

Star formation and stellar populations across nuclear rings in galaxies

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ABSTRACT

We present a study of the optical spectra of a sample of eight star-forming nuclear rings and the nuclei of their host galaxies. The spectra were obtained with the ISIS spectrograph on the William Herschel Telescope and cover a wide range in wavelength, enabling the measurement of several stellar absorption features and gas emission lines.

We compared the strength of the absorption lines to a variety of population synthesis models for the star-formation history in the nuclear rings, including also the contribution of the older bulge and disc stellar components. In agreement with our previous investigation of the nuclear ring of NGC 4321, which was based on a more restricted number of line-strength indices, we find that the stars in our sample of nuclear rings have most likely formed over a prolonged period of time characterised by episodic bursts of star-formation activity. Constant star formation is firmly ruled out by the present data, whereas a one-off formation event is an unlikely explanation for a common galactic component such as nuclear rings. The nuclear rings of NGC 4314 and NGC 7217 have distinct line-strength properties that set them apart from the rest of our sample, which are due to a larger contribution of bulge star in the observed spectra and, in the case of NGC 4314 to a younger stellar population in the ring.

We have used emission-line measurements to constrain the physical conditions of the ionised gas within the rings, using the ratio of the [S II] $\lambda\lambda$ 6716, 6731 lines to estimate the density of the gas, and photoionisation model grids within specific diagnostic diagrams to derive metallicity. We find that emission in all nuclear rings originates from H II regions with electron densities typical for these kinds of objects, and that the rings are characterised by values for the gas metallicity ranging from slightly below to just above Solar. We have also studied the spectra of the nuclei of our sample galaxies, all of which display emission lines. Consistent with previous studies for the nuclear activity and stellar populations, the majority of our nuclei appear to be dominated by old stellar populations and by LINER-like emission.

As 20% of nearby spiral galaxies hosts nuclear rings that are currently forming massive stars, our finding of an episodic star formation history in nuclear rings implies that a significant population remains to be identified of young nuclear rings that are not currently in a massive star formation phase. Nuclear rings may thus be a much more common galactic component than currently known.

Key words: galaxies: ISM – galaxies: star clusters – galaxies: stellar content – ISM: H II regions – galaxies: nuclei – galaxies: spiral

1 INTRODUCTION

Star-forming nuclear rings occur in approximately 20% of spiral galaxies (Knapen 2005). Generally, they are sites of intense active star formation, containing a mixture of gas, dust and young stars. This is deduced from their blue colours, bright hydrogen emission

lines in optical and infrared, enhanced radio continuum emission, and overall patchy appearance (Arsenault et al. 1988; Pogge 1989; García-Barreto et al. 1991; Benedict et al. 1992, 1996; Knapen et al. 1995a,b; Jogee et al. 2002; Allard Peletier, & Knapen 2005; Mazzuca et al. 2006, 2007). Additionally, red nuclear dust rings have been identified (e.g., Buta & Crocker 1991; Wozniak et al. 1995; Vila-Vilaró et al. 1995), as well as so-called ‘fossil rings’, which are dust-free and composed entirely of stars, and virtually

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indistinguishable from the surrounding stellar population (Erwin et al. 2001; Erwin & Sparke 2002).

The vast majority of nuclear rings appear in barred galaxies (Knapen 2005), where the bar has the ability to channel gas from the disc towards the nucleus (e.g., Huntley, Sanders & Roberts 1978; Sanders & Tubbs 1980; Simkin, Su & Schwarz 1980; van Albada & Roberts 1981; Schwarz 1984; Combes & Gerin 1985; Shlosman, Begelman & Frank 1990; Athanassoula 1992; Knapen et al. 1995a,b). During this process, the radial inflow of gas is slowed down near the location of the inner Lindblad resonances (ILRs), which allows for the accumulation of gas and which can, ultimately, lead to a star-forming ring (Combes & Gerin 1985; Shlosman et al. 1989; Wada & Habe 1992; Heller & Shlosman 1994; Knapen et al. 1995a,b; Fathi et al. 2005). In a few cases, two of which will be discussed in this paper, nuclear rings occur in host galaxies without an obvious kpc-scale bar. The formation of such rings may be related to the presence of a weak oval distortion (Buta et al. 1995), to a dissolved bar (Verdes-Montenegro et al. 1995), to the tidal effects of a companion galaxy (Combes 1998), or to a recent minor merger (Knapen et al. 2004; Mazzuca et al. 2006).

At least two thirds of all spirals are barred (de Vaucouleurs 1963; Sellwood & Wilkinson 1993; Knapen et al. 2000, Eskridge et al. 2000, Grøsbol et al. 2004). Jogee et al. (2004), Elmegreen, Elmegreen & Hirst (2004) and Zheng et al. (2005) showed that the bar fraction is roughly constant out to $z \approx 1$, indicating that bars are long-lived phenomena. Since gas is readily available in the disc, nuclear rings may continue to form stars as long as the bar continues to provide an inflow of fresh material. Even with continued inflow at the rates thought to be supplied by a typical bar (around a Solar mass per year), the high star formation rates within the rings can exhaust the gas relatively quickly (Elmegreen et al. 1998), effectively turning off the star formation. As more gas is supplied to the ring the density will gradually increase, until star formation is initiated again. The moderate inflow rates and observed elevated star formation rates thus indicate that the star-forming process in nuclear rings may cycle through active and quiescent periods. The fraction of galaxies with nuclear rings may thus be significantly larger than the fraction of rings seen to be forming massive stars at present (which is around 20%; Knapen 2005).

At the current time, however, observational confirmation of this longevity of nuclear rings is still limited. As such, the effect nuclear rings may have on the evolution of their host galaxies is unclear. The ages of individual star-forming regions, sometimes referred to as hot spots, in nuclear rings have been studied using a variety of techniques, almost all based on the use of optical or near-IR recombination emission lines via imaging or spectroscopy (e.g., Engelbracht et al. 1998; Ryder & Knapen 1999; Puxley & Brand 1999; Kotilainen et al. 2000; Alonso-Herrero, Ryder & Knapen 2001; Ryder, Knapen & Takamiya 2001; Díaz-Santos et al. 2007; Mazzuca et al. 2007). These lines trace primarily very young and massive stars, and as a consequence the ages derived using these techniques are usually below 10 Myr, or otherwise very sensitive to assumptions on the star-formation history. Broad-band colours have also been used to estimate the age of the stellar population in circumnuclear rings (e.g., Kotilainen et al. 2000; Harris et al. 2001). Such measurements, however, are affected by reddening and degeneracies between age and metallicities, and even in the case of near-IR data, where the impact of dust is mitigated, the interpretation of colour-colour diagrams is complicated by the fact that populations of very different ages have very similar colours (see, e.g., the models of Maraston 2005). In contrast, the technique employed in the present paper, which is based on the strength of several stellar

Table 1. Global parameters of the observed galaxies. Tabulated are the NGC number, the morphological type from NED, the nuclear activity class from Ho, Filippenko & Sargent (1997), and the distance D and the physical scales both from Knapen et al. (2006).

Galaxy	Type	Activity	D (Mpc)	Scale (pc/arcsec)
NGC 473	SAB(r)0/a		29.8	144.5
NGC 4314	SB(rs)a	L2	9.7	47.0
NGC 4321	SAB(s)bc	T2	16.8	81.4
NGC 5248	(R)SB(rs)bc	H	22.7	110.1
NGC 5383	(R')SB(rs)b	H	37.8	183.3
NGC 6951	SAB(rs)bc	S2	24.1	116.8
NGC 7217	(R)SA(r)ab	L2	16.0	77.6
NGC 7742	SA(r)b	T2/L2	22.2	107.6

absorption lines, is sensitive to a much larger range of intermediate ages, is unaffected by reddening and is known to break the age-metallicity degeneracy that limits broad-band estimations (Worthey 1994).

Based on such an interpretation of line-strength indices, in Allard et al. (2006, hereafter Paper I) we presented strong evidence that the nuclear ring in NGC 4321 (Messier 100) is indeed long-lived, though forming stars episodically in a rapid succession of bursts rather than continuously. Due to the limited wavelength range of the data we used, we could, however, not completely rule out the possibility that the rings are transient objects. With our long-slit data (presented in this paper), we cover a much wider wavelength range and aim to confirm the nature of the nuclear ring in NGC 4321, as well as seven other well known rings, with the goal of generalising the star formation activity pattern and evolutionary past within nuclear rings.

In the present paper we study the star formation histories of eight nuclear rings, by extracting information from longslit ISIS (Intermediate dispersion Spectrograph and Imaging System) spectra over a wide range in wavelength, analysing both the stellar and gaseous contributions to the spectra. For each nuclear ring, we have one to three spectrograph slit position angles (PAs) which each bisect the nucleus and the ring, yielding data on two to six H II regions, referred to as hotspots, for each ring (see Figure 1). Studying the stellar absorption and gas emission lines will thus allow us to determine the physical parameters and complex star formation properties of these rings.

The paper is structured as follows. Section 2 details the observations and data reduction, and Section 3 describes the analysis of the data. The results of the stellar absorption line analysis are presented in Section 4, and the analysis of the emission lines is presented in Section 5. Finally, we present our discussions and conclusions in Sections 6 and 7.

2 OBSERVATIONS AND DATA REDUCTION

The observed galaxies were chosen from the H α sample of Knapen et al. (2006), and are all known to possess strong H α -emitting nuclear rings. Our sample consists of six galaxies with moderate to strong bars, and two galaxies that appear to be unbarred, at least at first glance. These two unbarred galaxies, NGC 7217 and NGC 7742, are both known to have counter-rotating sub-systems in their central regions (Merrifield & Kuijken 1994; Sil'chenko &

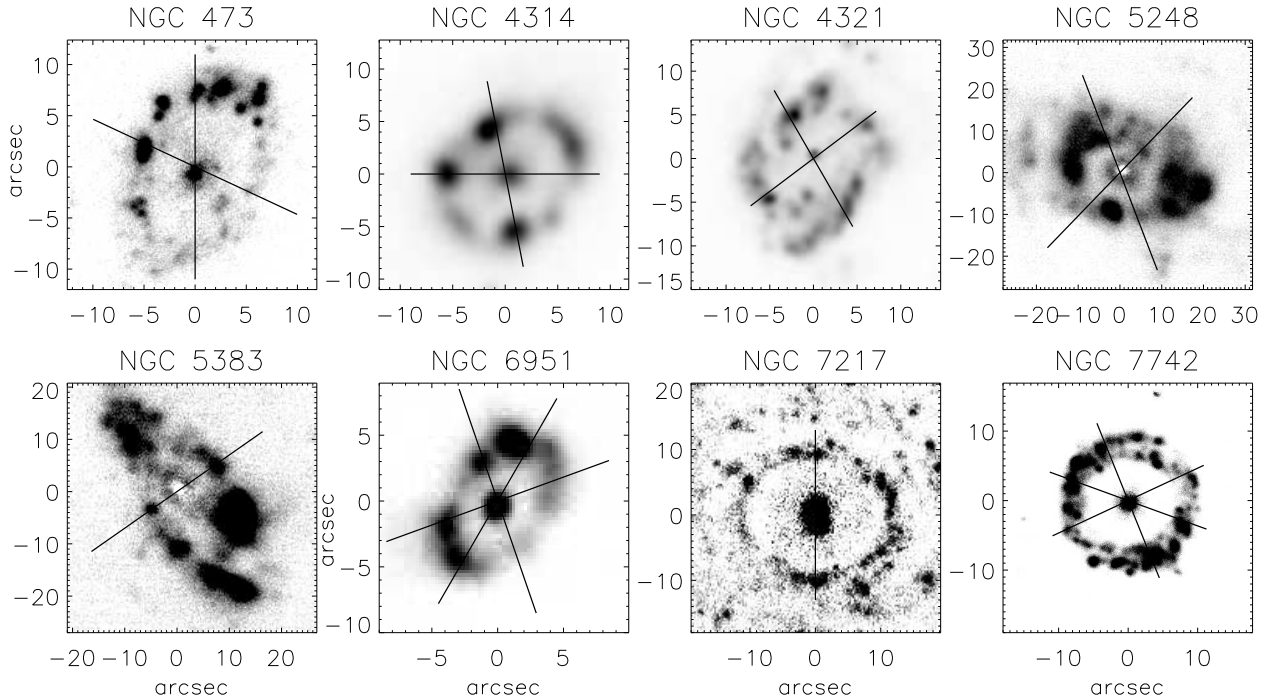


Figure 1. $H\alpha$ continuum-subtracted images of the nuclear rings in the sample (data from Knapen et al. 2006). The black lines show the slit positions of the spectrograph. North is up, East to the left.

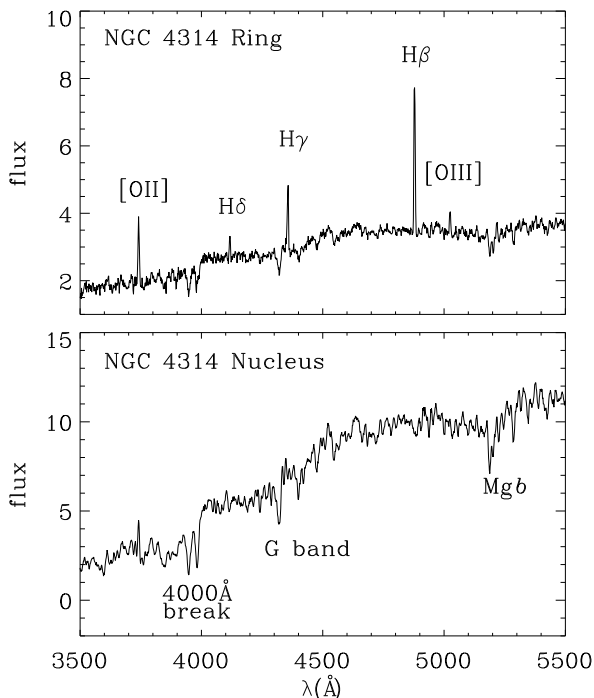


Figure 2. Two examples of the blue spectra obtained, one from the nuclear ring (*top*) and the other from the nucleus (*bottom*) of NGC 4314. The flux scale is in units of 10^{-17} ergs cm^{-2} s^{-1} \AA^{-1} . Some of the emission and absorption features used in the analysis are identified.

Table 2. Observing run details. Given are the galaxy name, the date of the observations, the exposure times, and the position angles of the spectrograph slit, measured N over E.

Galaxy	Date	Exp. Times (s)	PA ($^{\circ}$)
NGC 473	05/10/05	3×1200	0
	05/10/05	3×1200	65
NGC 4314	29/04/01	2×1800	11
	29/04/01	3×1800	90
NGC 4321	30/04/01	3×1200	127
	30/04/01	2×1200	210
NGC 5248	29/04/01	2×1800	22
	29/04/01	1×1800	136
NGC 5383	30/04/01	3×1200	125
NGC 6951	29/04/01	2×1800	150
	05/10/05	3×1200	19
	05/10/05	3×1200	110
NGC 7217	05/10/05	3×1200	0
NGC 7742	05/10/05	3×1200	22
	05/10/05	3×1200	70
	05/10/05	3×1200	115

Afanasiev 2000; de Zeeuw et al. 2002), which may suggest a history of interaction. Some global parameters for the eight galaxies are listed in Table 1. The ISIS spectrograph on the William Herschel Telescope (WHT) on La Palma was used to observe five galaxies on 2001 April 29 and 30. An additional three galaxies were observed on the 2005 October 5 using the same instrument. Details of the observations, including spectrograph slit PAs for each galaxy,

are listed in Table 2. $H\alpha$ images of all the nuclear rings and the slit PAs used in each case are shown in Figure 1.

The slit was always positioned so it targetted the nucleus and at least one bright hotspot in the ring. A slit width of 1 arcsec was used. We operated ISIS with a dichroic, which allows simultaneous observations with a red and a blue arm, covering wavelength ranges of 3500-5700 Å and 5900-8900 Å, respectively. The R158B grating was used for the blue arm, providing 1.62 Å/pixel and 0.2 arcsec/pixel scales with the EEV12 detector. For the initial observing run the R158R grating was used with the TEK4 detector on the red arm, which gave 2.90 Å/pixel and 0.36 arcsec/pixel scales. For the second observing run the TEK4 detector was no longer in operation, and the red MARCONI detector was used, which provides similar spatial and spectral scales to the blue EEV12 detector. The instrumental resolution was 180 km s⁻¹ ($\sigma = 6.8$ Å) for the blue, and 115 km s⁻¹ ($\sigma = 5.8$ Å) for the red arm. Standard CuAr+CuNe calibration lamp exposures were taken before and after each science exposure, along with a number of spectroscopic standard star observations for flux calibration.

Although the spectrograph slit passed through two hotspots in NGC 5383, neither had high enough signal to noise ratio to be useful. The two extracted spectra were instead combined. Additionally, the two hotspots measured in NGC 7217 had sufficient signal to noise in their stellar continuum, but not in their gas emission lines. The two spectra were thus averaged for the emission line measurements but not for the stellar index measurements.

The spectra were reduced within the IRAF package using standard methods. The data were first bias and overscan corrected, before trimming and flatfielding. A cosmic ray removal algorithm was applied next. The separate exposures were then checked for offsets in positions between adjacent exposures, shifted if necessary, and combined. The spatial regions along the slit containing the hotspots and the nucleus were extracted and median-combined to produce a one-dimensional spectrum. CuNe+CuAr lamp exposures were used for wavelength calibration, with typical errors of 0.1 Å. The spectra were traced to align the dispersion and spatial axes with the rows and columns of the CCD array. To remove the background sky contribution, regions at the outer edges of the slit were averaged to produce a one-dimensional spectrum which was subtracted from every row in the image. The spectra were flux calibrated to an absolute scale with units of ergs cm⁻² s⁻¹ Å⁻¹, with typical errors of 30%. A number of atmospheric absorption and emission lines is found towards the end of the red spectral range, which could not be removed sufficiently in all cases. Consequently, the red spectra were trimmed to give a wavelength coverage of 5800-6800 Å, which includes the important emission lines of $H\alpha$, [N II] and [S II].

Figure 2 shows two examples of blue spectra subtending the nucleus and one of the ring hotspots of NGC 4314.

3 DATA ANALYSIS

The stellar and gaseous contributions to the spectra were separated using the direct fitting method described in Sarzi et al. (2006)¹. We modelled the stellar continuum with linear combinations of synthetic spectral templates from Bruzual & Carlot (2003), adopting the same library used by Tremonti et al. (2004). This

includes 13 template spectra for each of the three metallicities $Z = 0.004, 0.02, 0.05$, corresponding to 10 instantaneous-burst models with ages from 5 Myr to 11 Gyr, a constant star formation model with an age of 6 Gyr, and two models with exponentially declining star formation histories with ages of 9 and 12 Gyr.

The spectral regions affected by nebular emission are not excluded from the fitting process. Instead, the emission lines are treated as Gaussian templates and fitted simultaneously with the stellar templates to the observed spectra. This has the advantage of maximising the spectral information available to the fitting algorithm.

As the blue and red spectra have different spectral resolutions they could not be fitted simultaneously. The blue spectra cover a much wider wavelength range than the red, and contain a large number of stellar absorption features that help constrain the mix of stellar templates. We therefore fit the blue spectra first, and use the resulting optimal combination of templates to match the red spectra, allowing only for a different velocity broadening. The fits to the blue spectra include reddening due to foreground interstellar dust, both in the Milky Way and in the sample galaxies, and due to dust in the emission-line regions. The latter affects only the fluxes of the emission line templates, and is constrained by the expected and observed decrement of the Balmer lines. Setting physically motivated limits on the intensity of the emission from high-order Balmer lines is of particular importance to ensure that the strength of the corresponding absorption features remains unbiased, and will thus not affect our stellar population analysis. A similar methodology was applied also by Shields et al. (2007). The derived weights of the stellar spectra that define the optimal template are used to reconstruct an unconvolved optimal template, which is free from the effects of velocity broadening. This unconvolved optimal template is used to measure the absorption line strengths.

Owing mostly to the varied nature of the Tremonti et al. library, the template-fitting procedure yield excellent results in matching the spectra extracted from both the ring and nuclear apertures in all but two cases. The two exceptions are the blue spectra of NGC 6951 at PA=110° and 150°. In the following, we will ignore the line strength measurements obtained from these spectra. Since the nebular emission is sufficiently strong to allow robust estimates of the emission-line fluxes, even where the fit to the stellar continuum is poor, we will use the emission line results derived from these two spectra.

3.1 Line strengths and indices

Stellar absorption lines provide information on the stellar content of the rings. The strength of an absorption line index is determined by the difference between the absorption line and the continuum level. An index is typically defined by a wavelength range that contains the feature and two wavelength ranges to either side that provide an estimate of the red and blue continuum levels. The mid-points of the continuum passbands are fitted by a linear relation, and the difference between this and the absorption feature provides the index value. The latter is sensitive to the shape of the continuum, the spectral resolution, and the velocity dispersion of the object. All these factors must be taken into account before one set of measurements can be compared with another. The Lick/IDS system (Worthey 1994) is commonly used to compare measurements from different observations. For the data used in this paper, however, we are mostly concerned with comparing our indices with model predictions, and for this we need only ensure that our indices are measured in the same way as they are in the models. By

¹ We have used a modified version of the *Gandalf* IDL code available at <http://www.strw.leidenuniv.nl/sauron/>, to include also reddening by dust.

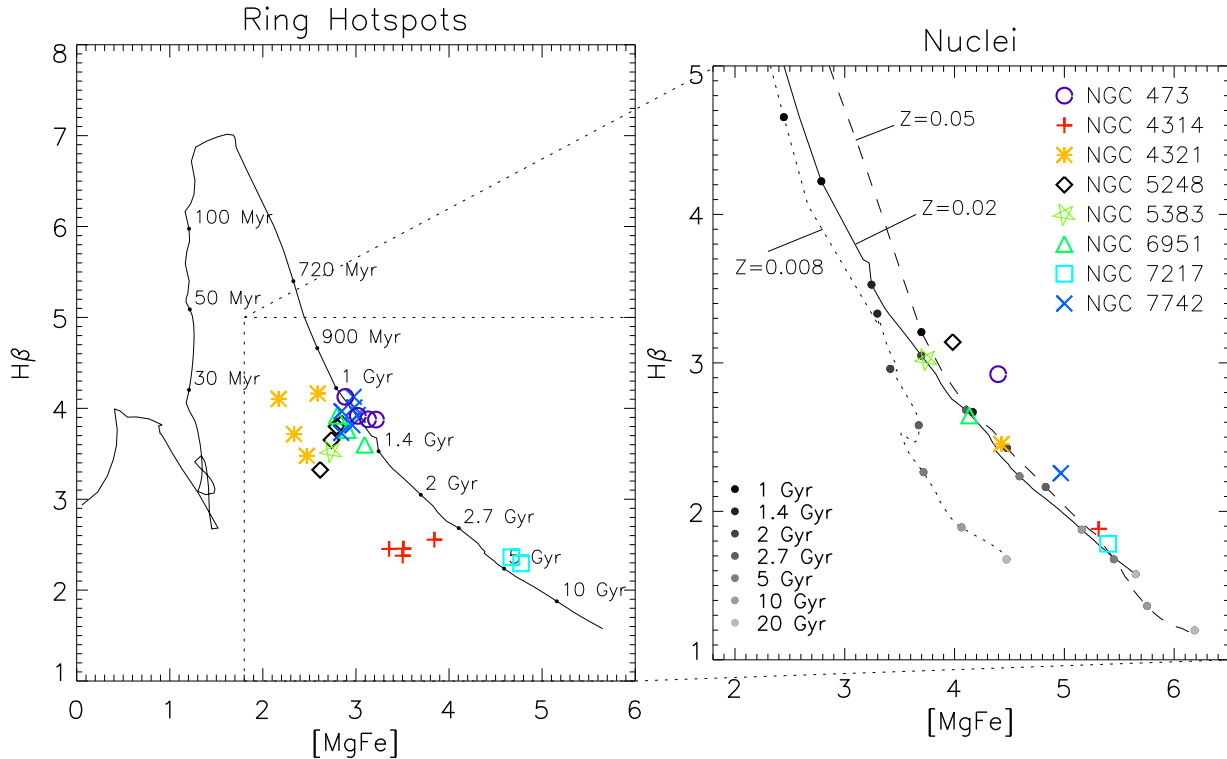


Figure 3. $H\beta$ vs. $[MgFe]$ diagram for the ring hotspots and the nuclear regions of our sample galaxies. *Left:* $H\beta$ and $[MgFe]$ line indices for the ring hotspots compared with the predicted time evolution of the same indices for an single starburst stellar population (SSP) of solar metallicity. *Right:* Same as left but showing the region in the $H\beta$ vs. $[MgFe]$ diagram occupied by our nuclear measurements, together with SSP predictions for three different metallicities, as labelled.

construction, the model predictions come from model spectra with identical resolution to our optimal templates, so it is appropriate to compare them. The line strengths were measured using INDEXF, a C++ program written by N. Cardiel², with the Lick/IDS wavelength definitions (but not calibrated to the Lick/IDS system).

3.2 Uncertainties

The uncertainties in the index measurements are largely determined by the quality of the optimal template fit to the observed galaxy continuum. Kuntschner et al. (2006) describe the errors associated with our emission and absorption line fitting method and subsequent measurements of line strengths. From a detailed analysis they find a constant error budget of 0.1 Å from the continuum fitting process, which we adopt for all the stellar absorption line indices presented here. With regard to the emission-line fluxes, Sarzi et al. (2006) find from simulations that the uncertainties associated with flux measurements scale with the level of fluctuations in the residuals of the fit to the spectrum. We convert such residual-noise levels into an estimate for the emission-line flux errors, adopting as an error for each line the flux of a Gaussian with amplitude equal to the residual-noise level and width equal to the width of the emission-line in question. Considering the weaker lines that will enter our emission-line analysis, $H\beta$ and $[O III]$, these come on average with 3% and 26% uncertainties, respectively, which translate to a typical error of 0.12 on the logarithm of the $[O III]/H\beta$ line ratio. Errors on

line ratios based on the stronger emission lines in our red spectra (e.g., $H\alpha$, $[N II]$, $[S II]$) will be smaller than that.

4 STELLAR ABSORPTION LINE DIAGNOSTICS: THE STAR FORMATION HISTORY

4.1 Index-index diagrams and single starburst models

To probe the properties of unresolved stellar populations, several combinations of absorption-line strength indices are traditionally used to separate age and metallicity effects, comparing the measured values to predictions for stellar populations that were born in an instantaneous burst of star formation and for a single metallicity. Using such single starburst population (SSP) models from Bruzual & Charlot (2003), we plot the evolution of the $H\beta$ and $[MgFe]$ ($= \sqrt{Mgb} \times Fe5015$; see Falcón-Barroso 2002) indices with time for a solar metallicity (Figure 3). The $H\beta$ absorption index is low in very young stars, increases with age until it peaks at around 100-200 Myr, then decreases with age. Conversely, the $[MgFe]$ index remains almost constant for a young population while the $H\beta$ index increases, and increases monotonically with age after the strength of $H\beta$ has peaked.

The values of the $H\beta$ and $[MgFe]$ indices for the nuclear ring hotspots in our sample galaxies are compared to the predicted time evolution of these indices for SSP models in the left panel of Figure 3. While some of the data points lie close to the solar metallicity SSP line, most do not, suggesting that a star formation history more complex than an SSP must be responsible for the observed val-

² See <http://www.ucm.es/info/Astrof/software/indexf/>

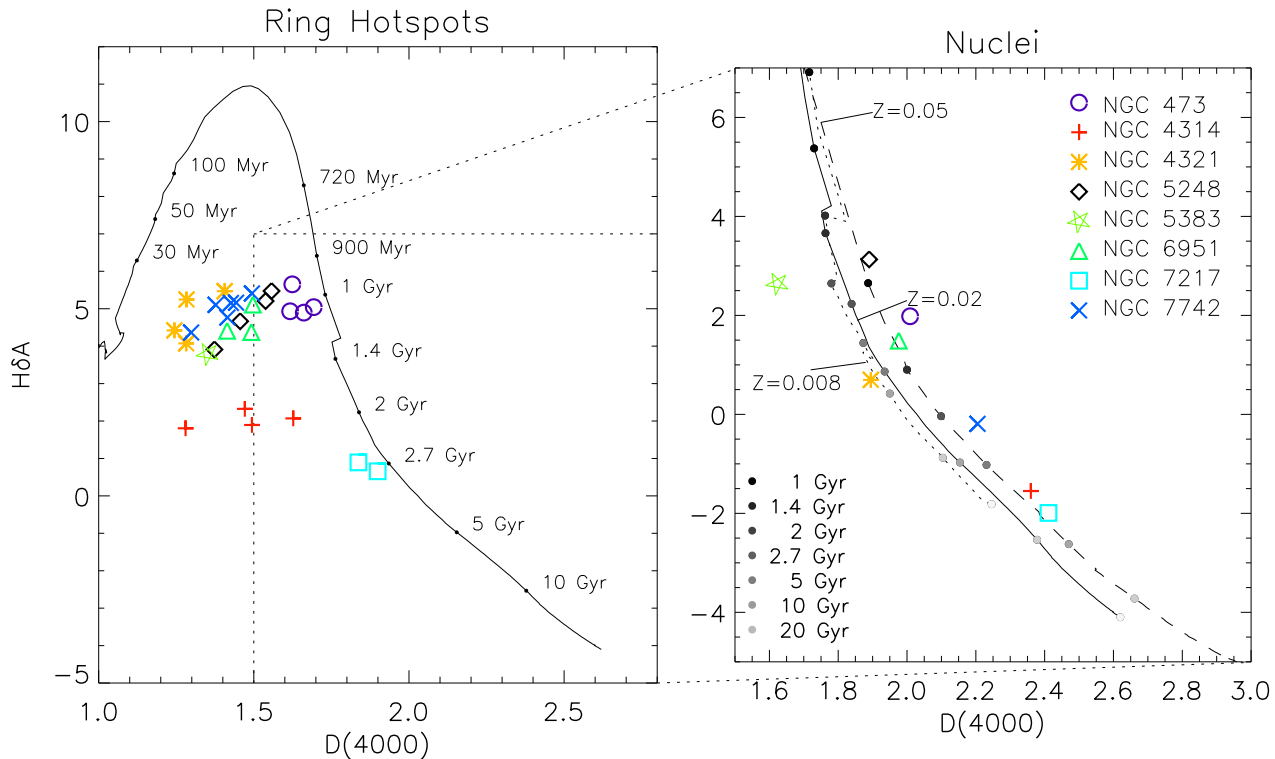


Figure 4. Same as Fig. 3, but now showing the $H\delta A$ and $D(4000)$ indices. Notice the more pronounced discrepancy between the position of the ring hotspots measurements and the predictions of the single starburst model.

ues. On the other hand, the stellar populations in the nuclei of our sample galaxies (Figure 3, right panel) are well described by SSP models of old ages, and are consistent with previous studies for the nuclear populations of bulges (Sarzi et al. 2005; González Delgado et al. 2004). The star-forming nuclear rings are undoubtedly observed along the same line-of-sight as an older stellar population in the disk and bulge of their host galaxies. As a consequence, the scenario most likely to match the line strengths of our hotspot spectra is that of a superposition of young stars in the ring, and old stars in the underlying disc and intervening bulge. This situation is similar to the one described in Paper I for NGC 4321, where we used the same indices as shown in Figure 3.

The larger wavelength range of our current data set allows us to analyse more indices than was possible in Paper I, which enables us to investigate the star formation history of the nuclear rings in more detail. In addition to $H\beta$ and $[MgFe]$, we have measured the $H\delta A$ (Worthey & Ottaviani 1997) and $D(4000)$ (Bruzual 1983) indices in all the hotspot and nuclear spectra. Like other Balmer indices, the $H\delta A$ index is an age-sensitive index that is particularly strong in stellar populations with ages 0.1–1 Gyr. The advantage of using higher order Balmer indices such as $H\delta A$ however, is that they are much less affected by the presence of emission. The $D(4000)$ index is derived from the ratio of two passbands that lie on either side of the 4000 Å break (see Figure 2), which occurs as a large number of stellar absorption features appear bluewards of this break in cooler, more opaque stars. In hotter, younger stars, the 4000 Å break is therefore smaller than it is in cooler, older stars.

Figure 4 shows how our $H\delta A$ and $D(4000)$ measurements compare with the SSP predictions. In the $D(4000)$ vs. $H\delta A$ diagram *none* of the ring hotspot data can be fitted by the SSP model,

confirming the need for a combination of young and old stars to explain the spectra of the nuclear ring regions. On the other hand, the nuclear data remain consistent with SSPs. The similarities between the results inferred from the two pairs of absorption line indices confirm the reliability of the emission-line correction. We note that although SSP models with subsolar metallicities could match the position of some of the hotspots data points in either of the $[MgFe]$ vs $H\beta$ or $D(4000)$ vs. $H\delta A$ diagrams, they could never do so in both diagrams with the same value of the metallicity. Furthermore, no SSP model can match the $D(4000)$ index values below 1.5 observed in many hotspots.

Using the SSP models as a baseline to interpret the index values for the hotspots (as plotted in Figures 3 and 4) as a superposition of young and old stellar populations, we can distinguish two separate groups of objects. The first group includes the majority of the hotspots, for which it would seem plausible to match their position in Figure 3 and 4 by combining $\sim 30 - 50$ Myr young stars with disc and bulge stars older than ~ 1 Gyr. On the other hand, considerably weaker $H\beta$ and $H\delta A$ lines in the hotspots of NGC 4314 and NGC 7217 suggest a mixture of even younger ring stars and a disc/bulge population older than ~ 2.7 Gyr. Assuming that the stellar populations within our nuclear apertures are a good approximation for the underlying disc and bulge populations encompassed by our hotspot spectra, the nuclear data points for NGC 4314 and NGC 7217 further suggest the presence of a much older underlying and intervening stellar population than in the case of our remaining sample galaxies.

In the next section, we will compare the position of the hotspots in the previous diagrams with detailed models featuring a combination of a young ring population with an older disc and

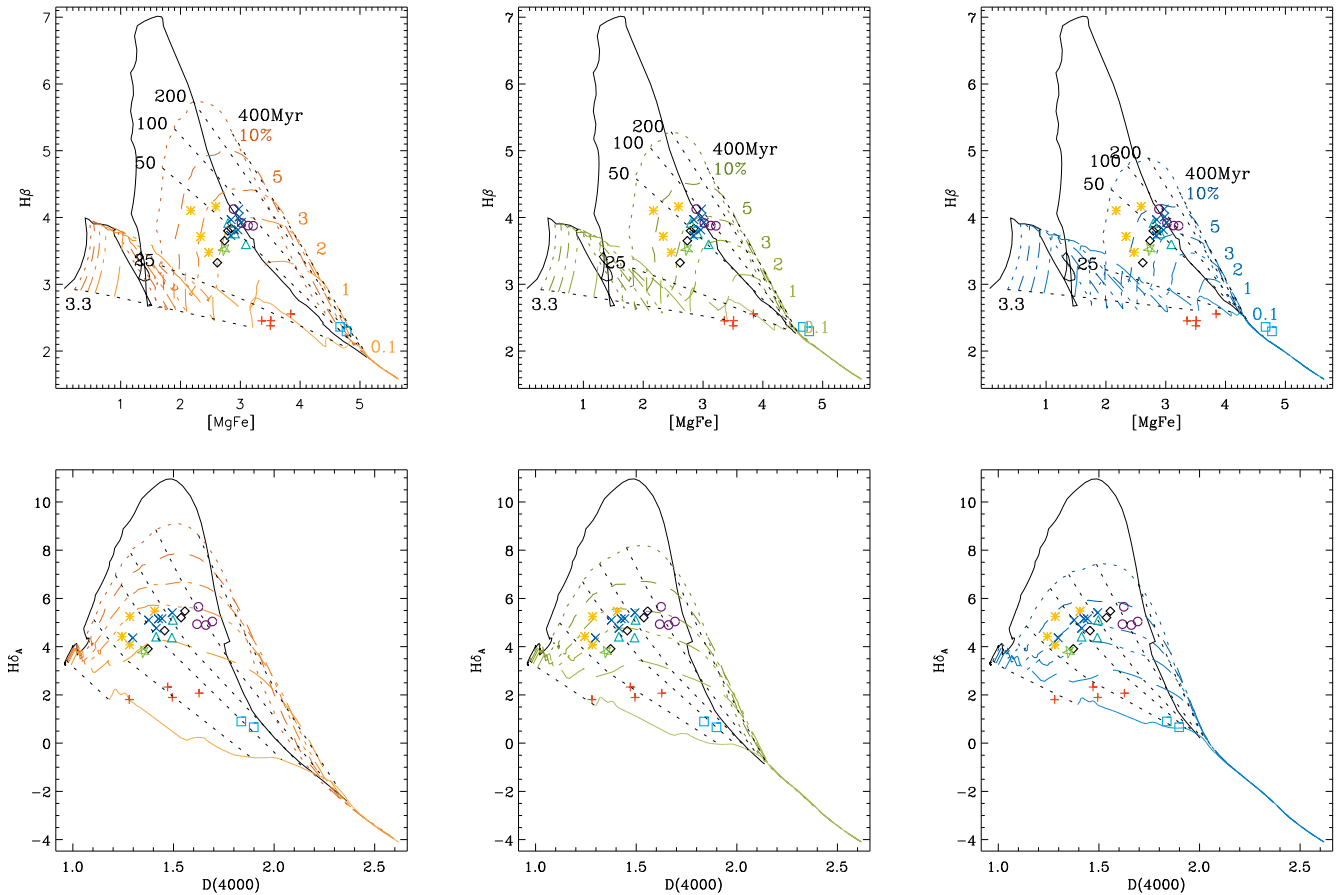


Figure 5. Composite stellar population models for the ring hotspots, assuming the superposition of an old intervening/underlying bulge/disc population and of young ring stars, the latter having formed in a single star-formation episode. Both old and young components are assumed to form instantaneously. The upper panels show the evolution of the $[\text{MgFe}]$ line-strength index vs. that of $H\beta$, whereas the lower panels show the evolution of $D(4000)$ vs. $H\delta_A$. From left to right the models include progressively younger disc and bulge populations, which formed 10, 5, and 3 Gyr before the stars in the ring. In all panels the solid black curve shows, similarly to Figures 3 and 4, the time evolution of the absorption features in the old bulge and disc population, whereas the coloured curves show the evolution of the same features in the hotspot spectra after the onset of star formation in the ring. In each panel, differently coloured lines show how the strength of the ring starburst is varied, adding from 0.1% to 10% of the mass in the older bulge and disc population, as identified in the top panels. The position of the hotspots data points are shown by the coloured symbols, as in Figures 3 and 4.

bulge stellar population. For simplicity, we will describe the disc and bulge stellar components with a single SSP model. We will allow for more complex star formation histories in the nuclear rings of our sample galaxies than simple instantaneous bursts, considering also a continuous star formation history and multiple starburst episodes.

4.2 Composite stellar population modelling

4.2.1 Instantaneous star formation in the ring

The simplest composite population model for the stellar populations at the hotspot locations assumes that both the young ring population and the older disc and bulge populations can be described by means of SSP models. Figure 5 shows several of such stellar population models, following the evolution of the line strength indices ($[\text{MgFe}]$ vs. $H\beta$ upper panels, $D(4000)$ vs. $H\delta_A$ lower panels) after the onset of a single instantaneous star formation episode in the ring. From left to right the models include progressively younger disc and bulge populations, which formed 10, 5, and 3 Gyr before the stars in the ring. In each panel, the strength of the ring starburst

is varied, adding from 0.1% to 10% of the mass in the older bulge and disc population.

Starting from the first group of objects, the $[\text{MgFe}]$ vs. $H\beta$ diagrams of Figure 5 indicate a rather coherent picture where the majority of the hotspots data points appear to trace the evolution of an SSP $\sim 30 - 100$ Myr after its formation. The figure shows that the bursts contribute $\sim 2\%$, $2-3\%$, or $3-5\%$ of the mass of the bulge and disc population, respectively, and indicate slightly older ages for the higher mass fractions. The measurements for NGC 4321 do not suggest such a clean evolution, however, although they indicate a relatively more massive ring starburst. Excluding this object, the $D(4000)$ vs. $H\delta_A$ diagrams yield a rather similar picture for this group of hotspot spectra, in particular when considering the models with a 3 Gyr old disc and bulge population. In this respect, we note that the template fitting for the hotspot spectra of NGC 4321 was quite poor compared to the rest of the sample, so that the line strength indices may be somewhat less reliable for this galaxy.

For the hotspots in NGC 4314 and NGC 7217, a bulge and disc population younger than 5 Gyr is ruled out by the $[\text{MgFe}]$ vs. $H\beta$ diagrams of Figure 5. For a 10 Gyr old disc and bulge compo-

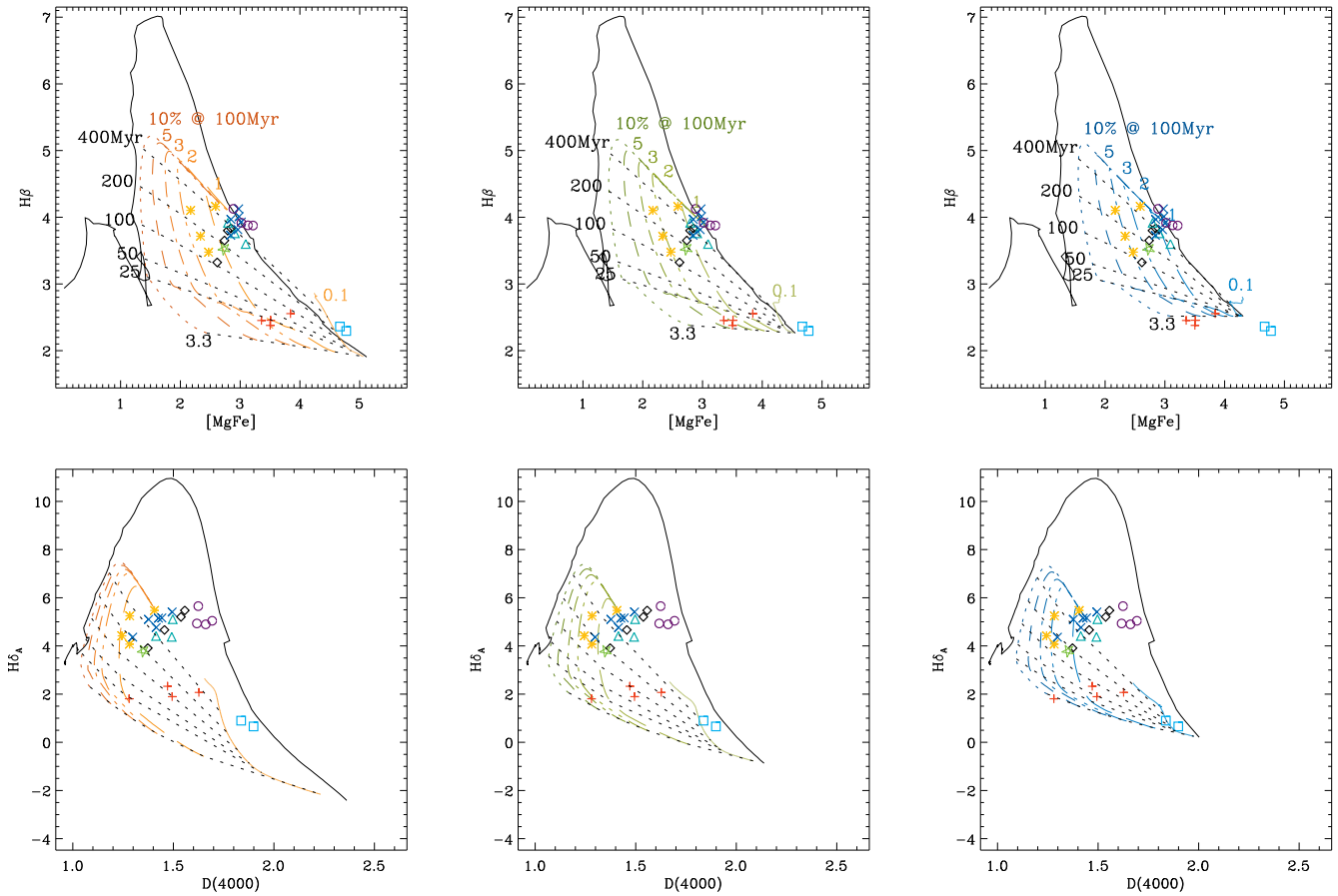


Figure 6. As Figure 5, but now assuming that the ring stars formed over a period of constant star formation. The strength of this activity is quantified by stellar mass that is built in the ring after 100 Myr, relative to the bulge and disc mass.

nent, the ring starburst in these galaxies appears to have occurred less than 50 Myr ago and to have contributed less than 1% of the mass. The case for a significantly younger ring population is particularly strong in the case of NGC 4314, since the position of the NGC 7217 datapoints in the $[\text{MgFe}]$ vs. $\text{H}\beta$ diagram cannot deliver a robust age estimate. Considering that NGC 4314 and NGC 7217 are the galaxies with the earlier Hubble type among our sample, it is possible that the position of their hotspots in Figure 5 is dictated by a larger intervening bulge population than in the other nuclear rings in our sample, rather than by weaker star formation activity.

Although the properties of an SSP superimposed on an older bulge and disc population can match well the hotspot line indices and provide estimates for the age and mass fraction of the ring populations, in practice such a scenario is quite implausible. The young age of stars in the rings inferred from such models ($\lesssim 30 - 100$ Myr), combined with the relatively high fraction of spiral galaxies with nuclear rings ($\sim 20\%$, Knapen 2005), would imply that we live in a special time in the history of spiral galaxies. Instead, it is more likely that star formation in nuclear rings has been either continuous in the last few hundred Myr, or characterised by multiple starbursting episodes.

4.2.2 Continuous star formation in the ring

To test the first of these classes of models, we compare (Fig. 6) the position of the hotspots in the $[\text{MgFe}]$ vs. $\text{H}\beta$ (upper panels)

and $\text{D}(4000)$ vs. $\text{H}\delta\text{A}$ diagrams (lower panels) with the predicted evolution of these indices since the onset of a period of constant star formation activity in the ring. As above, this phase follows the main formation episode for the bulge and disc stars by 10, 5, and 3 Gyr (left, middle and right panels, respectively). As in Figure 5, the strength of the star formation activity in the ring is a parameter that can be varied: we show models which have added from 0.1% to 10% of the bulge and disc mass after 100 Myr.

There are several inconsistencies between the data and the models in Figure 6. A continuous star formation scenario underpredicts the strength of the $\text{H}\delta$ absorption features in many of the ring hotspot spectra, and cannot account for the values of the $\text{H}\beta$ index observed in NGC 7217. Furthermore, the position of different hotspots within the same galaxies, like NGC 7742, NGC 5248 and NGC 4314, suggests that the different regions in the ring are subject to different levels of constant star formation activity that have begun at different epochs, several hundred Myrs in the past. This is, however, a most unlikely situation, given that stars and gas circulate along nuclear rings typically in a few tens of Myr.

4.2.3 Multiple-burst star formation in the ring

Discarding a history of constant star formation in the rings we now consider the possibility of multiple starbursting episodes. In Figure 7 we show the evolution of the line indices for models including from 1 to 5 instantaneous bursts, each adding 1% of the bulge and

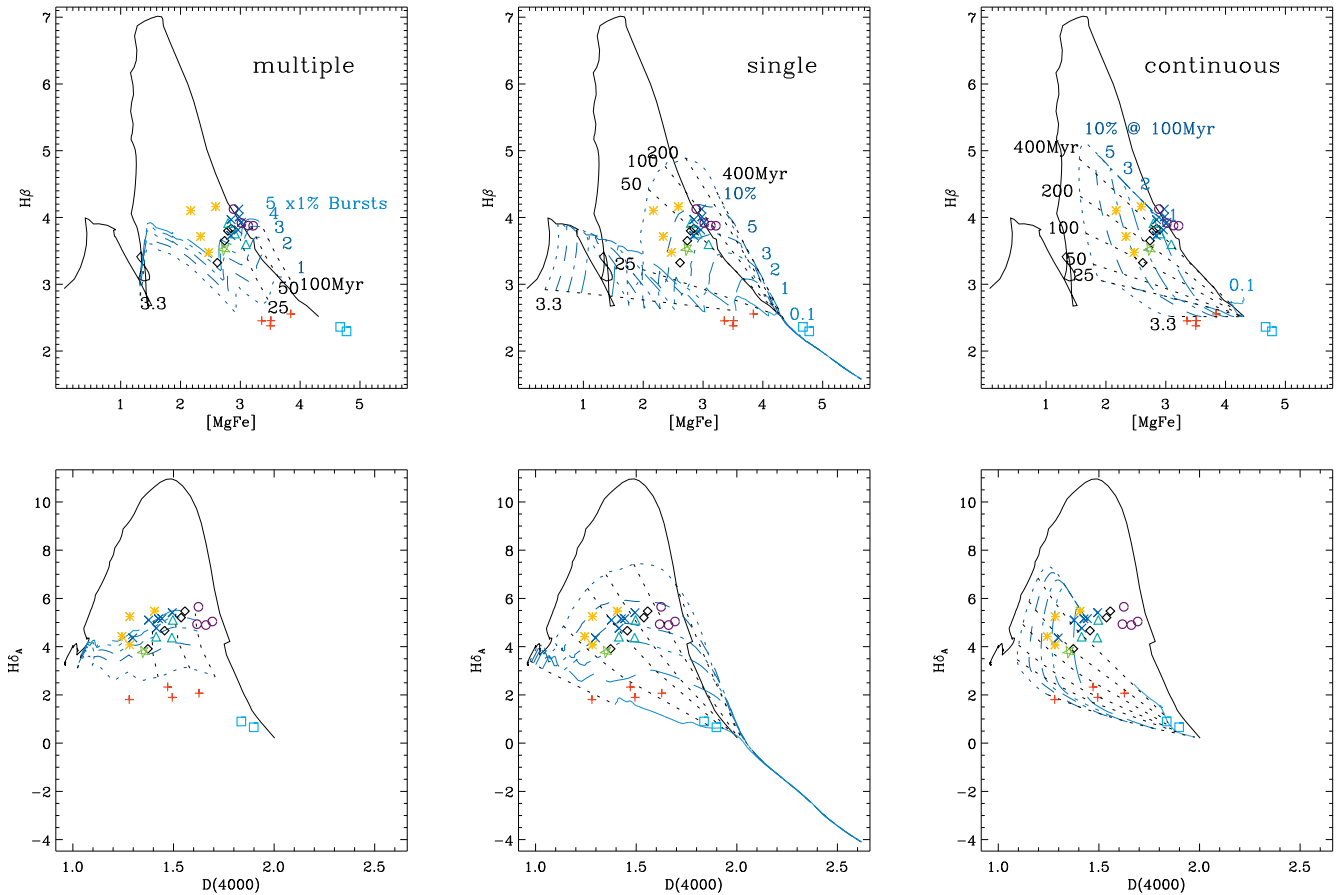


Figure 7. Composite stellar population models for the ring hotspots for the superposition of a 3-Gyr-old bulge/disc population and of young ring stars, which formed during a varying number of instantaneous star-formation episodes (from 1 to 5 bursts, *left*), during a single burst (*centre*), or over a period of constant star formation (*right*). As in Figures 5 and 6, the top panels show the evolution of $[\text{MgFe}]$ vs. $H\beta$, whereas the lower panels show $D(4000)$ vs. $H\delta A$. The central and right panels are similar to the right panels of Figures 5 and 6, respectively. The multi-burst model (*left*) shows the time evolution of the indices in the hotspot spectra since the onset of the last starburst, each of which is set to contribute 1% of the bulge and disc mass.

disc mass and occurring every 100 Myr. Because of this periodicity, the model evolution is shown only for the 100 Myrs following the last star formation episode. Each of the models includes a disc and bulge population that is 3 Gyr old at the onset of the latest burst, so that the age of the old stellar component is the same for all models, whereas the recent episodic star formation activity started earlier in models with more such episodes (e.g., star formation in the ring began 400 Myr ago, and 2.6 Gyr after the bulge/disc formation, in a 5-burst model). Figure 7 also shows, for comparison, the composite population models for an instantaneous and continuous star formation scenario in the ring and a 3-Gyr-old disc and bulge population.

Except for NGC 4321 and for the rings requiring very small fractions of young stars (NGC 4314 and NGC 7217), the hotspot data points on both the $[\text{MgFe}]$ vs. $H\beta$ (upper panels) and $D(4000)$ vs. $H\delta A$ diagrams (lower panels) agree remarkably well with these models for multiple starbursting episodes, suggesting that at least 4 or 3 bursts have occurred in the past, as judged from the $[\text{MgFe}]$ and $D(4000)$ diagrams, respectively. Similarly to the case of the instantaneous models, we note that the position of the hotspots in NGC 4314 and NGC 7217 in these diagrams can also be matched by models featuring periodic star-formation episodes, provided that each burst contributes to mass fractions smaller than 1% and that an older bulge and disc population is included.

4.2.4 Summary of star formation history modelling

Despite the success of the last class of models, the star formation history of nuclear rings is almost certainly more complicated than a simple superposition of instantaneous bursts evenly spaced in time. Some combination of the two latter scenarios is likely, in which star formation events occur episodically, but may vary in length and relative strength. At present, it is impossible to reproduce the *exact* sequence of star formation in the rings from these indices. What is apparent is that the models that most closely match the data points must have a small, but significant, intermediate age population that is the result of an extended period of recent star formation. They are *not* the result of either continuous star formation, or of one single burst of star formation (the current one).

5 EMISSION LINE DIAGNOSTICS: PHYSICAL CONDITIONS OF THE GAS

In nuclear rings, photoionisation by hot OB stars is the most likely source of nebular emission, although shocks may play an additional role. A number of factors determine the appearance of the emission line spectrum: the metallicity of the gas, the shape of the ionising radiation spectrum, and the geometric distribution of the gas and

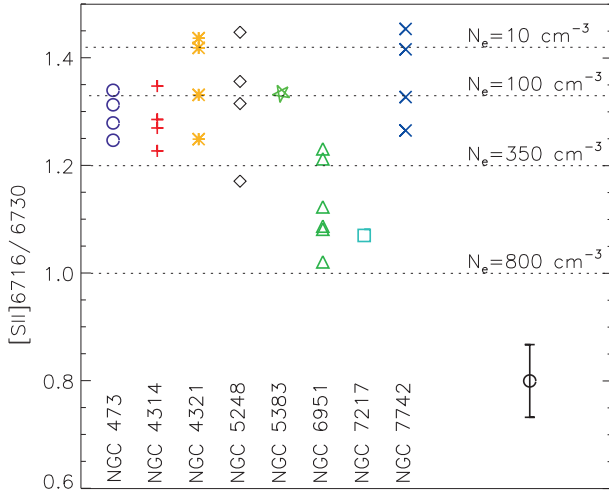


Figure 8. The $[\text{S II}]\lambda 6716/[\text{S II}]\lambda 6731$ ratio in the nuclear rings of our sample galaxies. Assuming a temperature of 10^4 K, the dashed lines give estimates of the electron density. For NGC 7217, the two hotspot spectra were combined to achieve a minimum signal to noise ratio of 3 for the $[\text{S II}]\lambda 6716/[\text{S II}]\lambda 6731$ ratio. The error bar shown at the bottom right of the plot is the average uncertainty measured within our sample.

ionising sources (Dopita et al. 2000). The geometry can be combined into one single factor, the mean ionisation parameter q (with dimensions cm s^{-1}). This is the ratio of the flux of ionising photons through a unit area, to the local number density of hydrogen atoms at the edge of the ionised cloud. In this section, we inspect the emission line spectra of our nuclear rings and nuclei, to determine the gas density, the starburst metallicity, and the ionisation parameter. To do this, we will measure the flux ratios of a number of emission lines and compare the observed values to photoionisation models.

5.1 Gas Density

The two lines in the $[\text{S II}]\lambda\lambda 6716, 6731 \text{ \AA}$ doublet have similar excitation levels, but different collisional de-excitation rates. This results in the relative populations of the two levels being mostly dependent on the gas electron density (Seaton 1954), which can therefore be estimated from the intensity ratio of these lines. Figure 8 shows the $[\text{S II}]\lambda 6716/[\text{S II}]\lambda 6731$ ratio for the nuclear rings in our sample. The electron densities, indicated by the dashed lines, are for a typical temperature of $T = 10^4$ K (Osterbrock 1989). The nuclear rings show a wide range in electron density, both within each ring, and across the sample. Most of the rings fall within the range $N_e = 10\text{--}350 \text{ cm}^{-3}$, with NGC 6951 and NGC 7217 having higher densities, of up to 800 cm^{-3} . This is consistent with previous studies: Kennicutt, Keel & Blaha (1989) found a wide range of electron densities, from $N_e = 10\text{--}1000 \text{ cm}^{-3}$, for a number of HII regions, which included both disc and circumnuclear HII regions. Similar results were found by Ho, Filippenko & Sargent (1997).

5.2 Metallicity and Ionisation Parameter

Veilleux & Osterbrock (1987; hereafter V087) devised a classification system based on the ratios of forbidden to hydrogen lines in

order to separate gas emission originating in HII regions from nebular activity powered by other sources of ionisation such as active galactic nuclei. Their ratios involve lines which are close together in wavelength, minimising errors in calibration and reddening correction, such as the $[\text{O III}]\lambda 5007/\text{H}\beta$ ratio in blue spectra, and the $[\text{N II}]\lambda 6583/\text{H}\alpha$, $[\text{S II}]\lambda\lambda 6716, 6731/\text{H}\alpha$ and $[\text{O I}]\lambda 6300/\text{H}\alpha$ in red spectra. When the $[\text{O III}]/\text{H}\beta$ ratio is plotted against any of the red lines ratios, different types of emission-line galaxies occupy different regions of the diagrams. HII regions and HII nuclei in particular tend to be located in narrow, well-defined zones (Kewley et al. 2001) in such diagnostic diagrams, which can be understood by means of sophisticated photoionisation models.

In this respect, Dopita et al. (2000) and Kewley et al. (2001) present valuable models for HII regions obtained with the photoionisation code MAPPINGS III (Sutherland & Dopita (1993) while using the PEGASE (Fioc & Rocca-Volmerange 1997) and STARBURST99 (Leitherer et al. 1999) codes to generate the stellar ionising-radiation fields that depend on the metallicity of the starburst. Figure 9 shows an example of a photoionisation grid, calculated in the case of the $[\text{O III}]/\text{H}\beta$ vs. $[\text{N II}]/\text{H}\alpha$ diagnostic diagram for metallicities 0.05, 0.2, 0.4, 1, and 2 times Solar, values of the ionisation parameter $q = 3 \times 10^8$, 1.5×10^8 , 8×10^7 , 4×10^7 , 2×10^7 , 1×10^7 , and $5 \times 10^6 \text{ cm s}^{-1}$, and for densities of $N_e = 10 \text{ cm}^{-3}$ and 350 cm^{-3} . The narrow zone occupied by HII-regions and HII-nuclei in this plot coincides with the folding of the ionisation parameter/metallicity surface: HII regions characterised by a large range in metallicity or ionisation parameter are projected into a narrow band on the figure. These starburst models set tight upper limits for the values of these line ratios, so that emission-line regions that lie above and to the right of the model grids must have other source of ionisation beside, or in addition to, O stars (Kewley et al. 2001).

Although star-forming regions are readily identified in V087 diagrams such as the one juxtaposing $[\text{O III}]/\text{H}\beta$ with $[\text{N II}]/\text{H}\alpha$, the folded nature of the models makes it difficult to determine unambiguously the metallicity and the ionisation parameter of star-forming regions, except for very low metallicities. Dopita et al. (2000) and Kewley et al. (2001) found that the best combination of line ratios for separating metallicity and ionisation parameter effects are $[\text{N II}]\lambda\lambda 6548, 6583/[\text{O II}]\lambda\lambda 3727, 3729$ vs. $[\text{O III}]\lambda 5007/[\text{O II}]\lambda\lambda 3727, 3729$, or $[\text{N II}]/[\text{O II}]$ vs. $[\text{O III}]/\text{H}\beta$. Although all these lines fall within the wavelength range of our spectra, we cannot measure the $[\text{N II}]/[\text{O II}]$ ratio with confidence, since we do not dispose of an accurate relative flux calibration of our red and blue spectra, where the $[\text{N II}]$ and $[\text{O II}]$ lines are found, respectively. Additionally, the $[\text{O II}]$ lines are not always observed. To estimate the metallicity and ionising parameter of the emission-line regions observed by our spectra we can instead use the diagnostic diagram based on the $[\text{N II}]\lambda 6583/[\text{S II}]$ and $[\text{O III}]/\text{H}\beta$ ratios. Rubin, Ford & Whitmore (1984) were the first to suggest the $[\text{N II}]/[\text{S II}]$ ratio as a metallicity indicator, and Kewley & Dopita (2002) recently confirmed the usefulness of this ratio for estimating metallicities from slightly sub-solar to super-solar values, making the $[\text{N II}]/[\text{S II}]$ quite complementary to $[\text{N II}]/\text{H}\alpha$ in this respect. This is illustrated by the MAPPINGS III models plotted in the right panel of Figure 9, where the model grid in the $[\text{N II}]/[\text{S II}]$ diagram folds only at very low metallicity.

Figure 9 shows the $[\text{O III}]/\text{H}\beta$, $[\text{N II}]/\text{H}\alpha$ and $[\text{N II}]/[\text{S II}]$ line ratios measured in the ring hotspots. The location of the ring data in the $[\text{N II}]/\text{H}\alpha$ diagram is consistent with nebular emission powered only by O stars, although no conclusion on the metallicity of the starburst can be drawn from this V087 diagram. On the other hand,

Nuclear Ring Emission Line Ratios

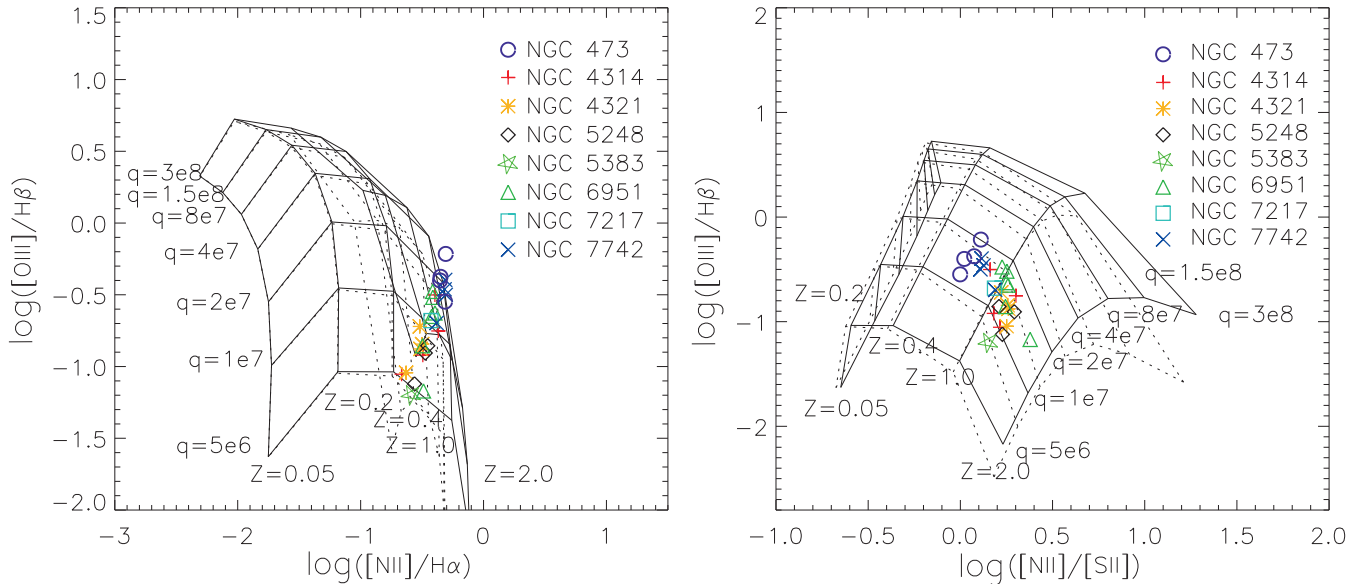


Figure 9. Diagnostic diagrams of $\log([\text{O III}]/\text{H}\beta)$ vs. $\log([\text{N II}]/\text{H}\alpha)$ (left) and $\log([\text{O III}]/\text{H}\beta)$ vs. $\log([\text{N II}]/[\text{S II}])$ (right), featuring the MAPPINGS III model prediction for the nebular emission arising in star forming regions. The models are based on STARBURST99 spectral energy distributions for continuous star formation over a period of 8 Myr. The theoretical grids assume different values for the ionisation parameter and for the starburst metallicity, and are shown with black lines for a density of 10 cm^{-3} and dashed lines for a density of 350 cm^{-3} . The data points measured from the nuclear ring hotspots are shown as coloured symbols. Uncertainties in the ratios are at most 30%, translating into errorbars of 0.1 or less along both the axes of these logarithmic plots.

the position of the data points in the $[\text{N II}]/[\text{S II}]$ vs. $[\text{O III}]/\text{H}\beta$ grid indicates that the ring hotspots are populated by H II regions with metallicities ranging from slightly below to just above Solar, with values for the ionisation parameter between 1 and $2 \times 10^7\text{ cm s}^{-1}$.

Two aspects of this emission-line analysis are also relevant to our stellar population results. First, Figure 9 firmly rejects starbursts of exceedingly low metallicity, thus further excluding the possibility discussed in § 4.1 that the position of some of the line-strength measurements in the ring hotspots could be consistent with SSP models with subsolar metallicity. Second, the models grid of Figure 9 use a spectral energy distribution that was obtained from STARBURST99 and assuming continuous star formation over a short period of 8 Myr. Models based on a truly instantaneous star formation event were found to be grossly inconsistent with the data, producing exceedingly high $[\text{O III}]/\text{H}\beta$ ratio compared to the values measured in the ring hotspots. This further supports the statement made in § 4.2, that the star-formation history of nuclear rings is likely to be a combination of continuous and episodic bursts.

5.3 Line ratios for the nuclei

All the observed nuclei in the sample have measurable emission lines. Some of the galaxies are classified as AGN in the literature, others as H II-nuclei or Low-Ionisation Nuclear Emission Regions (LINERs, Heckman 1980). Baldwin, Phillips & Terlevich (1981) and, later, VO87 reported that the $[\text{O III}]/\text{H}\beta$ vs. $[\text{N II}]/\text{H}\alpha$ diagram allows one to distinguish between the different types of nuclei. This work has been extended by Kewley et al. (2001), who determined a theoretical ‘maximum starburst line’: galaxies above this line are likely to be dominated by an AGN. Kauffman et al. (2003) modified this scheme to include an empirically derived line dividing pure

star-forming galaxies from Seyfert-HII composite objects. These classification lines can be seen in the top panel of Fig. 10, compared to the ratios derived for the nuclear regions of the galaxies in the current sample. NGC 5383 is closest to possessing a purely star-forming nucleus, NGC 473 and NGC 5248 are classified as composite, and the rest fall in the LINER and AGN category.

Kewley et al. (2006) have extended the scheme even further, using the $[\text{O III}]/\text{H}\beta$ vs. $[\text{S II}]/\text{H}\alpha$ plot to separate AGN from LINER activity. This can be seen for our data in the lower panel of Figure 10. In this diagram, NGC 6951 is the only Seyfert nucleus, NGC 7217 and NGC 7742 are well within the region occupied by LINERs, NGC5383 and NGC5248 remain close to the H II-region model grids, and each of the remaining nuclei lie on the line between LINER and star-forming activity, suggesting a composite nature. These results are in remarkable agreement with the Palomar classification for these nuclei (Table 1), with the possible exception of NGC4314, for which our data suggest a composite classification rather than a strict LINER activity. NGC 473 was not observed by Ho et al., and our data suggest a H2/T2 nuclear classification.

6 DISCUSSION

6.1 The star-formation history of nuclear rings

In Paper I we have investigated the star-formation history in the nuclear ring of NGC 4321 using the three line-strength indices that can be probed by the SAURON integral-field spectrograph, namely $\text{H}\beta$, Fe5015 and Mgb . For NGC 4321 we concluded that star formation in the ring was likely long-lived and episodic, thus arguing that the nuclear ring is a stable configuration that is intimately linked to the large bar in this galaxy (Knapen et al. 1995b).

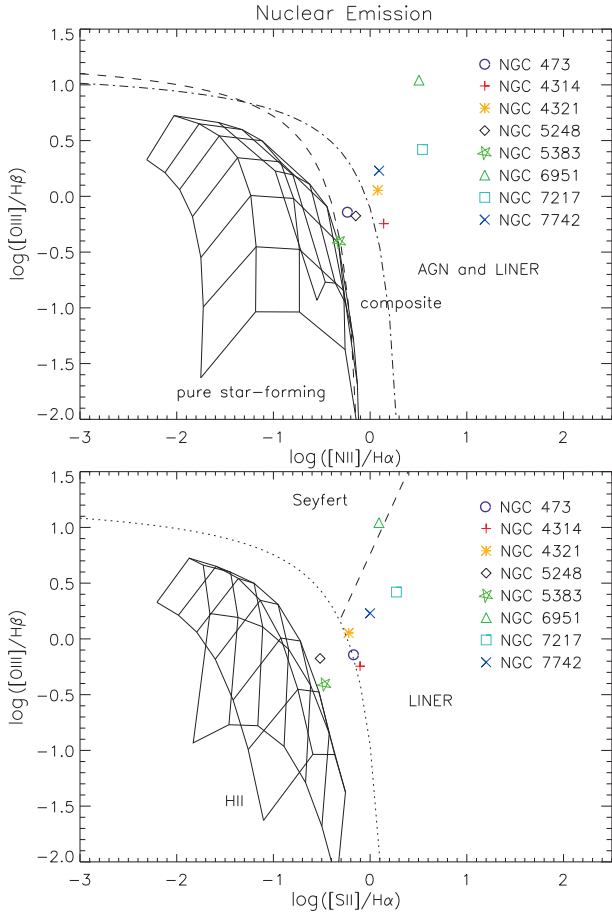


Figure 10. Diagnostic diagrams of $\log([O III]/H\beta)$ vs. $\log([N II]/H\alpha)$ (up) and vs. $\log([S II]/H\alpha)$ (down), compared with theoretical model grids as in Fig. 9. The data points measured from the nucleus of each galaxy are plotted as coloured symbols. Up: the dot-dashed line is the “maximum starburst line” of Kewley et al. (2001). The dashed line is the empirically derived starburst line from Kauffmann et al. (2003). Down: the dotted line is the “maximum starburst line” of Kewley et al. (2001), the dashed line from Kewley et al. (2006), to separate Seyferts and LINERs.

In the current paper we have measured the strength of two additional stellar features, the 4000Å break and the H δ absorption line, in the nuclear rings of eight nearby galaxies. By comparing the observed values for all five indices to the predictions of population synthesis models for the star-formation history in the ring we have reached a similar conclusion to Paper I - that star formation in nuclear rings is a prolonged and episodic phenomenon.

Models assuming that nuclear rings form single instantaneous burst of star formation yield predictions that are not incompatible with the data, but such a scenario is generally ruled out because it implies formation epochs for the rings that are too short and recent to be consistent with the relatively high frequency of occurrence of nuclear rings in nearby galaxies (§ 4.2.1). Furthermore, the inclusion of the D(4000) and H δ A indices in our analysis allowed us to firmly rule out the possibility of a history of continuous star formation for our nuclear rings (§ 4.2.2). On the other hand, the strength of the absorption lines in the ring hotspot spectra are well matched by models allowing for the formation of the ring stars over a number of instantaneous star-formation episodes, superimposed on an underlying or intervening old disc and bulge population (§ 4.2.3).

The success of this family of models, together with the demise of its alternatives, confirm the general understanding that after the initial formation of the bulge and disc component, gaseous material is transported toward the center over a prolonged period of time, where it accumulates near the location of the ILR and where the density threshold for the ignition of star formation is repeatedly crossed. The inflow of gaseous material can be driven by the presence of large scale bars, but this is not the only mechanism that can fuel the circumnuclear region (see, e.g., Knapen et al. 2004 for a case study of ring formation induced by a minor merger). In fact, two of our sample galaxies are classified as unbarred and they will be further discussed below. Another object that will deserve further attention is NGC 4314, for which our modelling suggest that the ring stars have formed very recently, only a few Myr ago. Below, we will discuss the possibility that for NGC 4314 we could be witnessing the initial phases of ring formation.

Our results on the star-formation history of nuclear rings have several important consequences. As previously stated, nuclear rings are common in spiral galaxies, and are characterised by high star formation rates. If nuclear rings form stars over a long timescale, this will lead to the accumulation of considerable stellar masses in the central regions of their host galaxies. Kormendy & Kennicutt (2004) estimated that for the typical mass of molecular gas and star formation rate of nuclear rings, stellar masses of 10^8 to $10^9 M_\odot$ will be formed. In Paper I, the nuclear ring in NGC 4321 was observed to be thicker when viewed in stellar indices than when viewed in H β emission, indicating that the new stars are diffusing out of the ring. It is possible that these stars will diffuse further in the galactic disc, contributing to the formation of a more bulge-like structure due to vertical instabilities triggered by the presence of a bar. First characterised as pseudo-bulges by Kormendy (1993), such structures half-way between bulges and discs may be an integral component of most spiral galaxies, in particular in those of later Hubble types. Kormendy & Kennicutt (2004) further discuss how pseudo-bulges are a consequence of slow secular processes, pointing out how secular evolution becomes more important than galaxy mergers or interactions in re-shaping the structure of galaxies as the Universe expands.

If nuclear rings are stable configurations in disk galaxies that add considerable stellar mass to the centers of their hosts over prolonged periods of star formation, nuclear rings should be regarded as a key component in the secular evolution of galaxies. Furthermore, nuclear rings may be even more frequent than previously thought. Most nuclear rings, and all those used by Knapen (2005) to derive the fraction of nuclear ring in local spirals, were identified using H α imaging that traces massive star formation. Yet, our stellar population modelling suggest that over most of their lifetime nuclear rings are not actively forming massive stars, which implies that a significant but so far unknown fraction of galaxies could host a young nuclear ring that is presently not forming massive stars. The confirmation of nuclear rings as an established feature of a galaxy also reinforces the view that nuclear rings are linked to the large-scale bar, and the connection between nuclear rings and ILR(s).

6.2 NGC 4314

Our stellar absorption-line measurements show how NGC 4314 stands apart from the majority of the rings in our sample, with a significantly older underlying or intervening disc and bulge population and much younger ring stars. This conclusion is consistent with the findings of Benedict et al. (2002), who analysed high-spatial resolu-

tion optical colour maps obtained with the Hubble Space Telescope (*HST*) to study the ages of the single star clusters in the ring. They found colours consistent with instantaneous star formation and little evidence for any cluster older than 40 Myr in the ring. Although the analysis of Benedict et al. did not cover the intra-cluster stellar population, which also contribute to our hotspot spectra, the absence of clusters older than 40 Myr suggests that no star-formation episode occurred in the ring of NGC 4314 previous to the current one.

It would thus appear that in the case of NGC 4314 we are witnessing the initial massive star formation event, which may well coincide with the formation of the nuclear ring. The observed blue stellar arms just outside the nuclear ring (Benedict et al. 2002) are evidence for star formation activity in the recent past (between 100–200 Myr ago) but whether this occurred within the present configuration of the ring, or within a larger past version of it (as suggested by Combes et al. 1992), is not presently clear. What is evident is that NGC 4314 is peculiar among our sample galaxies also because the massive star formation in the entire galaxy is practically confined to the nuclear ring (known since Burbidge & Burbidge 1962), and because the galaxy is particularly deficient of atomic hydrogen gas, H I (García-Barreto et al. 1991; Combes et al. 1992). These peculiarities make the conclusion that we are indeed witnessing the very first phase of massive star formation in the nuclear ring less unattractive than it might seem at first glance when compared to the results for the other rings in our sample.

6.3 Unbarred galaxies: NGC 7217 and NGC 7742

NGC 7217 and NGC 7742 are both classified as unbarred galaxies and indeed appear very symmetric in near-IR 2MASS images. Using ground-based and *HST* near-IR imaging, Laine et al. (2002) confirm that no bars can be found in NGC 7217, but find two small bars in NGC 7742 (with deprojected bar radii of 1.2 and 6.8 arcsec, corresponding to 130 and 730 parsec). The lack of a large bar in both cases may initially seem problematic, as the general picture of nuclear ring formation is often described as requiring a bar to drive gas towards the centre. There are other ways of achieving a non-axisymmetric potential which can stimulate inflow, however, such as the presence of an oval distortion, or the influence of external forces. Both NGC 7217 and NGC 7742 have counter-rotating sub-systems (Merrifield & Kuijken 1994; Sil’chenko & Afanasiev 2000; de Zeeuw et al. 2002), which hints at a turbulent, merger, history.

NGC 7742 has a counter-rotating gas system, and NGC 7217 has a counter-rotating stellar system. Sil’chenko & Moiseev (2006) suggest that the two galaxies have undergone a similar past interaction. They propose that NGC 7742 has only recently started accreting gas, while NGC 7217 is at a later stage of evolution and has already converted its counter-rotating gas into stars. Mazzuca et al. (2006) find that the metallicity of the gas in the ring of NGC 7742 is close to Solar, in agreement with our results. As there are no suitable large metal-rich companion galaxies with which NGC 7742 can have interacted, Mazzuca et al. propose that a smaller, metal-poor dwarf galaxy has been cannibalised. Part of its gas was then concentrated in the ring, where star formation proceeded long enough for the metallicity to reach a solar value. They estimate that this process takes a few tens of Myrs, which agrees with our stellar population modelling for this galaxy.

Buta et al. (1995) and Combes et al. (2004) suggest that the oval distortion present in NGC 7217 would be sufficient to create the resonances which shape the three rings which it possesses,

without invoking a minor merger explanation, and the detection of a counter-rotating stellar system could be attributed to a large bulge velocity dispersion. They also highlight that a number of nuclear rings is present in NGC 7217, all found at different radii. The smallest is a red dust ring, followed radially outwards by an H α ring, in turn followed by a broad red ring. Like NGC 4314, NGC 7217 is also deficient in H I gas (Buta et al. 1995), and both have much older underlying stellar populations (Fig. 3) than the other galaxies in our sample.

6.4 Absence of Wolf-Rayet features

Wolf-Rayet stars (WR) are the remnants of the most massive stars in galaxies. Their numbers therefore peak shortly after a major star-formation episode, typically when the starburst is only 3 to 4-Myr-old. The number and type of WR stars is also a strong function of the starburst metallicity, a fact that stimulated the study of WR stars as a means to trace the nature of massive star formation in external galaxies (e.g., Vacca & Conti 1992; Shaerer & Vacca 1998; Shaerer, Contini & Kunth 1999; Guseva, Izotov & Thuan 2000). In optical spectra, the most noticeable WR feature is the so-called 4650Å “bump”, which is due to a superposition of broad stellar emission lines.

In *none* of our ring hotspot spectra is such a feature observed. The absence of WR features suggests that the *bulk* of the young stars in the ring regions subtended by our spectra have formed over a longer period of time than just a few Myrs, consistent with our absorption-line analysis. The only exception to this statement is NGC 4314. For this galaxy we have evidence that the hotspot spectra are a superposition of an old bulge and disc stellar population with very young ring stars, less than 25-Myr-old. A 4650Å “bump” could therefore be expected in this case, and that this feature is not observed could be due to a strong contamination of intervening bulge stars, consistent with the early-type classification of this disc galaxy (see also § 4.2.1)

7 CONCLUSIONS

We present a study of the optical spectra of a sample of eight star-forming nuclear rings and the nuclei of their host galaxies. These spectra cover a wide range in wavelength, and allow us to measure a number of gaseous and stellar features. The stellar absorption indices show that along the line of sight to the nuclear ring we can detect the older underlying and intervening disc and bulge, as well as the young stars being formed in the ring. We use two absorption-line index diagrams, H β vs. MgFe and H δ A vs. D(4000), to test models for the star formation history of the rings. The simultaneous use of these indices allows us to rule out a constant star-formation history, whereas the possibility that these rings one-off events in a galaxy’s history is discarded on the basis that it would be unlikely to observe all these rings as they have just formed. Our models suggest instead that nuclear rings are in fact more long-lived structures with extended, although episodic, periods of star formation. The absence of Wolf-Rayet features in our spectra further shows that nuclear rings are not made exclusively of stars that formed only very recently. These results confirm not only the intimate dynamical connection between nuclear rings and their host galaxies, but also the important role that the rings can play in transforming disk gas to (pseudo-)bulge stars, thus stimulating secular evolution.

The gas emission lines of the nuclear rings reveal that the rings

possess a range of electron densities, most within a range of $10\text{--}350\text{ cm}^{-3}$. Diagnostic diagrams show that all rings are populated by H II-regions with similar ionisation parameters and with a small spread in metallicity around the Solar value.

The nuclear rings of NGC 4314 and NGC 7217 stand apart from the other nuclear rings in the sample, as they appear to have much older and prominent underlying populations. They also have much lower values of the $H\beta$ and $H\delta A$ indices, which in the case of NGC 4314 implies much younger ages for the ring stars. In this galaxy, which stands out from the rest of the sample for its lack of star formation in the disk and its deficiency of neutral gas, we may be witnessing the initial phases of the ring formation. The vast majority of the nuclear rings in the sample can thus be described by a scenario where the nuclear ring is a stable structure, in most cases induced by the bar, and confirming that all these rings have formed by dynamical means near the ILR(s). This is also true for the two galaxies in our sample which lack a prominent large bar, but for which a past minor merger event may well have caused a similar non-axisymmetry in the galaxy's gravitational potential.

Our study of the spectra of the nuclei of our sample galaxies shows that all display emission lines. Consistent with previous studies for the nuclear activity and stellar populations, the majority of our nuclei appear to be dominated by old stellar populations and by LINER-like emission.

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REFERENCES

- Allard E. L., Peletier R. F., Knapen J. H., 2005, *ApJ*, 633, L25
 Allard, E. L., Knapen, J. H., Peletier, R. F., & Sarzi, M. 2006, *MNRAS*, 371, 1087 (Paper I)
 Alonso-Herrero, A., Ryder, S. D., & Knapen, J. H. 2001, *MNRAS*, 322, 757
 Arsenault, R., Boulesteix, J., Georgelin, Y., & Roy, J. R. 1988, *A&A*, 200, 29
 Athanassoula, E. 1992, *MNRAS*, 259, 345
 Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5
 Barth, A. J., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1995, *AJ*, 110, 1009
 Benedict, G. F., Higdon, J. L., Tollestrup, E. V., Hahn, J. M., & Harvey, P. M. 1992, *AJ*, 103, 757
 Benedict, G. F., Smith, B. J., & Kenney, J. D. P. 1996, *AJ*, 111, 1861
 Benedict, G. F., Howell, D. A., Jørgensen, I., Kenney, J. D. P., & Smith, B. J. 2002, *AJ*, 123, 1411
 Bruzual A. G., 1983, *ApJ*, 273, 105
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000
 Burbidge, E. M., & Burbidge, G. R. 1962, *ApJ*, 135, 694
 Buta, R., & Crocker, D. A. 1991, *AJ*, 102, 1715
 Buta, R., van Driel, W., Braine, J., Combes, F., Wakamatsu, K., Sofue, Y., & Tomita, A. 1995, *ApJ*, 450, 593
 Combes, F., & Gerin, M. 1985, *A&A*, 150, 327
 Combes, F. 1988, in *Molecular Clouds in the Milky Way and External Galaxies*, eds. R. L. Dickman, R. L. Snell, & J. S. Young (Berlin: Springer-Verlag), 441
 Combes, F., Gerin, M., Nakai, N., Kawabe, R., & Shaw, M. A. 1992, *A&A*, 259, L27
 Combes, F., et al. 2004, *A&A*, 414, 857
 de Vaucouleurs, G. 1963, *ApJS*, 8, 31
 de Zeeuw, P. T., et al. 2002, *MNRAS*, 329, 513
 Díaz-Santos, T., Alonso-Herrero, A., Colina, L., Ryder, S. D., & Knapen, J. H. 2007, *ApJ*, 661, 149
 Dopita, M. A., Kewley, L. J., Heisler, C. A., & Sutherland, R. S. 2000, *ApJ*, 542, 224
 Elmegreen, B. G., et al. 1998, *ApJ*, 503, L119
 Elmegreen, B. G. 1999, *ASPC*, 187, 145
 Elmegreen, B. G., Elmegreen, D. M., & Hirst, A. C. 2004, *ApJ*, 612, 191
 Engelbracht, C. W., Rieke, M. J., Rieke, G. H., Kelly, D. M., & Achtermann, J. M. 1998, *ApJ*, 505, 639
 Erwin, P., Vega Beltran, J. C., & Beckman, J. E. 2001, *ASPC*, 249, 171
 Erwin, P., & Sparke, L. S. 2002, *AJ*, 124, 65
 Eskridge, P. B., et al. 2000, *AJ*, 119, 536
 Fathi, K., van de Ven, G., Peletier, R. F., Emsellem, E., Falcón-Barroso, J., Cappellari, M., & de Zeeuw, T. 2005, *MNRAS*, 364, 773
 Fioc, M., & Rocca-Volmerange, B. 1997, *A&A*, 326, 950
 García-Barreto, J. A., Downes, D., Combes, F., Gerin, M., Magri, C., Carrasco, L., & Cruz-Gonzalez, I. 1991, *A&A*, 244, 257
 Grobøel, P., Patsis, P. A., & Pompei, E. 2004, *A&A*, 423, 849
 González Delgado R. M., Cid Fernandes R., Pérez E., Martins L. P., Storchi-Bergmann T., Schmitt H., Heckman T., Leitherer C., 2004, *ApJ*, 605, 127
 Guseva N. G., Izotov Y. I., Thuan T. X., 2000, *ApJ*, 531, 776
 Harris, J., Calzetti, D., Gallagher, J. S., III, Conselice, C. J., & Smith, D. A. 2001, *AJ*, 122, 3046
 Heckman, T. M. 1980, *A&A*, 88, 365
 Heller, C., & Shlosman, I. 1994, *ApJ*, 424, 84
 Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, *ApJS*, 112, 315
 Huntley, J. M., Sanders, R. H., & Roberts, W. W. 1978, *ApJ*, 221, 521
 Jogee, S., Shlosman, I., Laine, S., Englmaier, P., Knapen, J. H., Scoville, N. Z., & Wilson, C. D. 2002, *ApJ*, 575, 156
 Jogee, S., et al. 2004, *ApJ*, 615, L105
 Kauffmann, G., et al. 2003, *MNRAS*, 346, 1055
 Kennicutt, R. C., Keel, W. C., & Blaha, C. A. 1989, *AJ*, 97, 1022
 Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, *ApJ*, 556, 121
 Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, *MNRAS*, 372, 961
 Kotilainen, J. K., Reunanen, J., Laine, S., & Ryder, S. D. 2000, *A&A*, 353, 834
 Knapen, J. H., Beckman, J. E., Shlosman, I., Peletier, R. F., Heller, C. H., & de Jong, R. S. 1995a, *ApJ*, 443, L73
 Knapen, J. H., Beckman, J. E., Heller, C. H., Shlosman, I., & de Jong, R. S. 1995b, *ApJ*, 454, 623
 Knapen, J. H., Shlosman, I., & Peletier, R. F. 2000, *ApJ*, 529, 93
 Knapen, J. H., Whyte, L. F., de Blok, W. J. G., & van der Hulst, J. M. 2004, *A&A*, 423, 481

- Knapen, J. H. 2005, *A&A*, 429, 141
- Knapen, J. H., Mazzuca, L. M., Böker, T., Shlosman, I., Colina, L., Combes, F., & Axon, D. J. 2006, *A&A*, 448, 489
- Kormendy, J. 1993, in *IAU Symp. 153, Galactic Bulges*, eds. H. DeJonghe & H. J. Habing (Dordrecht: Kluwer), 209
- Kormendy, J., & Kennicutt, R. C. 2004, *ARA&A*, 42, 603
- Kuntschner, H., et al. 2006, *MNRAS*, 369, 497
- Laine S., Shlosman I., Knapen J. H., Peletier R. F., 2002, *ApJ*, 567, 97
- Leitherer, C., et al. 1999, *ApJS*, 123, 3
- Maraston C., 2005, *MNRAS*, 362, 799
- Mazzuca, L. M., Sarzi, M., Knapen, J. H., Veilleux, S., & Swaters, R. 2006, *ApJ*, 649, L77
- Mazzuca, L. M., Knapen, J. H., Veilleux, S., & Regan, M. W. 2006a, *ApJ*, submitted
- Merrifield, M. R., & Kuijken, K. 1994, *ApJ*, 432, 575
- Osterbrock, D. E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, (Mill Valley: Univ. Science Books)
- Pogge, R. W. 1989, *ApJS*, 71, 433
- Puxley, P. J., & Brand, P. W. J. L. 1999, *ApJ*, 514, 675
- Ryder, S. D., & Knapen, J. H. 1999, *MNRAS*, 302, L7
- Ryder, S. D., Knapen, J. H., & Takamiya, M. 2001, *MNRAS*, 323, 663
- Rubin, V. C., Ford, W. K., Jr., & Whitmore, B. C. 1984, *ApJ*, 281, 21
- Sanders, R. H., & Tubbs, A. D. 1980, *ApJ*, 235, 803
- Sarzi, M., Rix, H. W., Shields, J. C., Ho, L. C., Barth, A. J., Rudnick, G., Filippenko, A. V., & Sargent, W. L. W. 2005, *ApJ*, 628, 169
- Sarzi, M. et al. 2006, *MNRAS*, 366, 1151
- Seaton, M. J. 1954, *MNRAS*, 114, 154
- Sellwood, J. A., & Wilkinson, A. 1993, *Rep. Prog. Phys.*, 56, 173
- Sil'chenko, O. K., & Afanasiev, V. L. 2000, *A&A*, 364, 479
- Sil'chenko, O. K., & Moiseev, A. V. 2006, *AJ*, 131, 1336
- Simkin S. M., Su H. J., Schwarz M. P., 1980, *ApJ*, 237, 404
- Shields J. C., et al., 2007, *ApJ*, 654, 125
- Shlosman, I., Frank, J., & Begelman, M. C. 1989, *Nature*, 338, 45
- Shlosman, I., Begelman, M. C., & Frank, J. 1990, *Nature*, 345, 679
- Schaerer D., Contini T., Kunth D., 1999, *A&A*, 341, 399
- Schaerer D., Vacca W. D., 1998, *ApJ*, 497, 618
- Sutherland, R. S., & Dopita, M. A. 1993, *ApJS*, 88, 253
- Tremonti C. A., et al., 2004, *ApJ*, 613, 898
- Vacca W. D., Conti P. S., 1992, *ApJ*, 401, 543
- van Albada, G. D., & Roberts, W. W. 1981, *ApJ*, 246, 740
- Veilleux, S., & Osterbrock, D. E. 1987, *ApJS*, 63, 295
- Verdes-Montenegro, L., Bosma, A., & Athanassoula, E. 1995, *A&A*, 300, 65
- Vila-Vilaró, B., et al. 1995, *A&A*, 302, 58
- Wada K., Habe A., 1992, *MNRAS*, 258, 82
- Worthey, G. 1994, *ApJS*, 95, 107
- Worthey, G., & Ottaviani, D. L. 1997, *ApJS*, 111, 377
- Wozniak, H., Friedli, D., Martinet, L., Martin, P., & Bratschi, P. 1995, *A&A*, 111, 115
- Zheng, X. Z., Hammer, F., Flores, H., Assémat, F., & Rawat, A. 2005, *A&A*, 435, 507