Scientific
Research
Publishing

Nuclear Activity in Circumnuclear Ring Galaxies

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Abstract

We have analyzed the frequency and properties of the nuclear activity in a sample of galaxies with circumnuclear rings and spirals (CNRs), compiled from published data. From the properties of this sample a typical circumnuclear ring can be characterized as having a median radius of 0.7 kpc (mean 0.8 kpc, rms 0.4 kpc), located at a spiral Sa/Sb galaxy (75% of the hosts), with a bar (44% weak, 37% strong bars). The sample includes 73 emission line rings, 12 dust rings and 9 stellar rings. The sample was compared with a carefully matched control sample of galaxies with very similar global properties but without detected circumnuclear rings. We discuss the relevance of the results in regard to the AGN feeding processes and present the following results: 1) bright companion galaxies seem not to be important for the appearance of CNRs, which appear to be more related to intrinsic properties of the host galaxies or to minor merger processes; 2) the proportion of weak bars in galaxies with a CNR is higher than expected; 3) the incidence of Seyfert (Sy) activity coeval with CNRs is significantly larger than the rate expected from the morphological distribution of the host galaxies; 4) the rate of Sy 2 to Sy 1 type galaxies with CNRs is about three times larger than the expected ratio for galaxies without CNRs and is opposite to that predicted by the geometric paradigm of the classical unified model for AGNs, although it does support the hypothesis that Sy 2 activity is linked to circumnuclear star formation. The possible selection effects of the sample are discussed, and we conclude that the detected trends are strong enough to justify high quality observations of as large as possible set of galaxies with circumnuclear rings and their matched control samples.

Keywords

Galaxies, Spiral, Nuclei, Structure, Dynamics, Active

1. Introduction

The unified standard model for active galactic nuclei stands on a geometric paradigm, which implies that many of the observed properties among the different kinds of objects arise from the observer position and not from intrinsic properties of the host galaxy or their environment; in particular this statement is essential when explaining the differences among Seyfert types or among radio galaxy types.

This strong constraint makes important any observational suggestion about systematic differences in the host galaxy properties that could not depend on the observer line of sight. A variety of statistical studies were carried out without conclusive results (e.g. [1]-[5]). The confirmation of systematic differences in the intrinsic properties would introduce a new ingredient in the unified standard model, an evolution process from less energetic nuclei (Type 2 AGN) toward more energetic ones (Type 1 AGN), making the study of feeding processes crucial for understanding the nature of AGN classes [5]-[7].

Consequently, the connection between nuclear activity, star formation and infalling gas has received growing attention over the past ten years, with nuclear bars and circumnuclear disk instabilities being invoked as preferred mechanisms for removing angular momentum from the gaseous fuel (e.g. [8]-[10]). In order to find any relation between AGN activity and environment, some structures present in the central regions of galaxies are particularly interesting; they are the star-forming circumnuclear rings and ring-like circumnuclear spirals (hereafter CNRs), which arise from the accumulation of infalling material at certain radius proving the active and effective removing of the gas angular momentum. Moreover, CNRs are morphological structures which are radially well differentiated from the active nucleus itself and other structures that can be associated to the active nuclei, like outflows or extended ionization regions. On the contrary, other circumnuclear star formation features as, for example, nuclear bars and hot spots can be confused at low resolution with AGN-related structures. Besides, CNRs represent a defined stage in the secular evolution of barred systems (e.g. [11]) making more probable the detection of any correlation with a defined AGN feeding stage [6].

The relationship between CNRs and the resonances (Inner Lindblad Resonance, ILR) that help to accumulate gas in these rings has been extensively discussed from both the theoretical (e.g. [12] [13]) and the observational (e.g. [14]-[16]) standpoints. These resonances are a dynamical consequence of the bar perturbation but, although bars seem to contribute significantly to circumnuclear star formation, there are no robust evidences of a close relation between bars and nuclear "non-stellar" activity [17] [18]. Furthermore, some non-barred galaxies exhibit CNRs in their nuclear region, suggesting differences in time scale evolution of bars and CNRs [19].

In the present study we analyze a sample of nearby galaxies with CNRs and compare the properties of the host galaxy with that of a control sample, including the presence of AGNs and their type of activity. This work is organized as follow: In Section 2, we present the selected sample of galaxies with CNRs, we describe their properties that were considered to construct the control sample with similar properties than first one but without CNRs. In Section 3, we present the main results obtained from the comparison of both samples of galaxies. In Section 4, we discuss the results presented in the previous section and offer the final remarks. The catalogue presented here contains the most comprehensive sample of circumnuclear rings extracted from the literature until the year 2009. The preliminary version of this work is available at 2004astro.ph.9101.

2. CNR Galaxy Sample

2.1. Sample Selection and Description

We selected galaxies harboring CNRs in their central region. The CNR galaxy compilation was made based on images, color maps and radial profiles from literature up to 2009. Radial profiles are required in order to be able to measure the CNR dimensions. The starting point in the search was the Catalog of CNR galaxies from [20], which was based on plate observations. The authors [20] present 64 CNR galaxies of which we managed to get visual confirmation of 51 of them.

In spite of the rings being well-defined structures, the classification of inner or circumnuclear rings is difficult when the global bar is not detected. For that reason we define some selection criteria in order to avoid misclassification of the observed ring. They are:

(1) The diameter ratio of CNR respect to the host galaxy should be less than 0.2.

(2) CNR radius between 100pc and 2 kpc. These restrictions were imposed based on the typical Inner Lindblad Resonances, limited for the Nuclear Lindblad Resonance and the inner ring at small and larger radii respectively.

A third criterion was added from the observational point of view. We are looking for well-resolved features. Additionally, we are considering a follow-up study of CNR galaxies, so we are interested in CNRs that can be observed from ground-based facilities and that could be compared with the ones detected in massive surveys. Therefore, we selected CNRs with:

(3) Apparent CNR radius larger than 1.5 arcsec (Distance up to 275 Mpc).

ESO 565-G11 was exhaustively analyzed by [21] who determine that this galaxy harbors an exceptionally large CNR with a radius of 2.6 kpc. In spite of the CNR radius is out of the selection criterion, the circumnuclear classification of this ring is certain, and then this galaxy was included in the sample. ESO 138-G1 is a E/S0 galaxy with no apparent bar, which present a relative radius of 0.23, just above the imposed limit of 0.20, but the absolute radius is 1.25 kpc, well below the upper radius limit, whereby ESO 565-11 was incorporated anyway.

Galaxies without a CNR published image, but with CNR parameters from two or more published sources are included, adopting the mean CNR radius value.

In **Table 1**, we list the 94 selected CNR galaxies. Over 30 additional galaxies seemed good candidates to have CNRs, however some of them do not fully satisfy our selection criteria and some others require detailed observations to confirm the presence of the ring.

The CNRs of the sample were classified depending on their evolutionary stage. The CNRs observed exclusively in the infrared bands or observed in absorption in optical bands were classified as Dust Rings; those observed in emission in optical bands were classified as HII Rings and, finally, the ringed structures only detected in color maps or using the imaging technique of "unsharp masking" were classified as Stellar Rings. The galaxy sample contains 73 HII Rings, 12 Dust Rings and 9 Stellar Rings. The galaxy diameter at 25 mag in B-band adopted from NED (NASA/IPAC Extragalactic Database), the measured CNR radius, and the ring class are included in **Table 1**. The bibliography references of the source of CNR detection are also presented in the table.

In **Figure 1**, we present the absolute and relative radius distribution of the sample. The median radius of a circumnuclear ring is 0.7 kpc (mean 0.8 kpc, rms 0.4 kpc). When considering only non-barred hosts the average is 0.87 kpc, there is a slight trend of larger CNR's residing in galaxies without bar. 91% of the catalogued CNR's (up to 2010) are between 200 pc and 1.85 kpc, reinforcing the election of radius limits adopted in the sample selection criteria. Additionally, the upper limit of 20% in relative size is in the tail of the distribution, warranting the loss of a few objects because of it.

The morphological type, bar classification, and nuclear activity for the selected galaxies are listed in **Table 2**. The first two characteristics were obtained from [22] and, for galaxies that were not catalogued by [22], from NED. The nuclear activity classification was based on the catalog of [23] who classify galaxies with strong nuclear activity, and we use [24] for classification of nuclei with lower activity. For the objects common to both catalogs, the activity type was almost coincident. This suggests that the relative distribution of Seyfert types is not strongly dependent on the two classification sources used here. The used nuclear activity classification is in agreement with that assigned by NED in all cases except for NGC 5850, which is classified as LINER in [24] but has no nuclear activity classification in NED.

The morphological distribution of the sample is shown in **Figure 2(a)**. As can be seen, the Sb and Sbc are the uppermost morphological types. In order to determine its significance, we compare this distribution with that expected from [22] (a sample of 2367 nearby galaxies), and with that expected from [24] (a sample of 486 spiral galaxies designed for a central region study). For both referencesthe distribution has a peak at Sc galaxies. In **Figure 2(b)**, we compare the CNR galaxy morphological distribution (from the catalog in [22]) with the expected distribution for 94 random galaxies in the mentioned catalogs ([22] and [24]). At this plot an excess of Sb-Sa type stands. $N^{1/2} = 6.2$; 5.7, for Sb and Sa galaxies respectively, with an excess of 10 objects respect to the expectation from data of the catalog [22], in both morphological types.

CNRs are thought to be related with the ILRs which are dynamically generated by the bar perturbation. However, some CNR galaxies are un-barred galaxies. In **Figure 3**, we display the distribution of bar intensity classification for CNR galaxies in comparison with the expected bar distribution from [22]. While the CNR galaxy sample presents, as expected, an excess of barred galaxies, the number of strong bars is the expected one. Indeed, the weak barred galaxies are out of the expectation respect of the [22] sample (16 objects above the expectation value, $N^{1/2} = 6.4$).

2.2. Nuclear Activity

The nuclear activity distribution of the sample is shown in **Figure 4**. The intermediate class of Seyfert galaxies,

Table 1. CNR galaxy sample.

Galaxy Name	D$_{25}$ [Kpc]	R$_{CNR}$ [Kpc]	Type	Ref.	Galaxy Name	D$_{25}$ [Kpc]	R$_{CNR}$ [Kpc]	Type	Ref.
ESO 138-G1	10.8	1.25	S	[7] [32]	NGC 3486	13	0.95	H	[46]
ESO 437-G33	19.4	0.6	H	[33]	NGC 3504	19.3	0.5	H	[33] [52]
ESO 437-G67	22.8	0.6	H	[33]	NGC 3516	26.1	0.9	H	[56]
ESO 507-G16	30.9	1.2	H	[33] [34]	NGC 3593	6.4	0.2	H	[39] [71]
ESO 565-G11	29.3	2.6	H	[21] [33]	NGC 3945	38.8	0.3	S	[72]
ESO 566-G24	21.7	1.1	D	[35]	NGC 3982	11.9	0.6	H	[56] [62]
IC 1438	22.7	0.65	H	[36]	NGC 4151	36.2	1.9	D	[73]
IC 4214	19	1.3	H	[33] [37]	NGC 4192	32.4	0.5	H	[50]
MARK 477	24.5	1.85	H	[7]	NGC 4303	26.2	0.6	H	[56] [74]
NGC 0278	11	0.33	H	[39] [40]	NGC 4314	12.2	0.5	H	[43] [75]
NGC 0300	6.7	0.16	D	[41]	NGC 4321	29.4	0.9	H	[39] [52]
NGC 0473	20	1.3	H	[42]	NGC 4340	13.7	0.7	S	[47]
NGC 0521	6.2	1.95	S	[43]	NGC 4371	21.1	0.7	S	[43] [72]
NGC 0613	25	0.6	H	[42] [44]	NGC 4526	28.9	0.6	D	[76] [77]
NGC 936	29.6	0.8	S	[6] [45]	NGC 4579	26	1	H	[39] [78]
NGC 1068	33.2	1.6	H	[46] [47]	NGC 4593	34.6	0.9	D	[7] [43]
NGC 1079	24.7	0.15	H	[48]	NGC 4736	14.8	1	H	[46]
NGC 1097	37.7	0.55	H	[44] [49]	NGC 4826	8.4	0.2	H	[39] [50]
NGC 1241	26.4	0.71	H	[50] [51]	NGC 5020	41.7	0.9	H	[43]
NGC 1300	35.7	0.5	H	[39] [52]	NGC 5055	24.6	0.7	H	[50]
NGC 1317	14.8	1	H	[43] [45]	NGC 5194	26.5	0.6	H	[45] [79]
NGC 1326	17.3	0.5	H	[35] [43]	NGC 5236	16.1	0.15	D	[80]
NGC 1343	19	1	H	[42] [53]	NGC 5248	37.8	0.9	H	[48] [81]
NGC 1365	48.4	1.7	H	[45] [54]	NGC 5371	44.2	0.5	H	[46]
NGC 1386	11.8	1.1	H	[32]	NGC 5377	33.5	0.8	D	[67] [82]
NGC 1433	19.6	0.5	H	[48] [55]	NGC 5427	25.6	1.4	H	[43] [45]
NGC 1512	29.1	0.27	H	[45] [48]	NGC 5643	28.6	0.5	D	[83]
NGC 1530	51.3	0.7	H	[45] [56]	NGC 5728	25.9	0.9	H	[33] [43]
NGC 1543	10.2	0.7	S	[47]	NGC 5806	21.6	0.5	H	[67] [82]
NGC 1566	31.3	0.9	H	[57] [58]	NGC 5850	38.3	1.4	S	[84] [85]
NGC 1672	24.1	0.5	H	[7] [15]	NGC 5905	55	0.6	H	[43]
NGC 1808	22.4	0.3	H	[59] [60]	NGC 5945	29.1	1.3	H	[34]
NGC 1819	22.2	0.7	H	[61]	NGC 5953	16.4	0.9	H	[42]
NGC 2273	27.4	0.27	H	[32] [47]	NGC 6221	23.8	0.9	H	[86]
NGC 2595	41.3	1	H	[45]	NGC 6699	19.5	0.75	D	[50]
NGC 2681	14	0.6	D	[45] [62]	NGC 6753	28.5	1.9	H	[43] [69]
NGC 2763	15.8	0.45	H	[63]	NGC 6782	30.4	1.2	H	[43] [69]
NGC 2903	18.4	0.4	H	[52] [64]	NGC 6890	13	1.1	H	[7]
NGC 2935	45.6	0.45	H	[33]	NGC 6951	31.7	0.5	H	[43]
NGC 2997	41.5	0.3	H	[48] [65]	NGC 7187	14.3	0.8	S	[43]
NGC 3081	20.9	0.7	H	[33] [66]	NGC 7217	17.8	0.9	D	[43]
NGC 3184	18.8	1.7	H	[46]	NGC 7469	34.4	0.7	H	[7] [59]
NGC 3277	17.5	0.4	D	[67]	NGC 7552	19.9	0.5	H	[87] [88]
NGC 3310	19.1	0.6	H	[68] [69]	NGC 7570	29.1	1.1	H	[42]
NGC 3313	40.8	0.75	H	[70]	NGC 7582	20	0.11	H+D	[38]
NGC 3344	11.8	1	H	[45] [46]	NGC 7690	8.1	0.45	H	[82]
NGC 3351	16.3	0.4	H	[45] [52]	NGC 7742	13	1	H	[43] [45]

Note: Col. 1: Galaxy Name. Col. 2: Radius of galaxy to the 25th mag isophote in B-band in Kpc (NED). Col. 3: CNR Radius in Kpc. Col. 4: CNR classification: "H" star-forming CNR; "D" Dust CNR, "S" Stellar CNR. Col. 5: Reference for images, color maps or radial profiles where the CNR was identified.
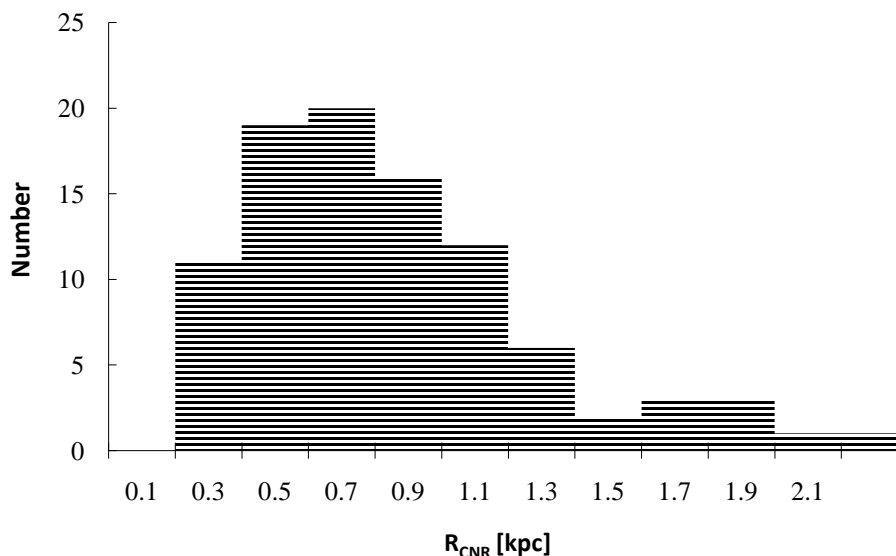
Figure 1. Distribution of circumnuclear ring radius for the sample of 94 CNR.

Sy1.2 and Sy1.5, were included in Sy1 class, while the intermediate class, Sy1.8 and Sy1.9 were added to the Sy2 class, as well as the Seyfert galaxies classified as Sy1 only in polarized light because this specific technique studies are available only for few galaxies, being classified as Sy2 in classic spectroscopic studies. The Sy2 galaxies are predominant in the CNR sample, even more frequent than nuclear star-forming galaxies.

Reference [25] established the frequency of Seyfert galaxies per morphological type for a sample of 1246 galaxies, whose nuclear activity classification was based on [26] catalog (Frequency of Sy1-Sy2: 2% - 0% in E/S0; 6.5% - 6.5% in Sa and Sab; 3.2% - 3.9% in Sb and Sbc; 0.5% - 0.8% in Sc). Considering the morphological distribution of the CNR galaxy sample shown in **Figure 2**, we determine the expected number of Sy1 and Sy2 galaxies in the sample, resulting in 3 Sy1 and 3 Sy2 galaxies. These expected values are very low respect to the observed ones of 6 Sy1 and 16 Sy2 galaxies. Thanks to the observational improvements, the number of discoveries of weak active nuclei was increasing respect to the active nuclei of higher activity. For that reason, we make a new comparison using as reference a study searching for signs of low activity in 486 nearby galactic nuclei [24]. For this study the frequency is Sy1-Sy2: 0% - 7% in E; 2% - 7% in S0; 7% - 12% in S0/Sab; 2% - 12.6% in Sb and Sbc; 1% - 4.5% in Sc and Scd; 0% - 5% in Sd/Sm.

It is worth to mention that this study was carried out with thorough spectroscopic analysis looking for weak nuclear activity. However the CNR sample was not analyzed as thoroughly as that of [24]. Nonetheless, the expectation from the thorough [24] sample is 3 Sy1 and 9 Sy2 galaxies, still below the observed values. One could expect that thorough spectroscopy of the CNR sample would add even more weak AGN's, enlarging the frequency of CNR's with AGN's respect to the expected from the galaxy sample of [25].

Considering the very low number of active nuclei in the CNR galaxy sample, we designed another test trying to determine if the excess of active nuclei is significant. We built a comparison galaxy sample as a control sample.

3. Galaxies with and without a CNR

As we want to assess the incidence of nuclear activity in the CNR galaxy sample, we excluded seven objects of the CNR galaxy sample because their CNRs were detected in studies of active galactic nuclei. Their active galaxy condition was decisive in the discovery of the CNR, conditioning the CNR and nuclear activity relationship. In order to avoid biases in the nuclear activity classification or global properties of CNR and comparison galaxies, we restricted the sample to those galaxies catalogued in [22] and we use exclusively the [23] catalog for nuclear activity classification.

The resulting non-biased subsample of CNR galaxies has 67 objects. For the assignment of the comparison galaxy we consider the following aspects:

Observationally, the probability to detect a CNR depends on the inclination of the galaxy and the apparent diameter. Therein, we want the same CNR detection probability that the hitherto known CNR galaxies.

Table 2. CNR galaxy properties.

Galaxy Name	T	Bar	Activity	Galaxy Name	T	Bar	Activity
ESO 138-G1	-3	A	S2	NGC 3486	5	X	S2
ESO 437-G33	1	X		NGC 3504	2	X	H2
ESO 437-G67	2	B		NGC 3516	-2	B	S1.5
ESO 507-G16	0	X		NGC 3593	0	A	H
ESO 565-G11	0	B		NGC 3945	-2	B	L2
ESO 566-G24	4	B		NGC 3982	4	X	S1.9
IC 1438	3	B		NGC 4151	2	X	S1.5
IC 4214	2	X		NGC 4192	2	X	S3
MARK 477			S1h	NGC 4303	4	X	S2
NGC 0278	3	X	H	NGC 4314	1	B	L2
NGC 0300	7	A		NGC 4321	4	X	T2
NGC 0473	0	X		NGC 4340	-2	B	
NGC 0521	4	B		NGC 4371	-2	B	
NGC 0613	4	B	S?	NGC 4526	-2	X	H
NGC 936	-2	B		NGC 4579	3	X	S3b
NGC 1068	3	A	S1h	NGC 4593	3	B	S1
NGC 1079	0	X		NGC 4736	2	A	S
NGC 1097	3	B	S3b	NGC 4826	2	A	S
NGC 1241	3	B	S2	NGC 5020	4	X	
NGC 1300	4	B		NGC 5055	4	A	T2
NGC 1317	0	X		NGC 5194	4	A	S2
NGC 1326	-2	X		NGC 5236	5	X	
NGC 1343	3	X		NGC 5248	4	X	H
NGC 1365	3	B	S1.8	NGC 5371	4	X	S?
NGC 1386	-2	A	S1i	NGC 5377	1	B	L2
NGC 1433	1	B		NGC 5427	5	A	S2
NGC 1512	1	B		NGC 5643	5	X	S2
NGC 1530	3	B		NGC 5728	1	X	S1.9
NGC 1543	-2	B		NGC 5806	3	X	H
NGC 1566	4	X	S1.5	NGC 5850	3	B	L2
NGC 1672	3	B	S	NGC 5905	3	B	H2
NGC 1808	0	X	H2	NGC 5945	2	B	
NGC 1819	-2	B		NGC 5953	-5		S2
NGC 2273	1	B	S1h	NGC 6221	5	B	S2
NGC 2595	5	X		NGC 6699	4	X	
NGC 2681	0	X	S3b	NGC 6753	3	A	
NGC 2763	6	B		NGC 6782	1	X	
NGC 2903	4	X	H	NGC 6890	3	A	S1.9
NGC 2935	4	X		NGC 6951	4	X	S2
NGC 2997	5	X		NGC 7187	-1	X	
NGC 3081	1	X	S1h	NGC 7217	2	A	S3
NGC 3184	6	X	H	NGC 7469	1	X	S1.5
NGC 3277	2	A		NGC 7552	2	B	H2
NGC 3310	4	X	H2	NGC 7570	1	B	
NGC 3313	2	B		NGC 7582	2	B	S1i
NGC 3344	4	X	H	NGC 7690	3	A	
NGC 3351	3	B	H	NGC 7742	3	A	T2/L2

Note: Col. 1: Galaxy Name. Col. 2: Morphological Type from Tully (1988: E = −5; S0 = −2; Sa = 1; Sb = 3; Sc = 7). Col. 3: Bar Intensity Classification ("B": Strong; "X" Weak; "A" Absent). Col. 4: Nuclear Activity Classification: (left) Veron-Cetty & Veron (2006) nuclear classification ("H2" nuclear star-formation; "S1", "S1.5", "S1.8", "S1.9", and "S2" Seyfert nuclei; "S1h" Sy2 nuclei with broad emission lines only in polarized light; "S3" LINER/Transition); (right) Ho *et al.* (1997) nuclear classification ("H" nuclear star-formation; "L2" LINER; "T2" Transition).
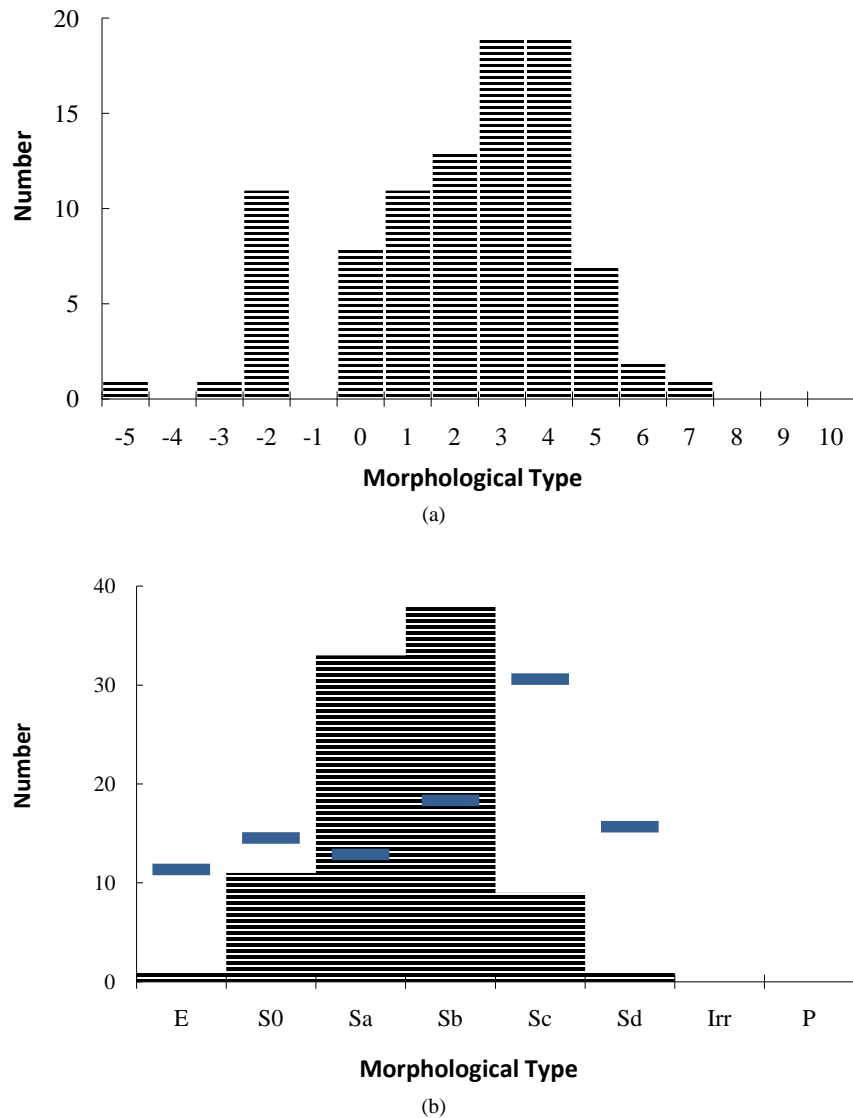
(a)

(b)

Figure 2. (a) Distribution of Morphological Type from [22] for the host galaxies of the CNR sample; (b) comparison between the observed morphological distribution with that expected for a random sample of 94 galaxies from [22] Catalog distribution.

Consequently, we impose the following conditions for comparison galaxies:

(1) The departure in inclination from the CNR galaxy must be $\Delta i < 10°$;

(2) The difference in corrected apparent sizes must be $\Delta D_{25} < 0.2\ D_{25}^{CNR}$

We aim to have comparison galaxies with similar global properties than the CNR galaxies in order to guarantee the same probability to have an active nucleus. Therefore, we designated the following criteria:

(3) The departure in morphological type numerical code from the CNR galaxy must be $\Delta T \leq 1$.

(4) The departure in B absolute magnitude from the CNR galaxy must be $\Delta M_B < 0.3$;

(5) The difference in projected real sizes must be ΔR_{25} (kpc) $< 0.4\ R_{25}^{CNR}$ (kpc);

We define a selection criteria index that includes the five selection criteria with the same weight each one. The galaxy in the [22] general galaxy catalog that has the lowest selection index was assigned as the comparison galaxy for each CNR host galaxy. The selected comparison galaxy was examined in the literature in order to guarantee that there is no indication of the presence of an unreported CNR. In **Table 3**, we list the selection properties for CNR and comparison galaxies. The mean differences between both samples are $(-4° \pm 10°)$ in inclination; $(0.8' \pm 1.7')$ in apparent diameter; (0.0 ± 0.2) mag in B-band absolute magnitude; (0 ± 1) in morpho-
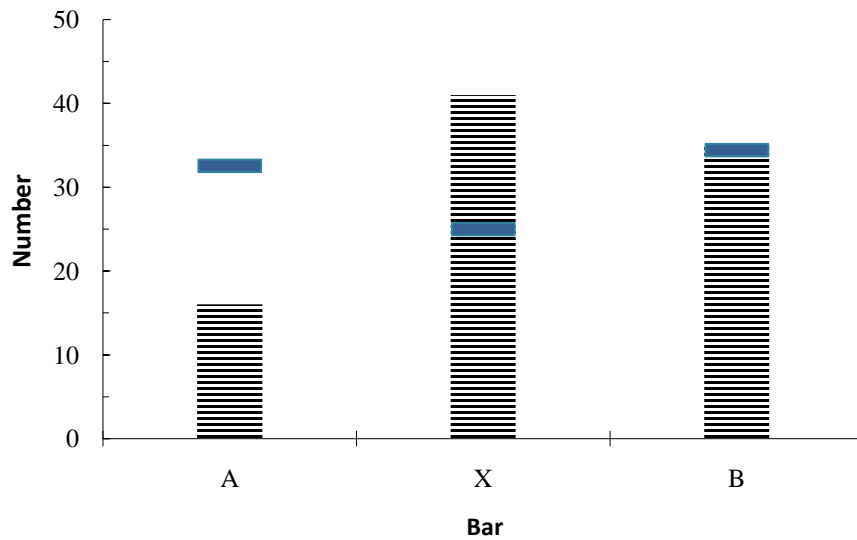
Figure 3. Distribution of bar classification for the host galaxies of the CNR sample. The horizontal marks indicate the expected distribution for a random sample of 94 galaxies from [22] Catalog distribution.
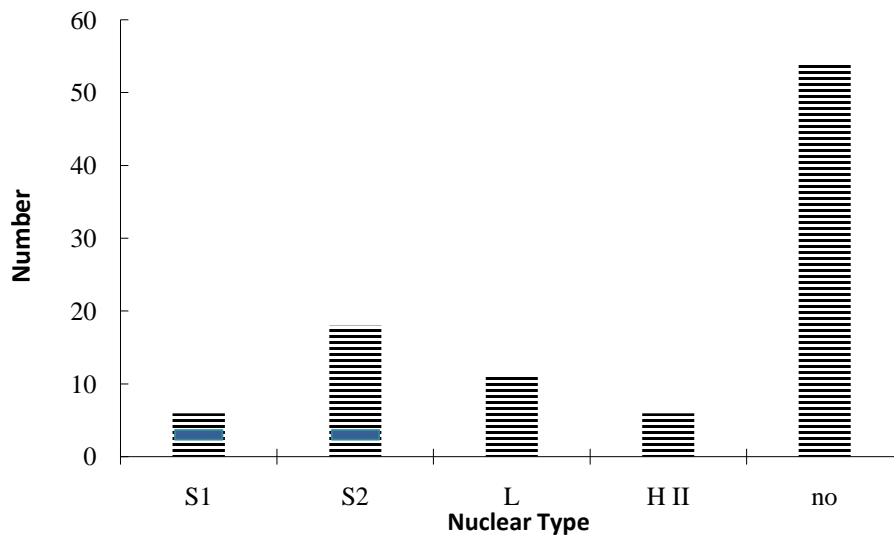

Figure 4. Distribution of nuclear emission spectroscopic classification for the CNR sample hosts. "S1" class includes Sy1 galaxies, Sy1.2, and Sy1.5; "S2" class includes Sy2 galaxies, Sy1.8, Sy1.9 and galaxies classified as Sy1 only in polarized light (Sy1i, Sy1h); "L" class includes LINER galaxies; "HII" class includes galaxies with star formation in the nucleus; "no" includes galaxies with stellar nuclei. Marks indicate the expected Seyfert galaxy numbers from the [25] active galaxy frequency distribution considering the morphological distribution of the CNR galaxy sample.

logical type; and (-0.9 ± 4.1) Kpc in absolute diameter.

The bar intensity distribution for both samples is shown in **Figure 5**. While the tendency is the same than the one observed in the full sample (an excess of weak bars in CNR galaxies respect to the comparison galaxies), this result is not conclusive due to the low number of objects.

In **Figure 6**, the incidence of AGN's is plotted for both samples. Unexpectedly, there are more galaxies with active and star-forming nuclei in the CNR subsample than in the comparison one. The expectation of Sy1 and Sy2 galaxies obtained from [25] is of 2 Sy1 and 2 Sy2 for both samples (they have the same morphological distribution). Therefore, the number of Sy1 galaxies observed in both samples (3 in CNR galaxy subsample and

Table 3. Properties of CNR galaxy subsample.

Name	Comp. Gal.	T	B	i	D_{25}	$2R_{25}$	M_B	M_K	D	rho	W_R	log (M_H)	log (M_T)	M_H/M_T	M_H/L_B	M_T/L_B
IC 1438	UGC 9837	3	B	25	2.3	22.7	−19.45	−23.34	33.8	0.17						
NGC 278	NGC 4369	3	XP	0	2.7	11	−19.62	−22.54	11.8	0.11		9.02			0.1	
NGC 300	UGC 5666	7	A	46	20.2	6.7	−16.88	−19.02	1.2	0.45	200	8.9	9.89	0.102	0.9	8.83
NGC 473	NGC 357	0	X	54	2.5	20	−19.77	−22.81	29.8	0.08						
NGC 613	NGC 4254	4	B	37	5	25	−20.53	−24.19	17.5	0.07	577	9.49	11.38	0.013	0.12	9.54
NGC 936	NGC 2217	−2	B	40	6.2	29.6	−20.08	−24.23	16.9	0.24						
NGC 1068	UGC 2953	3	A	29	8	33.2	−21.39	−25.00	14.4	0.34		9.22			0.03	
NGC 1079	NGC 1415	0	XP	49	5.4	24.7	−18.83	−22.80	16.9	0.2						
NGC 1097	NGC 3992	3	B	57	9.8	37.7	−20.79	−24.56	14.5	0.13	436	9.87	11.32	0.036	0.23	6.45
NGC 1241	NGC 7412	3	B	52	3.6	26.4	−19.83	−23.47	26.6	0.11						
NGC 1300	NGC 4123	4	B	43	6.8	35.7	−20.42	−23.81	18.8	0.71	373	9.55	11.16	0.025	0.15	6.28
NGC 1317	NGC 3729	0	X	38	3.1	14.8	−19.2	−23.41	16.9	1.3						
NGC 1326	NGC 3941	−2	B	53	3.8	17.3	−19.84	−23.69	16.9	1.36	305	9.26	10.67	0.039	0.13	3.47
NGC 1365	NGC 4569	3	B	63	11.2	48.4	−21.26	−24.77	16.9	1.58	410	10.04	11.37	0.046	0.22	4.75
NGC 1433	NGC 4665	1	B	27	5.9	19.6	−19.67	−23.26	11.6	0.55						
NGC 1512	NGC 1055	1	B	77	13.4	29.1	−19.02	−22.40	9.5	0.37	239	9.53	10.68	0.069	0.53	7.65
NGC 1530	NGC 1169	3	B	60	4.8	51.3	−21.32	−24.53	36.6	0.2	334	10.09	11.22	0.074	0.23	3.16
NGC 1543	NGC 4503	−2	B	65	3	10.2	−19.07	−23.19	13.4	0.95						
NGC 1566	NGC 1398	4	X	40	8.4	31.3	−20.45	−23.75	13.4	0.92	305		10.93			3.59
NGC 1672	NGC 2775	3	B	37	5.9	24.1	−19.84	−23.79	14.5	0.64						
NGC 1808	NGC 1371	0	X	50	7.6	22.4	−19.52	−23.51	10.8	0.3		9.26			0.18	
NGC 2273	NGC 5678	1	B	50	3.4	27.4	−20.76	−23.79	28.4	0.19	430	9.46	11.17	0.02	0.09	4.68
NGC 2681	NGC 4457	0	X	0	3.6	14	−19.59	−23.19	13.3	0.2		9.12			0.12	
NGC 2763	NGC 6412	6		0	2	15.8	−19.53	−22.49	25.7	0.22		9.46			0.29	
NGC 2903	NGC 3521	4	X	66	11.6	18.4	−19.85	−22.96	6.3	0.12	391	9.25	10.91	0.022	0.13	6.02
NGC 2935	NGC 2207	4	X	49	5.4	45.6	−21.74	−24.12	30.6	0.3	359	10.01	11.23	0.06	0.13	2.2
NGC 2997	NGC 3359	5	X	53	10.2	41.5	−20.74	−24.29	13.8	0.28	301	10.06	11.04	0.105	0.37	3.55
NGC 3081	NGC 5691	1	X	35	2.2	20.9	−20.05	−23.65	32.5	0.25						
NGC 3184	NGC 2835	6	X	26	7.5	18.8	−19.34	−22.44	8.7	0.17		9.36			0.27	
NGC 3277	NGC 718	2	A	26	2.4	17.5	−19.51	−23.06	25	0.35						
NGC 3310	NGC 3887	4	XP	25	3.6	19.1	−20.09	−22.76	18.7	0.27		9.69			0.29	
NGC 3344	NGC 1637	4	X	23	6.7	11.8	−18.47	−21.49	6.1	0.19		9.25			0.47	
NGC 3351	NGC 4274	3	B	56	7.5	16.3	−19.26	−22.87	8.1	0.54	302	8.92	10.64	0.019	0.1	5.48
NGC 3486	NGC 1249	5	X	47	6.4	13	−18.61	−21.35	7.4	0.27	285	9.27	10.48	0.061	0.43	7.06
NGC 3504	NGC 4750	2	X	35	2.6	19.3	−20.38	−23.85	26.5	0.25						
NGC 3516	NGC 5087	−2	B	34	2.3	26.1	−20.59	−24.44	38.9	0.19		9.38			0.09	
NGC 3593	NGC 4460	0	A	69	4.8	6.4	−17.01	−21.28	5.5	0.19	232	8.02	10	0.01	0.11	10.12
NGC 3945	NGC 5365	−2	B	55	6.5	38.8	−20.3	−24.23	22.5	0.5						
NGC 3982	UGC 3190	4	X	26	2.4	11.9	−19.45	−22.30	17	0.72		9.21			0.18	
NGC 4192	NGC 4216	2	X	83	8.7	32.4	−21.08	−24.24	16.8	1.44	429	9.75	11.24	0.033	0.13	4.11
NGC 4303	NGC 2442	4	X	17	5.9	26.2	−20.71	−24.43	15.2	1.06		9.66			0.15	
NGC 4314	NGC 1947	1	B	15	4.2	12.2	−18.65	−22.48	9.7	1.25						
NGC 4321	NGC 488	4	X	37	6.1	29.4	−21.13	−24.54	16.8	2.95	444	9.7	11.23	0.03	0.11	3.82

Continued

Nombre	Comp. Gal.	T	B	i	D₂₅	2R₂₅	M_B	M_K	D	r	W_R	log (M_H)	log (M_T)	M_H/M_T	M_H/L_B	M_T/L_B
NGC 4340	NGC 1387	−2	B	20	2.8	13.7	−19.17	−22.81	16.8	2.89						
NGC 4371	NGC 2685	−2	B	66	5	21.1	−19.3	−23.41	16.8	4.09						
NGC 4526	NGC 4438	−2	X	74	7.4	28.9	−20.55	−24.66	16.8	2.45		9.31			0.08	
NGC 4579	NGC 3631	3	X	36	5.4	26	−20.67	−24.64	16.8	3.26	605	9.36	11.44	0.008	0.08	9.57
NGC 4593	NGC 3223	3	B	58	3.3	34.6	−21.58	−24.99	39.5	0.21						
NGC 4736	NGC 3368	2	A	33	12.2	14.8	−19.37	−23.06	4.3	0.42	373	8.48	10.78	0.005	0.03	6.86
NGC 4826	NGC 2683	2	A	66	8	8.4	−19.15	−22.73	4.1	0.2		8.32			0.03	
NGC 5055	NGC 4559	4	A	55	13	24.6	−20.14	−23.68	7.2	0.4	447	9.65	11.15	0.032	0.26	8.05
NGC 5194	NGC 4258	4	AP	64	13.6	26.5	−20.75	−23.93	7.7	0.33		9.46			0.09	
NGC 5236	NGC 4051	5	X	24	11.5	16.1	−20.31	−23.74	4.7	0.18		10.01			0.5	
NGC 5248	NGC 1232	4	X	45	6.1	37.8	−21.07	−24.53	22.7	0.3	361	10.05	11.15	0.079	0.27	3.43
NGC 5371	NGC 2417	4	X	41	4.2	44.2	−21.57	−25.28	37.8	0.74	585	10.12	11.64	0.03	0.2	6.63
NGC 5377	NGC 5448	1	B	58	4.2	33.5	−20.69	−24.10	31	0.19						
NGC 5427	NGC 3367	5	AP	17	2.3	25.6	−20.94	−24.31	38.1	0.19						
NGC 5728	NGC 4699	1	X	65	2.3	25.9	−21.67	−24.96	42.2	0.18						
NGC 5806	NGC 5633	3	X	63	2.9	21.6	−20.36	−23.82	28.5	0.85						
NGC 5850	NGC 5375	3	B	28	4.6	38.3	−20.69	−24.17	28.5	0.65		9.62			0.14	
NGC 5953	NGC 5017	−5		43	1.8	16.4	−19.59	−23.43	33	0.3						

Note: Col. 1: CNR Galaxy Name. Col. 2: Comparison Galaxy Name. Col. 3: Morphological Type (E = −5; S0 = −2; Sa = 1; Sb = 3; Sc = 7). Col. 4: Bar Classification. Col. 5: galaxy inclination [*deg*]. Col. 6: Diameter of galaxy to the 25th mag isophote in B-band [*arcmin*]. Col. 7: Diameter of galaxy to the 25th mag isophote in B-band corrected by projection and extinction [*Kpc*]. Col. 8: Absolute Magnitude in B-band. Col. 9: Absolute Magnitude in K-band. Col. 10: Galaxy Distance (h = 0.75) [*Mpc*]. Col. 11: Local Density of Galaxies brighter than $M_B = −16$ [*Galaxy/Mpc³*]. Col. 12: Kinematic WidthW^i_R = 2 V_{max} [*Km/s*]. Col. 13: Mass of neutral gas [$M_\odot$]. Col. 14: Total Mass [$M_\odot$]. Col. 15: Fraction of nuclear gas. Col. 16: Mass-Luminosity ratio for neutral gas in B-band [$M_\odot/L_\odot$]. Col. 17: Total Mass-Luminosity ratio in B-band [$M_\odot/L_\odot$].
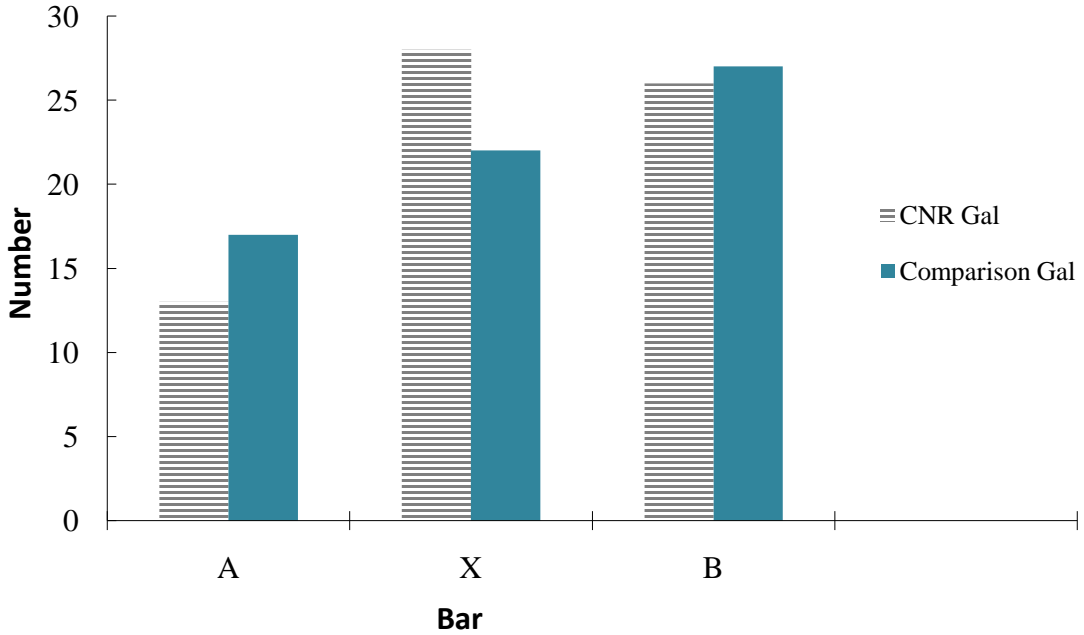

Figure 5. Distribution of bar classification for CNR and comparison galaxy samples.
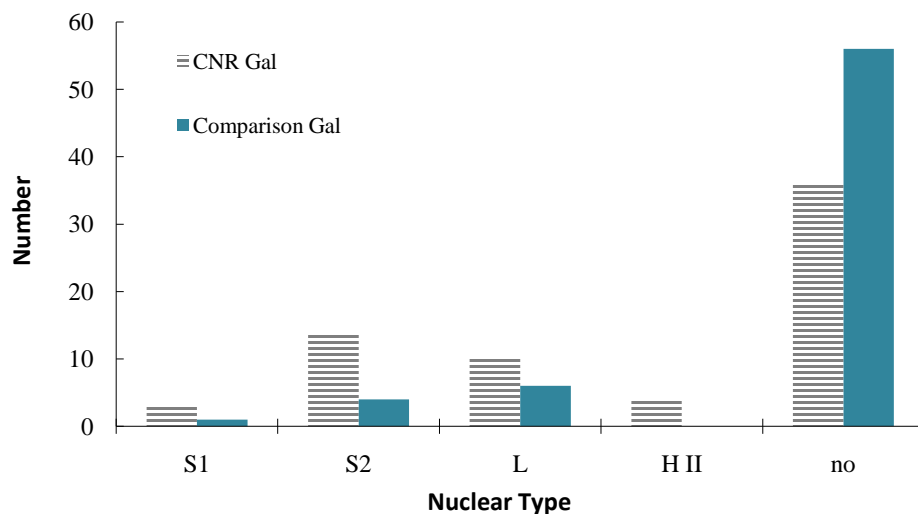
Figure 6. Distribution of nuclear classification for CNR and Comparison galaxy samples. "S1" class includes Sy1 galaxies, Sy1.2, and Sy1.5; "S2" class includes Sy2 galaxies, Sy1.8, Sy1.9 and galaxies classified as Sy1 only in polarized light (Sy1i, Sy1h); "L" class includes LINER galaxies; "HII" class includes galaxies with star formation in the nucleus; "no" includes galaxies with stellar nuclei.

1 in the comparison sample) is in agreement with the expected one, although the low number of objects make difficult to detect any different trend. However, the incidence of Sy2 galaxies in the CNR galaxy subsample is significantly higher than that of the comparison sample and the expected value, being 14 against 4 Sy2 galaxies.

Some properties that could be linked with the CNR formation and evolution are available in the [22] catalog. We compare these properties for both samples. For instance, the tidal interaction with nearby bright galaxies could favor the in falling gas and therefore the formation of the CNRs. However, very close encounters could perturb the dynamics of the disk deleting the ILR and the consequent accumulation of material in the CNR. The galaxy local density distribution for both samples is shown in **Figure 7**. There are no apparent differences in the environment of CNR and comparison galaxies.

The content of gas may promote the loss of angular momentum and the consequent feeding of the CNR. Therefore, we compare the amount of neutral gas ($M(HI)/M_{tot}$ and $M(HI)/L_B$) without finding significant differences between both samples. Actually, the $M(HI)/LB$ could present a tendency to be lower for CNR galaxies (**Figure 8**) although the mean values are indistinguishable.

The presence of massive dark matter halos is usually invoked for disk stability disfavoring the generation of bars and resonances. The kinematic width (W_{20}) distribution has a peak in 300 km/s for both samples. Nevertheless, the comparison distribution has a high velocity tail, which impacts the median W_{20} value (307 km/s for the CNR sample and 410 km/s for the comparison one). Therefore CNR host galaxies might have smaller dark matter halos, fairly consistent with the theoretical predictions.

Finally, we compare the Mass-Luminosity Ratio (**Figure 9**) observing no apparent differences between samples. The Tully-Fisher relation in B and K bands is consistent with the standard relation of [27] for both samples.

4. Discussion and Final Remarks

We carried out an exhaustive search of galaxies harboring CNRs in their central region from images, color maps and radial profiles available in the literature, which allowed determining the dimensions of the ringed structures. Additionally, we impose some conditions in order to guarantee the circumnuclear nature of the observed ring. Thus, we have set up the most complete sample of 94 CNR galaxies known up to 2009. The sample is useful for studying the CNR and host galaxy properties in order to understand the origin and evolution of such structures and the potential connection with the feeding of the central objects.

The CNRs in this sample exhibit a mean diameter of 1.6 Kpc, being the most common value (mode) of 1 Kpc. These results are in agreement with that of [20] who determine a CNR mean diameter of 1.1 Kpc for 20 bared galaxies. The linear diameter of the characteristic CNR is 6% of the host galaxy diameter.
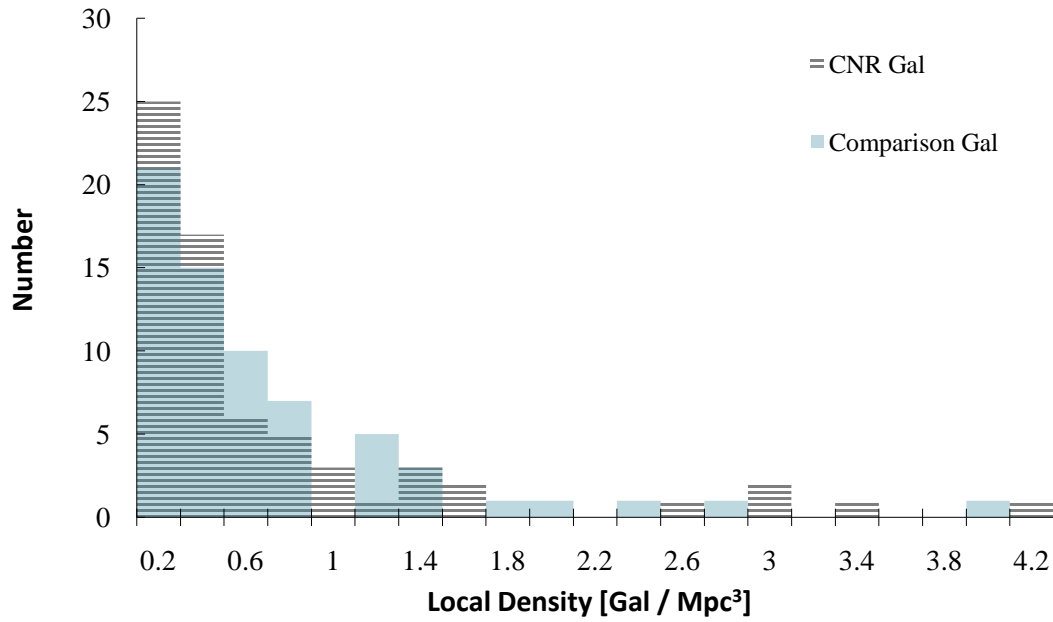
Figure 7. Distribution of local density of galaxies brighter than-16 B-mag for CNR and Comparison galaxy samples.
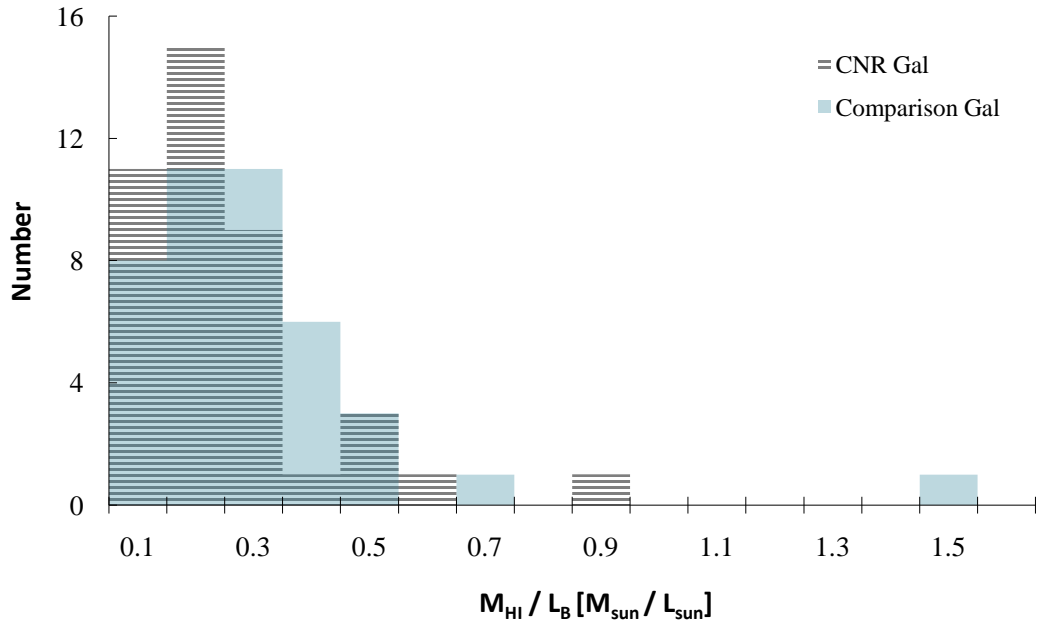

Figure 8. Distribution of Mas-Luminosity ratio in B-band for the neutral gas mass component.

The presence of CNR is more frequent in Sb-Sbc galaxies, and, comparing with the [22] catalog, the CNR galaxy sample present an excess of Sa and Sb galaxies respect to a random sample of 94 spiral galaxies. This morphological type excess could be explained if evolved disks favor these ringed structures. The CNR galaxies also prefer weak bars, opposite than expected taking into account that the bar perturbation is invoked as the mechanism of generation of the resonances associated to the CNRs. This result could indicate different evolution time scale for bar and CNR structures.

Dynamical studies propose that the galactic disks can be stabilized readjusting the mass distribution in the central region, increasing the central rotation velocity, which would lead in the ILR development. As a consequence, the density wave propagation is decelerated and the loss of angular momentum is favored [28]. Therefore,
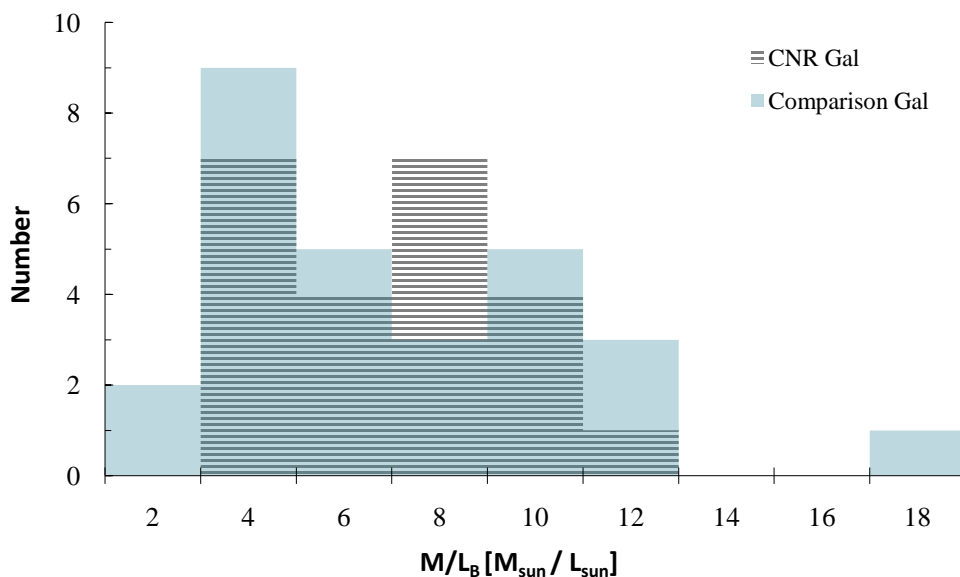
Figure 9. Distribution of mas-luminosity ratio in B-band for the galaxy total mass.

the incidence of CNRs, as evidence of the ILR presence, would be greater in galaxies with massive central regions. Considering that the mass of bulge component is related with the mass of the nuclear supermassive black hole [29], a potential connection between the CNRs and the nuclear activity is suspected. Indeed, a larger number of active nuclei are observed in the CNR galaxy sample respect to that expected for a random sample with the same morphological type distribution. Particularly, the main excess is presented in the number of Sy2 active galaxies.

Taking into account the possible selection bias of the sample, we design a comparison galaxy sample with galaxies having similar observational and physical characteristics. CNRs discovered in AGN searches were excluded in order to avoid the bias toward active objects. Moreover, single source catalogs of galaxy properties and nuclear activity classification were used, yielding to a 67 CNR galaxy subsample with their respectively comparison galaxy.

Although the same tendency of having more weak bars, observed in the full sample, is also insinuated in the subsample, this excess is not conclusive due to the low number of objects. However, the excess of active nuclei respect to the control sample is more robust (17 vs 5). Worth noting that the active galaxies observed in the comparison galaxy sample is in accordance with the expectation obtained from [19] (5 vs 4). Again, the excess of active nuclei is notorious in the Sy2 type, being 14 in the subsample against 4 in the control sample.

Within the framework of the classical unified model for Seyfert galaxies, the Sy1 and Sy2 galaxies are the same phenomenon, differing only in the orientation of the supermassive black hole accretion disk respect to the observer line of sight. Taking into account that the CNRs are more probably observed in galaxies with low inclination, in this sample, we would expect positive selection effect for Sy1 type, unless the accretion disks were not coplanar with the galactic disk in a statistical sense. Some authors propose an evolutionary scenario for Seyfert galaxies in which the active nuclei is powered as the material inflow is increasing (e.g. [1] [2] [30] [31]). In this context, as the gas is led to the central region and the star formation is triggered; the supermassive black hole is fed and the Sy2 stage is activated. As already mentioned, this increasing central mass concentration promotes the CNR formation. And therefore, the coexistence of the CNR and Sy2 phase is expected. However, the increasing inflows toward the nucleus should attenuate the CNR structures in order to when the Sy1 phase is triggered, the CNR is barely observed, as a possible explanation for the lack of excess of Sy1 in the CNR galaxy sample. However, no evolved CNRs are observed in Sy1 galaxies, being 4 CNRs of star formation and 2 dusty CNRs. The [22] catalog allowed us to study some other properties in the CNR galaxy subsample and the comparison one. The CNR existence seems to be unrelated with the presence of a bright companion galaxy, whereby the CNR formation would be related to intrinsic galaxy properties or to the merging with satellite dwarf galaxies.

The M/L ratio and Tully-Fisher relation do not show evidence for a relation with the CNR presence. However,

CNR host galaxies have consistently smaller kinematic widths (W_{20}) indicating that they might have smaller dark matter halos. References [89] [90] suggest that the dynamical friction of a massive dark halo should decelerate the bar perturbation preventing the long-lived resonance formation. CNRs seem to reside in galaxies with smaller dark halos, which would be consistent with the theoretical prediction. Such a trend is so far unreported in the literature and is worth to follow-up in a larger study.

The detected trends and their consequences seem significant enough to encourage researchers in the field to perform high quality observations of a large and complete set of galaxies with circumnuclear rings and its matched control sample.

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