. We have also found that the differences can be minimized in spectra with enough signal-to-noise.
• We find a negative luminosity-age gradient compatible with an inside-out formation scenario (e.g., Larson 1976; White & Frenk 1991; Mo et al. 1998; Naab & Ostriker 2006; Brook et al. 2006). However, even at \( \sim 2.0 \) scale-lengths the disc (assuming a disc scale-length of 3.2 kpc – Zou et al. 2011) is dominated, in mass, by old stars (\( \sim 10 \) Gyr).
• We find a metallicity gradient that is flatter in the internal region and change to a negative slope in the external parts. The break in the metallicity gradient is much more prominent in the old stars than in the younger components, which gradient is very similar to the gas-phase metallicity gradient. However, a break is visible in all the different components at about the same radius. We speculate that the metallicity gradient is the consequence of the gaseous flows and stellar migration produced by a \( m = 2 \) perturbation, either the spiral pattern of a bar. However, the position of the break is more coincident with the corotation radius of the oval distortion than that of the spiral pattern, which is beyond the radius sampled by our data. As the oval distortion is NGC 628 is too weak for this to happen very efficiently, it could be that there was a stronger bar present in this galaxy and that the oval perturbation is the consequence of the dissolution of this structure. We also argue that this structure cannot have evolved much in size in, at least, the last \( \sim 5 \) Gyr.
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APPENDIX A: EFFECT OF FIXING THE KINEMATICS

It is known that the measurement of the velocity dispersion depends on the metallicity of the stellar template (Laird & Levison 1985; Bender 1990; Koleva, Prugniel & De Rijcke 2008). A deeper absorption feature can be obtained by either increasing the metallicity decreasing the broadening, which leads to degeneracies when trying to derive both parameters at the same time. To quantify the differences in the derived parameters with and without fixing the kinematics, we have run STECKMAP allowing to fit both, the radial velocity and velocity dispersion of the voronoi-binned spectra in NGC 628 and compare the derived, mean parameters, with those obtained when fixing the kinematics (that is the approach followed in the main paper). The results are shown in Fig. A1.

As can be seen, while the mean ages are not strongly affected by fixing or not the kinematics, the metallicities can be by as much as $\sim 1$ dex. The net effect is that, without fixing the kinematics, the metallicities tend to be lower. Furthermore, there is a trend for which the differences increase with the mean metallicity of the population. We showed in Sánchez-Blázquez et al. (2011) that this effect is not exclusive of our employed technique to derive star formation histories, but that it is also seen if other codes, as starlight is used. The differences, also depend on the signal-to-noise. To further emphasize this, we also include some spectra resulting from a voronoi-binned spectra imposing a lower signal-to-noise cat (showed with different symbols in the figure). It can be seen that the lower the signal-to-noise, the larger the differences.

APPENDIX B: EFFECT OF FITTING THE CONTINUUM

Figure B1 shows the comparison of our derived mean stellar age and metallicity (weighted with both, light and mass) and that obtained when we allow for the continuum shape to be fit. We have used the spectra of the Voronoi-binned data. As can be seen in the figures, except for the luminosity-weighted age, the rest of the parameters are strongly affected by fitting or not the continuum. It is also clear that for those spectra with the highest signal-to-noise (dark colored symbols), the differences are much lower than for the spectra with the lowest signal-to-noise (light color and crosses).

APPENDIX C: LINE-STRENGTH LICK INDICES MAPS

The maps for all the Lick/IDS indices are available in the electronic edition of the paper. The indices have been measured in the voronoi-binned spectra broadened to the total resolution of 14 Å (FWHM), that is, matching the LIS-14 spectral system defined in Vazdekis et al. (2010). We measured all the Lick/IDS indices with the definitions of Trager (1998) and the 4000-break with the definition given in Bruzual et al. (1993).
Figure A1. Comparison of the mean stellar population parameters with and without fixing the kinematics. As can be seen, while the ages are not strongly affected by the choice of fixing or not the velocity and velocity dispersion, the metallicities are, due to the degeneracy between metallicity and line-broadening. The color of the symbols represent the S/N of the individual spectrum as indicated in the label.

Figure B1. Comparison of the mean stellar population parameters obtained when fitting (flux) and not fitting (rectified) the continuum. Darker symbols indicate higher signal-to-noise spectra. The crosses indicate the results for spectra with lower S/N than our minimum cut, included here to illustrate the effect of working with low S/N spectra.