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The stellar mass–size relation for the most isolated galaxies in the local Universe★

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ABSTRACT

Disentangling processes governing the formation and evolution of galaxies is a fundamental challenge in extragalactic research. In this sense, the current belief that galaxies grow by the action of minor mergers makes the study of the stellar mass–size relation in different environments an important tool for distinguishing effects of internal and external processes. The aim of this work is to study the effects of environment on the growth in size of galaxies. As part of Analysis of the Interstellar Medium of Isolated GAlaxies (AMIGA project), we examine the stellar mass–size relation for a sample of the most isolated galaxies in the local Universe interpreted as stellar systems where evolution has been mainly governed by internal processes. Effects of environment on the stellar mass–size relation are evaluated by comparing our results with samples of less isolated early- and late-type galaxies, as well as, for the first time, different spiral subtypes. Stellar masses in our sample were derived by fitting the SED of each galaxy with KCORRECT. We used two different size estimators, the half-light radius obtained with SEXTRACTOR and the effective radius calculated by fitting a Sérsic profile to the *i*-band image of each galaxy using GALFIT. We found good agreement between those size estimators when the Sérsic index fell in the range $2.5 < n < 4.5$ and $0.5 < n < 2.5$ for (visually classified) early- and late-type galaxies, respectively. We find no difference in the stellar mass–size relation for very isolated and less isolated early-type galaxies. We find that late-type isolated galaxies are ∼1.2 times larger than less isolated objects with similar mass. Isolated galaxies and comparison samples were divided into six morphological ranges (E/S0, Spirals, Sb, Sbc, Sc and Scd–Sdm) and five stellar mass bins between $\log(M_*) = [9,11.5]$. In all cases, the relation is better defined and has less scatter for the isolated galaxies. We find that as the morphological type becomes later the galaxy size (for a fixed stellar mass range) becomes larger. For the lowest stellar mass bins $\log(M_*) = [9,10]$, we find good agreement between sizes of AMIGA and comparison spirals (both mostly composed of Scd–Sdm types). The isolated spiral galaxies in the high stellar mass bins $\log(M_*) = [10,11]$ tend to be larger than less isolated galaxies. This difference in size is found for all spiral subtypes and becomes larger when we compare fully isolated galaxies with galaxies having two or more satellites (neighbours within 3 mag of difference at a distance less than 250 kpc from the galaxy). Our results suggest that massive spiral galaxies located in low-density environments, both in terms of major companions and satellites, have larger sizes than samples of less isolated galaxies. Hence, the environment has played a role in the growth in size of massive spiral galaxies.

Key words: galaxies: evolution – galaxies: fundamental parameters – galaxies: general – galaxies: interactions.

★ Full Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/MNRAS, and at the AMIGA VO interface (http://amiga.iaa.es).

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1 INTRODUCTION

Several recent studies find evidence for growth in size of galaxies from redshift 2–3 to the present (Daddi et al. 2005; Trujillo et al. 2006, 2007; Longhetti et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008). Evidence is especially strong for the most massive early-type galaxies which have increased in size by a factor of 4.3 since $z \sim 2.3$. There is also evidence that late-type systems have increased their size 2.6 times over the same z interval (Buitrago et al. 2008). Scenarios have been proposed to explain this size evolution including environmentally dependent and independent processes. While a part of the size growth could be explained by the addition over time of larger galaxies (Carollo et al. 2013), the most likely and accepted mechanism involves growth from dry minor mergers (Bell et al. 2005; van Dokkum 2005) believed to be more efficient for increasing the size than the stellar mass of galaxies. Consideration of this scenario and the fact that the number of compact objects is almost non-existent at $z = 0$ (Fernández Lorenzo et al. 2011) leads to the expectation of an increase with redshift in the number of galaxies with minor companions. However, the fraction of galaxies with satellites appears to remain constant from $z \sim 2$ to the present (Mármol-Queraltó et al. 2012). Different mechanisms, depending on the galaxy mass, would be needed if secular processes are responsible for the growth in galaxy size. For the most massive galaxies, growth in size would be driven by quasar feedback which could remove huge amounts of cold gas from the central regions thereby inducing an expansion of the stellar distribution. On the other hand, less massive galaxies would undergo adiabatic expansion as a consequence of mass-loss driven by stellar winds and supernova explosions (Fan et al. 2008). In both cases, a significant evolution of the velocity dispersion (larger at high redshift) is predicted for both small and large galaxies. The evidence so far shows only mild evolution in velocity dispersion (Cappellari et al. 2009; Cenarro & Trujillo 2009; Martinez-Manso et al. 2011).

If the observed differences are real and if they are due to environmental influences, then comparisons at low redshift of the stellar mass–size relation for galaxies in different environments might shed some light on this interpretation. Previous environmental studies of the stellar mass–size relation were made by comparing field and cluster early-type galaxies. Most of them find no dependence on the stellar mass–size relation with environment at both local (Maltby et al. 2010; Huertas-Company et al. 2012) and high redshift (Rettura et al. 2010; Valentinuzzi et al. 2010b). However, Cimatti et al. (2008) found a different stellar mass–size relation for cluster and field galaxies at redshift ∼1. Cluster early-type galaxies seem to be located closer to the stellar mass–size relation at $z = 0$ than those located in low-density environments, which present smaller sizes at high redshift. In addition, Cooper et al. (2012) found that early-type systems in higher density regions tend to be more extended than their counterparts in low-density environments. In the case of late-type galaxies, Maltby et al. (2010) find evidence for environmental dependence on the stellar mass–size relation. However, this evidence is marginal (2σ) and only for intermediate/low stellar masses. The most massive spirals follow the same stellar mass–size relation in field and cluster environments. They claim that there is a population of spirals containing extended discs only in the field.

Although minor mergers are the most popular explanation for the growth of galaxies in size, a dependence with environment is not clearly established, as we have seen before. Moreover, since the growth in size is stronger for massive early-type galaxies, the effect of environment should be larger for these objects. However, only spirals present a (weak) dependence with environment. Since field usually includes pairs and even groups of galaxies, interactions may have played an important role in the results found in previous studies. At this point, a well-defined environment can be crucial.

While it is easy to recognize a rich cluster, definitions of low-density environments can be confusing. In recent years, there has been an increased emphasis on identifying low-density or isolated galaxy populations. One of the most useful samples remains the visually selected catalogue of isolated galaxies (CIG) compiled by Karachentseva (1973), more recently vetted as the Analysis of the interstellar Medium of Isolated GAlaxies (AMIGA; Sulentic 2010, and references therein) sample. AMIGA galaxies show different physical properties than galaxies in denser environments (even field galaxies), including a lower infrared luminosity ($L_{\rm FIR} < 10.5$ L$\odot$) and colder dust temperature (Lisenfeld et al. 2007), a low level of radio continuum emission dominated by mild disc star formation (SF; Leon et al. 2008), no radio active galactic nuclei (AGN) selected using the radio–far-infrared correlation (0 per cent; Sabater et al. 2008) and a small number of optical AGN (22 per cent; Sabater et al. 2012), less molecular gas (Lisenfeld et al. 2011) or a smaller fraction of H I asymmetries (<20 per cent; Espada et al. 2011). In addition, early-type galaxies in AMIGA are fainter than late types, and most AMIGA spirals host pseudo-bulges rather than classical bulges, as well as different level of optical asymmetry, clumpiness and concentration (Durbala et al. 2008). The comparison of colours between AMIGA and pairs of galaxies has shown a passive SF and a Gaussian distribution of colours for isolated galaxies, while the galaxies in pairs present bluer colours and higher colour dispersions, which is indicative of an SF enhanced by interactions (Fernández Lorenzo et al. 2012). If environment is affecting the growth in size of galaxies, might isolated galaxies be smaller than other galaxies because they had undergone fewer minor mergers? Galletta et al. (2006) tried to answer this question by comparing the distribution in size between isolated and interacting galaxies. Their results suggest that isolated galaxies are smaller than objects in interaction, but a comparison of the size as a function of the stellar mass was not made in that work, which can lead to a wrong conclusion if the two samples do not have the same stellar mass distribution.

Here, we propose to analyse the stellar mass–size relation for the AMIGA sample of isolated galaxies. In Section 2, the sample selection and data analysis is described. The stellar mass–size relation is presented in Section 3, and the discussion of the results is provided in Section 4. Finally, the conclusions are exposed in Section 5. Throughout this article, the concordance cosmology with $\Omega_{\Lambda 0} = 0.7$, $\Omega_{\rm m0} = 0.3$ and $H_0 = 70$ km s^{-1} Mpc^{-1} is assumed for comparison with other studies about the stellar mass–size relation ($H_0 = 75$ km s^{-1} Mpc^{-1} is assumed in the other papers of AMIGA). Unless otherwise specified, all magnitudes are given in the AB system.

2 DATA AND SAMPLE SELECTION

This work is part of the AMIGA project (Verdes-Montenegro et al. 2005). Since its beginning, this project has made a refinement and multiwavelength characterization of the CIG. The data are being released and periodically updated at http://amiga.iaa.es, where a Virtual Observatory compliant web interface with different query modes has been implemented. We applied the same sample selection as in Fernández Lorenzo et al. (2012), considering both isolation and completeness criteria. The isolation criteria were defined in Verley et al. (2007), which reject galaxies with isolation parameters

Table 1. Data for the AMIGA sample.

CIG (1)	Type (RC3) (2)	Mag_g (mag) (3)	Mag_r (mag) (4)	Mag_i (mag) (5)	Mag_{K_S} (mag) (6)	log (M_*) ($\mathrm{M}_\odot$) (7)	R_{50} (kpc) (8)	n (9)	R_e (kpc) (10)	b/a (11)
2	6	14.83 ± 0.04	14.37 ± 0.03	14.11 ± 0.02	14.10 ± 0.12	10.18 ± 0.05	4.72 ± 0.14	1.09 ± 0.01	4.64 ± 0.02	0.59
4	3	12.22 ± 0.01	11.47 ± 0.01	11.04 ± 0.01	10.24 ± 0.01	10.63 ± 0.01	4.03 ± 0.03	0.67 ± 0.00	3.35 ± 0.00	0.26
5	0	15.24 ± 0.04	14.53 ± 0.03	14.16 ± 0.03	13.66 ± 0.04	10.45 ± 0.03	2.95 ± 0.10	1.14 ± 0.01	2.66 ± 0.01	0.38
6	7	14.28 ± 0.03	13.89 ± 0.02	13.70 ± 0.02	13.64 ± 0.10	9.88 ± 0.05	2.97 ± 0.08	1.72 ± 0.01	2.99 ± 0.02	0.43
7	4	14.75 ± 0.03	14.12 ± 0.02	13.79 ± 0.02	13.29 ± 0.07	11.00 ± 0.03	7.28 ± 0.16	1.92 ± 0.01	7.88 ± 0.05	0.70
9	5	14.84 ± 0.03	14.36 ± 0.03	14.07 ± 0.02	13.61 ± 0.07	10.43 ± 0.04	5.17 ± 0.19	1.00 ± 0.01	4.23 ± 0.02	0.28
12	3	15.17 ± 0.04	14.61 ± 0.03	14.34 ± 0.03	13.64 ± 0.09	9.95 ± 0.04	2.47 ± 0.11	1.23 ± 0.01	2.15 ± 0.01	0.31
13	-5	13.55 ± 0.03	12.82 ± 0.02	12.42 ± 0.01	12.04 ± 0.04	10.78 ± 0.02	2.24 ± 0.03	5.24 ± 0.01	3.21 ± 0.01	0.76
14	-3	13.62 ± 0.02	12.92 ± 0.02	12.51 ± 0.01	12.13 ± 0.04	10.77 ± 0.02	3.00 ± 0.04	5.82 ± 0.04	6.80 ± 0.08	0.74
15	4	15.56 ± 0.05	14.89 ± 0.04	14.51 ± 0.03	–	10.56 ± 0.03	3.96 ± 0.16	2.38 ± 0.02	4.16 ± 0.04	0.47
–	–	–	–	–	–	–	–	–	–	–

Notes: The full table is available in electronic form at http://amiga.iaa.es. The columns correspond to (1) galaxy identification according to CIG catalogue; (2) morphological type; (3) Galactic and *K*-corrected magnitude in the *g* band; (4) Galactic and *K*-corrected magnitude in the *r* band; (5) Galactic and *K*-corrected magnitude in the *i* band; (6) Galactic and *K*-corrected magnitude in the K_S band; (7) stellar mass; (8) half-light radius derived by SExtractor; (9): Sérsic index fitted by galfit; (10) effective radius fitted by galfit; (11) semi-axis ratio fitted by galfit. Values of radii and stellar masses are given in CDS and AMIGA VO interface for both the cosmology adopted here ($H_0 = 70$ km s^{-1} Mpc^{-1}) as for that used in the previous AMIGA studies ($H_0 = 75$ km s^{-1} Mpc^{-1}).

$Q > -2$ and $\eta_k > 2.4$ [the tidal strength created by all neighbours, Q, is more than 1 per cent of the internal binding forces (Athanassoula 1984) for the local number density, η_k, this translates into a value of 2.4] and with recession velocities $V_r < 1500$ km s^{-1} (for lower values, the area searched for neighbours spreads too much on the sky). These conditions imply that the evolution of all galaxies in our selected sample is dominated by their intrinsic properties. There are 657 objects in the complete AMIGA sample that fulfil the above isolation criteria.

For the following analysis, we downloaded the images of our galaxies from the Sloan Digital Sky Survey III (SDSS-III) (Data Release 8, DR8; Aihara et al. 2011) in *g*, *r* and *i* bands. A new approach for background subtraction was applied in DR8 that first models the brightest galaxies in each field so that the estimated sky background remains unaffected (Blanton et al. 2011). From the 657 AMIGA galaxies, we found that 497 were observed in the SDSS-DR8. In a few cases, more than one frame was needed in order to fully reconstruct the image of a galaxy. Frames were combined using the iraf task `imcombine`. Five galaxies were rejected because a bad combination of the images caused by a bad astrometry in some of the frames or because there is not adjacent image for combining. Through the direct analysis of the images, we found and removed 21 galaxies strongly affected by saturated stars. We also removed 16 galaxies with unknown redshifts because the redshift will be needed for the following analysis.

We masked the stars and derived the optical parameters of these galaxies using SExtractor (Bertin & Arnouts 1996) in the *g*, *r* and *i* bands. We chose the MAG_AUTO in the catalogues, which provides a good approximation to the total magnitude of the objects. These magnitudes were corrected for Galactic dust extinction by applying the reddening corrections computed by SDSS following Schlegel, Finkbeiner & Davis (1998). We calculated the rest-frame magnitudes and the stellar masses by fitting the spectral energy distribution (SED) using the routine kcorrect (Blanton & Roweis 2007), which assumes an initial mass function of Chabrier. We used also *Ks*-band photometry from 2MASS (Skrutskie et al. 2006) for the SED fitting when available. In this step, we rejected three galaxies because of an unrealistic stellar mass probably caused by an erroneous *Ks*-band magnitude. The final sample consists of 452 isolated galaxies. The radial velocities of these galaxies are mainly between 1500 and 15000 km s^{-1}, with 10 galaxies having velocities up to 24 000 km s^{-1}. Galactic extinction and *K*-corrected magnitudes in each band, as well as stellar masses are presented in Table 1. Since kcorrect assumes a cosmology with $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the stellar masses were transformed to our cosmology as log ($M_* h^{-2}$), where $h = H_0/100 = 0.7$. Note that the magnitudes presented in Table 1 are consistent with those presented in table 2 of Fernández Lorenzo et al. (2012) ($1\sigma \sim 0.1$ mag), since there model magnitudes taken from SDSS catalogue were used.

The structural modelling of the galaxies was made by fitting a Sérsic profile to the *i*-band SDSS images, using the galfit package of Peng et al. (2010). The model was convolved with a point spread function generated from the SDSS psField in each band, and we used the parameters derived by SExtractor as inputs in the galfit code. galfit was designed to work in counts and it underestimates the galaxy size if the image has very low intensity values. To solve this problem, DR8-images pixel values were transformed from nanomaggies to counts, dividing by the NMYU (calibration value translating counts to nanomaggies) parameter in the header. The galfit code provides the effective semimajor axis (a_e) rather than the circular effective radius (R_e). Since local works use structural parameters defined in a circular annuli, we used $R_\mathrm{e} = a_\mathrm{e} \times \sqrt{b/a}$, where b/a is the axis ratio given by galfit, for a proper comparison with other samples. Physical sizes were calculated using the updated distances of the AMIGA galaxies presented in Fernández Lorenzo et al. (2012). Since these distances were calculated using $H_0 = 75$ km s^{-1} Mpc^{-1}, the physical sizes were changed to the cosmology adopted here as $R_\mathrm{e} \times (0.75/0.7)$. Structural parameters derived using both methods are presented in Table 1 (the complete table is available online).

To check the fits we compared the Sérsic index (n) of each galaxy with its visual morphological classification (Sulentic et al. 2006, revised in Fernández Lorenzo et al. 2012), and the effective radius (R_e) with the half-light radius obtained with SExtractor (R_{50}). Our sample is composed of 385 late-type galaxies and 67 early types. While 77 per cent of late-type galaxies have $0.5 < n < 2.5$, only 22 per cent of early types were fitted with $2.5 < n < 4.5$. We found good agreement between R_e and R_{50} for objects into these Sérsic index ranges but large discrepancies for the rest of the sample, which indicates a bad fit for these galaxies.

3 STELLAR MASS–SIZE RELATION

In Fig. 1, we plot the size versus stellar mass values for our sample of galaxies. Our sample was separated into early- ($-5 < T < 0$) and late-type ($1 < T < 10$) galaxies. The relation between stellar mass and galaxy size was established in the local universe by Shen et al. (2003), based on the SDSS. For comparison with the stellar mass–size relation obtained here for isolated galaxies, we overplotted the fits given by Shen et al. (2003) for the SDSS galaxies (without any selection of environment), that provides the distribution of the Sérsic half-light radius as a function of the stellar mass. For early types, this function has the form:

$$\log R_{\rm e}({\rm kpc}) = \log b + a \log\left(\frac{M_*}{{\rm M}_\odot}\right), \tag{1}$$

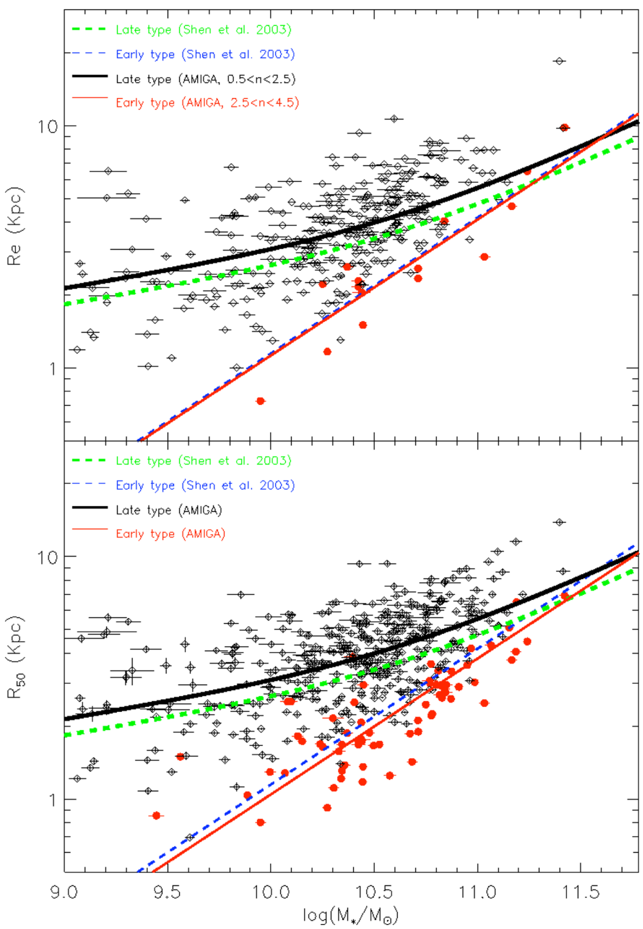

Figure 1. Stellar mass size relation for the AMIGA galaxies using the Sérsic effective radius (top) and the half-light radius (bottom). The open black diamonds represent the AMIGA late–types ($1 < T < 10$) and the solid red points represent the AMIGA early-type ($-5 < T < 0$) galaxies. In the top panel, we consider only late-type objects with Sérsic index $0.5 < n < 2.5$ and early types in the range $2.5 < n < 4.5$. The blue and green dashed lines represent the relations of Shen et al. (2003) for early and late types, respectively. The solid lines represent the fits to AMIGA early- (red) and late- (black) type galaxies using the same functions as Shen et al. (2003) (equations 1 and 2), but allowing a change only in the zero–point (equivalent to a change in the galaxy size).

where $a = 0.56$ and $b = 2.88 \times 10^{-6}$, according to the relation fitted by Shen et al. (2003). In the case of late-type galaxies, the function used in the fit is

$$\log R_{\rm e}({\rm kpc}) = \log\gamma + \alpha\log\left(\frac{M_*}{{\rm M}_\odot}\right) + (\beta-\alpha)\log\left(1+\frac{M_*}{M_0}\right), \tag{2}$$

where $\gamma = 0.1, \alpha = 0.14, \beta = 0.39$ and $M_0 = 3.98 \times 10^{10}\,{\rm M}_\odot$ are the values fitted by Shen et al. (2003).

We have represented these relations using both effective (GALFIT) and half-light (SEXTRACTOR) radius as size estimators, because not all of our galaxies could be fitted by an accurate Sérsic profile, as we have shown in the previous section. To check if there is some difference between AMIGA sample and Shen et al. (2003) sample, we have fitted to AMIGA galaxies the same functions as Shen et al. (2003) (equations 1 and 2), allowing a change only in the zero-point (in the case of Shen et al. 2003, $zp = \log b = -5.54$ and $zp = \log\gamma = -1$ for the early- and late-type galaxies, respectively), which can be interpreted as a change in the galaxy size. We found no difference in the stellar mass–size relation for early-type galaxies with respect to the Shen et al. (2003) one when using the Sérsic effective radius as size estimator, but a slight difference when using the half-light radius from SEXTRACTOR ($\Delta zp = \log R_{50,\rm AMIGA} - \log R_{\rm e,Shen} = -0.04 \pm 0.02$). However, the same difference in the zero-point of $\Delta zp = \log R_{50,\rm AMIGA} - \log R_{\rm e,Shen} = 0.07 \pm 0.01$ is found for late-type galaxies when using both size estimators, which means that the late-type isolated galaxies would be $\sim$1.2 times larger or would have $\sim$0.56 times less stellar mass than similar less isolated objects. There are 12 galaxies in the AMIGA sample with stellar masses $\log(M_*) < 9$ that were excluded from the fit since they can be considered as dwarf galaxies (Geha et al. 2012). In the later analysis, we used the half-light radius obtained with SEXTRACTOR as size estimator for all the AMIGA galaxies because it is independent of the fit given by GALFIT, but consistent with the Sérsic effective radius.

The result obtained in this work is in contrast with that of Galletta et al. (2006), who concluded that isolated galaxies are smaller than objects in interaction. Luminosities and dynamical masses of both their samples of isolated and interacting galaxies were compared in Varela et al. (2004). They found no isolated galaxies with high mass, whereas no perturbed galaxies with low mass. Then, the discrepancy of Galletta et al. (2006) with our work could be caused by a different mass distribution between the sample of isolated and interacting galaxies they compared. However, this conclusion is based on dynamical masses and the comparison between stellar masses of their samples could be different. In Varela et al. (2004), they also compared the luminosity and size of isolated and interacting galaxies. They found that both of their samples satisfy the same luminosity–size relation. Since no stellar mass–size relation is given in this paper, it is difficult to know whether this represents a real difference with our result or it is a consequence of a different luminosity–stellar mass relation for isolated and interacting galaxies.

3.1 The stellar mass–size relation in other environments

The comparison between samples analysed in a different way should be treated with special care as it can lead to wrong results. In the case of Shen et al. (2003), the sizes were calculated by fitting a Sérsic profile to the galaxy in the z band, and the criteria for morphological separation is based on Sérsic index, colour and concentration. Several works have investigated the accuracy of these relations since they are widely used as comparison in high-redshift studies. Valentinuzzi et al. (2010a) found systematically lower radii ($\sim$0.1 dex) in their cluster early- and late-type galaxies with respect to the Shen et al. (2003) relations. However, this difference could be explained with the systematic offset in mass they find with respect to SDSS masses. Contrary to Valentinuzzi et al. (2010a), Guo et al. (2009) claimed that the Sérsic index, magnitude and effective radius derived by Blanton et al. (2005) [the NYU Value-Added Galaxy Catalogue (NYU–VAGC)] and used by Shen et al. (2003) are underestimated.

To check the reliability of our results, we used the data of the NYU–VAGC catalogue (Blanton et al. 2005; Adelman-McCarthy et al. 2008; Padmanabhan et al. 2008). They provide Sérsic fits to the radial profile of each galaxy in the *i* band, and the NYU–VAGC stellar masses were computed using KCORRECT as our stellar masses. In Fig. 2, we compare our stellar masses and half-light radius with the NYU–VAGC data for the AMIGA galaxies in common. Our stellar masses are in good agreement with the NYU–VAGC ones. In the cases of effective radius, we found better agreement when considering only late-type galaxies with a Sérsic index $0.5 < n < 2.5$ and early types in the range $2.5 < n < 4.5$, as we found by fitting our galaxies with GALFIT Sérsic profiles. However, a large number of late types (60 per cent) are fitted with a Sérsic index higher than 2.5, which means that without a morphological visual classification, these objects would be considered as E/S0. We found a very similar result by fitting the stellar mass–size relation of this subsample of spiral ($\Delta zp = 0.018 \pm 0.018$) and early-type ($\Delta zp = -0.006 \pm 0.021$) galaxies using our data and the NYU–VAGC one. However, the zero-point obtained for this subsample of late-type galaxies is closer to the Shen et al. (2003) relation than the one found for our whole sample. We investigated the reason of this discrepancy and found that the spirals fitted with Sérsic index greater than 2.5 are the most massive and earliest. This means that the environmental dependence found previously in this work is most important for the most massive galaxies. However, the AMIGA sample has the characteristic of being composed mainly of late-type galaxies so we need to investigate the stellar mass–size relation for each morphological type.

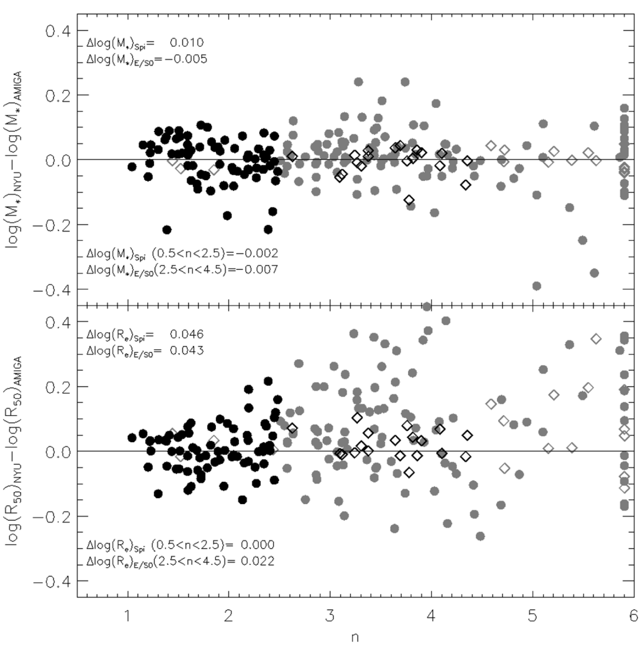

Figure 2. Comparison between AMIGA and NYU–VAGC stellar mass (top) and half-light radius (bottom) as function of the NYU–VAGC Sérsic index for visually classified late-type galaxies (solid points) and early types (open diamonds). Late types with $0.5 < n < 2.5$ and early types with $2.5 < n < 4.5$ are represented in black, while the rest of objects are represented in grey.

3.2 The stellar mass–size relation as function of the morphological type

Since, as explained above, we need a sample with visual determination of the morphologies, we used the sample of Nair & Abraham (2010), which includes detailed visual morphological classifications for 14 034 galaxies in the SDSS DR4. We selected only objects with available morphological classification and redshift $0.01 < z < 0.05$ (8976) to better match our AMIGA sample (98 per cent of our galaxies are in this redshift range). We also imposed a cut in magnitude in the *r* band of $\mathrm{mag}_r < 14.5$, which roughly correspond to our completeness limit in the *B* band ($\mathrm{mag}_B < 15.3$). For the stellar masses and structural parameters we used the data of the NYU–VAGC catalogue. We imposed a Sérsic index cut of $0.5 < n < 2.5$ for late-type galaxies and $2.5 < n < 4.5$ for early types. The final sample of comparison is composed of 353 late- and 824 early-type galaxies. We fitted the same function as Shen et al. (2003), allowing a change only in the zero-point (which can be interpreted as a change in galaxy size), as we did in Section 3 for the AMIGA galaxies. We found good agreement between the Nair & Abraham (2010) sample and the local relations of Shen et al. (2003) for both early- and late-type galaxies.

To check the environmental dependence of the stellar mass–size relation for each Hubble type, the AMIGA and Nair & Abraham (2010) samples were divided into six morphological ranges: the two main morphological groups: E/S0 ($-5 < T < 0$), and Spirals ($1 < T < 8$); and the four subgroups of spirals: Sb ($T = 3$), Sbc ($T = 4$), Sc ($T = 5$) and Scd–Sdm ($6<T<8$). An independent subgroup of Sa–Sab galaxies was not considered because there are only 19 objects in the AMIGA sample with this morphological classification. The results are presented in Fig. 3. To investigate a different environmental effect for high- and low-mass galaxies, we divided the stellar mass range into five bins. The mean half-light radius for each morphological type and stellar mass range was calculated when the bin was composed of more than five galaxies. These mean values and their mean standard errors (1σ) are also drawn in Fig. 3 and presented in Table 2. We find no significant difference at 3σ level in the case of early-type galaxies, with two of three stellar mass ranges having differences $\leq 1\sigma$. We also find no significant difference at 1σ level for less massive spirals ($\log(M_*) < 10$), while the most massive bins ($10 < \log(M_*) < 11$) present a clear difference $>3\sigma$. Looking at different spiral types, we observed that the latter is the morphological type, the larger is the galaxy size for a fixed stellar mass range. This means that a comparison between two samples with different spiral populations may lead to a wrong result. Then, a simple segregation between early-type and spiral galaxies would not be enough when comparing samples in different environments because their spiral population are probably different (more late types in low-density environments, e.g. Sulentic et al. 2006). We also observed that the difference in size found for the high-mass bins is significant for almost all spiral morphological types. For each stellar mass bin and morphological type, we have also calculated the probability, given by the Kolmogorov–Smirnov two-sample test, that the galaxy size distribution of the Nair & Abraham (2010) sample is indistinguishable from the AMIGA one

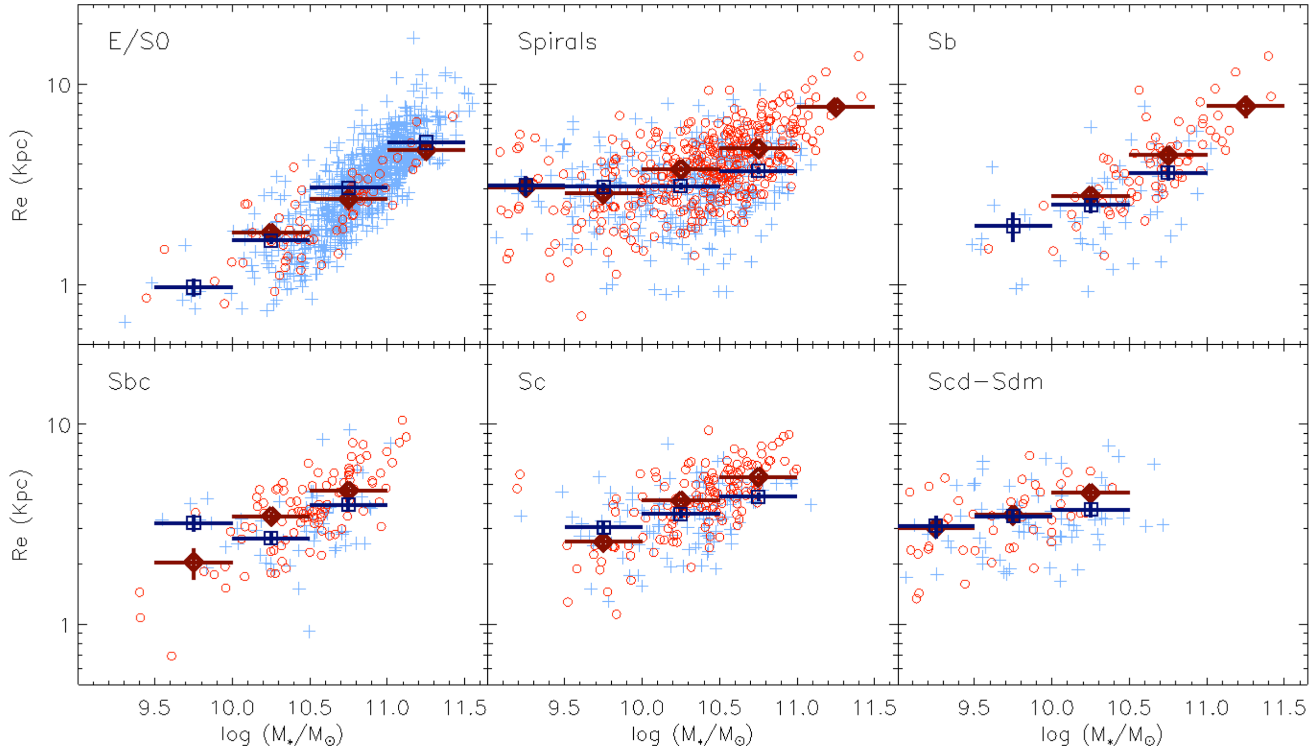

Figure 3. Stellar–mass size relation for galaxies in the AMIGA (red points) and the Nair & Abraham (2010) (blue crosses) samples. The mean half-light radius in each mass bin (represented by the error bars) for the AMIGA (red diamonds) and the Nair & Abraham (2010) samples (blue squares) are shown for each morphological type. The $\overline{Re}$ error bars represent the standard error in the mean in each case. The mean half-light radius was computed only for bins with more than five galaxies.

Table 2. Mean size values as function of the stellar mass for AMIGA and the Nair & Abraham (2010) sample (see Section 3.2).

$\log(M_*)$	$\overline{Re}$(AMIGA)	$\overline{Re}$(Nair)	$p(K-S)$	$\overline{Re}$(AMIGA)	$\overline{Re}$(Nair)	$p(K-S)$	$\overline{Re}$(AMIGA)	$\overline{Re}$(Nair)	$p(K-S)$
		E/S0			Spirals			Sb	
[9–9.5]	–	–	–	3.07 ± 0.32	3.13 ± 0.35	0.89	–	–	–
[9.5–10]	–	0.97 ± 0.10	–	2.85 ± 0.18	3.08 ± 0.15	0.12	–	1.96 ± 0.33	–
[10–10.5]	1.81 ± 0.12	1.65 ± 0.07	0.31	3.76 ± 0.11	3.10 ± 0.11	0.00	2.77 ± 0.20	2.49 ± 0.21	0.05
[10.5–11]	2.68 ± 0.14	3.04 ± 0.05	0.05	4.78 ± 0.12	3.70 ± 0.13	0.00	4.42 ± 0.24	3.62 ± 0.32	0.02
[11–11.5]	4.69 ± 0.51	5.13 ± 0.11	0.02	7.71 ± 0.65	–	–	7.76 ± 0.97	–	–
		Sbc			Sc			Scd–Sdm	
[9–9.5]	–	–	–	–	–	–	3.03 ± 0.31	3.10 ± 0.40	0.92
[9.5–10]	2.04 ± 0.36	3.21 ± 0.31	0.03	2.58 ± 0.25	3.05 ± 0.21	0.01	3.52 ± 0.30	3.47 ± 0.25	0.97
[10–10.5]	3.47 ± 0.18	2.69 ± 0.19	0.10	4.16 ± 0.16	3.56 ± 0.16	0.02	4.54 ± 0.30	3.74 ± 0.33	0.00
[10.5–11]	4.65 ± 0.21	3.96 ± 0.29	0.02	5.46 ± 0.20	4.35 ± 0.19	0.00	–	–	–
[11–11.5]	–	–	–	–	–	–	–	–	–

($p(K-S) > 0.05$). The values obtained from this statistical test, presented in Table 2, are in agreement with and confirm the above mentioned differences in size. The same test was performed for the distribution of stellar masses inside each bin. The only bin that is not comparable in stellar mass ($p < 0.05$) between Nair and AMIGA is that of E/S0 with $11 < \log(M_*) < 11.5$, probably because the number of AMIGA E/S0 in this stellar mass range is small (8).

This lack of dependence on galaxy size with environment for spiral galaxies with stellar masses $\log(M_*) < 10$ contrasts with the result of Maltby et al. (2010), who found that cluster spirals with $\log(M_*) < 10$ are smaller than similar field objects. In this work, Maltby et al. (2010) used the effective semimajor axis as size estimator (instead of the circularized radius), derived by fitting a Sérsic model with GALFIT. To compare with their results, we have calculated our mean size values using also the effective semimajor axis ($\overline{a}_e$) derived with GALFIT for our galaxies. Since only 22 per cent of our early types were fitted with $2.5 < n < 4.5$, we only have enough objects to compare in their stellar mass bin of [10, 11.5]. Our result of $\overline{a}_e = 4.07 \pm 0.74$ kpc agrees well with their value for elliptical galaxies (4.29 ± 0.59 kpc), but we do not have enough objects to separate between elliptical and lenticular galaxies. In the case of spirals, we found a mean size of 4.24 ± 0.46 kpc in the mass bin of [9,9.5], which is larger than their value of 3.14 ± 0.16 kpc, presumably because we have mostly very late type galaxies in this bin (Scd–Sdm). However, in the mass bin of [9.5,10] our result of 3.97 ± 0.26 kpc is very similar to their mean value (4.00 ± 0.18 kpc), and significantly larger than their mean size for cluster (3.42 ± 0.12 kpc) and core cluster (3.52 ± 0.39 kpc) spirals. Finally, in the mass bin of [10,11], we found a larger mean size of 5.81 ± 0.15 kpc compared with their field (4.85 ± 0.21 kpc), cluster

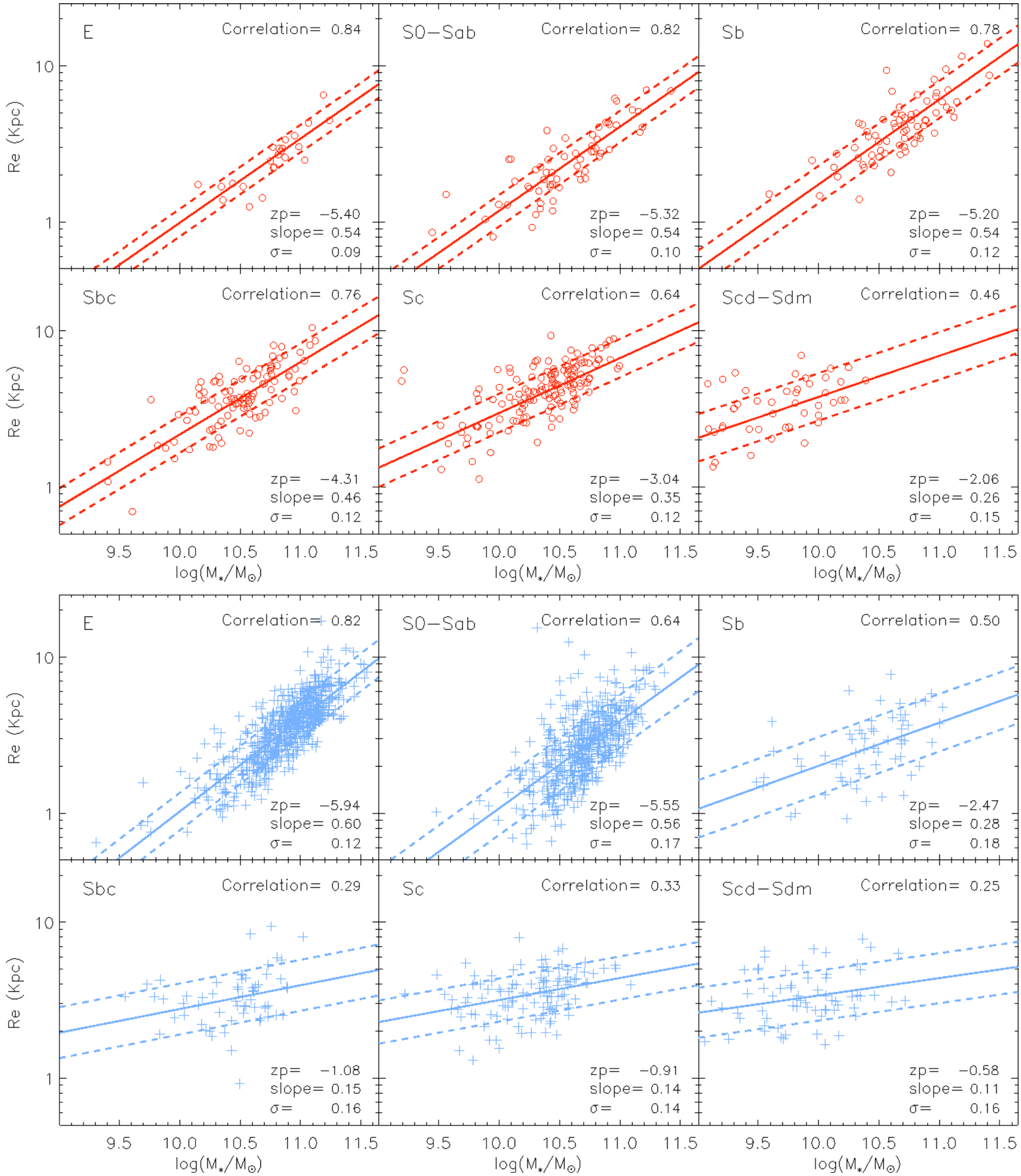

Figure 4. Stellar–mass size relation for galaxies in the AMIGA (red points) and the Nair & Abraham (2010) (blue crosses) samples. The solid and dashed lines represent the linear fit and its 1σ confidence interval for galaxies in each panel. The zero-point, slope and sigma are given in each case, as well as the correlation coefficient.

(5.10 ± 0.21 kpc) and core cluster (5.61 ± 0.46 kpc) spiral galaxies.

Looking at spiral subtypes in Fig. 3, we note a different trend in the stellar mass–size relation than that obtained when considering all spiral types together (equation 2). In Fig. 4, we fitted each morphological subtype with a linear function between $\log(R_e)$ and $\log(M_*)$, the same used by Shen et al. (2003) for early-type galaxies (equation 1). The same was done for the Nair & Abraham (2010) sample. In all cases, the relation is better defined and has less scatter for the isolated galaxies. Then, the AMIGA sample better clarifies the relations between fundamental parameters of galaxies because the blurring effects of environment are minimized. The slope obtained for elliptical galaxies is very similar to that of Shen et al. (2003), and remains constant up to Sb galaxies. Starting with Sb, the slope becomes less steep as we go to later types. This change in slope is probably caused by the changing bulge/disc ratio, and it is responsible for the function obtained when all spirals types are fitted together (equation 2). That function is strongly dependent on the percentage of each spiral type considered in the fit, and therefore, comparisons in different environments and redshifts should be done taking this in mind.

4 DISCUSSION

We find interesting differences between the stellar mass–size relation for very isolated galaxies and the Nair sample. (1) When we divide our sample into morphological subtypes, we find less scatter and a better defined correlation between size and mass for late-type spirals (which represent 2/3 of our sample). Assuming that the two samples are different only in environmental density, we suggest that the AMIGA sample provides a clearer view of the intrinsic physical relation between size and mass because the blurring effects of environment are minimized. This is likely true of all or most physical measures and correlations involving galaxies and has been seen since a larger scatter in colours was found for interacting galaxies (Larson & Tinsley 1978). (2) As the morphological type becomes later the galaxy size for a fixed stellar mass range becomes larger. Also the slope of the stellar mass–size relation changes systematically across the spiral sequence becoming less steep for later types. The change in size and slope across the Sb–Sc isolated galaxy majority population (where mean galaxy luminosity remains constant) is probably caused by the changing bulge/disc ratio. (3) We find a difference between the stellar mass–size relations for AMIGAs and the Nair sample especially for high-mass spirals $10 < \log(M_*) < 11$ which are the dominant population in a sample of *bright* isolated galaxies. The difference can be interpreted in several ways: (a) isolated galaxies have systematically lower stellar masses. (b) Isolated spiral galaxies could be larger in physical size than similar objects in denser environments. In the next subsections, we investigate possibilities (a) and (b). (c) Other explanations for the difference involve sample differences and differences in data processing. The former possibility includes systematic differences in galaxy classification. The latter has been checked and minimized through the comparison shown in Fig. 2.

4.1 Passive SF history of isolated galaxies

Are isolated galaxies less massive because they live in such low-density environments? One must consider their likely SF history and accretion rate. In addition to internal processes, a galaxy can gain stellar mass by accretion of neighbours and by stimulation of SF through interactions. Both are less likely to play an important role in very isolated galaxies where the cross-section for accretion and interaction stimulation by neighbours are assume to be low. It is known that galaxy interactions and the presence of companions are associated with enhanced SF (Larson & Tinsley 1978; Lambas et al. 2003). Larson & Tinsley (1978) were first to demonstrate an increased dispersion in $B - V$ colours, and an excess of bluer colours among interacting galaxies. This enhancement is stronger if the luminosities of companion and host are similar (Woods, Geller & Barton 2006; Scudder et al. 2012). AMIGA galaxies were selected with an isolation criterion that increases the probability that they have had few or no major interactions in at least the last 3 Gyr. Results obtained in previous AMIGA studies (lower $L_{\rm FIR}$, colder dust temperature, less molecular gas, redder colours, etc.; Lisenfeld et al. 2007, 2011; Fernández Lorenzo et al. 2012) point to a lower SF rate (SFR) compared to galaxies in denser environments. Assuming that the SF history of these galaxies has been passive during most of their live leads to the expectation that they may have less stellar mass than galaxies in denser environments. This may be a good qualitative explanation; however, we need to quantify whether the stellar mass increase is due to SF enhancement caused by interaction.

Lisenfeld et al. (2011) calculated an average SFR of $0.7\,M_*\,\mathrm{yr}^{-1}$ for the Sb–Sc isolated galaxies. On the other hand, Scudder et al. (2012) derived an average enhancement of 1.9 in the SFR of galaxies in close pairs. Considering this difference in the SFR during 3 Gyr, we find that an isolated galaxy with $\log(M_*) = 10.5$ (the average value for the Sb–Sc spirals) would only show a 5 per cent stellar mass deficit relative to a galaxy that suffered an interaction. In Section 3, we estimated that our isolated spirals show ∼44 per cent less stellar mass than galaxies in denser environments in order to explain the discrepancy with the relation of Shen et al. (2003). An enhancement in the SFR caused by interaction with close companions cannot account for a strong difference in stellar mass.

This is a simple test taking into account only one interaction and only in the last 3 Gyr, while the life of a galaxy is much more complicated. Perhaps 10 per cent of the Nair sample might involve galaxies in pairs since Xu & Sulentic (1991) found that 10 per cent of field galaxies are in pairs, while the number of pairs in AMIGAs is effectively zero. The main environmental difference between the two samples involves the local surface density of neighbours. Is the surface density around Nair galaxies high enough, and are interactions in loose groups frequent enough, to explain a mass difference due to interaction induced SF? Nevertheless, from the information we have, we only can conclude that the difference in the stellar mass–size relation is not mainly caused by a different SF history of objects in low and dense environments.

4.2 Growth in size of isolated galaxies

Evolution in the stellar mass–size relation is usually attributed to a growth in size of galaxies caused by minor mergers (Bell et al. 2005; van Dokkum 2005). Unlike the major merger rate which is higher in high-density environments, the rate of minor mergers might depend on the initial local density. In the case that galaxies in low-density environments had formed with a lower number of small companions, then these galaxies should have grown less than those in denser environments. On the other hand, if small companions are remnants of the galaxy formation process, an environmental dependence should not be expected for the growth in size of galaxies. We find in this study that isolated galaxies have grown at the same rate as galaxies in other environments, with massive spirals growing the most. Whatever the reason for the growth in size, it reflects that the same evolution has affected all galaxies. If we accept a role for minor mergers to explain the general growth of galaxies, then the small objects that have been accreted during the life of a galaxy should be remnants of the formation of that individual galaxy. In addition, the fact that isolated late-type galaxies in our sample are systematically larger than similar mass objects in other environments indicates that there is another environmental dependent process causing the larger sizes of isolated spirals. One possible explanation is that spiral galaxies in low-density environments are the norm while such extended discs do not survive in higher density environments (Maltby et al. 2010).

The criteria used by Karachentseva (1973) for selecting the sample have two effects in our galaxies. On one hand, they do not have major companions at large distances, minimizing effects of environment at large scale (tidal interactions, major mergers, etc.).

On the other hand, the number of small companions at close distances (satellites) until 4 mag of difference with the CIG galaxy is also minimized, implying that our sample presents a deficit of local neighbours with respect to other samples. Then, another possibility for the larger sizes found in this work would be that AMIGA galaxies have accreted more satellite galaxies and as a consequence of this local accretion have created a local deficit of satellites.

In order to check this option, we studied the influence of the local environment, calculating the number of satellites in a field of projected radius $R = 250$ kpc (using as criterion for defining satellite, the distance at which the 80 per cent of Milky Way satellites are found Fouquet et al. 2012), for the 207 AMIGA spiral galaxies with more than 80 per cent spectroscopic completeness in the SDSS DR8. Since the SDSS spectroscopic data base is complete until $r \sim 17.5$ and our sample, until $r \sim 14.5$, we consider only objects: (1) within 3 mag difference with respect to the central galaxy, and (2) with a difference in the recession velocity less than 1000 km s^{-1}. The same calculation was made for 336 spirals of Nair & Abraham (2010) that have more than 80 per cent completeness in SDSS DR8. We find that 6 per cent of AMIGA spirals have one satellite (and one galaxy with two satellites). In contrast, 43 per cent of the Nair sample show a satellite (19 per cent have two or more). We calculated again (see Table 2) the mean size for Nair spirals in the stellar mass ranges [10,10.5] and [10.5,11] considering only galaxies without satellites, galaxies with no or one satellite and galaxies with two or more satellites. The mean size for spirals without satellites in the Nair & Abraham (2010) sample is very similar to the value obtained in Section 3.2: $\overline{Re}[10–10.5] = 3.18 \pm 0.16$ kpc and $\overline{Re}[10.5–11] = 3.63 \pm 0.16$ kpc. The mean size, considering also galaxies with one satellite, is also consistent with the previous value. However, the mean size for spirals with two or more satellites is lower than the value obtained for the Nair & Abraham (2010) sample in Section 3.2: $\overline{Re}[10–10.5] = 2.87 \pm 0.22$ kpc and $\overline{Re}[10.5–11] = 3.35 \pm 0.33$ kpc.

In the case of individual spiral subtypes, we have calculated the mean size value for galaxies in the stellar mass range [10–11] for increasing the statistics. The same calculation was performed for the AMIGA sample, the Nair & Abraham (2010) sample of galaxies having zero or one satellite, and the Nair & Abraham (2010) galaxies with two or more satellites. The results are presented in Fig. 5. In the three cases, we find that spiral galaxies become larger as they become later types. Galaxies in the Nair & Abraham (2010) sample with no or one satellite are larger than those with two or more satellites for almost all morphological types. In all cases, the mean size of our isolated galaxies remains even larger than objects without satellites in the Nair & Abraham (2010) sample.

These results confirm that the local environment is affecting the growth in size of galaxies. However, the objects without satellites in the Nair & Abraham (2010) sample are still smaller than our isolated galaxies. Then, another effect of the environment is expected to be the cause of the difference in size, and a truncation of the extended discs caused by effects of the large scale environment (group, cluster, etc.) could be the reason (Maltby et al. 2010). In this sense, a study of the outer profiles of discs in different environments would be essential for disentangling the mechanisms involved in the growth in size of galaxies.

5 SUMMARY AND CONCLUSIONS

We have investigated the stellar mass–size relation for a sample of isolated galaxies. This sample was selected from the AMIGA sample according to its completeness and the isolation criteria defined in

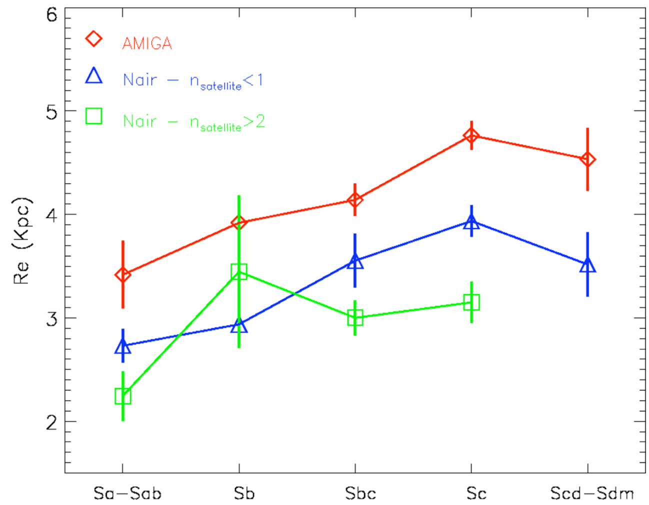

Figure 5. Mean size for galaxies in the stellar mass range [10–11] as function of each morphological spiral type, for the AMIGA sample (red diamonds), the galaxies in the Nair & Abraham (2010) sample having zero or one satellite (blue triangles) and galaxies in the Nair & Abraham (2010) sample with two or more satellites (green squares).

Verley et al. (2007), which ensure that the tidal strength created by all neighbours is less than 1 per cent of the internal binding forces. The stellar masses were derived by fitting the SED to the g, r, i and Ks-band photometry with KCORRECT. We used two different size estimations, the half-light radius obtained with SEXTRACTOR and the effective radius calculated by fitting a Sérsic profile to the i-band image of each galaxy with GALFIT. We found good agreement between both size estimations when the Sérsic index given by GALFIT was within $2.5 < n < 4.5$ for early-types and within $0.5 < n < 2.5$ for late-type galaxies.

The sample was divided in early ($-5 < T < 0$) and late-type galaxies ($1 < T < 10$) and both stellar mass–size relations were fitted using the same functions as in Shen et al. (2003), allowing a change only in the zero-point. We found no difference in the stellar mass–size relation for early-type galaxies with respect to the Shen et al. (2003) one when using the Sérsic effective radius as size estimator, but a slight difference when using the half-light radius from SEXTRACTOR ($\Delta zp = \log R_{50,\mathrm{AMIGA}} - \log R_{\mathrm{e,Shen}} = -0.04 \pm 0.02$). For late-type galaxies, we found a difference in the zero-point of $\Delta zp = \log R_{50,\mathrm{AMIGA}} - \log R_{\mathrm{e,Shen}} = 0.07 \pm 0.01$ independently of the size estimator used. This difference in the zero-point implies that the late-type isolated galaxies would be, on average, $\sim$1.2 times larger or would have $\sim$44 per cent less stellar mass than spiral galaxies in denser environments.

To check the environmental dependence of the stellar mass–size relation for each Hubble spiral subtype, we compared our data with the sample of Nair & Abraham (2010), which has no selection of environment and visually classified morphologies (necessary due to the differences between visual and Sérsic classifications). The stellar mass and effective radius of the Nair & Abraham (2010) galaxies were taken from the NYU–VAGC catalogue, after verifying that the NYU–VAGC data were consistent with those calculated by us for the AMIGA galaxies in common. Both samples were divided into six morphological ranges: E/S0 ($-5 < T < 0$), Spirals ($1 < T < 8$), Sb ($T = 3$), Sbc ($T = 4$), Sc ($T = 5$), and Scd–Sdm ($6 < T < 8$). To investigate a different environmental effect for galaxies of high and low mass, we also divided the stellar mass range into five stellar mass bins between $\log(M_*) = [9,11.5]$. The main results of this comparison includes:

(i) There is no significant difference at 3σ level in the case of early-type galaxies, with two stellar mass ranges having differences $\leq 1\sigma$.

(ii) In the case of spiral types, the latter is the morphological type, the larger is the galaxy size for a fixed stellar mass range. Therefore, if segregation of morphological spiral types is not done, the comparison of the stellar mass–size relation between samples of spiral galaxies in different environments may lead to a wrong result, since their spiral populations are probably different.

(iii) In the case of the less massive spirals ($\log(M_*) < 10$), no significant difference is found at 1σ level for AMIGA galaxies compared with similar objects in denser environments. This is in contrast with the result found by Maltby et al. (2010) of larger sizes for spiral galaxies in the field than in the cluster environment, but they did not perform a segregation by spiral subtype.

(iv) The high-mass AMIGA spirals ($10 < \log(M_*) < 11$) present a clear difference $>3\sigma$ when comparing with the Nair & Abraham (2010) sample. This difference is found for all spiral types in the sense that they are larger than objects in denser environments. The difference in size is also significative when comparing with the cluster sample of Maltby et al. (2010).

(v) We find less scatter and a better defined correlation between size and mass for late-type spirals when we break the samples into morphological subtypes. Also the slope of the stellar mass–size relation changes systematically across the spiral sequence becoming less steep for later types.

(vi) The number of satellites around a galaxy affects its size. The galaxies in the Nair & Abraham (2010) sample with zero or one satellite have larger sizes than galaxies having two or more satellites. In all cases, the mean size of our isolated galaxies remains even larger than objects without satellites.

The difference in the stellar mass–size relation for high-mass spirals ($10 < \log(M_*) < 11$) found in this paper can be interpreted as a lower stellar mass or as a larger size for isolated galaxies comparing with similar objects in denser environments. We rejected the first explanation since the increase in the SFR caused by an interaction cannot explain the difference in stellar mass found here. Our results suggest that the environment plays a role in the growth in size of spiral galaxies, but not in the case of early types.

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SUPPORTING INFORMATION

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

Table 1. Data for the AMIGA sample (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1020/-/DC1).

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