Nuclear activity in isolated galaxies

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ABSTRACT
We present a spectroscopic study of the incidence of active galactic nucleus (AGN) nuclear activity in two samples of isolated galaxies. Our results show that the incidence of non-thermal nuclear activity is about 43 and 31 per cent for galaxies with emission lines and 40 and 27 per cent for the total sample, respectively. For the first time we have a large number of bona fide isolated galaxies (513 objects), with statistically significant number of all morphological types. A large fraction (~70 per cent) of elliptical galaxies or early-type spirals have an AGN and ~70 per cent of them are low-ionization nuclear emission-line regions. We find a larger fraction of AGN in early morphological types, as also found in the general population of galaxies. Only 3 per cent of the AGN show the presence of broad lines (not a single one can be classified as type 1 AGN). This is an important result which is at odds with the unified model even if we consider warped or clumpy tori. Finally, we interpret the large fraction of AGN in isolated galaxies as the result of secular accretion.

Key words: galaxies: active – galaxies: evolution – galaxies: interactions.

1 INTRODUCTION

Along the last 25 years, many authors have studied the active galactic nucleus (AGN) nuclear activity in isolated galaxies (Stauffer 1982a,b; Dahari 1984, 1985; Kennicutt & Keel 1984; de Mello et al. 1995, 1996; Laurikainen & Salo 1995; Dultzin-Hacyan et al. 1999; Krongold, Dultzin-Hacyan & Marziani 2001, 2002; Schmitt 2001; Koulouridis et al. 2006a,b; Sorrentino, Radovich & Rifatto 2006; Márquez & Masegosa 2008). The incidence of nuclear activity in galaxies and their environment has become a topic of debate because there are different mechanisms that can possibly trigger nuclear activity depending on the galaxy’s environment. Interactions between galaxies are well known to produce enhancement in star formation in galaxies (Lonsdale, Persson & Matthews 1984; Kennicutt et al. 1987; Keel 1993; Barton, Geller & Kenyon 2000; Krongold et al. 2002; Lin et al. 2007; Woods & Geller 2007). Others authors also have evidence for a connection between circumnuclear starburst and AGN (Storchi-Bergmann 2008, and references therein). There are also suggestions for a connection between interactions and non-thermal nuclear activity specifically of type 2 (Dultzin-Hacyan et al. 1999; Krongold et al. 2001). Other studies have dealt with the AGN population of compact groups (Martínez et al. 2010) as well as in larger groups like clusters of galaxies (Ruderman & Ebeling 2005; von der Linden et al. 2010; Pimbblet & Jensen 2012; Pimbblet et al. 2013).

The general results of these studies show a tendency for AGN to be hosted in massive galaxies, and towards the centre of the clusters.

In this paper, we study the incidence of activity in isolated galaxies. In a forthcoming paper (Hernández-Ibarra et al., in preparation), we will present the results of a survey of AGN in paired galaxies of similar mass.

It is important to study galaxies in a restricted environment in order to elucidate what mechanisms could be determinant to trigger AGN activity. Isolated galaxies can be defined as those systems that are formed in low galactic density environments, but that evolved without major interactions with other galaxies of similar mass over the last 3 Gyr. In this context, any non-axisymmetric structures in these galaxies such as bars, tails plumes or stripping material must be the result of secular evolution.

The study of truly isolated galaxies is thus fundamental to benchmark the role of interactions in nuclear activity. Studies of field galaxies (e.g. Ho et al. 1997c) cannot provide this information as these samples may include galaxies that have undergone or are undergoing an interaction.

This is the first paper of a series involving a self-consistent and homogeneous way to study nuclear activity in galaxies in different environments. In this work, we study the incidence of nuclear activity in two samples of bona fide isolated galaxies using an efficient way to extract the stellar contribution (host spectrum). The purpose of this work is to have a well-defined sample of isolated galaxies with optical spectroscopic characteristics that allow us to classify them according to their type of activity. Studying the incidence of the nuclear activity in isolated galaxies alone is of great value to
establish if AGN is a common and/or persistent phenomenon even when strong tidal external perturbations have not been present during the last few Gyr of galaxy evolution. This would indicate that AGN activity can be triggered by secular evolution processes in galaxies. Our results on this sample will be further used as a benchmark to compare the incidence of activity in a sample of isolated pairs of galaxies (Hernández-Ilbarra et al., in preparation).

This paper is organized as follows. In Section 2 we describe our samples. In Section 3 we present the data analysis and classification. Results are given in Section 4, and Section 5 contains the discussion about the possible mechanisms for developing an AGN in isolated galaxies.

2 CHARACTERISTICS OF THE SAMPLES

As stated above the so-called field galaxies cannot be used as a proper sample in the study of the properties of truly isolated galaxies. Therefore, in this study we used two samples of rigorously defined isolated galaxies: the photometric catalogue of isolated galaxies (CIG) by Karachentseva (1973) and the northern isolated disc galaxies compiled by Varela et al. (2004).

We take all available spectra from Data Release 7 (DR7) of SDSS: Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009) for the two samples. The spectra have a wavelength coverage from 3800 to 9200 Å with a resolution power of 1800–2200 and a signal-to-noise (S/N) ratio of 9200 Å with a resolution power of 1800–2200 and a signal-to-noise (S/N) ratio.

The (CIG) catalogue contains 1051 galaxies. It is one of the best sources of isolated objects. The isolation criteria are still used as the basis for new catalogues of isolated galaxies (e.g. Verdés-Montenegro et al. 2005; Hernández-Toledo et al. 2010; Karachentseva et al. 2010; Coziol et al. 2011; Karachentsev et al. 2011). These isolation criteria guarantee that the galaxies have not experienced a major merger/interaction over the last 3 Gyr.

The catalogue was based on a visual search of northern-sky galaxies (δ ≥ −3°) with a magnitude limit of $m_{Zw} ≤ 15.7$ and a range in $z$ from ~0.01 to 0.05. Only objects which have high galactic latitude are considered in order to avoid galactic extinction.¹ This sample is reasonably complete (~90 per cent) in the magnitude range 13.5 ≤ $m_{Zw} ≤ 15.7$ (Hernández-Toledo et al. 1999). In this catalogue a galaxy is considered to be isolated when it does not have a neighbour of similar size (diameter > 1/2 of the target galaxy) within 20 diameters. This corresponds to a magnitude difference of ~3 (excluding any possible AGN luminosity contamination). Considering a ‘field’ velocity of 150 km s⁻¹ for a galaxy with a diameter of 25 kpc, it would require ~3 Gyr for a companion galaxy to abandon the area enclosed in the 20 diameters of the isolation criterion. A similar time would be required to erase morphological perturbations due to a merger. This means that these galaxies have been unperturbed on average by at least that time.

The second sample we examined is that of northern isolated disc galaxies compiled by Varela et al. (2004) which originally contains 203 disc galaxies. This sample considers different criteria for isolation. In particular, it is based on the logarithmic ratio $f$, between inner and tidal forces acting upon the candidate galaxy by a possible perturber (see Varela et al. 2004, equation 3). Only galaxies with low $f$ ratio ($f ≤ −4.5$) are considered as isolated because they do not show signatures of any perturbation. They estimated that the objects in their sample have not been affected by other galaxies during the last 2 Gyr. It is important to consider another sample obtained with different criteria in order to assess the reliability of our results.

We analysed 413 spectra for the CIG catalogue and 100 for Varela’s sample from SDSS DR7. After a meticulous inspection of the Sloan images, we excluded those spectra which: (1) do not have the optic fibre in the centre of the galaxy (KIG 479 and KIG 237) or incomplete spectra like in KIG 702 and KIG 479, (2) are blue compact/H II galaxies (six galaxies in Varela’s sample and one in CIG), (3) are galaxies showing traces of interaction (tidal tails, etc.) or present a companion, namely KIG 349, KIG 439, KIG 468, KIG 634 and KIG 687 (Sulentic et al. 2006; Verley et al. 2007) and (4) are galaxies that did not achieve 3σ detection in all their line intensities (37 galaxies of the CIG sample).

A visual inspection was performed for all galaxies to confirm the morphological classification according to NASA/IPAC Extragalactic Database (NED), SIMBAD Astronomical Database (SIMBAD) and HYPERLEDA Database for physics of galaxies. In those few cases, where an obvious misclassification was present, the morphology was corrected by us. In addition, we found that PGC 33255 could be part of a pair and excluded this galaxy of the sample. Strangely enough, we found two elliptical galaxies with a very blue compact core: PGC 29177 and PGC 43121 that show typical H II region spectra, and were also excluded from our analysis. Taking this into account, our spectroscopic sample from CIG consists of 367 galaxies while the spectroscopic sample from Varela consists of 93. Out of these galaxies, 18 and 10, respectively, do not present emission lines. In Table 1 we show the general statistics for both samples.

We were careful to distinguish between intrinsic no emission and a problem of detectability related to low S/N. For this purpose, we set a threshold of $10^{38}$ erg s⁻¹ in Hα luminosity. The galaxies below this threshold are the true no-emission objects with a probability of being an AGN of less than 2 and 4 per cent for the CIG and Varela’s samples, respectively. The distribution of morphology and Hα luminosity of our samples is presented in Fig. 1.

### Table 1. General statistics of both isolated galaxy samples.

| Sample | Total | No emission | Excluded | Fitted | AGN+Comp | H II | AGN type 1 |
|--------|-------|-------------|----------|--------|----------|------|------------|
| CIG    | 413   | 18 (4 per cent) | 47 (11 per cent) | 348 (84 per cent) | 150 (36 per cent) | 198 (48 per cent) | 12 (3 per cent) |
| Varela | 100   | 10 (10 per cent) | 7 (7 per cent) | 83 (83 per cent) | 26 (26 per cent) | 57 (57 per cent) | 1 (1 per cent) |
| Total  | 513   | 28 (5 per cent) | 54 (11 per cent) | 431 (84 per cent) | 176 (34 per cent) | 255 (50 per cent) | 13 (3 per cent) |

¹ We know that our results are insensitive to reddening because we use line emission ratios which cancel this effect.
we searched for Hβ, [O III] λ5007 Å, [O I] λ6300 Å, [N II] λλ6548, 6584 Å, Hα and the two sulphur ([S II] λλ6717, 6731 Å) lines. In many cases, the nebular emission is very weak or it can be even diluted in the strong stellar continuum of the galaxy. Since the integrated SDSS spectra are collected through 3 arcsec fibres, they include not only the nuclear emissions but also the surrounding stellar light coming from the host galaxy. This contamination turns out to be more significant at the central parts of the galaxies and as the spheroidal/bulge component becomes more relevant. In fact, it can even mask weak emission lines such as those detected in galaxies with an AGN. Therefore, to obtain a reliable nuclear classification based on the emission lines, it is mandatory to subtract the stellar contribution. We applied the principal component analysis (PCA) method following Hao et al. (2005) to subtract this contribution. We used their first eight eigenspectra from their low-redshift range. These eigenspectra are the resulting eigenvectors of a PCA applied to a sample of high-S/N spectra of non-emission galaxies. In addition, as they pointed out, we included two more components, an A-star spectrum accounting for the possible presence of post-starburst features and a power law to take into account the possible existence of a non-thermal component. The analysis is performed for all the spectra of our sample and it consists of a multiple regression of each spectrum to a linear combination of the eight eigenspectra plus the two additional components. Previously to the fit, each galaxy spectrum was moved to zero redshift which is the one of the template library. We also masked all those regions where emission lines may appear since the quality of the fit lies on the matching of the continua. Once the regression is performed, the direct subtraction of the resulting fit to the original (z = 0) spectrum provides us with a pure emission line spectrum where all the underlying absorption components and eventually a non-thermal component of the continuum are removed.

Line fluxes were calculated with the SHERPA software (http://cxc.cfa.harvard.edu/sherpa/) (which comes in the CIAO distribution, http://cxc.harvard.edu/ciao/). SHERPA reads the data and evaluates a given model on this data set. Then, it varies the free parameters to minimize a statistical goodness function to obtain the best set of parameters that fit the data. In our case, our model is composed only of Gaussians.

We evaluated two methods to fit the lines. The first one consisted in constraining the width and velocity to the same value in our fits for two separated groups of lines, forbidden and permitted. Therefore, these fits included four free parameters in our models: the width and velocity of the forbidden and the permitted lines. An additional free parameter for each line in the model was the intensity of each emission line. The second method we used was to constrain the width and velocity for all the detected lines (independently of whether they were permitted or forbidden) to have the same value (i.e. only two free parameters to model all lines) plus an additional free parameter for the intensity of each line. Our results show that both methods are equivalent without any substantial difference. We decided to fit the emission lines with the second method since it has less free parameters. For those objects where a broad component was required in addition to the narrow one, an individual broad Gaussian was fitted with fully independent free parameters (see Fig. 2 for fit examples).

We have used the Baldwin–Phillips–Terlevich optical diagnostic diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987) to separate star-forming galaxies from AGN. Line ratios adopted were ([O III]/Hβ), ([N II]/Hα), ([S II]/Hα) and ([O I]/Hα). With these ratios we produced the ([O III]/Hβ) versus ([N II]/Hα) diagram (hereafter [N II] diagram), the ([O III]/Hβ) versus ([S II]/Hα) diagram and the ([O III]/Hβ) versus ([O I]/Hα) diagram.

We used two demarcations to identify the galaxy type. The first one is the theoretical division line proposed by Kewley et al. (2001) (K01 line hereafter) where objects above this line on the diagrams have nuclear activity. The second one is the empirical line derived by Kauffmann et al. (2003) (K03 line hereafter); this empirical line is based on the location of star-forming galaxies for the SDSS. Galaxies that lie between these two lines are called composite (or transition) objects. These objects need non-thermal processes to produce the line ratios (in addition to star-forming processes). Therefore, we will take these objects as AGN in this work. Further support comes from the work done by Trouille, Barger & Tremonti (2011) where they found that composite galaxies on the BPT [N II] diagram are X-ray hard sources and have a high X-ray luminosity to total infrared luminosity.

We have performed the analysis of the CIG catalogue studying the effects of galactic morphology. Fig. 3 shows a histogram of morphological types for both samples, and Fig. 4 shows the mass distribution for both samples. It is clear from Fig. 3 that around 70 per cent of the galaxies in the CIG have morphologies between Sb and Sc. This result is consistent with a work done by Hernández-Toledo et al. (2010) for other isolated galaxy sample. The fraction of AGN for each morphological type in both samples is shown in Fig. 5. We can see that within the large statistical errors, the comparison is valid.

In Fig. 6, we show the mass distribution of galaxies with AGN and Hα activity. Considering that the sample is reasonably complete (~90 per cent), we can clearly see a trend were the incidence of AGN...
Figure 2. Examples of fits in an Hα region for galaxies with and without broad line, respectively. The black data points denote the spectrum with the stellar contribution subtracted and the red line shows the fit.

Figure 3. Morphological type distribution of the samples considered in this work. The continuous (red) line corresponds to the CIG sample and the dashed (green) line to the Varela sample.

Figure 4. Mass distribution for the two samples. Labels as in Fig. 3.

Figure 5. Statistical comparison between isolated samples. Labels as in Fig. 3.

From the above analysis, we can confirm the well-known tendency for later-type morphology galaxies to be also relatively lower mass galaxies.

4 RESULTS

Our main results are summarized in Tables 2–5, and also in Figs 5–10. Line ratios with their errors and AGN type are presented in Tables 6 and 7 for CIG and Varela’s samples, respectively. The last column in these tables gives the nuclear type. We have used the quantitative definition by Winkler (1992) to measure the contribution of a broad component when present, and thus establish the Seyfert type.

In Table 2 we show numbers and percentages of activity and morphological classes for the CIG sample. Column 1 presents the...
morphological type, and the total number of galaxies is listed in column 2. Columns 3 and 4 list the number of galaxies with H\textsc{ii} and composite (hereafter Comp) activity and their percentages, respectively. Column 5 contains the number of galaxies in the AGN+Comp region and their percentages. In column 6 we present the total number of galaxies including those with no-emission lines. Columns 7, 8 and 9 show the number and percentages for H\textsc{ii}, Comp and AGN+Comp activity, respectively. In Table 3, we present the same data as in Table 2 for Varela’s sample.

In Fig. 7, we show the [N\textsc{ii}] BPT diagram. All galaxies in the composite region are taken as AGN as argued in Section 3.

We can clearly see that the incidence of nuclear activity is statistically higher in early-type galaxies and decreases gradually as we go to late types in this subsample of emission line galaxies only. The dependence on morphology is quite significant: going from 70 per cent in E galaxies to 10 per cent in Sm. The incidence of nuclear starburst activity decreases in the opposite sense: going from 90 per cent for Sm to 30 per cent for E. Meanwhile, if we consider the total sample (including galaxies without emission lines), the incidence gives a flatter distribution from E to Sb and decreases only for late types (compare columns 5 and 9 in Tables 2 and 3). This is clearly observed in Fig. 5.

In Fig. 8, we show the position of our objects in the BPT [N\textsc{ii}] diagram for Varela’s sample. In this sample, there are only four ellipticals, whereas the majority (27) are Sc. Considering that early types have a larger incidence of AGN, this can explain the fact that we find a total incidence of AGN of only 31 per cent as compared to 43 per cent in the CIG sample.

In Fig. 9, we present the [S\textsc{ii}] diagnostic diagram for the CIG sample. This diagram is useful to separate between Seyferts and low-ionization nuclear emission-line regions (LINERs).

In Fig. 10, we show yet another diagram [O\textsc{i}]. This diagram differs only slightly from the one in Fig. 9. The main difference is in the relative proportion of Seyferts and LINERs except for ellipticals. We point out that the [O\textsc{i}] line is weaker than the [S\textsc{ii}] line and thus the mean error is large.

In Table 4, we quantify the incidence of AGN activity and morphology distribution derived from the [S\textsc{ii}] and [O\textsc{i}] diagrams for CIG sample. Columns 1 and 2 show the morphological type and the number of galaxies in each type. In column 3 we list the number of AGN and the percentage in parentheses. The number of Seyfert galaxies and the percentage are listed in column 4. The number of LINERs is given in column 5. Columns 6 to 9 contain the same data of columns 2 to 5 but this time for the [O\textsc{i}] diagram. Table 5 is analogous to Table 4 for Varela’s sample.

From these tables we can confirm the result that the incidence of AGN activity is higher for early-type galaxies in the sample with emission lines only. When all galaxies are considered, the distribution flattens as found before for the CIG sample (see Fig. 5). Again, the incidence of Seyfert galaxies is more frequent in morphologies from Sa to Sc, but especially in Sb.

Figure 6. Fraction of AGN and H\textsc{ii} galaxies as a function of stellar mass. AGN are represented by (blue) empty circles and H\textsc{ii} objects by (black) filled circles. Errors in the y-direction are the standard deviation per bin and ‘errors’ in the x-direction simply denote the full range of mass in each bin.

Figure 7. [N\textsc{ii}] BPT diagnostic diagram for Varela’s sample.

Figure 8. Position of our objects in the BPT [N\textsc{ii}] diagnostic diagram for the CIG sample.

Table 2. Morphology distribution and incidence of nuclear activity for the CIG sample derived from the [N\textsc{ii}] BPT diagnostic diagram.

| M.T. | Total | Galaxies with emission lines | Total | Galaxies with emission lines |
|------|-------|------------------------------|-------|------------------------------|
|      |       | H\textsc{ii} | Comp | AGN+Comp | H\textsc{ii} | Comp | AGN+Comp |
| E    | 14    | 4 (29 per cent) | 1 (7 per cent) | 10 (71 per cent) | 23 | 4 (17 per cent) | 1 (4 per cent) | 10 (43 per cent) |
| S0   | 30    | 9 (30 per cent) | 5 (17 per cent) | 21 (70 per cent) | 38 | 9 (24 per cent) | 5 (13 per cent) | 21 (55 per cent) |
| Sa   | 38    | 13 (34 per cent) | 8 (21 per cent) | 25 (66 per cent) | 38 | 13 (34 per cent) | 8 (21 per cent) | 25 (66 per cent) |
| Sb   | 122   | 67 (55 per cent) | 20 (16 per cent) | 55 (45 per cent) | 124 | 67 (54 per cent) | 20 (16 per cent) | 55 (44 per cent) |
| Sc   | 124   | 87 (70 per cent) | 22 (18 per cent) | 37 (30 per cent) | 124 | 87 (70 per cent) | 22 (18 per cent) | 37 (30 per cent) |
| Sm   | 20    | 18 (90 per cent) | 1 (5 per cent) | 2 (10 per cent) | 20 | 18 (90 per cent) | 1 (5 per cent) | 2 (10 per cent) |
| Total| 348   | 198 (57 per cent) | 57 (16 per cent) | 150 (43 per cent) | 367 | 198 (54 per cent) | 57 (16 per cent) | 150 (41 per cent) |

Table 3. Morphology distribution and incidence of nuclear activity in Varela’s sample derived from the [N\textsc{ii}] BPT diagnostic diagram.

| M.T. | Total | Galaxies with emission lines | Total | Galaxies with emission lines |
|------|-------|------------------------------|-------|------------------------------|
|      |       | H\textsc{ii} | Comp | AGN+Comp | H\textsc{ii} | Comp | AGN+Comp |
| E    | 4     | 3 (75 per cent) | 0 (0 per cent) | 1 (25 per cent) | 7 | 3 (43 per cent) | 0 (0 per cent) | 1 (14 per cent) |
| S0   | 14    | 8 (57 per cent) | 1 (7 per cent) | 6 (43 per cent) | 20 | 8 (40 per cent) | 1 (5 per cent) | 6 (30 per cent) |
| Sa   | 11    | 8 (73 per cent) | 1 (9 per cent) | 3 (27 per cent) | 11 | 8 (73 per cent) | 1 (9 per cent) | 3 (27 per cent) |
| Sb   | 21    | 11 (52 per cent) | 4 (19 per cent) | 10 (48 per cent) | 22 | 11 (50 per cent) | 4 (18 per cent) | 10 (45 per cent) |
| Sc   | 27    | 22 (81 per cent) | 3 (11 per cent) | 5 (19 per cent) | 27 | 22 (81 per cent) | 3 (11 per cent) | 5 (19 per cent) |
| Sm   | 4     | 4 (100 per cent) | 0 (0 per cent) | 0 (0 per cent) | 4 | 4 (100 per cent) | 0 (0 per cent) | 0 (0 per cent) |
| Total| 81    | 56 (69 per cent) | 9 (11 per cent) | 25 (31 per cent) | 91 | 56 (62 per cent) | 9 (10 per cent) | 25 (27 per cent) |
Table 4. Incidence type of nuclear activity for different morphologies from the [S\textsc{ii}] and [O\textsc{i}] diagnostic diagrams for the CIG sample.

| M.T. | Total | AGN | Seyfert | LINER | [S\textsc{ii}] diagram | Total | AGN | Seyfert | LINER | [O\textsc{i}] diagram |
|------|-------|-----|---------|------|------------------------|-------|-----|---------|------|------------------------|
| E    | 14    | 11 (79 per cent) | 3 (27 per cent) | 8 (73 per cent) | 13 | 10 (77 per cent) | 3 (30 per cent) | 7 (70 per cent) |
| S0   | 30    | 15 (50 per cent) | 3 (20 per cent) | 12 (80 per cent) | 28 | 16 (57 per cent) | 12 (75 per cent) | 4 (25 per cent) |
| Sa   | 38    | 15 (39 per cent) | 3 (20 per cent) | 12 (80 per cent) | 36 | 17 (47 per cent) | 11 (65 per cent) | 6 (35 per cent) |
| Sb   | 122   | 31 (27 per cent) | 15 (48 per cent) | 16 (52 per cent) | 120 | 39 (33 per cent) | 30 (77 per cent) | 9 (23 per cent) |
| Sc   | 124   | 21 (17 per cent) | 8 (65 per cent) | 13 (62 per cent) | 123 | 22 (18 per cent) | 11 (50 per cent) | 11 (50 per cent) |
| Sm   | 20    | 6 (30 per cent) | 1 (17 per cent) | 5 (83 per cent) | 20 | 3 (15 per cent) | 2 (67 per cent) | 1 (33 per cent) |
| Total | 348   | 99 (28 per cent) | 33 (33 per cent) | 66 (67 per cent) | 340 | 107 (31 per cent) | 69 (64 per cent) | 38 (36 per cent) |

Table 5. Incidence type of nuclear activity for different morphologies from the [S\textsc{ii}] and [O\textsc{i}] diagnostic diagrams for Varela’s sample.

| M.T. | Total | AGN | Seyfert | LINER | [S\textsc{ii}] diagram | Total | AGN | Seyfert | LINER | [O\textsc{i}] diagram |
|------|-------|-----|---------|------|------------------------|-------|-----|---------|------|------------------------|
| E    | 4     | 2 (50 per cent) | 0 (0 per cent) | 2 (100 per cent) | 4 | 1 (25 per cent) | 1 (100 per cent) | 0 (0 per cent) |
| S0   | 14    | 6 (43 per cent) | 2 (33 per cent) | 4 (67 per cent) | 14 | 6 (43 per cent) | 5 (83 per cent) | 1 (17 per cent) |
| Sa   | 11    | 3 (27 per cent) | 0 (0 per cent) | 3 (100 per cent) | 11 | 2 (18 per cent) | 0 (0 per cent) | 2 (100 per cent) |
| Sb   | 21    | 5 (24 per cent) | 1 (20 per cent) | 4 (80 per cent) | 21 | 6 (29 per cent) | 6 (100 per cent) | 0 (0 per cent) |
| Sc   | 27    | 5 (19 per cent) | 3 (60 per cent) | 2 (40 per cent) | 27 | 5 (19 per cent) | 4 (80 per cent) | 1 (20 per cent) |
| Sm   | 4     | 0 (0 per cent) | 0 (0 per cent) | 0 (0 per cent) | 4 | 0 (0 per cent) | 0 (0 per cent) | 0 (0 per cent) |
| Total | 81    | 21 (26 per cent) | 6 (29 per cent) | 15 (71 per cent) | 81 | 20 (25 per cent) | 16 (80 per cent) | 4 (20 per cent) |

Figure 7. The [N\textsc{ii}] diagnostic diagrams for the CIG sample with different morphologies. This diagram separates between three different kind of activity in galaxies such as AGN, composite and H\textsc{ii}-like region galaxies. The green dashed line (Ke01) separates galaxies with an AGN from composite (AGN+starburst activity). The continuous red line (Ka03) divides pure star-forming galaxies from AGN–starburst composite objects. Elliptical galaxies are shown as filled grey triangles, lenticular as green crosses, Sa as blue asterisks, Sb as pink empty squares, Sc as filled cyan squares and Sm as filled yellow pentagons. The cross at the lower-right part of the diagram denotes the mean error in the line ratios.
Figure 8. (a) The [N ii], (b) [S ii] and (c) [O i] diagnostic diagrams for Varela’s sample. Labels as in Fig. 7. The low incidence of nuclear activity is present on Sc and Sm types. The filled circles represent objects which cannot be classified.

Figure 9. The [S ii] diagnostic diagram for the CIG sample. The blue dashed line represents Seyfert/LINER line and others labels as in Fig. 7.

In Tables 4 and 5, we show the data for the [S ii] and [O i] diagrams. The AGN fractions are different from those in Tables 2 and 3. The reason is that we do not consider composite nuclei in the [S ii] and [O i] diagrams. Unfortunately, models by Kauffmann et al. (2003) for these particular diagnostic diagrams ([S ii] and [O i]) are not available. In consequence, we only take into account the AGN activity with the Kewley limit for self-consistency.

We want to point out to recent models developed by Stasińska et al. (2006). These models predict lower values for the ratios of [N ii]/Hα and [O iii]/Hβ for AGN. In a figure analogous to Fig. 7, the models by Stasińska et al. (2006) would produce an even larger zone of composite objects.

The most notable result is the absence of type 1 AGN in both isolated samples. In the CIG sample, there are 12 galaxies which show lines with a broad component. Five of these galaxies (all of them classified as Seyfert nuclei) have a clear broad component, three are Sy 1.5 (KIG 214, KIG 747 and KIG 1008), one is Sy 1.8 (KIG 749) and one is Sy 1.9 (KIG 349). Other three objects (KIG 204, KIG 603 and KIG 605) are classified as LINERs. For two additional AGN (KIG 553 and KIG 591) a Seyfert/LINER classification was not possible. The remaining two objects are H II galaxies with broad components. Broad components in H II regions are rare but have indeed been found (e.g. Binette et al. 2009).

In Varela’s sample there is only one 1.8 type Seyfert galaxy (PGC 48521). This object was classified as Sy 1 in SIMBAB and Sy 1.9 in NED. It has been shown that a few galaxies can vary their type with time (e.g. Shapovalova, Popović & Collin 2008; Shapovalova et al. 2012). Whether this is the case or this object
Nuclear activity in isolated galaxies

Figure 10. The [O\textsc{i}] diagnostic diagram for the CIG sample. Labels as in Fig. 7.

Table 6. Logarithm intensity ratios with their errors and AGN type for the CIG sample. Complete table is available in the electronic version.

| Object       | M.T. | log([O\textsc{iii}]/H\textbeta) | log([N\textsc{ii}]/H\alpha) | log([S\textsc{ii}]/H\alpha) | log([O\textsc{i}]/H\alpha) | Type   |
|--------------|------|---------------------------------|-------------------------------|-------------------------------|----------------------------|--------|
| Elliptical   |      |                                 |                               |                               |                            |        |
| KIG 378      | E    | 0.2831 ± 0.1763                 | 0.2970 ± 0.0806               | 0.0332 ± 0.1534               | −0.7559 ± 0.3383           | LINER  |
| KIG 393      | E-SO | −0.0234 ± 0.0074                | −0.4586 ± 0.0066              | −0.6059 ± 0.0091              | −1.9412 ± 0.0287           | H\text{\textsc{ii}} |
| KIG 437      | E-SO | 0.0909 ± 0.1939                 | 0.0919 ± 0.0589               | −0.1233 ± 0.1182              | −0.8432 ± 0.2380           | LINER  |
| KIG 462      | E    | −0.7172 ± 0.0384                | −0.4667 ± 0.0098              | −0.5874 ± 0.0155              | −1.8481 ± 0.0740           | H\text{\textsc{ii}} |
| KIG 555      | E    | 0.2234 ± 0.0401                 | −0.0856 ± 0.0429              | −0.3204 ± 0.0298              | −1.2193 ± 0.0865           | H\text{\textsc{ii}} |
| KIG 556      | E    | 0.8151 ± 0.5101                 | 0.5997 ± 0.2621               | 0.8841 ± 0.2651               | −0.0295 ± 0.4288           | LINER  |

*M.T.: morphological type. AGN classification denotes those galaxies that are AGN according to the [N\textsc{ii}] diagrams but not according to the [S\textsc{ii}] and/or [O\textsc{i}] diagrams. †L-S classification means that galaxies fall in the separation line for Seyfert and LINER according to the [S\textsc{ii}] and [O\textsc{i}] diagrams. *Type with weak broad component in permitted lines. Seyfert quantitative classification according to Winkler (1992).

Table 7. Logarithm intensities ratios and their errors for Varela's sample. Labels as in Table 7. Complete table is available in electronic version.

| Object       | M.T. | log([O\textsc{iii}]/H\beta) | log([N\textsc{ii}]/H\alpha) | log([S\textsc{ii}]/H\alpha) | log([O\textsc{i}]/H\alpha) | Type   |
|--------------|------|--------------------------------|-------------------------------|-------------------------------|----------------------------|--------|
| Elliptical   |      |                                 |                               |                               |                            |        |
| PGC 29177    | E-SO | −0.0385 ± 0.0075                | −0.4953 ± 0.0064              | −0.6389 ± 0.0090              | −1.9657 ± 0.0284           | H\text{\textsc{ii}} |
| PGC 36037    | E-SO | 0.6757 ± 0.2136                | −0.0778 ± 0.0767              | −0.0145 ± 0.1076              | −0.8049 ± 0.2415           | S-L†   |
| PGC 36211    | E    | 0.1761 ± 0.0310                | −0.5803 ± 0.0225              | −0.2478 ± 0.0225              | −1.3349 ± 0.0808           | H\text{\textsc{ii}} |
| PGC 43121    | E-SO | 0.4754 ± 0.0048                | −0.9475 ± 0.0054              | −0.8785 ± 0.0066              | −1.9157 ± 0.0141           | H\text{\textsc{ii}} |

*Spheroidal   |     |                                 |                               |                               |                            |        |
| PGC 25467    | S0-a| −0.4046 ± 0.0283                | −0.3493 ± 0.0119              | −0.4011 ± 0.0177              | −1.5501 ± 0.0721           | H\text{\textsc{ii}} |
| PGC 28259    | S0  | 0.5808 ± 0.0168                | −0.4437 ± 0.0169              | −0.2733 ± 0.0206              | −0.8945 ± 0.0330           | Sy2    |
was classified in SIMBAD has little relevance for our general conclusions.

To be conservative, we consider these 13 galaxies as the fraction of possible AGN with broad components (including the two H II galaxies) to allow for any possible misclassification. These numbers indicate that the fraction of type 1 objects is ≤3 per cent.

5 DISCUSSION

The large number of galaxies of all morphological types permits us to quantify the link between morphology and nuclear activity. Our results indicate a close link between these two properties. This implies that any result of the incidence of activity without this consideration reflects the particular morphological distribution of the sample and therefore is not reliable. Our sample includes for the first time a statistically significant number of isolated early-type galaxies (E+S0).

We found that elliptical and SO galaxies have the highest incidence of nuclear activity in isolated environments when only galaxies with emission lines are considered [a similar result was found by Varela et al. (2004), Coziol et al. (2011) and Sabater et al. (2012)]. However, when the total sample is taken into account (including galaxies without emission lines), these apparent excess disappears and all early types (including Sa and Sb types) have similar fractions (see Fig. 5). This important difference could be found thanks to the large number of elliptical and spheroidal galaxies in our sample. These results are consistent with those found for ‘field’ galaxies (Heckman 1980; Keel 1983; Kauffmann et al. 2003; Miller et al. 2003). Finding the same trend between isolated and field galaxies could be expected if we consider that AGN require super-massive black holes (SMBHs) and black holes (BH) are correlated with the incidence of AGN in a sample of isolated close pairs of similar luminosity (Moles, Marquez & Perez 1995; Ho, Filippenko & Sargent 1997a,b) and Ho (2002, and references therein). However, it has been shown that most probably bars do not enhance nuclear activity (Moles, Marquez & Perez 1995; Ho, Filippenko & Sargent 1997c; Lee et al. 2012). The three latter works look for the incidence of AGN activity in barred galaxies. Alonso, Coldwell & Lambas (2013) compare only AGN galaxies with and without bars. They find a trend for higher luminosity in the [O iii] line for barred AGN. This effect is more noticeable for the more massive and luminous galaxies.

The most common non-axisymmetric internal potential is due to the presence of a bar. However, in the particular case of barred galaxies, it has been shown that most probably bars do not enhance nuclear activity (Moles, Marquez & Perez 1995; Ho, Filippenko & Sargent 1997c; Lee et al. 2012). The three latter works look for the incidence of AGN activity in barred galaxies. Alonso, Coldwell & Lambas (2013) compare only AGN galaxies with and without bars. They find a trend for higher luminosity in the O [iii] line for barred AGN. This effect is more noticeable for the more massive and luminous galaxies.

However, the samples used in those studies were not rigorously isolated and thus the effects of the environment cannot be disentangled from those of the bar. The samples used in this work provide the opportunity to perform a rigorous test of the effect of a bar. This can be achieved due to both the selection criteria and the quality of the data. A detailed analysis of the bar fraction requires a deep photometric study. This analysis will be presented in a forthcoming paper (Hernández-Toledo et al., in preparation).

We note that although a large fraction of isolated galaxies are active, their SMBH has not grown significantly over the last 3 Gyr. Given that most of our galaxies are representative of the low-luminosity end of AGN, the mass accretion rate should be in the range $10^{-5}$–$10^{-3}$ $M_\odot$ yr$^{-1}$, and the radiative efficiency $\eta$ should be significantly smaller than 10 per cent (Ho 2003, 2009). Such low efficiencies are predicted for low-luminosity AGN (Narayan & McClintock 2008). Assuming that the AGN in our sample have accreted at a constant rate over the last 3 Gyr, the growth of their SMBH ranges between $10^3$ and $10^6$ $M_\odot$. Then, it is clear that isolated galaxies in poor environments have failed to accrete enough material (at least during the last Gyr) to present higher luminosities and significant BH growth. Thus, our results support a hierarchical scenario in which the environment is crucial to determine properties such as luminosity, mass and central SMBH mass, fulfilling the expectations of the downsizing for SMBH growth (Pérez-González et al. 2010).

The spiral isolated galaxies will not migrate from the blue to the red sequence since feedback is not efficient in these faint AGN (Krongold et al. 2007). The later result supports again that secular evolution in these galaxies is the important mechanism to establish the bulge–BH relation. This is in contrast to the case of massive galaxies transitioning from the blue to the red branch of the colour–colour diagram which require a major merger followed by a substantial feedback in the quasi stellar object (QSO) phase.

On the other hand, our isolated ellipticals are already in the red branch of galaxies that probably have experienced a major merger in the distant past. The fact that essentially all of them are AGN may simply reflect the fact that it is easier to drive gas to the centre of spheroidal systems. The remanent interstellar medium in these galaxies is typically in the range $10^9$–$10^4$ $M_\odot$. Therefore, they contain enough gas to power their SMBH over the last 3 Gyr. This does not exclude, however, the possibility of an external supply of material as suggested by several authors (Bertola, Buson & Zeilinger 1992; Caon, Macchetto & Pastoriza 2000; Sarzì et al. 2006). The large fraction of AGN in these galaxies suggests that the presence of a large bulge facilitates the mass infall to the centre. We note, however, that a small fraction of this LINERs could be fake AGN (‘retired galaxies’; Cid Fernandes et al. 2011).

All these results indicate that the presence of AGN activity is a common phenomenon. This is an important result as traditionally it has been assumed that an external perturbation is required to induce nuclear activity. Our results indicate that a low-luminosity AGN phase is a part of the secular evolution of a large number of galaxies. These findings are consistent with those by Ho, Filippenko & Sargent (1997a,b) and Ho (2002, and references therein). However, in those studies it was impossible to disentangle the environmental effects from those of internal galactic evolution, given that the isolation history was not known a priori in their samples. Our results do not deny the possibility that external perturbations may enhance the frequency of nuclear activity among galaxies, as has been suggested by previous studies (Dultzin-Hacyan et al. 1999; Krongold et al. 2002; Krongold, Dultzin-Hacyan & Marziani 2003; Rogers et al. 2009; Ellison et al. 2010, 2011). The effect of a strong gravitational interaction will be studied in a forthcoming paper where the incidence of AGN in a sample of isolated close pairs of similar mass galaxies will be analysed.

We note that the absence of type 1 AGN in these samples of isolated galaxies is outstanding. There is not a single type 1.0 AGN among the 175 active galaxies in our samples. The fraction of types 1.5–1.9 is less than 3 per cent in both isolated galaxy samples. There have been indications in the past for very low fractions of type 1
activity in physical pairs of galaxies (Dultzin et al. 2008) and in compact groups (Martínez et al. 2010). These results are at odds with a simple interpretation of the unified model, and suggest that an additional evolutionary trend is at work. The appearance of a type 1 nucleus may be delayed by as much as 1 Gyr, as required by the evolutionary model proposed by Krongold et al. (2002), where an interaction triggers first a circumnuclear starburst, and subsequently non-thermal nuclear activity. For the brightest end of nuclear activity, a similar evolutionary trend is possible (from UltraLuminous InfraRed Galaxies (ULIRGs) to luminous quasars). In this case, a major merger would be required, affecting the overall properties of the host galaxy and moving it to the blue branch of the colour–colour diagram.

The evolutionary scheme can explain the lack of Sy 1 in both interacting and isolated galaxies. In the former, there has not been enough time for the Sy 1 nucleus to appear. In the latter (where no interactions took place over the last 3 Gyr), either there has never been a Sy 1 phase, or if a strong interaction occurred in the past, the type 1 activity has already faded out.

We also note that the lack of high-luminosity AGN in our samples points towards a dependence between environment/interactions and AGN luminosity. In this scenario, the extremely low fraction of type 1 AGN can also be understood if a broad-line region (BLR) can be formed only at higher accretion rates/luminosities (Nicastro 2000; Elitzur & Ho 2009).

If AGN in isolated galaxies have low accretion rates, low efficiencies, low luminosities and almost a complete absence of broad lines in their spectra, it is probable that the BLR under these circumstances is not even able to be formed. This is in accordance with the result by Tran (2003a,b) for the absence of broad components in polarized light for ~50 per cent of the galaxies in his sample. Several studies show evidence that the Sy 2s with and without broad lines in polarized lines (in other words, with and without a hidden BLR) are truly different in other respects as well (e.g. Gu, Dultzin-Hacyan & de Diego 2001a; Gu, Maiolino & Dultzin-Hacyan 2001b; Bianchi et al. 2012).

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REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Alonso M. S., Coldwell G., Lambas D. G., 2013, A&A, 549, A141
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Barton E. J., Geller M. J., Kenyon S. J., 2000, ApJ, 530, 660
Bertola F., Buson L. M., Zeilinger W. W., 1992, ApJ, 401, L79
Bianchi S. et al., 2012, MNRAS, 426, 3225
Binette L., Drissen L., Ubeda L., Raga A. C., Robert C., Kronold Y., 2009, A&A, 500, 817
Caon N., Macchetto D., Pastoriza M., 2000, ApJS, 127, 39
Cid Fernandes R., Stasińska G., Mateus A., Vale Asari N., 2011, MNRAS, 413, 1687
Coziol R., Torres-Papaqui J. P., Plachu-Frayn L, Islas-Islas J. M., Ortega-Minakata R. A., Neri-Larios D. M., Andernach H., 2011, Rev. Mex. Astron. Astrofis., 47, 361
Dahari O. A., 1984, PhD thesis, California Univ., Santa Cruz, USA
Dahari O., 1985, ApJS, 57, 643

Nuclear activity in isolated galaxies 345

de Mello D. F., Keel W. C., Sulentic J. W., Rampazzo R., 1995, in van der Kruit P. C., Gilmore G., eds, Proc. IAU Symp. 164, Stellar Populations. Kluwer, Dordrecht, p. 434
de Mello D. F., Sulentic J. W., de Souza R. E., Reduzzi L., Rampazzo R., 1996, A&A, 308, 387
Dultzin D. et al., 2008, arXiv:preprints
Dultzin-Hacyan D., Kronold Y., Fuentes-Guridi I., Marziani P., 1999, ApJ, 513, L111
Elitzur M., Ho L. C., 2009, ApJ, 701, L91
Ellison S. L., Patton D. R., Simard L., McConnachie A. W., Baldry I. K., Mendel J. T., 2010, MNRAS, 407, 1514
Ellison S. L., Patton D. R., Mendel J. T., Scudder J. M., 2011, MNRAS, 418, 2043
Gu Q., Dultzin-Hacyan D., de Diego J. A., 2001a, Rev. Mex. Astron. Astrofis., 37, 3
Gu Q., Maiolino R., Dultzin-Hacyan D., 2001b, A&A, 366, 765
Hao L. et al., 2005, AJ, 129, 1783
Heckman T. M., 1980, A&A, 87, 142
Hernández X., Lee W. H., 2010, MNRAS, 404, L6
Hernández-Toledo H. M., Dultzin-Hacyan D., Gonzalez J. J., Sulentic J. W., 1999, AJ, 118, 108
Hernández-Toledo H. M., Vázquez-Mata J. A., Martínez-Vázquez L. A., Choi Y.-Y., Park C., 2010, AJ, 139, 2525
Ho L. C., 2002, in Green R. F., Khachikian E. Y., Sanders D. B., eds, ASP Conf. Ser. Vol. 284, IAU Colloq. 184: AGN Surveys. Astron. Soc. Pac., San Francisco, p. 13
Ho L. C., 2003, in Collin S., Combes F., eds, ASP Conf. Ser. Vol. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy. Astron. Soc. Pac., San Francisco, p. 379
Ho L. C., 2009, ApJ, 699, 626
Ho L. C., Filippenko A. V., Sargent W. L. W., 1997a, ApJS, 112, 315
Ho L. C., Filippenko A. V., Sargent W. L. W., 1997b, ApJ, 487, 568
Ho L. C., Filippenko A. V., Sargent W. L. W., 1997c, ApJ, 487, 591
Karachentsev I. D., Makarov D. I., Karachentseva V. E., Melyonk O. V., 2011, Astrophys. Bull., 66, 1
Karachentseva V. E., 1973, Soobshch. Spets. Astrofiz. Obs., 8, 3
Karachentseva V. E., Mitronova S. N., Melyonk O. V., Karachentsev I. D., 2010, in Verdes-Montenegro L., Del Olmo A., Sulentic J., eds, ASP Conf. Ser. Vol. 421, Galaxies in Isolation: Exploring Nature Versus Nurture. Astron. Soc. Pac., San Francisco, p. 11
Kauffmann G. et al., 2003, MNRAS, 346, 1055
Keel W. C., 1983, ApJ, 269, 466
Keel W. C., 1993, AJ, 106, 1771
 Kennicutt R. C., Jr, Keel W. C., 1984, ApJ, 279, L5
Kennicutt R. C., Jr Roettiger K. A., Keel W. C., van der Hulst J. M., Hummel E., 1987, AJ, 93, 1011
Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J., 2001, ApJ, 556, 121
Koulouridis E., Plionis M., Chavushyan V., Dultzin-Hacyan D., Kronold Y., Goudis C., 2006a, ApJ, 639, 37
Koulouridis E., Chavushyan V., Plionis M., Kronold Y., Dultzin-Hacyan D., 2006b, ApJ, 651, 93
Kronold Y., Dultzin-Hacyan D., Marziani P., 2001, AJ, 121, 702
Kronold Y., Dultzin-Hacyan D., Marziani P., 2002, ApJ, 572, 169
Kronold Y., Dultzin-Hacyan D., Marziani P., 2003, in Collin S., Combes F., Shlosman I., eds, ASP Conf. Ser. Vol. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy. Astron. Soc. Pac., San Francisco, p. 523
Kronold Y., Nicastro F., Elvis M., Brickhouse N., Binette L., Mathur S., Jiménez-Bailón E., 2007, ApJ, 659, 1022
Lauringer E., H., 1995, A&A, 293, 683
Lee G.-H., Woo J.-H., Lee M. G., Hwang H. S., Lee J. C., Sohn J., Lee J. H., 2012, ApJ, 750, 141
Lin L. et al., 2007, ApJ, 660, L51
Lonsdale C. J., Persson S. E., Matthews K., 1984, ApJ, 287, 95
Márquez I., Masegosa J., 2008, Rev. Mex. Astron. Astrofís. Conf. Ser., 32, 150
Martínez M. A., Del Olmo A., Coziol R., Perea J., 2010, AJ, 139, 1199
SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table 6.** Logarithm intensity ratios with their errors and AGN type for the CIG sample.

**Table 7.** Logarithm intensities ratios and their errors for Varela’s sample (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1021/-/DC1).

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