Trabajo de Investigación Tutelada
Máster en Física y Matemáticas – FisyMat
Universidad de Granada

A search for neighbours around isolated galaxies using the SDSS

Maria del Carmen Argudo Fernández
(Instituto de Astrofísica de Andalucía – CSIC)

Diciembre 2010

Tutores

Dr. Simon Verley
Dr. Jack Sulentic
Dr. Gilles Bergond

A Germán y los Judas Priest

Contents

1 Introduction **11**
- 1.1 Isolated galaxies . . . 12
- 1.2 The AMIGA project . . . 13
- 1.3 Plan of the present work . . . 14

2 Data analysis **17**
- 2.1 The Sloan Digital Sky Survey . . . 18
- 2.2 AMIGA galaxies in SDSS . . . 19
- 2.3 Star-galaxy separation . . . 19

3 Catalogues of neighbours **25**
- 3.1 Looking for neighbours in 0.5 Mpc . . . 26
- 3.2 Catalogue of galaxies with spectra . . . 26

4 Revising the isolation **29**
- 4.1 Revision of Karachentseva's criterion . . . 30
- 4.2 Comparison with NED . . . 31
  - 4.2.1 NED . . . 31
  - 4.2.2 Comparison with NED . . . 33
- 4.3 Comparison with previous AMIGA work . . . 36
  - 4.3.1 The catalogue of neighbours around isolated galaxies . 36
  - 4.3.2 Comparison with previous AMIGA work . . . 36

5 Discussion **41**
- 5.1 Revision of Karachentseva's criterion . . . 42
- 5.2 Comparison with NED . . . 43
- 5.3 Comparison with previous AMIGA work . . . 43

6 Conclusions **45**

7 Future work **47**

A Star-galaxy separation images **51**

B CASJOB query **55**

C SDSS color images **59**

List of Figures

2.1 Legacy DR7 Imaging Sky Coverage 18
2.2 Spatial distribution of CIG galaxies in the SDSS 19
2.3 Histograms of some properties of the selected subsample . . . 20
2.4 Size/magnitude diagram in the CIG 233 field 23

4.1 Histogram of magnitude differences in our SDSS catalogue of neighbours 32
4.2 Histogram of velocity differences in our SDSS catalogue of neighbours 32
4.3 Histogram of differences in velocity in the range $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$ in our SDSS catalogue of neighbours 33
4.4 Histogram of magnitude differences for galaxies with $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$ 36
4.5 Magnitude differences in Verley et al. 37
4.6 Histogram of magnitude in Verley et al. (2007c) and SDSS . . 39

A.1 Star-galaxy separation in the CIG 233 field: galaxies 52
A.2 Star-galaxy separation in the CIG 233 field: stars 53

C.1 SDSS colour images of the subsample of 21 CIG-AMIGA galaxies 60

List of Tables

2.1 Sample of 21 CIG galaxies 21

3.1 Search for neighbours in 0.5 Mpc 27
3.2 Number of objects in the catalogues 28

4.1 Revision of Karachentseva's criterion 30
4.2 Neighbours from NED 34
4.3 Comparison with NED 35
4.4 Comparison with Verley et al. (2007c). 38

Chapter 1

Introduction

Contents

1.1 Isolated galaxies 12
1.2 The AMIGA project 13
1.3 Plan of the present work 14

1.1 Isolated galaxies

The distribution of galaxies in space is very complex. Before 1970 it was thought that clusters of galaxies (like large cities) were embedded in a "field" of much lower density. Later the idea of a field lost favour and more complex view emerged where clusters and groups of galaxies were associated in large supercluster assemblies (similar to large cities and their associated suburbs).

The structure and evolution of galaxies are affected by their environment but these effects are difficult to quantify. Thus we see today a growing interest in the most isolated galaxies for use as controls for studies of galaxies in richer environments (e.g. we might study people who live between Madrid and Granada in order to gain a better understanding of how life in Madrid or Granada affects their inhabitants). This project is the first step in trying to better understand galaxies that spend most of their life alone.

Few good lists of isolated galaxies exist with the best having been published by a Russian scientist (Valentina Karachentseva) in 1973. This systematic search for isolated galaxies, applied a two-dimensional isolation criterion while searching for candidate galaxies on the first Palomar Observatory Sky Survey (POSS-1) photographic plates. Since the distances of few galaxies were known at that time, isolation in the third dimension was estimated by considering only similar size galaxies as possible neighbours. The resulting Catalogue of Isolated Galaxies (CIG) Karachentseva (1973) included 1050 galaxies which was many more than any other compilation. Not many additional studies of isolated galaxies were carried out in the following 20+ years. Recently Verley et al. (2007b,c) revised the isolation parameter for the whole CIG sample using an automated search for neighbours on the Digitised POSS (DPOSS) providing an exhaustive list of $\sim$ 54,000 possible satellites and a re-estimation of the isolation degree of each CIG.

This was the photographic era but the mid to late 80's saw the advent of electronic CCD detectors in astronomy. Sophisticated versions of the same chips that power commercially available digital cameras, CCDs are much more sensitive to faint light and respond in a more predictable (i.e. linear) fashion. The Sloan Digital Sky Survey (SDSS) represents an attempt to map much of the sky using CCD detectors. The SDSS also provides spectroscopic measures that allow us to estimate galaxy distances (the third dimension) enabling a 3D revision of the degree of isolation for $\sim$ 400 CIG galaxies included in the SDSS Data Release 7 (DR7) catalogue.

In this study we use the final DR7 release of the SDSS to perform a 3D revision of the Verley et al. survey. Each SDSS data release provides a large number of database tables and images of automatically extracted objects, with positions and estimated redshifts among other measures. Some examples of data-mining using the SDSS are cited in the bibliography including: a) the Catalogue of Very Isolated Galaxies Allam et al. (2005) using SDSS DR1, b) Koester et al. (2007), who created an algorithm to define cluster membership and c) Park et al. (2007) who designed an algorithm with adaptive kernel to calculate the local density.

1.2 The AMIGA project

While it is known that galaxy evolution is affected, or even driven, by influences of nearby galaxies (nurture), a well defined baseline for assessing its frequency and amplitude has been lacking. The AMIGA project (Analysis of the interstellar Medium of Isolated GAlaxies[1]) was initiated in 2002 at Instituto de Astrofísica de Andalucía (IAA-CSIC) to provide such a baseline by quantifying the properties of a well defined sample of "nature-dominated" galaxies.

The AMIGA project adopted the Catalogue of Isolated Galaxies (CIG) as a starting point and proceeded to extract a refined sample of the most isolated galaxies in the local Universe.

The AMIGA project involves the identification and study of a statistically significant sample of the most isolated galaxies in the local Universe. The AMIGA goal is to quantify properties of different phases of the interstellar medium (hot/warm/cold gas and dust) in these galaxies which are likely to be less affected than any other population by their external environment.

The main goals of AMIGA are:

1. To compare and quantify the properties of different phases of the interstellar medium (ISM) in the galaxies, as well as the level of star formation and nuclear activity.

2. To quantify the role of nature versus nurture, distinguishing between environmental density and one-on-one interactions.

3. To use this control sample as a template in studies of star formation and galaxy evolution in denser environments.

All CIG galaxies are also found in the Catalogue of Galaxies and Clusters of Galaxies (CGCG) (Zwicky & Kowal 1968) with apparent magnitudes $m_{\rm pg} < 15.7$. These very isolated systems represent $\sim 3\%$ of the CGCG – a small but important galaxy population.

The CIG catalogue was assembled with the requirement that no similar size galaxies with angular diameter D_i between 1/4 and 4 times the diameter D_P of the CIG galaxy lie within $20D_i$:

[1] http://amiga.iaa.es

$$R_{ip} \geq 20 \times D_i \quad (1.1)$$

$$\frac{1}{4} \times D_P \leq D_i \leq 4 \times D_P \quad (1.2)$$

The AMIGA project refines the pioneering CIG in several ways including:

1. Revision of all the CIG positions (Leon & Verdes-Montenegro 2003);
2. Optical study, including sample redefinition, magnitude correction, and full-sample analysis of the optical luminosity function (Verdes-Montenegro et al. 2005);
3. Morphological revision and type-specific optical luminosity function analysis (Sulentic et al. 2006);
4. Re-evaluation of the degree of isolation of the CIG (Verley et al. 2007b,c).

The above AMIGA papers also started the characterization of the ISM and was extended in the following works:

1. Characterization of mid- and far-infrared (MIR and FIR) properties (Lisenfeld et al. 2007);
2. Hα study of a redshift-limited subsample (Verley 2005, PhD);
3. Study of the dynamical influence of bars on star formation for a sub-sample of AMIGA (Verley et al. 2007a);
4. A survey of radio-continuum properties (Leon et al. 2008);
5. Study in FIR and radio-continuum of the nuclear activity (Sabater et al. 2008);
6. HI and CO study of the sample (Espada 2006, PhD; Espada et al. 2010 in prep.).

1.3 Plan of the present work

The structure of the present work is as follows: in Chapter 2, we present the SDSS data used for our work (Sect. 2.1), the selection of the subsample of 21 AMIGA CIG galaxies that we used for this pilot study (Sect. 2.2) and the problems we found (Sect. 2.3). In Chapter 3 we explain how we constructed our catalogue of neighbours with spectroscopic data in a radius of 0.5 Mpc around each CIG galaxy in our subsample. We revised the isolation in Chapter 4 making a comparison with Karachentseva's criteria (Sect. 4.1), the NED database (Sect. 4.2) and the previous AMIGA work by (Verley et al. 2007b,c) (Sect. 4.3). We discuss the results in Chapter 5. Finally we present our conclusions in Chapter 6 and future developments in Chapter 7.

Chapter 2

Data analysis

Contents

2.1 The Sloan Digital Sky Survey 18
2.2 AMIGA galaxies in SDSS 19
2.3 Star-galaxy separation 19

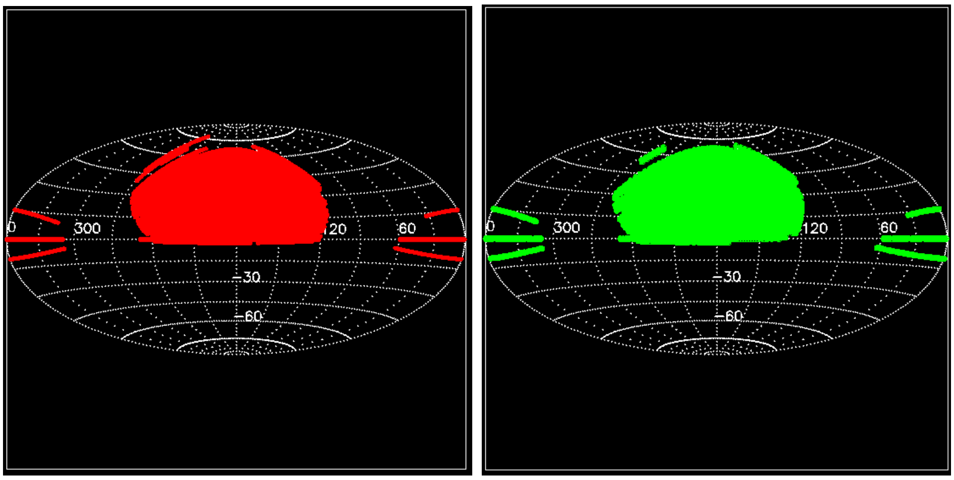

Figure 2.1: *Left:* Legacy DR7 Imaging Sky Coverage, 11663 sq. deg. (Aitoff projection of Equatorial coordinates). *Right:* Legacy DR7 Spectral Sky Coverage, 9380 sq. deg. (Aitoff projection of Equatorial coordinates).

2.1 The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS) (York et al. 2000; Abazajian et al. 2009) is a large optical survey that provides images and spectra covering ∼10,000 deg^2 of sky in the Northern Galactic Cap and ∼ 200 deg^2 in the Southern Galactic Hemisphere (Fig. 2.1). SDSS uses a dedicated wide-field 2.5-m telescope located at Apache Point Observatory (APO) near Sacramento Peak, in Southern New Mexico (USA). The telescope uses two instruments.

The first is a wide-field imager with 30 2048 × 2048 pixel CCDs in the focal plane that observes the sky in drift-scan mode. The SDSS database provides homogeneous and moderately deep (r-band magnitude $r < 22.5$) photometry in five pass-bands (u, g, r, i, and z). The images are mostly taken under good/average seeing conditions (the median is about 1.4 arcsec in r) on moonless nights. The 95% completeness limits for the CCD images are $(u, g, r, i, z) = (22.0, 22.2, 22.2, 21.3, 20.5)$, respectively.

The photometric catalogues of detected objects are used to identify the targets for spectroscopy with the other instrument on the telescope: a 640-fiber-fed multi-object double spectrograph giving coverage from 3800 Å to 9200 Å at a resolution of $\lambda/\Delta\lambda \simeq 2000$. The data are reduced with automatic pipelines and made public periodically in data releases. Each new data release improves the sky coverage and the quality of the data reduction. The final data release available is DR7[1].

[1] `http://www.sdss.org/dr7/`

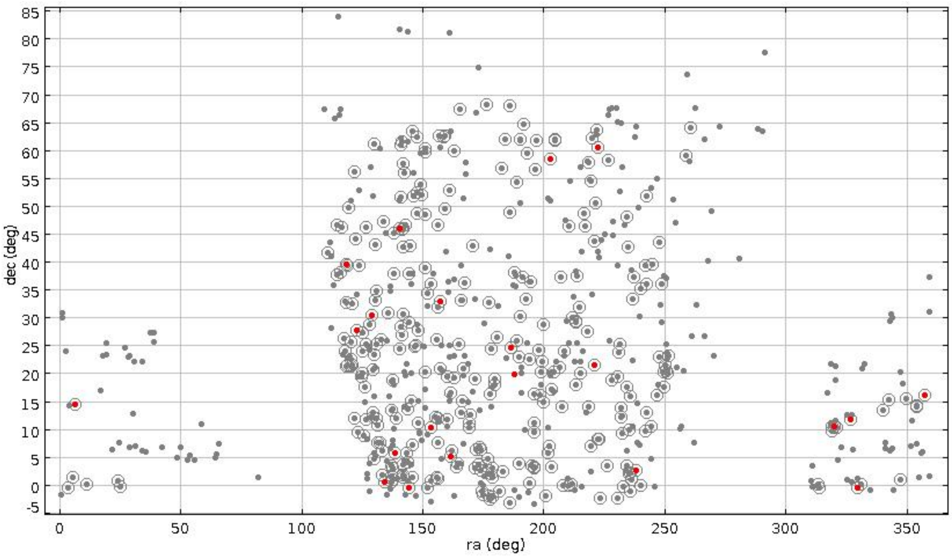

Figure 2.2: Spatial distribution of CIG galaxies in the SDSS. There are 654 CIG galaxies in the SDSS photometric catalogue (grey points) and 420 in the SDSS spectroscopic catalogue (grey circles). Our subsample of 21 CIG galaxies and their r=0.5 Mpc environments (red points) are included/covered in both catalogues.

2.2 AMIGA galaxies in SDSS

We found 654 AMIGA-CIG galaxies in the SDSS DR7 database by searching the photometric table (PhotoObjAll table). 420 of these galaxies also have spectroscopic data (SpectObj table) (See Fig. 2.2). We selected a test sample of 21 galaxies (see Table. 2.1) as representative of our full sample in terms of velocity, luminosity, morphological type, isolation parameters and spatial distribution on the sky, see Fig. 2.3. This pilot study allows us to estimate the feasibility and time needed in order to re-evaluate the degree of isolation of the galaxies in the full AMIGA sample using the SDSS data.

2.3 Star-galaxy separation

No sample is perfect and one of our first goals was to assess the relative strengths and weakness of the AMIGA and SDSS samples. Our study involves comparison of results based on visual evaluation of photographic images (CIG/AMIGA), digital processing of the same photographic images (Verley et al. 2007b,c) with automated processing of digital images (SDSS). The first step involved discrimination between galaxies and stars. We found some CIG classified galaxies misidentified as stars in the SDSS: 627 out of

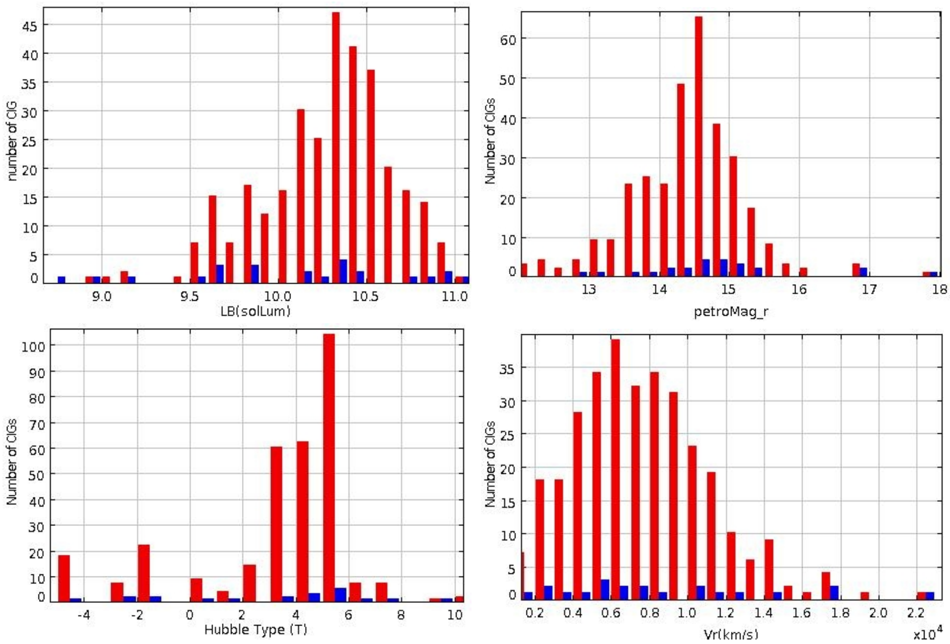

Figure 2.3: *Upper left:* distribution of the blue luminosities, the red histogram shows all spectroscopic CIG galaxies in the SDSS DR7, while the blue concerns only the selected subsample. *Upper right:* same colour code for distributions of the Petrosian magnitudes of CIG galaxies in both samples. *Lower left:* same colour code for distributions of the morphological types of CIG galaxies in both samples. *Lower right:* same colour code for distributions of the recession velocities of CIG galaxies in both samples.

CIG	objID	RA(J2000.0) deg	DEC(J2000.0) deg
19	587730773354479638	6.06748434	14.23684812
213	587725469052698697	118.60366697	39.3715286
233	588297864710062280	122.9074276	27.53820239
264	587735044686348347	129.0062891	30.26641117
291	588848900429447351	134.16946306	0.37500486
318	587732578837201105	138.30173976	5.61086889
322	587731680658325539	140.2950296	45.88781956
354	588848899360096462	144.10961758	-0.5713543
406	588017702919077921	153.53357998	10.14833527
418	587739408382623760	157.00605485	32.76388361
440	588010359614931156	161.29160618	4.94449392
529	587741725505421363	186.24095988	24.38285487
582	587724649803022358	200.82297644	-2.15108424
589	587732590109589672	202.63209325	58.34236692
643	587739845921538175	220.74024907	21.42060455
651	588007005795319822	222.44204731	60.39853753
709	587729158448545968	238.10649945	2.45055492
907	587730773871624375	320.08796452	10.32059796
928	587727221936095299	326.47779778	11.67829088
937	587734303802392898	329.60404503	-0.73955435
1041	587727223559815423	357.18782973	15.92877231

Table 2.1: Sample of 21 CIG galaxies. Col. 1: CIG name. Col. 2: Object identification from SDSS. Col. 3–4: Right ascension and declination of the CIG galaxy.

654 AMIGA-CIG galaxies were recognized as galaxies by SDSS while 22 were classified as stars and 5 as "unknown" objects. The SDSS photometric pipeline classifies an object as "unknown" if the image contains an interpolated pixel (i.e., a bad column or a cosmic ray) at or near the centre of the object (Yasuda et al. 2001). We are not able to use these 5 objects (CIG 149, 304, 514, 573, 966) because they do not have any magnitude measure leaving us with 649 usable CIG galaxies in SDSS DR7. We made our test sample selection from the 627 CIG galaxies without these problems.

In order to check the star-galaxy classifications in SDSS, we searched for neighbours within a minimum physical radius of 0.5 Mpc for 17 of 21 galaxies with recession velocities $V > 4687$ km/s. This corresponds to a maximum companion search radius of 27.5 arcmin. We compared our SDSS search results with the catalogue of neighbours around isolated galaxies compiled by Verley et al. (2007c).
We constructed size/magnitude diagrams (in g-band) from both catalogues calculating the object area from the Petrosian radius ($area = \pi r^2_{\rm petro}$) which does not depend on the model fits (Bernardi et al. 2010).

In Fig. 2.4 we show this diagram for the CIG 233 field. The resolution of SDSS images allows us to determine that some objects classified as galaxies in the neighbour catalogue (red points) are star-like objects. We carried out a similar analysis for the other 16 CIGs with velocities $V > 4687$ km/s. The star-galaxy classification from SDSS works well for objects with Petrosian magnitude $g < 20$. After visual inspection of SDSS images class 3 (cl=3) objects in the "horizontal branch" are either stars or very compacts galaxies.

The SDSS star-galaxy default pipeline misclassified many objects in our study. Size/magnitude diagrams like Fig. 2.4 provide a robust method to remove the confusion between stars and galaxies as a function of these parameters within the magnitude range $\sim 14 < g <\sim 22$. Out of 608 galaxies in the catalogue of neighbours we found that 69 (11.35%) were classified as stars. Our visual verification revealed that 57 (9.4%) were correctly classified as stars and 12 (2%) were in fact galaxies. The size/magnitude diagrams and visual inspection for neighbours reveal that many POSS (Palomar Observatory Sky Survey) objects were misclassified as galaxies using the DPOSS images – some were in fact double stars (see examples in Appendix A for the field of the CIG 233). SDSS provides higher depth and accuracy photometry as well as higher angular resolution which helps us to better separate blended or very close objects.

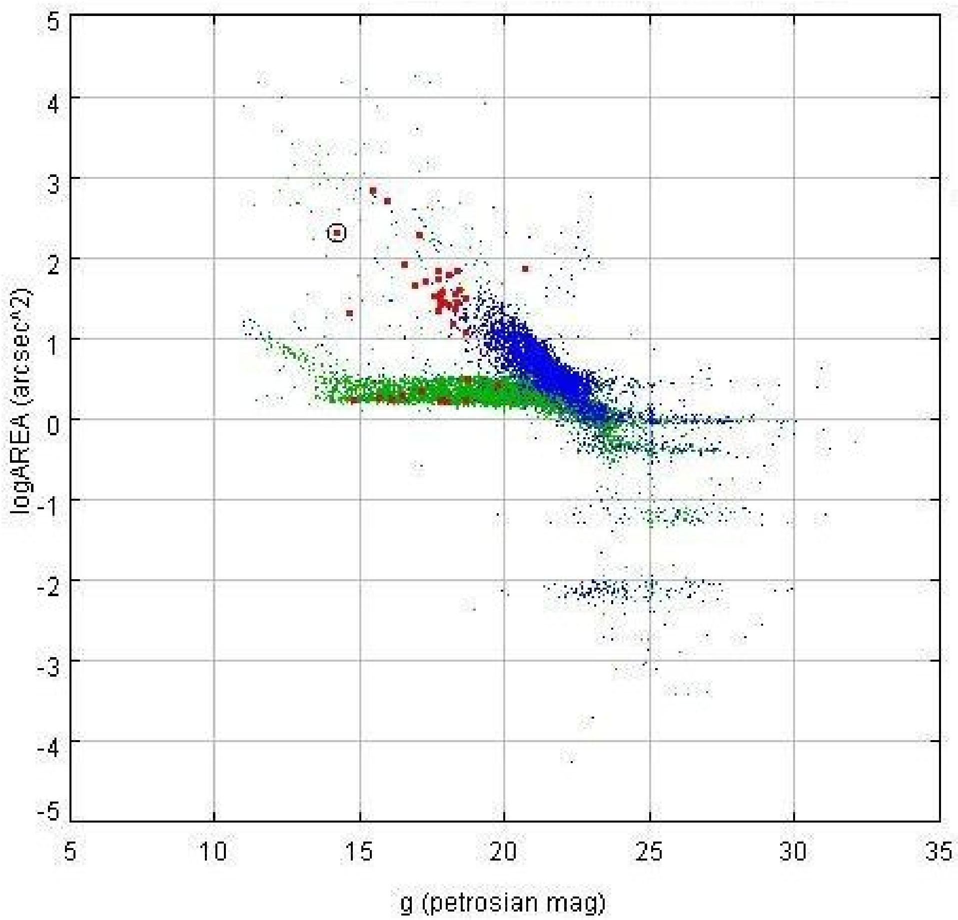

Figure 2.4: Star-galaxy identifications using SDSS photometric classifications for a cone search within 27.5 arcmin around CIG 233 (circle point). Blue and green points indicate objects classified as galaxies and stars respectively. 41 objects from the catalogue of neighbours (Verley et al. 2007c) in this field correspond to red points, 13 of these neighbouring "galaxies" were classified as stars by SDSS.

Chapter 3

Catalogues of neighbours

Contents

3.1 Looking for neighbours in 0.5 Mpc 26
3.2 Catalogue of galaxies with spectra 26

3.1 Looking for neighbours in 0.5 Mpc

According to Karachentseva's CIG criteria: a galaxy with diameter D_P must be searched for galaxy companions out to a radius of $80 \times D_P$. This corresponds to a very large search area motivating us to evaluate isolation degree in a physical radius of 0.5 Mpc centred on each CIG galaxy. If we assume a typical field velocity dispersion of 150 km s^{-1} it would require about 3×10^9 years for a companion to cross this distance. At the same time we will be able to compare our catalogues with the catalogues of neighbours from Verley et al. (2007c).

We searched for all objects in the photometric table of the SDSS making SQL queries from the CasJobs tool of the SDSS[1]. We performed the search using the projected distance in arcmin that corresponds to 0.5 Mpc for each galaxy based on a distance derived from measured recession velocities (for $H_0 = 75$km s^{-1}Mpc^{-1}) (See Table 3.1).
In the query (Appendix B) we chose unflagged $0 < g < 22$ magnitude objects (according to the star-galaxy separation, section 2.3).

3.2 Catalogue of galaxies with spectra

In order to produce the final catalogues, we proceeded as follows: first, we downloaded all objects with a magnitude less than 22 (stars and galaxies, see Table 3.2, second column). Then, we selected galaxies with $14 < g < 22$ because the original SDSS star-galaxy discrimination worked best in this magnitude range (Table 3.2, third column).

These catalogues contain many very small galaxies and irrelevant objects (i.e. spurious detections) for our study. Objects that lie in the overlap between adjacent scan-lines in two strips of a stripe, and those that lie in the overlap between adjacent frames, appear more than once in the photometric catalogue. Each of these detections is flagged as primary or secondary, based on its position in the individual frames. Detections flagged as primary define a unique detection of each object. We have primary, secondary and family objects in our catalogues.

SDSS pipeline misclassifications are frequent for brighter objects ($g < 14$, Table 3.2, fourth column) requiring us to take special care by visually inspecting each field. Only one galaxy has been added this way in the field of CIG 322. The final step involved selecting objects with available spectroscopy (see Table 3.2, last column). Due to the completeness of the spectroscopic SDSS catalogue (catalogue complete up to Petrosian $r < 17.77$), this last condition removed many small and faint objects unlikely to be physically related the CIG galaxies.

[1] `http://casjobs.sdss.org/CasJobs/`

CIG	RA(J2000) deg	DEC(J2000) deg	velocity $km\,s^{-1}$	r arcmin
19	6.06754	14.2368	5390	24.21
213	118.60287	39.3718	5965	21.76
233	122.90766	27.5383	11225	11.54
264	129.00616	30.2662	7715	16.85
291	134.1695	0.3748	2521	52.08
318	138.30158	5.6101	17593	7.35
322	140.295	45.8881	1858	71.61
354	144.10945	-0.5707	3878	33.7
406	153.53345	10.1484	8355	15.49
418	157.00612	32.7638	6519	19.99
440	161.29158	4.9445	20658	6.25
529	186.24083	24.3828	10245	12.64
582	200.82295	-2.1511	10492	12.37
589	202.63154	58.3422	18008	7.16
643	220.74025	21.4208	12528	10.29
651	222.43983	60.3995	2292	57.29
709	238.10645	2.4503	14469	8.95
907	320.08754	10.3204	5257	24.55
928	326.478	11.6781	6985	18.48
937	329.60337	-0.7394	4881	26.44
1041	357.18791	15.9292	7850	16.53

Table 3.1: Looking for neighbours in a physical radius of 0.5 Mpc. Col. 1: CIG name. Col. 2–3: Right ascension and declination of the CIG galaxy. Col. 4: Velocity of each CIG. Col. 5: Projected radius around each CIG corresponding to 0.5 Mpc.

CIG	CasJobs-SDSS	Subsample 1	Subsample 2	Final catalogue
19	4665	2070	82	51
213	11108	4094	234	32
233	2981	1202	74	10
264	4929	1781	76	20
291	86177	30269	1432	243
318	766	312	24	4
322	49347	25930	952	308
354	15209	6043	261	67
406	1797	872	47	17
418	4442	2711	58	31
440	385	177	6	5
529	1312	745	13	15
582	2022	880	9	12
589	537	324	6	6
643	914	462	11	5
651	32389	16792	457	185
709	1118	285	5	5
907	14065	2487	166	33
928	5614	1179	55	18
937	8792	2705	112	63
1041	2262	989	29	16

Table 3.2: Number of objects in the catalogues. Col. 1: CIG name. Col. 2: Number of objects in the catalogue from the SDSS. Col. 3: Number of objects targeted as galaxy and with $14 < g < 22$. Col. 4: Number of objects with $g < 14$. Col. 5: Number of objects in the catalogue of neighbours.

Chapter 4

Revising the isolation

Contents

4.1 Revision of Karachentseva's criterion 30
4.2 Comparison with NED 31
4.2.1 NED 31
4.2.2 Comparison with NED 33
4.3 Comparison with previous AMIGA work 36
4.3.1 The catalogue of neighbours around isolated galaxies 36
4.3.2 Comparison with previous AMIGA work 36

CIG	# neighbours	1st condition	Karachentseva	$-1500 < V < 1500$ $\mathrm{km\,s^{-1}}$
19	51	49	4	2
213	32	15	0	0
233	10	8	0	0
264	20	20	0	0
291	243	47	2	0
318	4	4	0	0
322	309	266	0	0
354	67	19	0	0
406	17	17	0	0
418	31	18	0	0
440	5	1	0	0
529	15	15	0	0
582	12	10	0	0
589	6	6	0	0
643	5	2	0	0
651	185	111	0	0
709	5	2	0	0
907	33	22	0	0
928	18	17	1	0
937	63	12	0	0
1041	16	11	1	0

Table 4.1: Revision of Karachentseva's criterion. Col. 1: CIG name. Col. 2: Number of galaxies in the catalogue of neighbours. Col. 3: Number of galaxies with $0.25D_{CIG} < D_i < 4D_{CIG}$. Col. 4: Number of galaxies with $0.25D_{CIG} < D_i < 4D_{CIG}$ and $R_{iCIG} \geq 20 \times D_i$. Col. 5: Number of physical companions.

4.1 Revision of Karachentseva's criterion

Our first task was to verify the original Karachentseva's isolation criterion. Our catalogues of neighbour galaxies identify all galaxy neighbours within 0.5 Mpc from the central CIG galaxy. The second Karachentseva's condition allows neighbours with diameter $4 \times D_{\mathrm{CIG}}$ to be 20 times their own diameter away from the CIG. This means that one would have to check neighbours in a field as large as 80 times the diameter of each CIG galaxy. This is a very large field and 0.5 Mpc only corresponds to the inner part of it. So, despite the fact that we cannot verify the criterion in the entire search field of Karachentseva, we can determine if neighbour galaxies close to the CIG galaxy are violating the original isolation criterion. In order to fullfil this we applied both of the original isolation criteria to the neighbour galaxies around each CIG galaxy. We first selected only neighbours with a size similar (Petrosian radius in g band) to their nearby CIG galaxy (Karachentseva's first condition). Depending on the considered field, a high or low number of neighbours can be removed by this first condition. The final number of neighbours kept is shown in the third column of Table 4.1. They represent the galaxies considered as potential perturbers by Karachentseva.

The second step was to determine which of the latter objects were closer than 20 times their own diameter to the central CIG galaxy. The number of objects violating Karachentseva's criterion is hence shown in the fourth column of Table 4.1. Only two of the neighbour galaxies violating Karachentseva's show a similar recession velocity, defined as $\pm 1500\,\mathrm{km\,s^{-1}}$ within the velocity V of the CIG galaxy. Both neighbours lie near CIG 19.

In order to better understand which kind of galaxies have been considered as potential neighbours by Karachentseva, we compared their properties (magnitude and velocities) to those of the entire sample of neighbours. Figure 4.1 shows the difference in magnitude between the neighbours and their corresponding CIG galaxy including all neighbours (red histogram) and only similar sized neighbours (grey histogram).

The second histogram, Fig. 4.2 shows the velocity difference between the neighbour galaxies and their corresponding CIG galaxy. First we see that the difference in velocity has a peak at about $30{,}000\,\mathrm{km\,s^{-1}}$, which reflects the redshift distribution in the SDSS catalogue. The distribution of velocity differences for the neighbours considered by Karachentseva (grey histogram) span a very wide range. We present in the third histogram, Fig. 4.3 the same distribution restricted to the velocity difference range $\pm 1500\,\mathrm{km\,s^{-1}}$. We discuss theses results in Sect. 5.1.

4.2 Comparison with NASA/IPAC Extragalactic Database (NED)

4.2.1 NED

The NASA/IPAC Extragalactic Database (NED)[1] is built around a master list of extragalactic objects for which cross-identifications of names has been established. Accurate positions and redshifts are included to the extent possible and some basic data collected. Bibliographic references relevant to individual objects have been compiled, and abstracts of extragalactic interest are kept on line. Detailed and referenced photometry, positions, and redshift data, have been taken from large compilations and from the literature. Over 645,000 detailed photometric measurements, and 250,000 detailed position measurements, taken from catalogues and the published literature, are currently available through NED. It is also possible to search the main NED

[1] `http://nedwww.ipac.caltech.edu/`

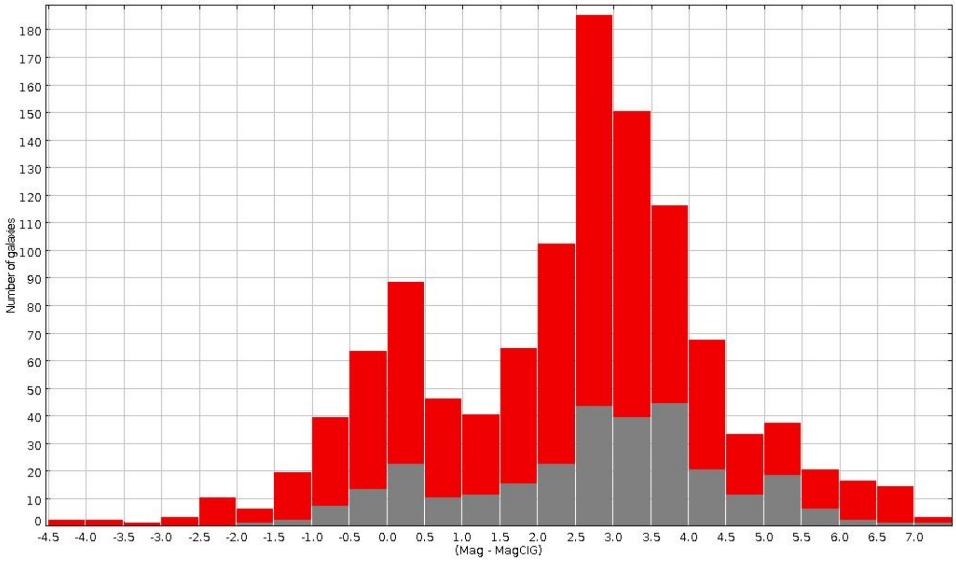

Figure 4.1: Histogram of magnitude differences in our SDSS catalogue of neighbours

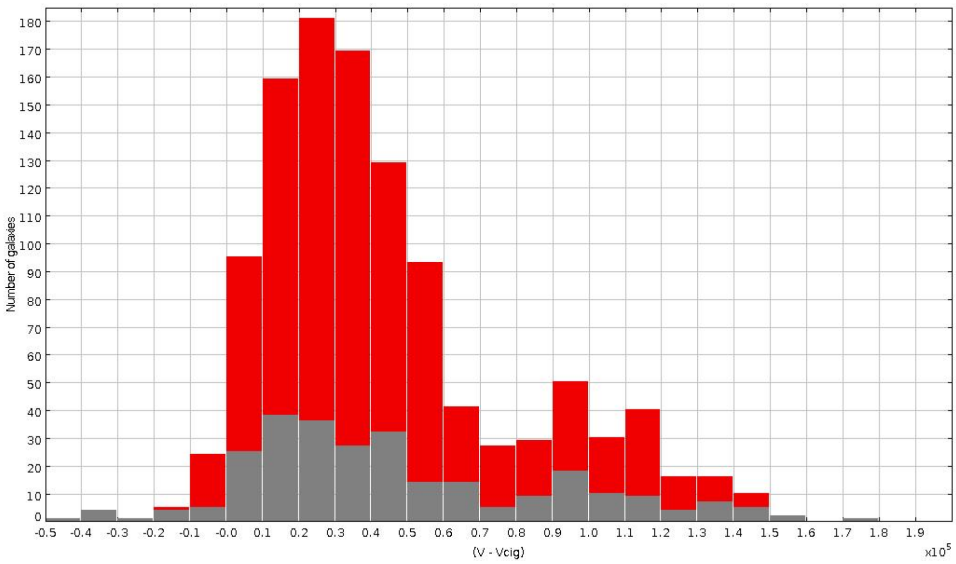

Figure 4.2: Histogram of velocity differences in our SDSS catalogue of neighbours

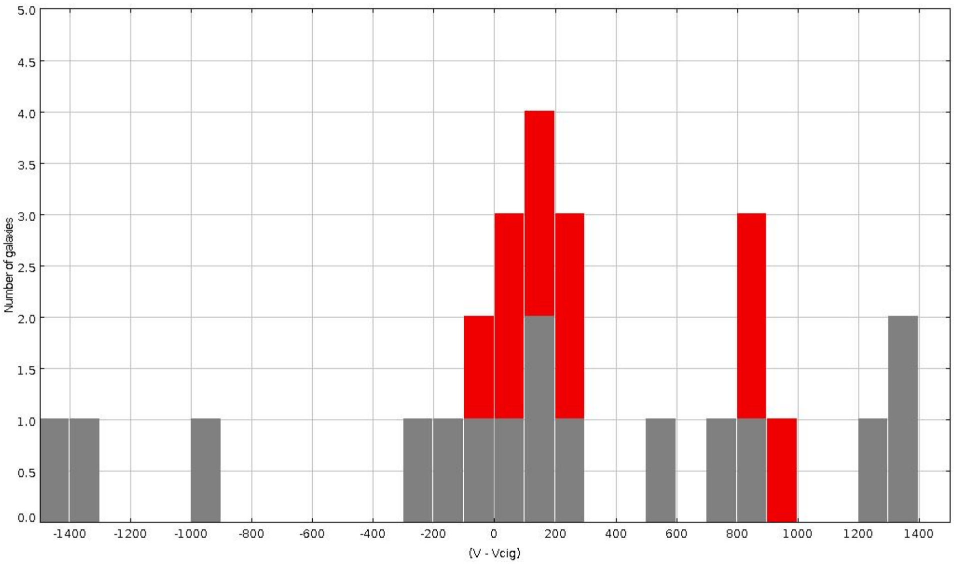

Figure 4.3: Histogram of differences in velocity in the range $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$ in our SDSS catalogue of neighbours

database for objects selected by redshift (NED currently has over 45,000 velocities), in addition to the selection by name, by position, or by type. NED's data and references are being continually updated, with revised versions being put on-line every 2–3 months.

4.2.2 Comparison with NED

Recently, NED has developped a new tool to search for nearby objects (physical companions) entering some preferred values and submitting an environment search. To mimic our pure SDSS study, we made a search for all objects within 0.5 Mpc and velocity range $\pm 1500\,\mathrm{km\,s^{-1}}$ around each CIG galaxy in our subsample (see Table 4.2). The results of this search are shown in the third column of Table 4.3. We include in the second column of the table a selection of galaxies within the same velocity range of our spectroscopic catalogue of neighbours in order to compare with NED results. For these objects, we make an histogram of magnitude differences (see Fig. 4.4). We discuss the difference in Sect. 5.2.

CIG	$V_{\rm CIG}$ km s^{-1}	r_{search} arcmin	$V_{\rm CIG} - 1500$ km s^{-1}	$V_{\rm CIG} + 1500$ km s^{-1}
19	5390	24.21	3890	6890
213	5965	21.76	4465	7465
233	11225	11.54	9725	12725
264	7715	16.85	6215	9215
291	2521	52.08	1021	4021
318	17593	7.35	16093	19093
322	1858	71.61	358	3358
354	3878	33.7	2378	5378
406	8355	15.49	6855	9855
418	6519	19.99	5019	8019
440	20658	6.25	19158	22158
529	10245	12.64	8745	11745
582	10492	12.37	8992	11992
589	18008	7.16	16508	19508
643	12528	10.29	11028	14028
651	2292	57.29	792	3792
709	14469	8.95	12969	15969
907	5257	24.55	3757	6757
928	6985	18.48	5485	8485
937	4881	26.44	3381	6381
1041	7850	16.53	6350	9350

Table 4.2: Searching for neighbours from NED. Col. 1: CIG name. Col. 2: Velocity of the corresponding CIG galaxy in km s^{-1}. Col. 3: Ratio of search for neighbours in arcmin coresponding to 0.5 Mpc around each CIG galaxy. Col. 4: Minimum value of the velocity range for our search for physical companions in km s^{-1}. Col. 5: Maximum value of the velocity range for our search for physical companions in km s^{-1}.

CIG	SDSS	NED
19	7	10
213	1	1
233	1	1
264	1	1
291	6	6
318	0	0
322	1	4
354	0	0
406	1	1
418	2	2
440	0	0
529	1	0
582	0	0
589	1	1
643	2	0
651	0	1
709	0	0
907	0	0
928	1	1
937	0	0
1041	0	0

Table 4.3: Comparison with NED. Col. 1: CIG name. Col. 2: Number of galaxies in our catalogue of neighbours with $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$. Col. 3 : Number of galaxies in NED with $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$.

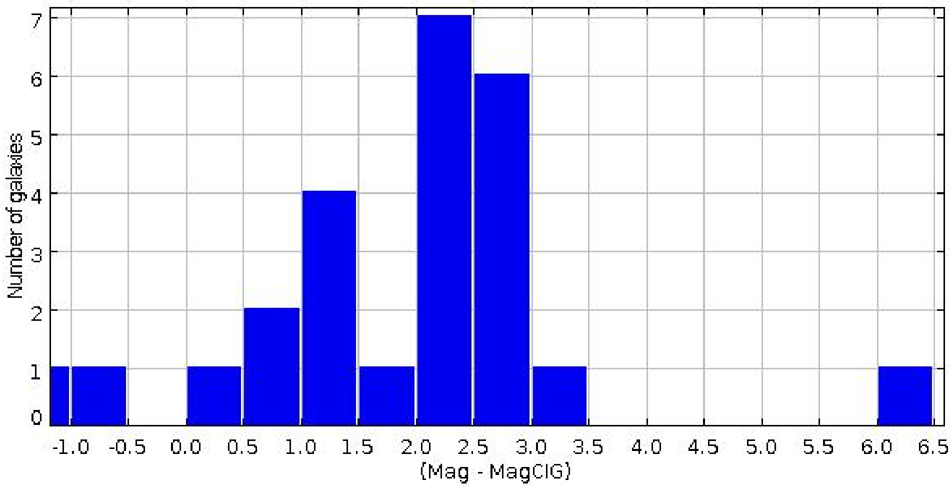

Figure 4.4: Histogram of magnitude differences for galaxies with $-1500 < V < 1500\,\mathrm{km\,s^{-1}}$.

4.3 Comparison with previous AMIGA work

4.3.1 The catalogue of neighbours around isolated galaxies

One of the AMIGA revisions of the CIG sample involved revision and quantification of the isolation criteria. Verley et al. (2007c) used digitised POSS-I images for this revision. The digitised images enabled them to revise the environment description for all 950 CIG galaxies with radial velocities larger than $1500\,\mathrm{km\,s^{-1}}$ within a minimum physical radius of 0.5 Mpc. All galaxy candidates in each field brighter than $B = 17.5$ were identified with a high degree of confidence using the LMORPHO software. A catalog of approximately 54,000 potential neighbours was created (redshifts exist for ∼30% of this sample).

Verley et al. (2007c) chose to evaluate the isolation degree for a minimum physical radius of 0.5 Mpc ($H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) centred on each CIG galaxy. Pipeline capacity and server limits prevented them from processing fields larger than 55' × 55' which translates into a search radius of 27.5 arcmin for galaxies with velocity $V > 4687$ $\mathrm{km\,s^{-1}}$, 55 arcmin for galaxies with $2343 < V < 4687\,\mathrm{km\,s^{-1}}$ and 82.5 arcmin for galaxies with $1500 < V < 2343\,\mathrm{km\,s^{-1}}$.

4.3.2 Comparison with previous AMIGA work

In order to compare our spectroscopic catalogue of neighbours with the catalogue compiled by Verley et al. (2007c) we restricted the radius to 0.5 Mpc centred on each CIG galaxy. The number of objects found in the catalogue

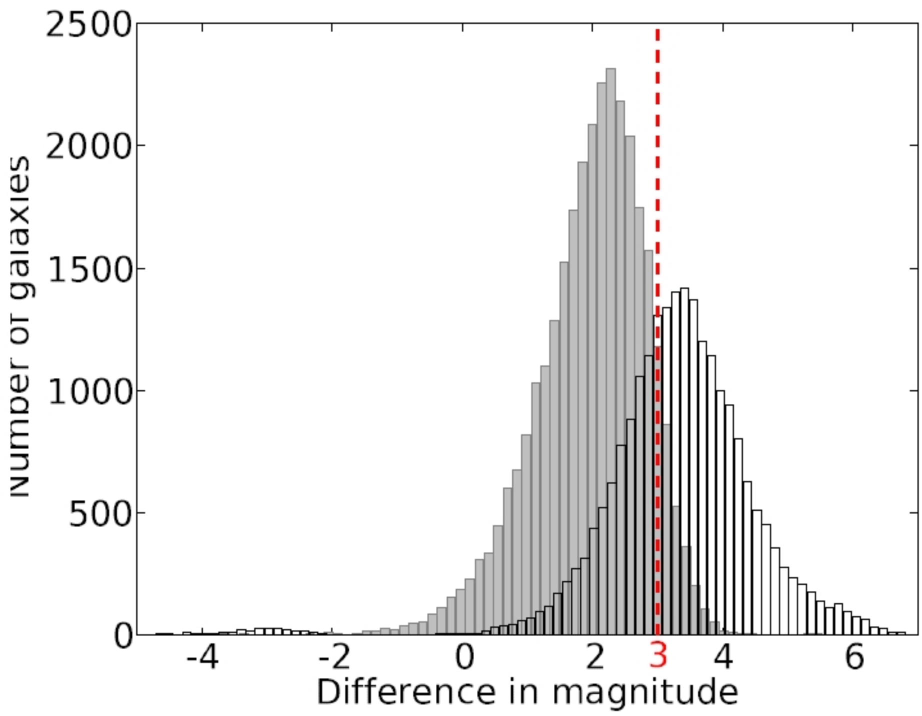

Figure 4.5: Comparison of the magnitude difference distributions for the neighbour galaxies considered by Karachentseva's criterion (factor 4 in size with respect to their associated CIG galaxy, grey histogram) and for the remaining neighbours (outside the factor 4 in size, unfilled histogram). Source: Verley et al. (2007c).

CIG	# SDSS	# Verley	# SDSS∩Verley
19	51	20	17
213	32	11	11
233	10	5	4
264	20	11	11
291	243	124	115
318	4	4	3
322	308	72	60
354	67	13	11
406	17	28	14
418	31	23	17
440	5	2	2
529	15	12	8
582	12	8	6
589	6	2	2
643	5	4	3
651	185	66	60
709	5	6	2
907	33	11	9
928	18	7	5
937	63	33	21
1041	16	6	5

Table 4.4: Comparison with Verley et al. (2007c). Col. 1: CIG name. Col. 2: Number of galaxies in our catalogue of neighbours. Col. 3: Number of galaxies in the catalogue of neighbours around isolated galaxies from Verley et al. (2007c). Col. 4: Number of galaxies in common

of neighbours in this restricted radius is shown in the third column in Table 4.4. In this way, we were able to cross-match (fourth column in Table 4.4) both catalogues in order to make a comparison between them. We show the distribution of magnitudes produced by this cross-match in Fig. 4.6 (pink histogram) overplotted with the histogram of magnitudes from our spectroscopic catalogue (red histogram).

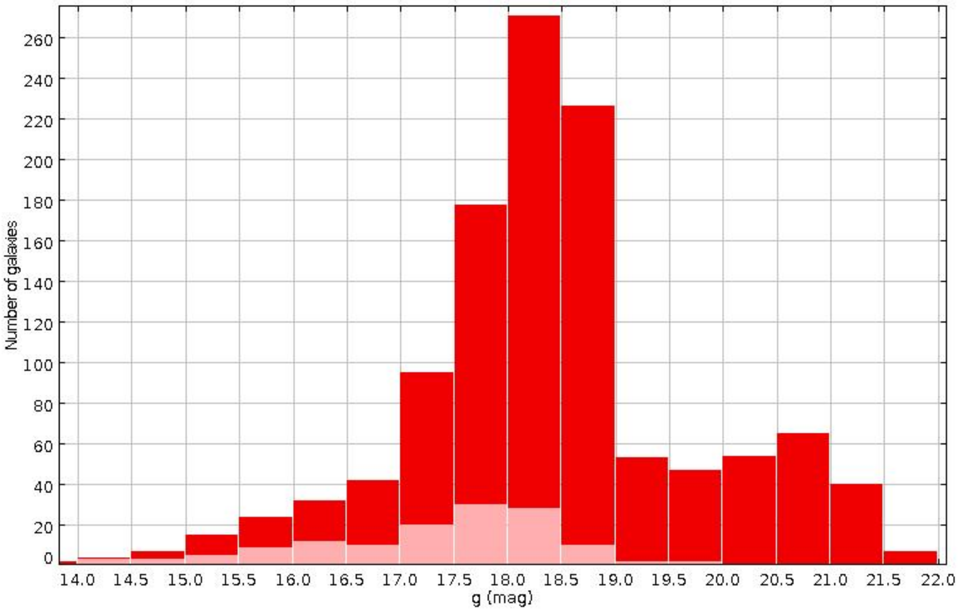

Figure 4.6: Histogram of magnitude in Verley et al. (2007c) and SDSS. The distribution of magnitudes in our SDSS spectroscopic catalogue corresponds to red histogram, in pink the neighbour in common between both catalogues.

Chapter 5

Discussion

Contents

5.1 Revision of Karachentseva's criterion 42
5.2 Comparison with NED 43
5.3 Comparison with previous AMIGA work 43

5.1 Revision of Karachentseva's criterion

In Sect 4.1 we reevaluated Karachentseva's isolation criterion and found that four CIG galaxies (out of 21 CIG galaxies) violated the original criterion. These galaxies are CIG 19, 291, 928, and 1041. We find that 4, 2, 1 and 1 neighbours, respectively, violate the original criterion. All the remaining 17 CIG fields were verified as isolated according to the definition of Karachentseva's within a radius of 0.5 Mpc. For 9 CIG galaxies (CIG 19, 264, 291, 322, 354, 406, 651, 907 and 928) the 0.5 Mpc corresponds to $\geq 80D_P$ and we can check the Karachentseva's criterion, but for the other CIG galaxies we can not assure that those galaxies would remain isolated if we could search for all neighbours within 80 times the diameter of each CIG galaxy.

Concentrating on the four fields where violations were found we check to see if the violating neighbour galaxies are physically linked to the central CIG galaxies. Only two objects near CIG 19 show recession velocities comparable ($\pm$ 1500 km s^{-1}) to the corresponding CIG galaxy. Those two neighbours are likely to be physical companions to the CIG galaxy and may have an effect on its evolution. In the case of the other three CIG galaxies which violated the Karachentseva criterion we find that they are projected companions which cannot have any significant influence on the central galaxy. In general, the neighbours are projected background galaxies, with recession velocities between 15,000 and 45,000 km s^{-1}. These three CIG galaxies would hence really be isolated despite the fact that they do not agree with the original isolation criterion.

Following Verley et al. (2007c), we expect that the galaxies which have a diameter within four times the diameter of the CIG galaxy span a range of ± 3 in magnitude (see Fig. 4.5). The histogram in Fig. 4.1 clearly shows that the difference in magnitude can reach 4 or even 5 magnitudes. This means that the constant surface brightness hypothesis is not totally verified in our case. In Fig. 4.1 we observe a very interesting peak centred at zero. This implies that there is a reasonable probability to find galaxies of similar brightness in the vicinity of isolated galaxies, rather than a homogeneous distribution of magnitudes. Even isolated galaxies have neighbours but their neighbours are too far away to violate the isolation criterion and hence too far away to affect gravitationally on timescales shorter than billions of years.

The histogram of Fig. 4.2 shows that the condition (factor four in size) proposed by Karachentseva in order to remove fore- and background companions is not fully efficient. Indeed, we can see that lots of neighbours have very high recession velocities: some of the neighbours are even receding at more than 150,000 km s^{-1}. If we restric ourselves to the range of velocity difference $\pm$1500 km s^{-1} (Fig. 4.3) we can see that the Karachentseva's criterion requiring similar size companions accounts for most of the physically linked neighbours (16 neighbours in all 21 fields) but we also find 10 galaxies which were not considered by Karachentseva and yet show recession velocities similar to the corresponding CIG galaxy. This means that nearby dwarf galaxies linked to the corresponding CIG galaxy were not taken into account by Karachentseva. This may not be a problem if their masses are less than e.g. a few percent of the CIG because they will have little gravitational imfluence.

5.2 Comparison with NED

In the second column in Table 4.3 in Sect 4.2, we show for each CIG field the number of all neighbours in our spectroscopic catalogue within velocity difference $\pm$ 1500 km s^{-1}. We made this selection to take into account the dwarf galaxies missed by Karachentseva as we discuss in Sect 5.1. SDSS provides extensive information on the environment of each CIG galaxy with a small amount of additional information provided by NED. We checked each galaxy from Table 4.3 in both samples and, in general, we obtained the same results using the two methods. For all the CIG galaxies with physical companions in both samples (CIG 19, 213, 233, 264, 291, 322, 406, 418, 589 and 928) we found that they are the same galaxies. Figure 4.4 shows that 23 of 25 galaxies within velocity difference $\pm$ 1500 km s^{-1} with respect to the central CIG galaxy have magnitude differences within $\pm$ 3 magnitudes in g band.

5.3 Comparison with previous AMIGA work

Figure 4.5 compares the magnitude difference distributions for neighbour galaxies considered by Karachentseva's criterion and for the remaining neighbours in Verley et al. (2007c). The overlap between the two distributions shows that a cut in magnitude at 3 is a rather good approximation because it misses only 10% of the neighbours selected by Karachentseva on the basis of the factor 4 in size. However the contamination also shows that the hypothesis that galaxies show flat surface brightness profiles is not always true: the cut in magnitude includes a large number of galaxies not considered by Karachentseva. Hence, the two definitions of search for the neighbours are not fully equivalent. So, as we discuss in Sect. 5.1, criteria based on magnitude differences to select the neighbours are not fully consistent with Karachentseva's criterion based on the linear sizes.

The fourth column in Table 4.4 allows us to make a comparison between the two methods used to search for neighbours. In a physical search radius of 0.5 Mpc, our SDSS spectroscopic catalogue gives more companions for nearby CIG galaxies. We can see in Fig. 4.6 that galaxies which are not in common with the catalogue of neighbours from the digitised POSS-I images are in general fainter.

The SDSS spectroscopic sample has a Petrosian magnitude limit of $r < 17.77$ for galaxies and PSF magnitude limit of $i < 19.1$ (20.2 for objects likely at $z > 2.3$) for quasar candidates, although the red histogram in Fig. 4.6 shows a magnitude limit at g ~ 22. We visually confirmed that objects in this faint magnitude range are galaxies.

Chapter 6

Conclusions

As a preliminary study, we examined the SDSS data fields to check the isolation for 21 galaxies from the Catalogue of Isolated Galaxies (CIG) compiled by Karachentseva (1973).

Following Karachentseva (1973)'s isolation criterion, we found that four galaxies (CIGs 19, 291, 928, 1041) are not isolated according to the original cirterion. Nevertheless, we could only check the original isolation criterion in a projected radius of 0.5 Mpc around each CIG, so we cannot discard that other CIG galaxies could also fail the original isolation criterion. We were able to verify that 8 CIG galaxies are isolated according to Karachentseva, because for those, the field inspected was larger than $80 \times D_{\rm p}$ and no perturbers were found.

Using the spectroscopic information provided by the SDSS, we could reject a physical association for three CIG galaxies (CIGs 291, 928, 1041) out of four: hence, those galaxies are physically isolated even if they fail the original isolation criterion which only considers projected objects. One galaxy, CIG 19, has four companions, two of which are background galaxies while the other two are dwarf galaxies physically linked to the CIG galaxy (the difference in velocity is minor than $1500\,{\rm km\,s^{-1}}$.)

The availability of the spectroscopic data also allows us to verify if some small objects are dwarf galaxies physically linked to the isolated one rather than large background galaxies projected as small objects near the CIG galaxy. We find that 25 neighbour galaxies, distributed in 12 fields, have a recession velocity comparable ($\pm 1500\,{\rm km\,s^{-1}}$) to the one of their respective CIG galaxy. Most of those objects are hence dwarf galaxies not considered by Karachentseva (1973), which can nevertheless affect the evolution of the isolated galaxy candidate.

We could also use the NED database in order to look for neighbours at the same velocities with respect to each isolated galaxy. In general, the results agree well with our work, as we could recover most of the objects we identified using the SDSS catalogue.

By comparing our work with Verley et al. (2007c), we found fainter objects with respect to the catalogue of neighbours in the previous AMIGA work, as we were able to recover many more small-size satellites. The SDSS confirms earlier works indicating that we do have a list of galaxies that are as isolated as galaxies can be in our local Universe. In this way, the catalogue shows great promise as a control sample for studies of environmental effects on galaxies. The construction of a catalogue of neighbours around isolated galaxies using the SDSS provides a potential method to re-estimate the degree of isolation of AMIGA-CIG isolated galaxies.

During the present pilot study, 21 CIG galaxies were selected as a representative subsample of the full AMIGA sample, so we expect similar results for the other 633 AMIGA galaxies covered by the SDSS.

Chapter 7

Future work

With all that we have learnt from this work, we can now extend our study to the other 399 CIG galaxies which are in the DR7 SDSS spectroscopic sample. That work will provide a re-estimation of the tidal force exerted by satellites on each isolated CIG following the previous work in Verley et al. (2007b). Isolation was previously calculated using 2D data because little spectroscopic data existed. We were therefore only able to estimate the *minimum* level of interaction required to produce nurture effects.

New algorithms will be defined in close collaboration with the SVO team from the full picture of the environment around CIG galaxies, to prepare an all-DR7 coverage catalogue with user-friendly interface in the AMIGA website. We will develop data-mining techniques for the implementation of the 3D selection criteria for candidate objects in the SDSS.

We shall also extract from the SDSS matching samples of pairs and groups in order to compare their parameters with our sample of isolated galaxies in the most homogeneous way possible. In this way we will be able to quantify the effects of interactions on global parameters for samples of galaxies in pairs and groups. Eventually we will also apply the same techniques to the multiwavelength AMIGA database.

Bibliography

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Allam, S. S., Tucker, D. L., Lee, B. C., & Smith, J. A. 2005, AJ, 129, 2062

Bernardi, M., Shankar, F., Hyde, J. B., et al. 2010, MNRAS, 404, 2087

Karachentseva, V. E. 1973, Astrofizicheskie Issledovaniia Izvestiya Spetsial'noj Astrofizicheskoj Observatorii, 8, 3

Koester, B. P., McKay, T. A., Annis, J., et al. 2007, ApJ, 660, 221

Leon, S. & Verdes-Montenegro, L. 2003, VizieR Online Data Catalog, 341, 10391

Leon, S., Verdes-Montenegro, L., Sabater, J., et al. 2008, A&A, 485, 475

Lisenfeld, U., Verdes-Montenegro, L., Sulentic, J., et al. 2007, A&A, 462, 507

Park, C., Choi, Y., Vogeley, M. S., Gott, III, J. R., & Blanton, M. R. 2007, ApJ, 658, 898

Sabater, J., Leon, S., Verdes-Montenegro, L., et al. 2008, A&A, 486, 73

Sulentic, J. W., Verdes-Montenegro, L., Bergond, G., et al. 2006, A&A, 449, 937

Verdes-Montenegro, L., Sulentic, J., Lisenfeld, U., et al. 2005, A&A, 436, 443

Verley, S., Combes, F., Verdes-Montenegro, L., Bergond, G., & Leon, S. 2007a, A&A, 474, 43

Verley, S., Leon, S., Verdes-Montenegro, L., et al. 2007b, A&A, 472, 121

Verley, S., Odewahn, S. C., Verdes-Montenegro, L., et al. 2007c, A&A, 470, 505

Yasuda, N., Fukugita, M., Narayanan, V. K., et al. 2001, AJ, 122, 1104

York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579

Zwicky, F. & Kowal, C. T. 1968, "Catalogue of Galaxies and of Clusters of Galaxies", Volume VI, ed. Zwicky, F., Herzog, E., & Wild, P.

Appendix A

Star-galaxy separation images

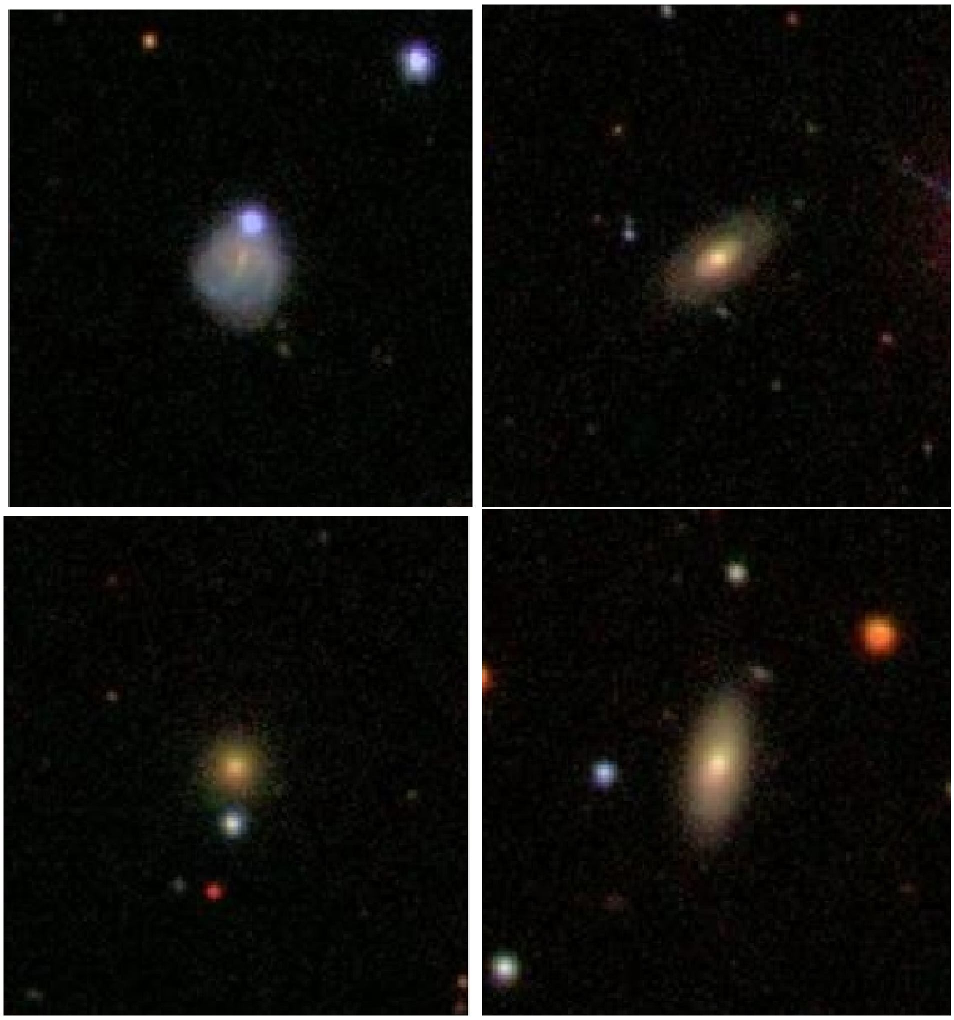

Figure A.1: Star-galaxy separation in the CIG 233 field: images of objects corresponding to galaxies by SDSS and well classified by Verley et al. (2007).

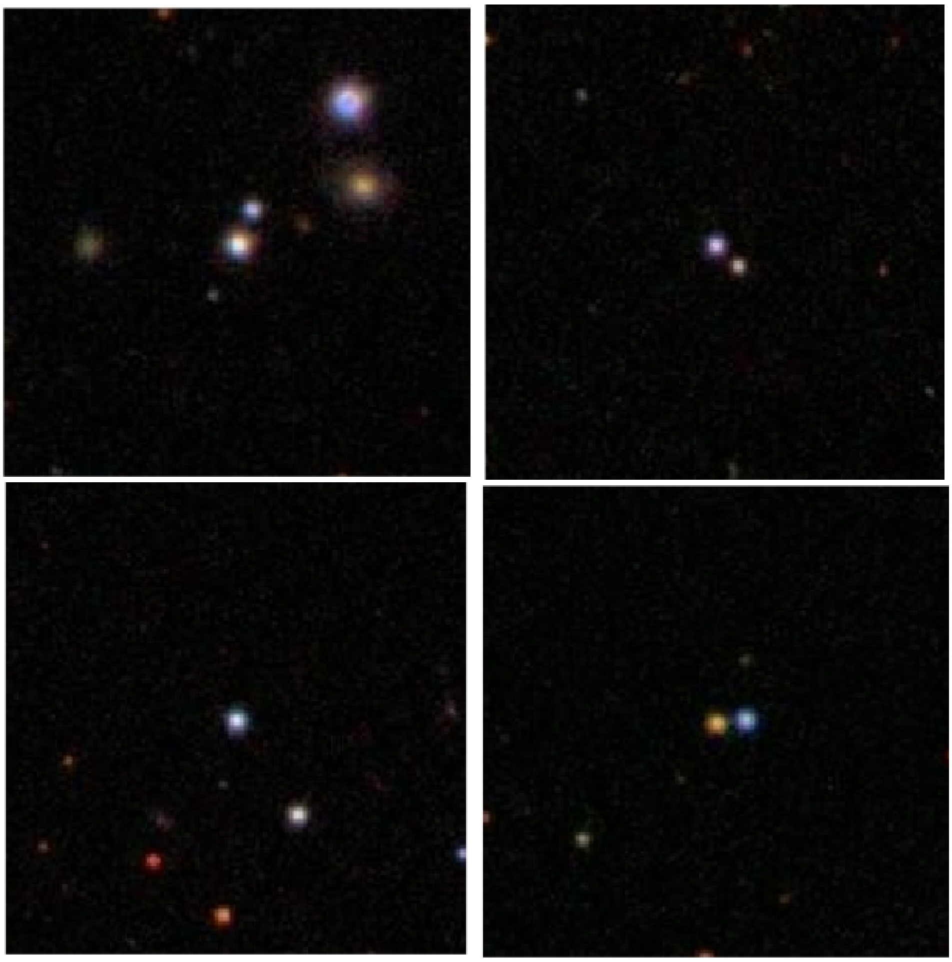

Figure A.2: Star-galaxy separation in the CIG 233 field: images of objects corresponding to stars by SDSS and misclasified as galaxies by Verley et al. (2007).

Appendix B

CASJOB query

```
SELECT p.objID, p.specObjID,
   p.fieldID, p.parentID,
   p.skyVersion, p.run, p.rerun, p.camcol, p.field,
   p.mode, p.nChild, p.clean, p.probPSF, p.insideMask, p.flags,
   p.type, p.ra, p.dec, p.b, p.l, p.rho, n.distance,
   p.u, p.g, p.r, p.i, p.z,
   p.petroMag_u, p.petroMag_g, p.petroMag_r, p.petroMag_i, p.petroMag_z,
   p.petroRad_u, p.petroRad_g, p.petroRad_r, p.petroRad_i, p.petroRad_z,
into CIG0019_05
FROM fGetNearbyObjAllEq(6.06754, 14.2368, 24.21) n, PhotoObjAll p
WHERE n.objID=p.objID and p.g > 0 and p.g <= 22
```

- objID: Unique SDSS identifier composed from (skyVersion,rerun,run,camcol,field,obj).
- specObjID: Pointer to the spectrum of object, if exists, else 0.
- fieldID: Link to the field this object is in.
- parentID: Pointer to parent (if object deblended) or BRIGHT detection (if object has one), else 0.
- skyVersion: 0 = OPDB target, 1 = OPDB best.
- run: Run number.
- rerun: Rerun number.
- camcol: Camera column.
- field: Field number.
- mode: 1: primary, 2: secondary, 3: family object, 4: outside chunk boundary.

- nChild: Number of children if this is a composite object that has been deblended. BRIGHT (in a flags sense) objects also have nchild == 1, the non-BRIGHT sibling.
- clean: Clean photometry flag for point sources (1=clean, 0=unclean).
- probPSF: Probability that the object is a star. Currently 0 if type = 3 (galaxy), 1 if type = 6 (star).
- insideMask: Flag to indicate whether object is inside a mask and why.
- flags: Photo Object Attribute Flags.
- type: Morphological type classification of the object.
  - 0: Object type is not known.
  - 1: Cosmic-ray track (not used).
  - 2: Defect: Object is caused by a defect in the telescope or processing pipeline. (not used)
  - 3: Galaxy: An extended object composed of many stars and other matter.
  - 4: Ghost: Object created by reflected or refracted light. (not used)
  - 5: KnownObject: Object came from some other catalogue (not the SDSS catalog). (not yet used)
  - 6: Star: A a self-luminous gaseous celestial body.
  - 7: Trail: A satellite or asteriod or meteor trail. (not yet used)
  - 8: Sky: Blank sky spectogram (no objects in this arcsecond area).
  - 9: NotAType.
- ra: J2000 right ascension (r').
- dec: J2000 declination (r').
- b: Galactic latitude.
- l: Galactic longitude.
- rho: Log size for surface brightness: 5xlog(Petro radius in i band).
- distance: Distance in arc minutes to one object from the ra,dec.
- u, g, r, i, z: Magnitudes in u, g, r, i and z bands (Models magnitudes better of DeV/Exp magnitude fit).
- petroMag_u, petroMag_g, petroMag_r, petroMag_i, petroMag_z: Petrosian flux in each band.

- petroRad_u, petroRad_g, petroRad_r, petroRad_i, petroRad_z: Petrosian radius in each band.

Appendix C

SDSS color images

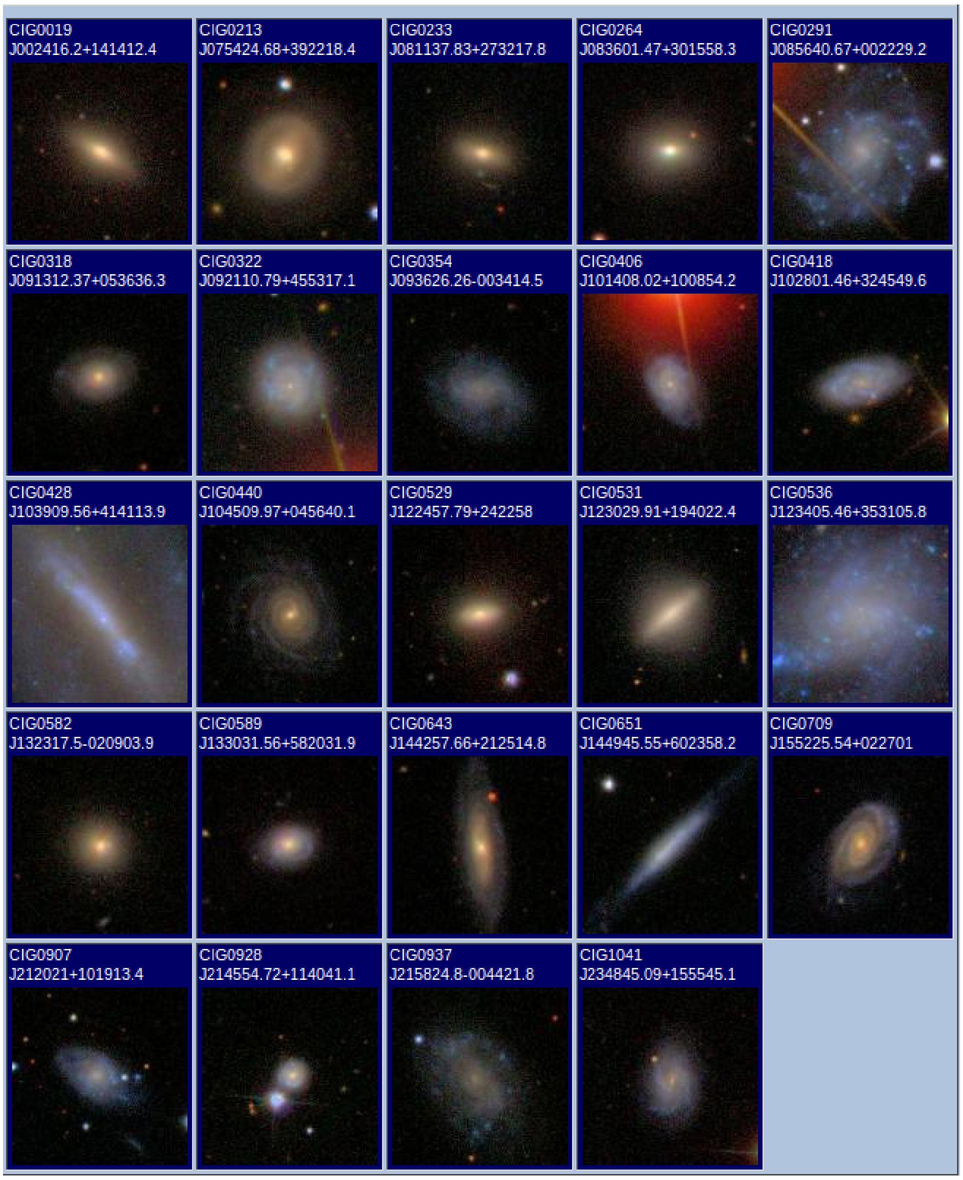

Figure C.1: SDSS colour images of the subsample of 21 CIG-AMIGA galaxies