NUCLEAR vs. CIRCUMNUCLEAR ACTIVITY

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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). This sample was compared with a control sample of galaxies with very similar global properties but without circumnuclear rings. We discuss the relevance of the results in regard to the AGN feeding processes and present the following results: (i) 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; (ii) the proportion of strong bars in galaxies with an AGN and a CNR is somewhat higher than the expected ratio of strongly barred AGN galaxies from the results of Ho and coworkers; (iii) the incidence of Seyfert activity coeval with CNRs is clearly larger than the rate expected from the morphological distribution of the host galaxies; (iv) 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.

Subject headings: Galaxies: spiral, nuclei, structure, dynamics, active

1. INTRODUCTION

The unified standard model for active galactic nuclei stands on a geometric paradigm, which implies that most of the observed properties among the different kinds of objects arise from the observer position and not from intrinsic properties of the host environment or galaxy, in particular this statement is more clear for the differences among Seyfert galaxies or

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among radio galaxies. This strong constraint makes important any observational suggestion about systematic differences in the host properties and has lead to a variety of statistical studies without strong results. The subject of AGN environment is still open to discussion and clearly more studies and correlation searches are needed.

In particular, 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. Shlosman et al. 1989, Heller & Shlosman 1994, Maiolino et al. 2000). The relationship between the star-forming circumnuclear rings and ring-like circumnuclear spirals (hereafter CNRs) and the resonances that help to accumulate gas in these rings has been extensively discussed from both the theoretical (e.g. Piner, Stone & Teuben 1995, Wada & Habe 1995) and the observational (e.g. Storchi-Bergmann et al. 1996, Díaz et al. 1999) standpoints. It has been claimed that bars and rings are more prevalent in active and starburst galaxies than in otherwise normal objects (Arsenault 1989). Specifically, some studies have yielded evidence that Seyferts have a preference for systems with global inner or outer rings (Simkin et al. 1980, Arsenault 1989, Moles et al. 1995, Hunt et al 1999). Notwithstanding, the subject of bars is still controversial, bars seem to contribute significantly to circumnuclear star formation, but without an evident relation with nuclear “non-stellar” activity (Ho et al. 1996).

We have been using observational methods to study the mechanisms related to nuclear activity and star formation in the central regions of spiral galaxies. In particular, our research program has been focused in kinematical and dynamical detailed studies of the central region of CNR galaxies (Díaz 2004). In the case of NGC 1241 (Díaz et al. 2003) we have shown the presence of several perturbations in the hundred parsec scale linked to the CNR where active star formation takes place with nuclear symmetry, some of this perturbations being good candidates for gas angular momentum removal and feeding of the Seyfert 2 nucleus of NGC 1241. Our results encouraged us to perform a systematic search for the presence of nuclear activity in galaxies with circumnuclear rings or ring-like nuclear spirals (hereafter CNR galaxies).

We have concentrated the present study in CNRs because they 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. In disadvantage 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. Combes 2000) making more probable the detection of any correlation with a defined AGN feeding stage. In
the present paper we describe how was statistically compared the nuclear activity of galaxies of similar morphological type, with and without CNRs.

2. CATALOG AND ANALYSIS

A list of 81 CNR bright galaxies (available on request) was compiled by us, 64 of which were obtained from Buta & Crocker (1993) Catalog. Nine objects came from various authors: NGC 1672, Storchi-Bergmann et al. (1996); NGC 1667 and NGC 4151, Kotilainen & Ward (1997); NGC 3032 and NGC 7743, Erwin & Sparke (2002), NGC 3516 and NGC 3982, Pérez-Ramírez et al. (2000); NGC 5327 and NGC 5643, Laine et al. (1997). The remaining eight objects came from our studies: NGC 1241, Díaz et al. (2003); NGC 1566, Agüero et al. (2004); NGC 300, Mrk 1066, NGC 6221, NGC 6300, NGC 7479 and NGC 7582, Díaz (2004). Most of the objects (64) come from morphological studies of galaxies through CCD imaging surveys and atlases searches, compiled or performed by Buta and Crocker (1993). The others added here were included if they have undoubtedly defined rings from ground based observations and are nearby well resolved features ($z < 0.002$), without searching in specific AGN studies. From the whole sample, we detected two “interlopers (NGC 7469, Wilson et al. 1991; NGC 1566, Agüero et al. 2004) originated in a specific paper on AGN study which reported a new circumnuclear ring. We plotted the global properties of the sample and they do not differ from that shown by Buta and Crocker (1993), and there is no apparent difference between those corresponding to circumnuclear rings and the comparison sample presented below, due to the strong matching requirements.

It is intended to include most of the circumnuclear rings known from global morphological searches (available in the literature for $z < 0.002$), and the number of objects is enough for some of the trends found to be well over the $N^{1/2}$ threshold, which is reported as uncertainty for each result.

The activity class of the 81 objects was obtained from the catalog of Véron-Cetty & Véron (2003) and the observations of nearby galaxies by Ho et al. (1997). The activity types compiled by Veron-Cetty and Veron (1998) are almost coincident with those independently reported in the deep spectral survey of Ho et al. (1997), whenever the objects are common, which suggests that the relative distribution of Seyfert types is not strongly dependent on the two classification sources used here.

Of the 81 CNR galaxies which we studied, 60 are included in Tully’s (1988) “Catalog of Nearby Galaxies”, which was used as source for the global properties. Hereafter we refer the complete list of 81 objects as the full sample, and the selected 60, as the partial sample.
In order to assess any possible relationships between nuclear and circumnuclear activity we made a list of comparison galaxies, each one selected as the best match in Tully’s (1988) Catalog, based on the following criteria:

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

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

(iii) the difference in projected real sizes must be $\Delta R_{25}(kpc) < 0.4 R_{25}^{CNR}(kpc)$;

(iv) the departure in inclination from the CNR galaxy must be $\Delta i < 9^\circ$;

(v) the departure in morphological type numerical code from the CNR galaxy must be $\Delta T \leq 2$.

60 comparison galaxies were found without trace of CNR according to the visual inspection in the 2MASS and the DSS2 archives (with about 1 arcsec resolution). Moreover, the selected matching objects from Tully (1988) have the same distributions of distances, inclinations and brightness, therein they have the same detection probability that the hitherto known CNR galaxies. One should not forget the possible presence of interlopers in the comparison sample, but all of the comparison objects are bright nearby galaxies and were not found reported as CNR galaxies.

3. RESULTS

Environment. The local density of bright galaxies around each object in the partial and matched comparison sample (i.e. CNR or comparison galaxy) from Tully’s (1988) Catalog shows that (within the uncertainty levels) there is no marked environmental effect associated with the phenomenon of circumnuclear star formation in disk galaxies (Figure 1). The distributions of local densities have peaks in $0.34 \pm 0.12$ and $0.52 \pm 0.14$ galaxies/Mpc$^3$ for the CNR and the comparison samples, respectively.

Strong Bars. We investigated the presence of optical bars in different subsets of the partial sample and we found that $46 \pm 12\%$ of 30 CNR+AGN galaxies (Sy1, Sy2, LINER) and $42 \pm 8\%$ of all (i.e. with and without AGN) CNR galaxies were strongly barred, i.e. they are classified as SB in the RC3 Catalog (de Vaucouleurs et al. 1991). This proportion was higher (without overlapping of both $N^{1/2}$ uncertainties) than that in the sample of Ho et al. (1997), who found that $20 \pm 4\%$ of 129 AGN galaxies and $25 \pm 3\%$ of 319 spiral galaxies with and without AGN were classified as SB in the RC3 Catalog. Notwithstanding, in order to make a suitable comparison, the morphological bias must be considered. Hence, we rearranged the data with
the same morphological type grouping used by Ho and coworkers (who excluded the category S0/lenticular objects), with the following results: 38 ± 5% of 55 CNR galaxies and 43 ± 12% of 30 AGN+CNR ones, have strong bars, compared with 24 ± 6% and 20 ± 8% respectively predicted using Ho and co-workers results for each morphological type. Consequently, we find some statistical excess (without overlapping of both N^{1/2} uncertainties) of strong bars in both CNR and AGN+CNR galaxies, when compared with the spiral galaxies sample of Ho and co-workers.

**Incidence of AGNs.** 26 of the 81 objects (32 ± 6% of the full sample) were galaxies Sy 1 or 2, being this percentage unusually high, as shown in the histogram of Figure 2. For example, the value predicted considering the analysis of Woltjer (1990) of the galaxies in the Revised Shapley-Ames Catalog -by using the catalog of Véron-Cetty & Véron (1989) as AGN classification source- would be 8 ± 3% if we weight it for the distribution of morphological types in our sample. The excess is statistically significative, without overlapping of almost three times both N^{1/2} uncertainties.

To check our results, we constructed a histogram (Figure 3) for the partial sample and its comparison one. The predicted percentage for the last one, weighted by morphological type was 8 ± 3%, which is close to the proportion (6/60) of Sy 1 and Sy 2 galaxies found in this comparison sample and validates the use of Woltjer (1990) data. For the objects with CNR, the value is still clearly over the expected, with 24 Seyfert nuclei instead of 6.

**Activity Classes.** Following Maiolino & Rieke (1995) we considered the class Sy1 as the sum of classes Sy1+Sy1.2+Sy1.5. The ratio of Sy 2 to Sy 1 galaxies was 3:1 (Figures 2 and 3) instead of the expected ratio of about 1:1 for the distribution of morphological types in the samples (considering Table 5 in Woltjer 1990). This result being statistical significant even for the 24 Seyfert galaxies in the partial sample (75 ± 18% Sy 2 against 25 ± 10% Sy 1 nuclei).

21 of the pairs CNR+Comparison galaxies in the partial sample are included in the high quality spectral survey of Ho et al. (1997), which is a complete survey and represents a more uniform AGN classification source than Véron-Cetty & Véron (2003). We confirmed that all the mentioned trends in environment, bar frequency, AGN incidence and Sy2:S1 ratio, are sustained, within the uncertainties arisen in the lower number of objects of the resulting sub-sample.
4. DISCUSSION AND FINAL REMARKS

Inclination. In order to assess the effect of inclination on the detection of CNRs we constructed another comparison sample for the partial one, but this time with free inclination value. In general, CNRs are assumed to be coplanar with the main disk and the result was as expected, there being lack of galaxies with high inclinations in the CNR partial sample due to a marked selection effect, because of the fact that a highly inclined galactic disk precludes the detection of CNRs. This result also indicates that there is a constraint to the fuelling mechanisms for central starbursts and AGNs because the fact that the rings are coplanar with the global disk implies that the angular momentum direction of the disk is conserved by the infalling material down to the hundred parsecs scale. Any AGN feeding scenario for the central hundred parsecs should take into account that between a few hundred parsec to a few parsecs radii the material in the putative accretion disk and the torus ceases to be influenced by the original direction of the angular momentum of the global disk (see the “Activity Classes” Section, below).

Environment and Bars. The results shown in Figure 1 suggest that CNRs are directly associated with certain phenomena such as self instabilities, minor mergers or the capture of giant HI clouds, unless they belong to very late phase of interactions between galaxies, but the work of Corbin (2000) suggests that this would be not the case. It should be noted that most of the galaxies in the full sample had a global bar at optical or IR wavelengths (e.g. Buta & Crocker 1993) and about half of them were strongly barred, which supports the widely accepted theory that bars are the main mechanism which drives gas towards the central region of non-interacting galaxies.

Incidence of AGNs. The observational bias must be assessed when collecting data related to AGN galaxies. For example, it could be argued that the high rate of AGN reported here might be because the central region of galaxies possessing Sy activity and the CNRs are more closely studied than galaxies which do not have this features and there is therefore a greater chance of detecting the remaining counterpart. Notwithstanding, most of the CNR galaxies were discovered by morphological searches (see Buta & Crocker 1993 and Section 2). After a careful search we have found 2 “interlopers” in the sample which came from an AGN dedicated paper reporting the CNR feature. This 2 AGN+CNRs do not alter at a level of significance the results presented here, and even if a high interlopers number of 10 CNRs discovered in AGN works was allowed in the sample, the main trends reported on overabundance of AGNs still hold. In particular, the ratio of Sy 2 to Sy 1 objects (3 times), is valid even allowing for any bias toward AGN observations, unless one is forced to assume
that researchers would largely prefer to observe Seyfert 2 galaxies and would consequently detect more frequently their rings. Therein the correlation reported here must have some statistical significance and presents an important restriction to the models that describe the fuelling not only of AGN but also of circumnuclear star formation.

**Activity Classes.** The high ratio of Sy 2 to Sy 1 galaxies seen by us is not in accord with the classical unified model for AGNs, because inclination of the host galaxy should have an important impact on this model, unless one is forced to accept that the inclination of the putative molecular torus has no relation, even in the statistical sense, with the host global disk that eventually provides the fuel with a specific angular momentum orientation. It should be noted that there is an important bias towards face on CNR hosts, so the observed incidence of Sy 2 galaxies opposes the expected incidence. In any case, the absence of correlation between galaxy inclination and AGN orientation (e.g. Kinney et al. 2000) would impose important restrictions on the way the gas is funneled to the central engine in spiral galaxies.

Our results are in accordance with the observations of Malkan et al. (1999), who determined that the morphology of the nuclear region in the hundred parsec scale seems not to be an important factor in the distribution of Sy classes, but that appearance of circumnuclear filamentary dust is more related with Sy 2 galaxies. The intense star formation that occurs in most CNRs, could provide the dust that, in some still undefined way, causes the generally accepted obscuration of a Sy 1 nucleus needed to be observed as a Sy 2. We expect soon to report the results of a study on the correlation between the rate of star formation in CNRs and the degree of AGN activity, such a study could help us better understand the parallelisms between and co-evolution of these interesting phenomena.

Hunt & Malkan (1999) have found that outer rings but not bars are abnormally frequent in Sy 1 nuclei, while LINER galaxies appear to have unusually high incidence of inner rings. As these authors suggested, a possible explanation might be to postulate that LINERS and Sy nuclei are the same objects, but seen at different evolutionary stages. How does this scenario fit with our results? Again the evolutionary solution must be recalled and becomes reinforced:

i) LINER nuclei seem more coeval with inner rings (1.5 times the ratio for normal spirals, Hunt & Malkan 1999), which appear in the first stage of bar evolution scenarios, between 2 and $5 \times 10^8$ yr to form (e.g. Combes & Elmegreen 1993);

ii) Sy 2 nuclei occur in large numbers in galaxies with circumnuclear rings (4 times the ratio for normal galaxies, see Figures 2 and 3 in this paper), which would require a large
central mass concentration fuelled by the bar (e.g. Combes 2000) what in turn means that the bar is somewhat evolved and has had enough time to sweep and remove the interstellar medium inside the co-rotation radius, say more than $5 \times 10^8$ yr;

iii) Sy 1 nuclei have 3-4 times more outer rings than normal spirals and, as already pointed out by Hunt & Malkan (1999), this implies that Sy 1 nuclei would be older enough, in an evolutionary scheme, to coincide with the lifetime of outer rings ($3 \times 10^9$ yr), long after the bar has dissolved, due to the expanding circularization of the orbits in the galaxy central region (e.g. Combes 2000).

The trend pointed in paragraph (iii) would be equivalent to say that Sy 2 nuclei occur more at the stage of largest bar dimensions (just before the dissolution), being this last idea consistent with the results of Pogge (1989) and Maiolino et al. (1997) which show that bar percentage in Sy 2 galaxies appears higher than in other AGN types.

The pointed correlation trends would be reinforced by the fact that inner and circumnuclear rings can have lifetimes as short as $10^8$ yr, although these short time would preclude the detection of larger fractions of the corresponding active counterparts. Therefore, it seems plausible that the AGN evolutionary sequence is from LINER to Sy 2 and from this to Sy 1, with the Sy 2 class coeval with the “dustier” star formation era in the bar-fed evolution of the circumnuclear environment.

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Woltjer, L. 1990, in Active Galactic Nuclei, eds. Courvoisier T., Mayor M., Springer-Verlag, Table 5
Fig. 1.— Local density distribution of the CNR and comparison galaxies.
Fig. 2.— Level of nuclear activity of the full sample of CNR galaxies. The sources of the activity type are Véron-Cetty & Véron (2003) and Ho et al. (1997). We have separated the galaxies into categories as follows: S1-2 (Seyfert), L (LINER), T (transition object), HII (starburst or normal HII region nucleus). Depending on each object, “no” means that the object is not reported in these sources, or is reported as not having line emission.
Fig. 3.— Level of nuclear activity in the partial sample, both CNR and comparison galaxies. The source of the activity type is Véron-Cetty & Véron (2003). In this Catalog, “no” means that the object is not reported in the sources as AGN or strong HII nucleus.
Type of Nuclear Activity

- S 1
- S 2
- L
- H II
- no

CNR Galaxies
Comparison Galaxies