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A multiwavelength view of isolated galaxies

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Abstract. In the last few years interest in isolated galaxies has been renewed within a context regarding secular evolution. This adds to their value as a control sample for environmental studies of galaxies. This presentation will review important results from recent studies of isolated galaxies. I will emphasize work involving statistically significant samples of isolated galaxies culminating with refinement of the CIG in the AMIGA program. The AMIGA project (Analysis of the interstellar Medium of Isolated Galaxies, http://amiga.iaa.es) has identified a significant sample of the most isolated (T_{cc}(nearest-neighbor) ∼ 2-3Gyr) galaxies in the local Universe and revealed that they have different properties than galaxies in richer environments. Our analysis of a multiwavelength database includes quantification of degree of isolation, morphologies, as well as FIR and radio line/continuum properties.

Properties usually regarded as susceptible to interaction enhancement show lower averages in AMIGA–lower than any galaxy sample yet identified. We find lower MIR/FIR measures, low levels of radio continuum emission, no radioexcess above the radioFIR correlation, a small number of AGN, and lower molecular gas content. The late-type spiral majority in our sample show very small bulge/total ratios(largely < 0.1) and Sersic indices consistent with an absence of classical bulges. They have redder g-r colors and lower color dispersion for AMIGA subtypes and larger disks, and present the narrowest (gaussian) distribution of HI profile asymmetries of any sample yet studied.

1. Isolated galaxies: an historical perspective

1.1. Different approaches to the study of environmental studies

In 2009 the first international conference on isolated galaxies: " Galaxies in Isolation: Exploring Nature vs. Nurture" took place in Granada. A quotation of Sulentic (2010) review presented there seems in place to put the study of isolated galaxies in context:

"Studies of isolated galaxies can be said to begin at about then same time it was realized that galaxy nurture was important - e.g. Sulentic (1976); but see also Tovmassian (1966). I remember well the criticism for suggesting in my thesis that radio emission from interacting galaxies was enhanced. Of course within a decade the role of nurture on galaxy structure and evolution was established - Larson & Tinsley (1978); Stocke (1978); Lonsdale et al. (1984); Cutri & McAlary (1985)"

In these past 40 years since the role of interactions in galaxy properties was realized, a variety of widely different criteria to define galaxy isolation have been used:

- magnitude limited samples,
- redshift information used or not,

- distance to the nearest galaxies different from one definition to the other, etc

See e.g., Turner & Gott (1975); Balkowski & Chamaraux (1981); Vettolani et al. (1986); Zaritsky et al. (1993); Aars et al. (2001); Colbert et al. (2001); Pisano et al. (2002); Prada et al. (2003); Marquez & Moles (1996); Márquez & Moles (1999); Márquez et al. (2002); Márquez et al. (2003); Varela et al. (2004); Verley et al. (2009); Argudo-Fernández et al. (2013).

Furthermore, field galaxies have frequently been used as a reference for environmental studies. However this definition only concerns the large-scale environment, while the small-scale environment is ignored, so that pairs or even groups are often part of these samples. Sometimes the environment of galaxies is not considered in the selection of a reference sample, being replaced by the concept of "normal" galaxy, which implies an a prioristic definition of normalcy.

Even when a definition of isolation has been used, sometimes galaxies with no redshift information have been discarded as companions (e.g. Kelm & Focardi 2004) presenting a sample of galaxies isolated from companions brighter than 15.5mag), while later redshift surveys have revealed those galaxies without velocity data to be physical companions. Isolated galaxies are both interesting *per se* or as a reference for studies of samples in different environments. This last aim ideally requires a statistically significant sample with multifrequency information, so that the use of the same comparison sample for different physical parameters/wavelengths can be possible. However, monochromatic observations of large samples or alternatively multiwavelength observations of small samples (typically $\sim$ 10 - 100/200 members) is usually found (e.g. Huchra & Thuan 1977; Vettolani et al. 1986; Márquez & Moles 1999; Colbert et al. 2001; Pisano et al. 2002; Varela et al. 2004).

The pioneer work of Karachentseva led to the Catalogue of Isolated Galaxies (Karachentseva 1973), selected from POSS1 and exhibiting several key strengths:

- Size: 1050 galaxies
- Well defined criterion of isolation: no similar sized galaxies (within a factor 4) within 40 $\times$ the radius of the companion, implying nearest neighbor crossing times t_c= 1-3Gyr;
- Depth: the Optical Luminosity Function (OLF) can be sampled up to $\sim$ 15.000 km/s.
- Complementarity: the CIG is complemented by catalogs of galaxy pairs (CPG, Catalog of Paired Galaxies; Karachentsev 1972), triplets (Karachentseva et al. 1979) and compact groups (HCG; Hickson 1982, largely quartets)

No other catalog appeared over the next 30 years with same or equivalent strengths, hence it constituted in 2003 the starting point of AMIGA project, which we describe in the next section. After the launch of AMIGA project other studies/samples of isolated galaxies are worth mentioning, as the "Catalog of Very Isolated Galaxies From The Sloan Digital Sky Survey Data Release 1" (Allam et al. 2005), or "An Atlas Of Ha and R Images and Radial Profiles of 29 Bright Isolated Spiral Galaxies" (Koopmann & Kenney 2006). In the work "Effects of Interactions on Galaxy Properties in the Main Galaxy Sample of SDSS Data Release 5", Deng et al. (2008) find that the early-type fraction of paired galaxies is far higher than that of isolated galaxies, and that faint, blue, and late-type galaxies are located preferentially in low-density regions. Recent efforts to compile catalogs of isolated galaxies are the UNAM-KIAS Catalog of Isolated Galaxies (Hernández-Toledo et al. 2010), and the Catalog of Isolated Galaxies Selected from the 2MASS survey - 2MIG (Karachentseva et al. 2010), while Toribio et al. (2011) studied the "HI Content and Optical Properties of Field Galaxies from the ALFALFA Survey". Karachentseva et al. (2011) presented a catalog of 520 most isolated nearby galaxies with radial velocities V_{LG}<3500 km/s covering the entire sky, called the "Local Orphan Galaxies" (LOG). A half of the LOG catalog is occupied by the Sdm, Im and Ir morphological type galaxies without a bulge.

1.2. AMIGA project

AMIGA (Analysis of the interstellar Medium of Isolated GAlaxies; http://amiga.iaa.es) project started in 2003 aiming to identify and study a statistically significant sample of the most isolated galaxies in the local Universe, and so far constitutes the most extensive multiwavelength study of a reference sample of isolated galaxies. AMIGA was designed to provide a sample with strict isolation criteria (Verley et al. 2007) implying that its galaxies have likely been unperturbed for $\sim$ 3 Gyr (Verdes-Montenegro et al. 2005). The sample has been evaluated, refined, and improved in different ways including: 1) revised positions (Leon & Verdes-Montenegro 2003), 2) sample redefinition, magnitude correction, and full-sample analysis of the Optical Luminosity Function (OLF) (Verdes-Montenegro et al. 2005), 3) morphological revision and type-specific OLF analysis (Sulentic et al. 2006), showing that Sb, Sbc and Sc galaxies dominate the CIG), 4) subsequent reevaluation and quantification of the degree of isolation for the sample: Verley et al. (2007) found that CIG galaxies show a continuous spectrum of isolation, as quantified by two complementary parameters, the local number density of the neighbour galaxies and the tidal forces affecting the galaxies. The fraction of CIG galaxies whose properties are expected to be influenced by the environment is however low (159 out of 950 galaxies). The isolated parameters derived for the comparison samples gave higher values than for the CIG and we found clear differences for the average values of the 4 samples considered, proving the sensitivity of these parameters. In Argudo-Fernández et al. (2013) the environment and the isolation degree of AMIGA galaxies is quantified, for the first time, using digital data. Data from the SDSS allows us to recover fainter and smaller-size satellites than in previous AMIGA works. The AMIGA sample gets improved from this study, by modifying the sample of isolated galaxies used in previous AMIGA works by about 20%. The availability of the spectroscopic data allowed us to check the validity of the CIG isolation criteria, which is not fully efficient. About 50% of the neighbours considered as potential companions in the photometric study are in fact background objects. We also find that about 92% of neighbour galaxies showing recession velocities similar to the corresponding CIG galaxy are not considered by the CIG isolation criteria as potential companions, which may have a non negligible influence on the evolution of the central CIG galaxy.

2. Do we really know all about environmental effects?

Since the realization that galaxy evolution is affected by environment many open questions/controversial results exist, which demonstrate the value of studying a well defined reference sample. Some examples of these questions and references (including AMIGA works) illustrating the controversy are:

- Is AGN Activity frequency driven by the environment? (De Robertis et al. 1998; Krongold et al. 2003; Miller & Veilleux 2003; Best et al. 2005; Sabater et al. 2012)
- Is H2 increased by interactions? (Braine & Combes 1993; Perea et al. 1997; Verdes-Montenegro et al. 1998; Leon et al. 1998; Lisenfeld et al. 2011; Martinez-Badenes et al. 2012)
- Is HI asymmetry rate similar in low and high-density environments? (e.g. Haynes et al. 1998; Swaters et al. 1999; Richter & Sancisi 1994; Espada et al. 2011)
- Can HI extended envelopes be generated/sustained by secular evolution? (Heald et al. 2011; Mapelli et al. 2008; Fraternali et al. 2002)
- Have XUV disks be ascribed to interaction events or are internal mechanisms needed (Gil de Paz et al. 2005; Thilker et al. 2007, 2009; Bush et al. 2010)

3. Multiwavelength results

One of the main results of AMIGA studies is that properties usually regarded as susceptible to interaction enhancement show lower averages than any galaxy sample yet identified. Next we will revise the results for different physical parameters.

3.1. Morphology

Sb-Sc are the prototype CIG population (Sulentic et al. 2006), with small bulges (Durbala et al. 2008). Most of the types later than Sd are low luminosity galaxies concentrated in the local supercluster where isolation is difficult to evaluate. Although early type galaxies are not the topic of this conference, it is worth mentioning that about 14% of the CIG are early-type E-S0 galaxies. The sample is extreme because the spiral population is more luminous that the elliptical one, with few E/S0 more luminous than 21.0, supporting that these galaxies are not products of major mergers. AMIGA appears to have found the most nurture-free population of luminous early-type galaxies. Different aspects of isolated early type galaxies have been studied in the bibliography. E.g. Adebusola Bamidele (2013) studied the globular cluster system (GCS) of three isolated elliptical galaxies using data obtained from the Gemini South telescopes, finding bimodal color distributions in the GCS in all of them, dominated by GCS belonging to the metal-poor sub-population. A similar study has been performed by Lane et al. (2013), finding GC colours and specific frequencies highly indicative that the host galaxy environment plays a role in shaping its GC system. We note that in this study isolated is defined as having no companion galaxies within 75 kpc. Fuse et al. (2012) describe the properties of a sample of extremely isolated early-type galaxies selected from the spectroscopic Sloan Digital Sky Survey. Their galaxies are isolated from nearest neighbors more luminous than MV = 16.5 by a minimum distance corresponding to 2.5 Mpc and 350 km/s in redshift space, finding fainter luminosities than in cluster and group environments, bluer colors, and smaller physical sizes.

Durbala et al. (2008) and Durbala et al. (2009) studied in detail a sample of 100 isolated CIG galaxies in the Sb-Sc morphological range. Comparison with a similar sample of disk galaxies (same morphological range) extracted from the OSUBGS (Ohio State University Bright Galaxy Survey; Eskridge et al. 2002) survey indicated that the isolated AMIGA galaxies host significantly longer Fourier bars and possibly show a different distribution of spiral torque Qs. Isolated galaxies tend also to be more symmetric, less concentrated and less clumpy. Furthermore, most spirals in our sample show very small bulge/total ratios (largely <0.1) and Sersic indices consistent with an absence of classical bulges. Assuming that the bulge Sersic index and/or Bulge/Total luminosity ratios are reasonable diagnostics for pseudo- versus classical bulges, we conclude that the majority of late-type isolated disk galaxies likely host pseudobulges. Our parametrization of galactic bulges and disks suggests that the properties of the pseudobulges are strongly connected to those of the disks. This may indicate that pseudobulges are formed through internal processes within the disks (i.e. secular evolution) and that bars may play an important role in their formation.

3.2. FIR emission

A subsample of 476 CIG galaxies with redshifts and PSC fluxes were used as a control sample for a study of FIR emission from isolated pairs (Xu & Sulentic 1991). Verdes-Montenegro et al. (1998) constructed a reference sample of 68 CIG galaxies with redshift and blue luminosity distributions matching their target set of Hickson (1982) compact groups. Hernández Toledo et al. (1999) obtained SCANPI data for 465 CIG galaxies (those with available redshift data) to use them as a reference in a study of galaxy pairs.

In Lisenfeld et al. (2007) we find that the distribution of log(LFIR) of AMIGA sample sharply peaks from 9.0-10.5, with very few (<2%) galaxies above 10.5. The majority of FIR luminous galaxies are likely to be interacting systems missed in our earlier morphological reevaluation. The results support that the FIR emission is a variable enhanced by interaction, and that our sample probably shows the lowest possible mean value, e.g. when compared with the magnitude limited sample of the Center for Astrophysics, that was selected without environmental discrimination. A study of one of the brightest AMIGA galaxies in the FIR is presented in Cardenas et al (2013).

3.3. Atomic gas

If asymmetries can only be generated by tidal interactions, lopsidedness in isolated galaxies should not be observed. However, studies of atomic gas (HI) for isolated galaxies find a similar fraction (50 - 75%) with asymmetric HI spectra profiles as in field and richer environments (e.g. Richter & Sancisi 1994; Haynes et al. 1998). Whether this implies that asymmetries can develop in galaxies free from interactions is closely linked to a proper definition of isolation, which is the core of the AMIGA study. Having minimised environmental effects, a key finding in our single dish HI study of isolated galaxies (Espada et al. 2011) was that the distribution of the spectral asymmetry parameter (A_{flux} defined as the flux ratio of the receding and approaching halves of the HI spectrum) is Gaussian ($1\sigma \sim 0.12$). By contrast all samples from denser environments show a much wider non-Gaussian distribution of A_{flux}.

3.4. Molecular gas

Most previous studies investigating the properties of molecular gas in isolated and interacting galaxies (Solomon & Sage 1988; Sage 1993; Boselli et al. 1997; Nishiyama & Nakai 2001; Helfer et al. 2003; Leroy et al. 2009) have generally not defined any very clear criterion for isolation. In Perea et al. (1997) we carried out a CO study comparing isolated and interacting galaxies. Our sample of isolated galaxies was composed of 68 galaxies from various available sources. The only survey explicitly focusing on isolated galaxies, and in particular on galaxies from the CIG, is the one by Sauty et al. (2003), although they do not present a detailed analysis of the properties of that sample. Kaneko et al. (2013) compared MH2 in early and mid stages of interaction, finding a central concentration lower in interacting than in isolated galaxies. However their sample of isolated galaxies had v < 1500 km/s and excluded galaxies from Virgo Cluster and the Coma Cluster as a definition of isolation.

In Lisenfeld et al. (2011) we characterize the molecular gas content using the CO emission of a redshift-limited subsample of isolated galaxies from AMIGA (n = 173), which was the basis for our statistical analysis, studying the relationships between MH2 and other galactic properties. We find correlations between MH2 and LB, D^2_{25}, LK, and LFIR. The tightest correlation of MH2 holds with LFIR and, for T = 3 - 5, with LK, and the poorest with D^2_{25}. The correlations with LFIR and LK are very close to linearity. The correlation with LB is nonlinear so that MH2 /LB increases with LB. The molecular gas column density and the surface density of the star formation rate (the Kennicutt-Schmidt law) show a tight correlation with a rough unity slope. We compare the relations of MH2 with LB and LK found for AMIGA galaxies to samples of interacting galaxies from the literature and find an indication for an enhancement of the molecular gas in interacting galaxies of up to 0.2-0.3 dex.

3.5. Nuclear activity

The radio-FIR correlation is very tight and can be used to distinguish galaxies for which their radio continuum emission is due to star formation, and those with an AGN causing an enhancement of the radio continuum emission, which lie above the correlation. In Sabater et al. (2008) we presented a study of the nuclear activity in AMIGA, using the radio continuum-FIR correlation, but also the FIR colours to find obscured AGN-candidates. We also used the existing information on nuclear activity in the Veron-Cetty catalogue and in the NASA Extragalactic Database. A final catalogue of AGN-candidate galaxies was produced and we found that our sample is mostly radio quiet, consistent with its high content of late-type galaxies. At most 1.5% of the galaxies show a radio excess with respect to the radio-FIR correlation, and this fraction even goes down to less than 0.8% after rejection of back/foreground sources using FIRST. We find that the fraction of FIR colour selected AGN-candidates is 28%, with a lower limit of 7%. Our final catalogue contains 89 AGN candidates. A comparison with the results from the literature shows that the AMIGA sample has the lowest ratio of AGN candidates, both globally and separated into early and late types. Field galaxies as well as poor cluster and group environments show intermediate values, while the highest rates of AGN candidates are found in the central parts of clusters and in pair/merger dominated samples. For all environments, early-type galaxies show a higher ratio of radio-excess galaxies than late types, as can be expected, since massive elliptical galaxies are the usual hosts of powerful radio continuum emission. We conclude that the environment plays a crucial and direct role in triggering radio nuclear activity and not only via the density-morphology relation. Isolated, early-type galaxies show a particularly low level of activity at radio wavelengths.

In a later work (Sabater et al. 2012) we presented a catalogue of nuclear activity, traced by optical emission lines. Spectral data were obtained from the 6th Data Release of the Sloan Digital Sky Survey. Standard emission-line diagnostics diagrams were applied, using a new classification scheme that takes into account censored data, to classify the type of nuclear emission. The prevalence of optical active galactic nuclei (AGN) in AMIGA galaxies is 20.4%, or 36.7% including transition objects. The fraction of AGN increases steeply towards earlier morphological types and higher luminosities. We compare these results with a matched analysis of galaxies in isolated denser environments (HCGs). After correcting for the effects of the morphology and luminosity, we find that there is no evidence for a difference in the prevalence of AGN between isolated and compact group galaxies, and conclude that a major interaction is not a necessary condition for the triggering of optical AGN.

3.6. Optical colours

Environment is also thought to play a role in the mix of morphological types for a sample of galaxies, which is reflected by the morphology-density relation (Dressler 1980; van der Wel et al. 2010, and references therein). In dense environments luminous red early-type galaxies predominate while in the lowest density environment blue late-type spirals are the defining population (Dressler 1980; Capak et al. 2007).

We take a first look at SDSS (g - r) colors of galaxies in the AMIGA sample. This alerted us at the same time to the pitfalls of using automated SDSS colors. We focused on median values for the principal morphological subtypes found in the AMIGA sample (E/S0 and Sb-Sc) and compared them with equivalent measures obtained for galaxies in denser environments. We find a weak tendency for AMIGA spiral galaxies to be redder than objects in close pairs. We find no clear difference when we compared this with galaxies in other (e.g. group) environments. However, the (g - r) color of isolated galaxies shows a Gaussian distribution, as might be expected assuming nurture-free evolution. We find a smaller median absolute deviation in colors for isolated galaxies compared to both wide and close pairs. The majority of the deviation on median colors for spiral subtypes is caused by a color-luminosity correlation. Surprisingly, isolated and non-isolated early-type galaxies show similar (g- r).We see little evidence for a green valley in our sample because most spirals redder than (g - r) = 0.7 have spurious colors. We conclude that the redder colors of AMIGA spirals and lower color dispersions for AMIGA subtypes compared with close pairs are likely caused by a more passive star formation in very isolated galaxies.

3.7. Optical size

Fernández Lorenzo et al. (2013) has studied the effects of environment on the growth in size of galaxies. As part of AMIGA project the stellar masssize relation was examined, and compared with samples of less isolated early- and late-type galaxies, as well. We used two different size estimators, the half-light radius obtained with SExtractor and the effective radius calculated by fitting a Sersic profile to the i-band image of each galaxy using GALFIT. We found good agreement between those size estimators when the Sersic 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 6 morphological ranges and in all cases the relation is better defined and has less scatter for them 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 2 or more satellites (neighbors within 3 magnitudes 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.

4. Conclusions

In this paper we have revised samples of isolated galaxies used in the bibliography as a reference to separate environmental effects, and illustrated the variety of isolation criteria used by different authors. The CIG is found the best compilation of the most isolated galaxies in the local Universe and served as a basis for a continous refinement as part of AMIGA project. AMIGA was designed to provide a sample with strict isolation criteria implying that its galaxies have likely been unperturbed for ~ 3 Gyr (Verdes-Montenegro et al. 2005). We find that variables expected to be enhanced by interactions are lower in isolated galaxies than in any other sample (e.g. LFIR, radio continuum emission, optical and HI symmetry, AGN rate). Furthermore, most spirals in our sample likely host pseudo-bulges rather than classical bulges (Durbala et al. 2008) and show redder colours and larger disks (Fernández Lorenzo et al. 2012, 2013). All this makes of AMIGA a nurture-free zero point for isolating secular processes, as close as we can hope to come towards achieving a local field population.

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