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THE CIRCUM-GALACTIC ENVIRONMENT OF LINERS

Y. Krongold,[1,2] D. Dultzin-Hacyan,[1] P. Marziani,[3] and J. A. de Diego[1]

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RESUMEN

En este artículo, analizamos el entorno circun-galáctico de galaxias LINER a partir de 166 objetos, muestra que se tomó del Catálogo de Multifrecuencias de LINERs realizado por Carrillo et al. (1999). El objetivo de nuestro trabajo consiste en comparar el entorno de distintos tipos de LINERs y, por lo tanto, subdividimos nuestra muestra en tres grupos: LINERs de tipo 1, LINERs de tipo 2 y objetos de transición (TL, por sus siglas en inglés). La búsqueda de compañeras se llevó a cabo en el Digitized Sky Survey (DSS) hasta una distancia lineal proyectada de 300 kpc, mediante la utilización de métodos aplicados en varios estudios previos. Encontramos que los LINERs de tipo 2 y los TLs parecen poseer un entorno más rico que el de las galaxias activas de tipo 1. Además, los LINERs de tipo 2 y los TLs muestran grandes compañeras con una frecuencia similar a aquella de las galaxias brillantes IRAS y las galaxias Seyfert 2. Sugerimos que una secuencia evolutiva —de los sistemas Starbursting a las galaxias de tipo 2 y, finalmente, a los AGN de tipo 1— puede ser apropiada para la mayoría de los AGN e independiente de su luminosidad.

ABSTRACT

In this paper, we study the circumgalactic environment of LINER host galaxies, in a sample of 166 objects drawn from a Multifrequency Catalogue of LINERs by Carrillo et al. (1999). The aim of our work is to compare the environment of different types of LINERs, therefore we subdivided our sample in three groups: LINERs type 1, type 2, and transition objects (TL). The search has been carried out on the Digitized Sky Survey (DSS) up to a projected linear distance of 300 kpc using methods applied in several previous studies. We found that type 2 LINERs and TLs seem to possess a richer environment than those of type 1. In addition, type 2 LINERs and TLs show large companions with frequency similar to that of bright IRAS galaxies and Seyfert 2 host galaxies. We suggest that an evolutionary sequence from starbursting systems, to type 2 and eventually to type-1 AGN, may be appropriate for most AGN and may be independent of luminosity.

Key Words: **GALAXIES: ACTIVE — GALAXIES: LINERS — GALAXIES: NUCLEI**

1. INTRODUCTION

Low Ionization Nuclear Emitting Regions (LINERs) are sources whose spectrum is dominated by low ionization emission lines at moderate luminosity, and with line widths similar to those of Narrow Line Regions (NLRs) of Seyfert galaxies. The "low ionization level" is understood with respect to Seyfert nuclei, and was quantitatively defined by Heckman (1980), with the following conditions on strong emission line intensity ratios: [O II] $\lambda3727 \gtrsim$ [O III] $\lambda5007$, and [O I] $\lambda6300 \gtrsim 0.33$ [O III] $\lambda5007$. Some of the objects studied by Heckman also showed a compact nuclear radio source, and he proposed a connection between LINERs and AGN in that seminal paper.

Prototype LINERs show large [N II] $\lambda6583$/Hα ($\gtrsim 0.6$), and [S II] $\lambda6716, 6731$/Hα intensity ratios (where for Hα only the narrow component is considered). Since these lines lie in a very accessible region of the spectra, and are very close in wavelength, some authors have used *only* the above line

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México.
[2]Harvard-Smithsonian Center for Astrophysics, USA.
[3]Osservatorio Astronomico, INAF, Italy.

TABLE 1

PROPERTIES OF LINER'S SAMPLES

Parameter	LINER 2 Average	LINER 2 σ[a]	Transition LINER Average	Transition LINER σ	LINER 1 Average	LINER 1 σ
B	12.0	1.3	12.1	1.4	11.3	1.1
V	11.3	1.5	10.6	0.7	10.7	0.9
$(U-B)$	0.32	0.21	0.23	0.24	0.44	0.13
$(B-V)$	0.84	0.14	0.78	0.16	0.86	0.12
J	9.7	1.3	9.3	1.0	9.0	1.5
$(J-H)$	0.72	0.08	0.74	0.05	0.75	0.05
$(H-K)$	0.25	0.06	0.26	0.04	0.25	0.04
[O III] λ5007/Hβ	1.7	0.7	1.4	0.7	2.7	2.1
[O I] λ6300/Hα	0.26	0.16	0.10	0.04	0.5	0.3
[N II] λ6583/Hα	1.6	0.8	0.96	0.44	1.8	0.9
[S II] λ6716, 6731/Hα	1.1	0.5	0.59	0.28	1.4	0.5
$L_{\rm FIR}/L_{\odot}$[b]	1.0×10^{10}	1.9×10^{10}	3.0×10^{10}	6.5×10^{10}	8.3×10^{9}	2.1×10^{10}
L60[c]	6.0×10^{30}	1.3×10^{31}	2.2×10^{31}	5.2×10^{31}	4.8×10^{30}	1.4×10^{31}
L25[c]	8.5×10^{29}	1.6×10^{30}	3.2×10^{30}	7.8×10^{30}	6.0×10^{29}	1.4×10^{30}
F25/F60	0.33	0.36	0.16	0.10	0.24	0.26
F60/F100	0.42	0.34	0.38	0.20	0.35	0.11
F12/F25	0.77	0.38	0.82	0.35	0.94	0.46

[a] Sample standard deviation.

[b] IRAS FIR luminosity in units of solar luminosity.

[c] Units are ergs s^{-1} Hz^{-1}.

ratios to identify LINERs. This approach is usually satisfactory, although a look at the set of the three Veilleux & Osterbrock (1987) 2D diagnostic diagrams shows a rather large spread in these emission line ratios (Filippenko, Ho, & Sargent 1993). While Seyfert 2 and LINERs are well separated on the basis of their [O III] λ5007/Hβ ratio (and also of their ratio [S II] λ6716, 6731/Hα) which is a reliable diagnostic of the ionization degree for a fixed metallicity, the distribution of LINERs partly overlaps that of low-ionization H II regions. As pointed out by Ho, Filippenko, & Sargent (1997), objects closer to the loci of H II regions turn out not to meet both criteria of Heckman's definition of "pure" LINERs. These objects are known in the literature as "transition" LINERs. Generally speaking, the strength of the low ionization lines of "transition" objects is intermediate between those of low-metallicity H II regions and "pure" LINERs. For instance the [S II] λ6716, 6731/Hα intensity ratio is typically ≈ 1 for "pure" LINERs, but can be ≈ 0.3 for transition LINERs; similarly we have [O I] λ6300/H$\alpha \approx 0.5$ for "pure" LINERs, but only ≈ 0.1 for transition LINERs, which are, on the basis of this ratio, indistinguishable from H II regions.

It is therefore not surprising if, after twenty years of debate, there is no consensus on whether *all* LINERs represent the low-luminosity end of Active Galactic Nuclei (AGN). While AGN show evidence of ionization by a non-stellar source (i.e., a strong power law continuum), the source of ionization for LINERs is still amply debated. The main possibility is ionization by a non-thermal continuum much weaker than in Seyfert nuclei, whose detection is cumbersome just because of its weakness. However, the low ionization spectrum and the low luminosity of LINERs does not demand—as for luminous radio loud AGN—a unique ionization mechanism (see also § 5.1). Some LINERs have been indeed explained in the context of shock ionization (Fosbury et al. 1978; Dultzin-Hacyan & Ruano 1996; Veilleux et al. 1999). Others have been understood as due to photoionization by stellar sources (Filippenko & Terlevich 1992; Binette et al. 1994). Filippenko & Halpern (1984) found the first LINER with broad permitted lines present in the spectrum. Since then, several objects with broad Balmer emission lines have been observed (the so-called LINER 1s in analogy with Seyferts). As we will further review in § 5.1, only these LINER 1s are straightforwardly explained with models of non-thermal power-law photoionization sources, like AGN.

In this paper we study the circumgalactic environment of 166 LINERs from the Multifrequency Catalog of LINERs (hereafter MCL, Carrillo et al. 1999). The diversity of results suggest that this kind of AGN should not be considered a particular class of objects but rather a heterogeneous ensemble. However, the above summary of the emission line phenomenology suggests that these objects can be prudently divided into three major groups: (1) "pure" LINERs (the so-called LINER 2s) which show only "narrow" emission lines satisfying the original Heckman's definition; (2) "transition" objects, whose low ionization line strength appears to be intermediate between LINERs and H II systems, and for which ionization by stellar sources seems to play a major role (Ho et al. 1997); and (3) "pure" LINERs which show evidence of broad Balmer line emission (the so-called LINER 1s). We compare the environment of these subsets of LINERs with those of Seyfert 1 (Sy1), Seyfert 2 (Sy2), and Bright IRAS (BIRG) host galaxies. The value of H_0 adopted for calculations in this work was 75 km s^{-1} Mpc^{-1}, and we assumed $q_0 = 0$.

2. SAMPLE SELECTION

We generated a LINER sample of 166 objects from the catalogue by Carrillo et al. (1999), and we then split it into three groups. The first one consists of 85 objects and contains only type-2 LINERs (hereafter L2). The second group includes 57 transition LINERs which may represent a combination of H II and LINER characteristics (hereafter TL). The third group includes 24 LINERs with broad Hα emission (hereafter L1). For the L2s, we considered only objects with redshift within the range $0.003 \leq z \leq 0.017$. The lower limit was chosen to avoid objects with very big angular size, while the upper limit was set to include a large number of objects and at the same time to avoid very small angular sizes, especially for the companions, which could be confused with stars (see § 3.1). For L1 and TL this criterion had to be softened in order to include a statistically significant amount of these objects in our sample. While the lower redshift limit for L1s was set to 0.0023, the upper limit for TLs was chosen at 0.034 (i.e., twice the distance, however we did not find any redshift dependence on the environment). Only objects whose Galactic latitude is $|b_{\rm II}| \geq 35°$ were taken into account to avoid sampling the Galactic plane. LINERs discovered by their presence in mergers or interactions were excluded from our sample to avoid any possible bias.

All the LINERs in the Ho et al. (1997) sample that follow the above criteria were included. They comprise $\approx 70\%$ of our sample (56% of the L2s, 77% of the TL, and 100% of the L1s). The Ho et al. sample is complete for galaxies brighter than $B_{\rm T} = 12.5$ mag ($\delta \geq 0°$). We included several other objects within this magnitude limit from the southern sky. A $V/V_{\rm max}$ test (Schmidt 1968) yields a value of 0.476 ± 0.021 down to magnitude $B_{\rm T} \leq 12.5$ for our sample. Therefore, our sample is highly complete for galaxies brighter than $B_{\rm T} = 12.5$. Only $\lesssim 17\%$ of the 166 LINERs are fainter than this magnitude limit.

Several average photometric and spectroscopic parameters (and the sample standard deviation) extracted from the compilation of the MCL are reported in Table 1 for our samples of L2s, TLs, and L1s. Defining characteristics of TLs are present also in our sample: TLs show lower ratio [O III] λ5007/Hβ (probably due to dilution by low-excitation H II regions), as well as lower intensity of all low ionization lines (with respect to the Balmer lines) than L2s and L1s. The IRAS colors reported in the last rows of Table 1 suggest that thermal emission by warm dust around 60 μm in TLs may be enhanced with respect to other LINER types, again pointing toward a significant role of ionization by hot, obscured stars in TLs.

We did not build a control sample. Low ionization emission lines are present in an important fraction of "normal" galaxies (see § 5.1). Therefore, any control sample would include a contamination by non-detected LINERs, making the comparison unreliable.

3. ANALYSIS

3.1. *Identification of Companion Galaxies*

The search for galaxy companions was performed automatically on the DSS with the latest version (1998) of FOCAS (Faint Object Classification and Analysis System; Jarvis & Tyson 1981), and was limited to galaxy companions that could be unambiguously distinguished from stars by the FOCAS algorithm ($\approx$ 7 arcsec; see Krongold, Dultzin-Hacyan, &

Marziani 2001 for details). We restrict our search to companion galaxies of diameters $D_C \geq 4$ kpc, since with our methodology we cannot study smaller objects because the distribution of companions is dominated by optical pairs (i.e., not physically associated). Methods and effect of plate quality, point spread function, sky background, and automatic identification and measurement of companion and background galaxies have been discussed in Krongold et al. (2001). They will not be re-discussed here; the same effects are still influencing the data analysis in this work. However, we would like to stress that we checked by eye on the computer screen each object classified by FOCAS as a galaxy to avoid mis-classifications. As it is customary (e.g., Dultzin-Hacyan et al. 1999; Krongold et al. 2001), the fraction of objects with *physical* companions $f_{\rm phys}$ is the fraction with observed companions $f_{\rm obs}$, diminished by the fraction of galaxies with an expected optical companion, namely $f_{\rm phys} = f_{\rm obs} - f_{\rm opt}$. The $f_{\rm opt}$ has been obtained from Poisson statistics, as described by Krongold et al. (2001).

4. RESULTS

4.1. *LINERs Environment*

4.1.1. *Companions within 3$D_{\rm L}$*

We looked for companions in a circular area with radius equal to 3 times the diameter of the central object (3$D_{\rm L}$).

Companions with diameter $D_C \geq 4$ kpc Of 85 L2s, ≈ 68% have at least one companion of diameter ≥ 4 kpc within 3$D_{\rm L}$, vs. 61% of the 57 "Transition" LINERs (TLs), and 50% of the 24 L1s. If optical companions (computed according to Poissonian statistics) are subtracted, $f_{\rm phys}$ is ≈ 36%, 27%, and 12% for the L2, TL, and L1 samples, respectively. According to a χ^2 test, there is no significant excess of companions between the L2 and TL samples (see § 4.2). However, the same test shows that there is an excess (at a 97.5% confidence level) of companions among L2s with respect to L1s.

Companions with diameter $D_C \geq 10$ kpc Of 85 L2s ≈ 38% have at least one companion of diameter $D_C \geq 10$ kpc, within a search radius of 3$D_{\rm L}$. 40% of 57 TLs show this property. On the other hand, only ≈ 21% of the 24 L1s showed a companion with $D_C \geq 10$ kpc, within 3$D_{\rm L}$. If optical companions are subtracted, f_{phys} is ≈ 26%, 21%, and 1.5% for the L2s, TLs, and L1s, respectively. These values indicate a clear excess of large companions ($D_C \geq 10$ kpc) among L2s with respect to L1s. A χ^2 test gives a confidence level of 99% for this result. Our results are summarized in Table 2.

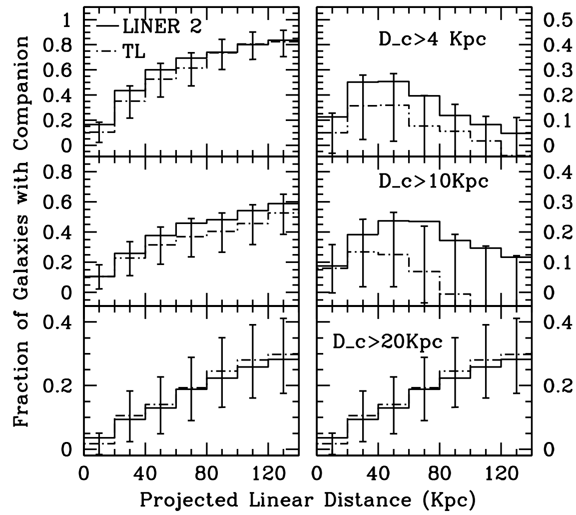


Fig. 1. LINER 2 (solid line) vs. TL (dotted line) environment. Left: Cumulative distributions of nearest observed companion binned over 20 kpc, within a projected linear distance limit of 140 kpc. Right: Distributions of "physical" companions. The upper panels show the distribution for galaxies with diameter $D_{\rm C} \geq 4$ kpc, the middle panels show "bright" companion galaxies whose diameters are $D_{\rm C} \geq 10$ kpc, and the lower panels show companions with $D_{\rm C} \geq 20$ kpc. The error bars are at a 2σ confidence level.

4.1.2. *Cumulative Distribution of the Nearest Companions and Distribution of Physical Companions*

The search radius for companions was *in all cases* equal to 300 kpc of projected linear distance, above which we assumed a "non detection". In Figures 1, 2, and 3 the left panels show the cumulative distribution of LINERs belonging to different classes as a function of the nearest companion projected linear distance, computed *without subtraction of optical companions*. Restrictions on nearest companion diameters are, from top to bottom, $D_{\rm C} \geq 4$ kpc (all companions recognizable as galaxies on the DSS), $D_{\rm C} \geq 10$ kpc, and $D_{\rm C} \geq 20$ kpc. The abscissa is limited to a projected linear distance of 140 kpc, beyond which no statistical variation is found in the cumulative distribution of companions for the various samples.

From Poisson statistics, we calculated the expected f_{opt} at distances 20 kpc, 40 kpc, etc. We built the distribution of the "physical" companions

TABLE 2

FRACTION OF OBSERVED, OPTICAL, AND PHYSICAL COMPANIONS

Sample Id.	Sample Size	Frequency of Companions (%)			Significance[a]
		Observed	Expected	Physical	%
		All LINERs (Companion Diameter $\geq$ 4 kpc)			
LINER 2	85	68%	32%	36%	...
TL	57	61%	34%	27%	not signif.
LINER 1	24	50%	38%	12%	97.5%
		All LINERs (Companion Diameter $\geq$ 10 kpc)			
LINER 2	85	38%	12%	26%	...
TL	57	40%	19%	21%	not signif.
LINER 1	24	21%	19.5%	1.5%	99%
		LINERs from Ho et al. (1997)(Companion Diameter $\geq$ 4 kpc)			
LINER 2	48	69%	31%	38%	...
TL	44	55%	33%	22%	not signif.
LINER 1	24	50%	38%	12%	97.5%
		LINERs from Ho et al. (1997) (Companion Diameter $\geq$ 10 kpc)			
LINER 2	48	40%	14%	26%	...
TL	44	32%	17%	15%	not signif.
LINER 1	9	21%	19.5%	1.5%	99%

[a]Statistical significance for the hypothesis that the listed samples are different from the L2 sample.

from the value of f_{phy}. The right sides of Figs. 1, 2, and 3 show this distribution. The distribution of physical companions with $D_{\rm C} \geq 20$ kpc is very similar to the cumulative distribution of observed companions, since the density of objects with this diameter is nearly zero, and therefore the probability of finding optical companions is negligible.

The error bars on the comparison samples frequencies were set with a "bootstrap" technique (Efron & Tibshirani 1993) by randomly re-sampling the comparison galaxies into a large number of pseudo-samples (we built 3000 pseudo-control samples for the L1 and the TL samples). The uncertainty on the companion frequency was set as equal to twice the standard deviation measured from the distribution of 3000 companion frequencies computed for each pseudo control sample, as done in our previous works (Dultzin-Hacyan et al. 1999; Krongold et al. 2001).

LINER 2s vs. Transition LINERs Fig. 1 compares the environments of L2s and TLs. There is a barely significant excess of physical companions with $D_{\rm C} \geq 10$ kpc among L2s (but see § 4.2). For large companions ($D_{\rm C} \geq 20$ kpc) the difference definitely vanishes.

LINER 2s vs. LINER 1s As it can be deduced from Fig. 2, there is a statistically significant excess of companions in the L2 sample for diameters $D_{\rm C} \geq 10$ kpc, both total and physical, up to $d_P \approx 120$ kpc. This result is especially robust for $d_P \lesssim 40$ kpc, since it is visible also for $D_{\rm C} \gtrsim 20$ kpc. Although the difference between L1s and L2s persists beyond 40 kpc for $D_{\rm C} \gtrsim 20$ kpc, due to small number statistics the difference cannot be considered to be significant in this diameter range.

Transition LINERs vs. LINER 1s Fig. 3 shows the cumulative distribution of the nearest companion for TLs vs. L1s. If the environments of TLs and L1s is compared, an excess of companions can be observed in the TLs sample for companion diameters $D_{\rm C} \geq 10$ kpc up to a projected linear distance of ≈ 60 kpc.

Infrared selected LINERs It could be argued that some L2s and TL from our sample have been discovered on the basis of their high IR emission, which is regarded to be an effect of interaction. This would introduce a bias for these samples in favor of rich environments. We repeated our analysis excluding IRAS selected LINERs (which account for $\approx 12\%$ of the 166 objects) and found no difference in our results.

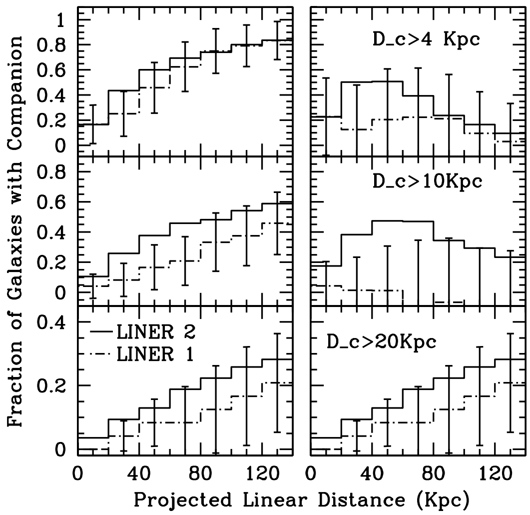


Fig. 2. LINER 2 (solid line) vs. LINER 1 (dotted line) environment. Left: Cumulative distributions of nearest observed companion binned over 20 kpc, within a projected linear distance limit of 140 kpc. Right: Distributions of "physical" companions. The upper panels show the distribution for galaxies with diameter $D_{\rm C} \geq 4$ kpc, the middle panels show "bright" companion galaxies whose diameters are $D_{\rm C} \geq 10$ kpc, and the lower panels show companions with $D_{\rm C} \geq 20$ kpc. The error bars are at a 2σ confidence level.

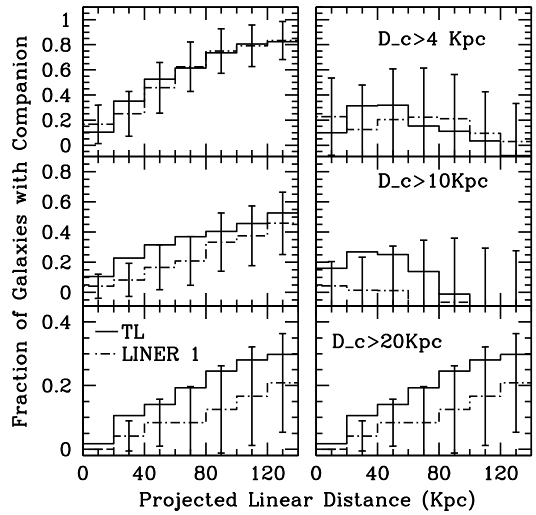


Fig. 3. Transition LINER (solid line) vs. LINER 1 (dotted line) environment. Left: Cumulative distributions of nearest observed companion binned over 20 kpc, within a projected linear distance limit of 140 kpc. Right: Distributions of "physical" companion. The upper panels show the distribution for galaxies with diameter $D_{\rm C} \geq 4$ kpc, the middle panels show "bright" companion galaxies whose diameters are $D_{\rm C} \geq 10$ kpc, and the lower panels show companions with $D_{\rm C} \geq 20$ kpc. The error bars are at a 2σ confidence level.

4.1.3. *LINERs from the Ho et al. (1997) Sample*

In this section we present environmental results only for those LINERs that were selected from the survey by Ho et al. (1997). We do this because our LINER sample was compiled from different studies and, therefore, our results could be reflecting selection effects rather than the actual LINER environment. Since Ho et al. (1997) is a complete and homogeneous survey and 70% of our sample comes from it, the results presented here are independent of any possible bias outlined above. Our subsample consists of 48 L2s, 44 TLs, and 24 L1s.

In Table 2 we present the fraction of observed, optical, and physical companions within $3D_{\rm L}$ for this subsample. The results in this case are completely consistent with our results for the general sample, showing that the environmental difference for L1s and L2s is real and not an effect of selection. The level of significance for the results remains intact, being 97.5% for companions with $D_{\rm C} \geq 4$ kpc, and 99% for companions with $D_{\rm C} \geq 10$ kpc.

The cumulative distributions of the nearest companions and the distributions of physical companions (plots not shown) are also very similar to those obtained for the whole sample.

4.2. *LINERs with Different Morphological Type*

It has been suggested that LINERs in early type hosts have ~ 2 times richer environment than those hosted in late type galaxies (Schmitt 2001). To test this result, we decided to split our samples in two groups: early type objects (defined hereafter as elliptical or SO galaxies) and late type galaxies (defined as those with morphological type Sa or later). Since the L1 sample contains a small number of objects, it was not included in this case. Including only objects with known morphological types, the sample of early-type objects consisted of 30 L2s and 11 TL, and the sample of late-type LINERs of 55 L2s and 41 TLs. Table 3 presents the results for the separation of the samples according to morphological type. Within $3D_{\rm L}$, objects hosted in early types show ~ 2 times higher frequency of companions than those hosted in late types (both for companions with $D_{\rm C} \geq 4$ kpc and $D_{\rm C} \geq 10$ kpc). This result has a confidence level of 97.5% for the L2s, and systematically lower for the TL sample because of the small number of TLs hosted in early type galaxies. This result suggests that a morphology-density effect may be operating also in our sample. In fact, this effect is responsible for the differences between the envi-

TABLE 3

SEPARATION OF THE SAMPLES BY MORPHOLOGICAL TYPE

Sample Id.	Sample Size	Frequency of Companions (%)			Significance[a]
		Observed	Expected	Physical	%
LINERs 2 (Companion Diameter ≥ 4 kpc)					
Early Type	30	80%	28%	52%	...
Late Type	55	62%	35%	27%	97.5%
LINERs 2 (Companion Diameter ≥ 10 kpc)					
Early Type	30	47%	10%	37%	...
Late Type	55	33%	16%	17%	95%
Transition LINERs (Companion Diameter ≥ 4 kpc)					
Early Type	11	73%	26%	47%	...
Late Type	41	54%	36%	18%	95%
Transition LINERs (Companion Diameter ≥ 10 kpc)					
Early Type	11	55%	13%	42%	...
Late Type	41	41%	20%	21%	not signif.

[a] Statistical significance for the hypothesis that the early and late type samples are different.

ronment of L2s and TLs found in § 4.1, since our L2 sample is slightly skewed towards early type galaxies with respect to the TL sample. On the other hand, the distribution of morphological types cannot be responsible for the difference found between L2s and L1s: 2/3 of L2s are in late type galaxies, against 1/2 of L1s. If the morphology density relationship were governing the circumnuclear environment of L1 and L2, we should observe more companions for L1s than for L2s, in conflict with our results. It is also noteworthy that a role of environment affecting morphology does not affect the results of previous works by Dultzin-Hacyan and collaborators on the environment of Seyferts, Narrow Line Seyfert 1 galaxies, and bright IRAS galaxies, since (1) dense regions like clusters were avoided; (2) a control sample closely matching the morphological type of the active galaxies sample under scrutiny was always defined.

Finally, we stress that excluding objects that are members of the Virgo Cluster has a negligible effect on our analysis.

4.3. *LINERs vs. Sy1s, Sy2s, and BIRGs*

In order to study the difference between the environment of LINERs, Seyfert 1, and Seyfert 2 galaxies we used the data obtained for the Seyfert environment by Dultzin-Hacyan et al. (1999). A similar comparison between BIRGs and LINERs is possible using the environmental data by Krongold, Dultzin-Hacyan, & Marziani (2002). The redshift range of our LINER samples is the same as the one of the Seyfert 2 sample of Dultzin-Hacyan et al. (1999) and of the BIRG sample of Krongold et al. (2002). The comparison of LINERs, Sy1s, and Sy2s, and BIRGs is very straightforward from our previous work, since as in Dultzin-Hacyan et al. (1999) and Krongold et al. (2002), we also searched for companion galaxies of diameters $D_{\rm C} \geq 10$ kpc within a search radius up to 140 kpc. We calculated the cumulative distribution for the projected linear distance of the first observed companion for the different sets of objects. The error bars were set with the bootstrap technique, and are at a 2σ confidence level.

LINER 2s The upper left panel of Figure 4 shows that there is a statistically significant excess of companions in the L2 sample with respect to the Sy1, as found between Sy2s and Sy1s by Dultzin-Hacyan et al. (1999). The left middle and lower panels of Fig. 4 show that there is no statistical difference between the environments of BIRG, Sy2 galaxies, and L2s.

Transition LINERs The middle and lower central panels of Fig. 4 show that the environments of Sy2s, BIRGs, and transition LINERs are almost equal. On the other hand, there is an marginally significant excess of objects with companions in TLs, with respect to Sy1s for projected distances $\lesssim 60$ kpc (central upper panel of Fig. 4).

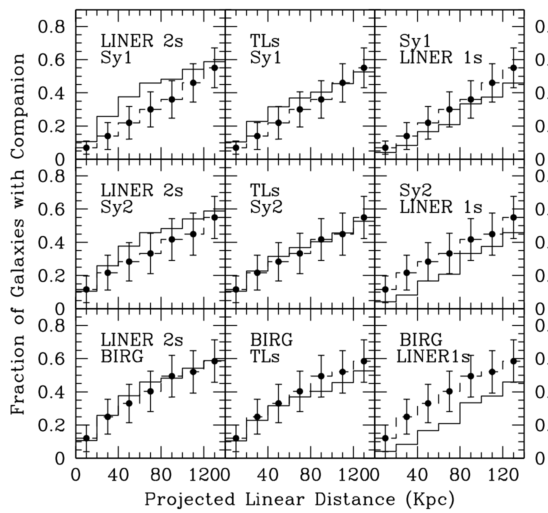


Fig. 4. The distributions of the nearest observed companion with diameter $D_C \geq 10$ kpc, binned over 20 kpc, up to a projected linear distance of 140 kpc, for Sy1, Sy2, BIRG, and LINER 2, TL, and LINER 1 galaxies. Upper panel: LINERs vs. Sy1 galaxies. Middle panel: LINERs vs. Sy2s. Lower panel: LINERs vs. BIRG galaxies. The 3 left panels show the results for L2s, while the central and the right panels for the TLs and L1s, respectively. In all cases, solid lines correspond to the LINER sample, while dashed lines refer to Sy1 in the upper panel, Sy2 in the middle, and to BIRG in the lower panel. The error bars are at a 2σ confidence level.

LINER 1s The right upper panel of Fig. 4 shows that there is no statistical difference between the environments of L1s and Sy1 galaxies. On the contrary, the right middle and lower panels of the figure show a significant excess of companions in the environment of Sy2s and BIRGs with respect to L1s.

5. DISCUSSION

The main point from the previous analysis is an intrinsic difference in the environment richness among L2s and L1s, with the first having richer environment than the latter, and companion frequency very similar to those of Sy2s, BIRGs, and TLs. Before discussing the implications of our results, we will briefly review our present understanding of the three distinct LINER classes analyzed in this paper.

5.1. *On the Nature of LINERs*

LINER 1s From observations in X-rays, radio, and optical range, it is now clear that most L1s are low luminosity AGN (LL-AGN). The Hα luminosity of L1s is positively correlated with the X-ray luminosity in the 2–10 keV band (Terashima, Ho, & Ptak 2000a; Terashima et al. 2000b), as in Sy1s. Compact sources have been detected in several of these objects in the hard X, radio, and UV domain (Iyomoto et al. 1996; Terashima et al. 1998; Weaver et al. 1999). The X-ray spectra of L1s is well represented by a two component model: a power law component plus soft thermal emission (Terashima et al. 2000a).

L1 spectra may be produced by "turned off" AGN. As already pointed out, the low ionization emission line spectrum and the relatively low luminosity can be produced under diverse circumstances. A fading AGN continuum is an intriguing possibility and must be considered in some detail. If an AGN continuum is turned off, high ionization emission from the Narrow Line Region (NLR) will be first affected, leaving a low-ionization spectrum that may be classified as a LINER spectrum (Eracleous, Livio, & Binette 1995). Therefore a Sy1 nucleus could evolve into a L1. In the past ten years, a few LINERs have developed strong Balmer line broad components (turned "on"), so that their classification has changed into Seyfert 1 (or BLRGs; see the case of Pictor A: Sulentic et al. 1995; Halpern & Eracleous 1994). It remains to be seen if there will be a change also in the narrow line emission.

LINER 2s The origin of L2s is less well understood. L2s are the more abundant form of low level activity in nearby galaxies. In the optical spectroscopic survey by Ho et al. (1997) L2s were detected in 28% of the galaxies with $B_T \leq 12.5^m$ in the northern sky. On the other hand, Seyfert and L1 nuclei appeared in only 11% and 5% of these galaxies. If L2s are also genuine LL-AGN, the emission from their nuclei should be obscured, in analogy with the expectations of the Unified Scheme for Seyfert galaxies (see for example Halderson et al. 2001). A polarized broad Hα line has been indeed detected in some LINER 2s (e.g., Barth, Filippenko, & Moran 1999), and strong fluorescent iron Kα emission lines with equivalent width of $\approx$ 300 eV have been observed (Weaver, et al. 1999). In some of these objects the X-ray spectrum is absorbed by a column density $\gtrsim 10^{23}$ erg cm^{-2}. Radio observations have shown the occurrence of compact cores in 50% of L2s (Nagar et al. 2000; Falcke et al. 2000). These characteristics resemble the ones of luminous Sy2 galaxies. Thus, at least $\approx 1/2$ L2s are the low ionization, low luminosity analogs of Sy2 galaxies. This number represents only a lower limit to the actual fraction of

AGN LINERs, since (1) the spatial resolution may not be good enough to constrain the size of the core and (2) the AGN contribution to the total emission might be masked by the shock or/and star-formation contribution in composite systems.

Evidence of an obscured AGN has not always been found in Seyferts 2s and L2s. Absence of polarized broad lines in several objects may indicate either extreme obscuration (a column density $\gtrsim 10^{24}\mathrm{cm}^{-2}$), or a truly absent AGN. It is possible to show that the line emitting gas of such L2s may be ionized by sources other than an AGN. Among the processes that may account for L2 spectra there are (1) photoionization by a evolved binary systems or even (2) by a cluster of hot, young stars, and (3) collisional ionization from shocks. Terashima, Ho, & Ptak (2000) and Terashima et al. (2002) found evidence of extended hard X-ray emission in L2s. They suggested that the origin of X-rays arises from a collection of discrete sources, probably evolved binary systems, rather than from an AGN. These systems account for 4 of the 11 L2s surveyed by Terashima et al. (2002). Maoz et al. (1998) suggested, from UV observations, that at least in some L2s the source of ionization may be a cluster of massive stars (however, to reproduce the spectra, they need stellar masses $\gtrsim$ 100 $M_\odot$, see below). These authors also suggested that even in those L2s where a LL-AGN has been detected, a stellar component is still necessary to account for the observed emission line ratios. In this case, the non-thermal component should become more prominent only at high energies. The situation regarding the actual relevance of hot, young stars (which are very short-lived) in producing L2 phenomenology is at present unclear.

Shock heating can be produced by collision of molecular clouds without having necessarily any accreting black hole. Intriguing examples are produced by colliding pairs of galaxies like Kar 29 (Marziani et al. 1994; Hearn & Lamb 2001; Marziani et al. 2001). In this case the host galaxy is of morphological type Sc. LINERs produced by molecular cloud collisions may fade away since formation of a massive black hole may not occur in bulge-less Sc galaxies. In objects similar to Kar 29, the occurrence of shock heating can be easily demonstrated since line emission from clouds is partially resolved both spectroscopically and spatially. These systems are probably not unique cases in which shock heating is actually occurring and dominating over other emission processes. Although they are probably rare, it is difficult to even tentatively assess their frequency in the currently available spectroscopic surveys.

Summing up, L2s are probably a heterogeneous class which includes (1) "edge-on" L1s; (2) systems in which binary stars provide significant X ray emission, and (3) shock heated systems.

Transition LINERs The origin of TLs is also not understood, although the evidence of ubiquitous thermal photoionization seems stronger in the case of TLs than in the case of L2s. Photoionization by hot stars can reproduce very well the optical spectra of these objects (Shields 1992; Filippenko & Terlevich 1992). However, star formation models need very massive stars, and they can reproduce the spectra only if the UV continuum is dominated by Wolf-Rayet stars (Barth & Shields 2000). Wolf-Rayet features (like broadened He II λ4686) have not been observed in TL. On the other hand, shock heating can also reproduce very well the optical spectra of these objects (Dopita & Sutherland 1995). An intriguing possibility is that TLs might be composite systems in which the optical signal of a very weak active nucleus has been spatially blended by circumnuclear star forming regions (Ho, Filippenko, & Sargent 1993; Ho 1996). Therefore, emission line ratio could result from the blending of a high ionization component due to the NLR and low ionization H II emission (Rafanelli & Marziani 1992; Rafanelli et al. 1993, for the cases of NGC 7592 and Mkn 739) or H II and LINER emission (Ho et al. 1993). To test this idea, some authors have observed TLs at radio frequencies, since the radio range is not affected by dust obscuration or photoelectric absorption. For instance, Filho, Barthel, & Ho (2000) studied the radio properties of a sample of transition LINERs, and made a comparison with H II galaxies. They found that, unlike H II galaxies, some TLs did have compact cores of radio emission. They concluded that TLs may be divided in two categories: a first one, with only an extended, steep radio spectrum of low surface brightness; and a second one which shows, in addition to extended emission, also compact radio emission. In their study, one out of five TLs belong to the second category, and can therefore be considered an obscured/low-luminosity AGN. As the authors stress, objects without compact radio emission may still harbor a very weak nuclear component masked by dominant emission from surrounding star-forming regions. Concluding, TL are perhaps better understood supposing dominant thermal emission, but with the non-negligible contribution of a heavily obscured and/or low-power non-thermal source.

5.2. *The Role of Environmental Effects*

TLs are objects that show evidence of strong star formation and, in several cases, of a hidden low-luminosity AGN. Their environment is similar to the one of L2s, Bright IRAS galaxies and Seyfert 2s, with a relatively high fraction of nearby large companions ($\approx 30\%$ with $D_{\rm C} \gtrsim 10$ kpc within 60 kpc of projected linear distance; see Fig. 4). Also, the TL environment is richer than that of Seyfert 1s by a 1.5 factor for companions with $D_{\rm C} \gtrsim 10$ kpc. Even if the statistical significance of this last result is not very high, the trend is consistent with the one relating TLs and Sy2s. TLs should be considered as "young" objects in a sense that a fraction of their host galaxies is experiencing strong tidal forces.

L2s show the highest frequency of interacting systems among all LINERs. However, as shown in § 4.2, when the effects of morphology are accounted for, they show environments similar to those of TLs. The merger fraction seems to be significantly higher (by a factor of $\gtrsim 3$) than in L1s. Several L2s hosted in mergers may be purely shock heated systems. Strong interactions and merging favor the occurrence of molecular gas cloud collision (and hence of a LINER spectrum without accretion). As stressed by Marziani et al. (1994), a collision between galaxies is a very efficient way to produce molecular cloud collisions, which are a very likely agent in the production of shock-heated gas, and this could produce L2s.

Definitely, L1s look different from L2s. Their circumgalactic environment is similar to that of the Seyfert 1, and probably also to that of field galaxies. L1s fewer less companions than Sy2, TLs, and Bright IRAS galaxies. The observation of very broad, faint Balmer lines in L1s may hint at accretion occurring at very low Eddington ratio (Sulentic, Marziani, & Dultzin-Hacyan 2000). From our data, if our interpretation in the interaction scenario is correct, fading AGN (§ 5.1) may not be significantly present among L2s, since L2s are the ones showing the largest excess of bright companions, and should be therefore regarded, at least in a statistical sense, as young objects. The low frequency of interacting systems among L1s is instead consistent with some L1s being fading/unstable type-1 AGN. L1s definitely look like more evolved objects, in which tidal effects may have been long gone.

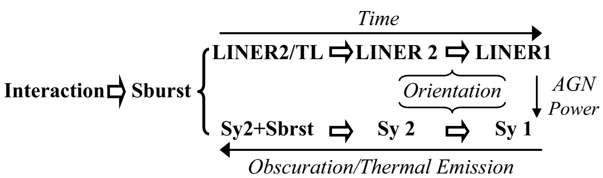
The results obtained for LINERs in this study are consistent with the ones by Schmitt (2001). Including *all* the objects in the Ho et al. (1997) sample, Schmitt found that $\sim 41\%$ and $\sim 29\%$ of the LINER and transition objects, respectively, had a physical companion within $3D_{\rm L}$. He did not consider L1s and L2s separately. By mixing type 1 and 2 in our sample, we found 29% for LINERs and 27% for TL (for companions with $D_{\rm C} \geq 4$ kpc, the closest case to Schmitt's method). The apparent difference of companions for LINERs between Schmitt's method and ours may be qualitatively explained if we consider that (1) Schmitt's sample contains a higher fraction of early type objects (and, according to § 4.2, this increases the fraction of galaxies with companion in his sample), and that (2) Schmitt's method may include objects with diameter $D_{\rm C} < 4$ kpc.

However, Schmitt (2001) claims that LINERs do not have an excess of companions when compared to a control sample of non-active galaxies, nor do Seyferts or H II galaxies. We think that this effect is due to a bias in his control sample. 92% of the objects in it have early type morphology (i.e., are Ellipticals or S0s), while only 8% of them are hosted in spiral galaxies. This means that Schmitt's absorption line galaxy control sample consists basically of bright early type objects. As was shown in § 4.2 (and also in Schmitt's paper and references therein), galaxies with early type morphology are found in interaction more often than late types galaxies. Thus, Schmitt's environmental results may be influenced by the preferential occurrence of earlier morphological types in denser environment. There is an obvious morphological type distribution mismatch between the absorption line control sample and the other Schmitt samples: in the Seyfert sample, the percentage of early type galaxies is 29% vs. 92% in the control sample. The mismatch is even more severe for H II galaxies (5% early type). This means that Schmitt control sample is not comparable to his Sy and H II samples. Furthermore, the comparison with separation of different morphological types (E+S0 vs. Spirals) is ultimately based on small numbers.

In the case of LINERs, when only early type galaxies (E+S0) are considered, Schmitt's data show 57% vs. 35% objects with companions within $3D_{\rm L}$ among LINERs and absorption line galaxies (he does not give a value for spirals due to the small number of objects in his control sample). Any difference with our results on LINERs could be exclusively due to the mixing of L1s and L2s done by Schmitt (2001).

5.3. *A Low-Luminosity Evolutionary Sequence*

Interaction with a massive companion galaxy is likely to affect the evolution and obscuration of an AGN. The properties summarized in the previous sections on environment and spectroscopic properties may suggest an inception in an interaction-induced Starburst, with gradual development of a LINER, and evolution to higher non-thermal luminosity and lower obscuration. A possible sequence driven by interactions can be outlined as follows:



There are several lines of evidence that support this simple evolutionary pattern for Seyfert galaxies (extensively reviewed by Dultzin-Hacyan & Ruano 1996, and by Krongold et al. 2002). Basically, the contribution of thermal emission to the bolometric luminosity on the one hand and obscuration effects on the other, appear to decrease along the sequence for Seyferts. The results summarized previously suggest that this may be also the case for LINERs.

In the horizontal direction the sequence begins from fully-obscured type 1 activity i.e., from objects seen first as TLs and some L2s in which non-thermal activity is minimally detectable. TLs will be eventually seen as type 2 AGN with mixed Seyfert/Starburst properties and some of them as L2s. Later, they may appear as type 1 AGN whose obscuration is dependent on viewing angle (objects with a hidden BLR as supposed in the "unification" scenario). A final stage may be fully unobscured type 1 activity (without molecular torus). In this sequence, TLs are considered younger objects than L2s, and therefore, in principle, one would expect their incidence of companions to be larger than that of L2s. A similar result has been proposed at higher luminosity by Storchi-Bergmann et al. 2001: they found that mixed Starbursts/Sy2 objects are more likely to be in interaction than non-composite Seyferts 2s. However, this is not observed between L2s and TLs; both types of objects show similar environments. A possible explanation is that non-AGN LINER 2s (i.e., shock heated LINERs), possibly triggered also by interactions, may be biasing our L2 sample to a larger fraction with companions. Even if this is the case, this possible "contamination" cannot change our results on environment between type 1 and type 2 AGN, as discussed below.

The obscuration scenario is supported by the detection of polarized broad line components and compact radio cores in several Sy2s, and L2s, and by the presence of compact radio cores in Sy2s, L2s, and in a minority of TLs. These features can be considered the signatures of a hidden AGN. The AGN to non-AGN (thermal emission) power ratio may increase along with decreasing obscuration. Terashima et al. (2000) found that the contribution of an AGN in L2s could be as low as 5% of the observed Hα luminosity (without obscuration). Nagar et al. (2000) found that L2s and TLs have smaller radio core luminosity than L1s, with TLs having the smallest values. At higher luminosity, a strong support for this idea is the finding by Cid Fernandes et al. (2001) that $\approx$ 50% of Sy2s are composite objects with Starburst + Seyfert characteristics. Storchi-Bergmann et al. (2001) have also proposed an evolutionary trend from composite to non-composite Sy2s, as suggested by their results (see above). Furthermore, Tran (2003) showed that only 50% of Sy2s really host a hidden broad line region (HBLR), and suggested that rather than obscuration, non-HBLR Sy2s are weak AGN, where a broad line region do not form. Tran (2003) concluded that an evolutionary scenario from non-HBLR to HBLR Sy2s could be present, an idea similar to the one presented here.

Ultra Luminous Infrared Galaxies (ULIRGs) have been considered to be the precursors of quasars, and have been found to be in strong interacting systems (Sanders, Surace, & Ishida 1999 and references therein). Therefore, the evolutionary sequence proposed for LINERs (as well as the one for Seyfert and BIRGs suggested by Krongold et al. 2002) may be considered as an extension to the more luminous end of AGN. The sequence of the scheme above goes in the sense of a decreasing thermal/non thermal ratio, from pure starburst, TLs (which may eventually evolve into L2s or Sy2s), L2s, and ultimately L1s.

An additional caveat is that we know very little about the nature of L2s. As summarized in § 5.2, $\leq$ 1/2 of L2s may miss a true AGN, and may be ascribed to other ionization processes. Such systems may be biasing our statistics in favor of a richer environment. Therefore, our conclusion could be overturned, but only in the extreme case that *almost all* L2s with extended X-ray emission (non-AGN LINERs) were strongly interacting (the worst possible scenario). This case cannot be formally excluded; however if these systems were interacting even as frequently as BIRG galaxies (i.e., a sample strongly biased toward interactions and high SFR processes), the evolutionary scheme would still be appropriate, since BIRGs have environment so similar to the one of L2s. As an attempt of estimate the fraction of non-AGN LINERs in interaction, a quick check of the environment of 4 L2s with extended X-ray emission (studied by Terashima et al. 2002) was performed. Only 2 of the objects showed a close companion. These numbers are too small to provide any reliable conclusion, but they suggest that the extreme scenario outlined above may not be appropriate. Rather, they are consistent with the assumption of environmental similarity between non-AGN LINERs and BIRG galaxies, and therefore, with the proposed evolutionary sequence.

6. CONCLUSION

If interactions play a role in triggering nuclear activity, an important consideration is that type 1 AGN may require a long timescale to emerge. The time needed for a type-1 AGN could be longer than the escape time of an unbound companion from the very close environment, or comparable to the timescale needed for an evolved merger ($\sim 10^9$ yr; see Krongold et al. 2002). This explains why BIRGs and type-2 AGN are found more often with closer companions (Krongold et al. 2001; 2002).

LINERs are the least energetic AGN; LINERs can be produced without accretion on compact sources by shocks in strongly interacting galaxies. The commonality of observed parameters in systems with different ionization sources is likely to explain why LINERs are so frequently observed. Nevertheless, we have emphasized what appears to be a common property of type 2 AGN (L2s and Sy2s): a circumgalactic environment that is significantly richer than that of type-1 AGN, and similar to that of star forming galaxies (i.e., the Bright IRAS sample). Not surprisingly, TLs and L2s show evidence of nuclear/circumnuclear star formation, as do $\approx 50\%$ of Seyfert 2s. An evolutionary sequence from Starburst, Sy2, to Sy1 seems to be applicable to LINERs as well, along a path from TLs, L2s, and L1s. We suggest that this sequence may be very general and basically independent of luminosity, since an analogous sequence has been proposed for luminous quasars as well (from ULIRG to QSO).

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José Antonio de Diego and Deborah Dultzin-Hacyan: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D. F., México (jdo,deborah@astroscu.unam.mx).
Yair Krongold: Instituto de Astronomía, UNAM; Present address: Harvard-Smithsonian Ctr. for Astrophysics, MS 31, 60 Garden Street, Cambridge, MA 02138 USA (krongold@head-cfa.cfa.harvard.edu).
P. Marziani: Osservatorio Astronomico, INAF, Vicolo dell'Osservatorio 5, I–35122, Padova, Italy (marziani@pd.astro.it).