ACTIVE GALACTIC NUCLEI IN VOID REGIONS

ANCA CONSTANTIN
Department of Physics, Drexel University, Philadelphia, PA 19104

FIONA HOYLE
Department of Physics and Astronomy, Widener University, Chester, PA 19013

AND

MICHAEL S. VOGLEY
Department of Physics, Drexel University, Philadelphia, PA 19104

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ABSTRACT

We present a comprehensive study of accretion activity in the most underdense environments in the universe, the voids, based on the SDSS DR2 data. Based on investigations of multiple void regions, we show that active galactic nuclei (AGNs) are definitely common in voids, but that their occurrence rate and properties differ from those in walls. AGNs are more common in voids than in walls, but only among moderately luminous and massive galaxies ($M_r < -20$, $L_{[O_\alpha]}/L_{[O_\beta]} < 10^5$), and this enhancement is more pronounced for the relatively weak accreting systems (i.e., $L_{[O_\alpha]} < 10^{39}$ erg s$^{-1}$). Void AGNs hosted by moderately massive and luminous galaxies are accreting at equal or lower rates than their wall counterparts, show lower levels of obscuration than in walls, and have similarly aged stellar populations. The very few void AGNs in massive bright hosts accrete more strongly, are more obscured, and are associated with younger stellar emission than wall AGNs. These trends suggest that the accretion strength is connected to the availability of fuel supply, and that accretion and star formation coevolve and rely on the same source of fuel. Nearest neighbor statistics indicate that the weak accretion activity (LINER-like) usually detected in massive systems is not influenced by the local environment. However, H$\alpha$ galaxies, Seyferts, and transition objects are preferentially found among more grouped small-scale structures, indicating that their activity is influenced by the rate at which galaxies interact with each other. These trends support a potential H$\alpha$—Seyfert/transition object—LINER evolutionary sequence that we show is apparent in many properties of actively line-emitting galaxies, in both voids and walls. The subtle differences between void and wall AGNs might be explained by a longer, less disturbed duty cycle of these systems in voids.

Subject headings: galaxies: active — large-scale structure of universe — methods: statistical — quasars: emission lines

1. INTRODUCTION

The regions that are apparently devoid of galaxies (Kirshner et al. 1981) and clusters (Einasto et al. 1980), the voids, are arguably the best probes of the effect of the environment and cosmology on galaxy formation and evolution. If, as suggested by the standard cosmological paradigm, structure in the present-day universe formed through hierarchical clustering, with small structures merging to form progressively larger ones, galaxies in the currently most underdense regions must be the least “evolved” ones, as they must have formed at later times than those in the dense regions. Therefore, void and cluster galaxies must follow different evolutionary paths. Disturbing processes like stripping and harassment, that operate preferentially in crowded environments, should occur rarely in voids. Studies of the properties of the void galaxies, in contrast to those in relatively crowded regions, or walls, should provide some of the strongest constraints for distinguishing the intrinsic properties, which characterize a galaxy when it is first assembled, from properties that have been externally induced, over the whole history the universe: the “nature versus nurture” problem.

Statistically significant conclusions regarding the distinctness of the void galaxies relative to those in denser regions, hereafter the walls, emerged only recently, with the advent of large surveys such as SDSS and 2dF. Such data, and in particular SDSS, offered for the first time the possibility to find and analyze both photometrically and spectroscopically large samples of extremely low density regions (i.e., $\delta \rho/\rho < -0.6$ measured on a scale of $7\ Mpc$; Rojas et al. 2004, 2005), and allowed for accurate estimates of the void galaxy luminosity and mass functions (Hoyle et al. 2005; Goldberg et al. 2005). These studies show that void galaxies are fainter, bluer, have surface brightness profiles more similar to those of late-type systems, and that their specific star formation rates are higher than those in denser regions. The mass and luminosity functions are found to be clearly shifted toward lower characteristic mass and fainter magnitudes ($M^\star$). Moreover, the faint-end slopes of the wall and void luminosity functions are very similar, which suggests that voids are not dominated by an excess population of low-luminosity galaxies. Consistently, no significant excess in the amount of dark matter is apparent. This means that, although largely devoid of light, the most underdense regions conform to a galaxy formation picture which is clearly not strongly biased.

All these peculiarities demonstrate that the cosmological evolution of void systems is different from that of those living in environments of average cosmic densities. Given the tight correlations between the mass of black holes ($M_{BH}$) and the dispersions and the masses of the galactic bulges within which they reside (Magorrian et al. 1998; Ferrarese & Merrit 2000; Gebhardt et al. 2000; Marconi & Hunt 2003), one would then expect that the growth of massive BHs in galaxy centers (and therefore the accretion process within active galactic nuclei [AGNs]) also
differs among distinct environs. Extension of environmental studies of AGN properties to extreme regions like cosmic voids is thus crucial to understand the coevolution of galaxies and their central BHs. Moreover, while there is general agreement that the growth of black holes must be closely related to galaxy assembly (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000; Begelman & Nath 2005), there is no consensus on how exactly accretion and star formation are coupled. The void galaxies could be, arguably, the best test-bed for understanding whether these processes are synchronized, or precede one another, and whether feedback from the actively growing BHs facilitates star formation (e.g., by dynamically compressing gas clouds through radio jets), or suppresses it (e.g., by blowing away the gas).

To date, studies of the spectral properties of the void AGNs remain limited to individual voids, e.g., the Bootes void (Kirshner et al. 1981), permitting the identification of only a few AGNs among only a few dozen void galaxies (Cruzén et al. 2002). Quite surprisingly, such investigations find that the AGN fraction and their emission-line properties are similar in voids and in their field counterparts. Moreover, their associated stellar populations appear to share similar characteristics in the two extreme environs. The conclusions of these studies are based on small number statistics and do not however exclude the hypothesis that the void emission-line activity, whether originating in star formation or accretion, could be connected with, e.g., filaments within voids; such structures would provide local environs similar to those in the field. The present SDSS samples of voids and void galaxies offer us for the first time the possibility to test and observationally constrain such ideas.

It is important to note that previous investigations of the environmental dependence of nuclear activity in the relatively nearby universe do not reach the extreme spatial densities representative of voids. For example, in Kauffmann et al. (2004) the lowest density regions include over 25% of the galaxies, which is more than 3 times more galaxies than the true void regions encompass. Their conclusions are interesting, and an extension of such an investigation at truly low densities is clearly desirable. In particular, it is important to quantify the degree to which the finding that, at fixed stellar mass, twice as many galaxies host strong-lined AGNs in low-density regions than in high-density regions, extends to cosmic voids. Our work provides such an analysis.

We employ in this work the most accurately classified samples of voids identified within SDSS to date, which yield \( \sim 10^3 \) void galaxies. Motivated by our recent study on the AGN clustering phenomena (Constantin & Vogele 2006), which shows that there are differences in the large-scale structure of active galaxies, and that their clustering amplitude correlates with their strength or rate of accretion, and possibly with the availability of fuel, we compare void and wall active galaxies of different types as classified based on their emission-line properties. Through such a comparison we aim to understand (1) how the large- and small-scale structures influence accretion onto their central black holes, and (2) to what degree AGN activity is triggered by interactions or mergers between galaxies. To answer these questions, we investigate the occurrence rate of different types of spectrally defined AGNs, and how their accretion activity relates to their associated black hole mass, the mass and age of their associated stellar populations, host morphology, brightness, and nearest-neighbor distance.

We organize the paper as follows. In § 2 we present the void and wall sample selection, and the spectral classification we use in defining various types of actively emitting galaxies. We compare and discuss the AGN occurrence rate in voids and walls, both globally and at fixed host properties in § 3. We examine in § 4 the accretion rates, the fuel supply, and the properties of the associated star formation in void and wall actively line-emitting systems, while in § 5 we discuss potential differences in their small-scale environments. We summarize our findings in § 6, and discuss the possible implications on the nature of the power sources in the low-luminosity AGNs, the AGN-host connection, and current models of galaxy formation. In particular, we show empirical evidence for a possible evolutionary sequence that links different types of strong line-emitting galaxies defined based on their spectral characteristics. Throughout this work, unless otherwise noted, we assume \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and \( H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \).

2. THE DATA

We employ for this study \( 10^3 \) void galaxies identified from the large-scale structure sample10, as described in the NYU Value-Added Galaxy Catalog (Blanton et al. 2005), which is a subset of the SDSS Data Release 2 that Strauss et al. (2002) describe in detail. This sample covers nearly 2000 deg\(^2\) and contains 155,126 galaxies. Technical details about the photometric camera, photometric analysis, and photometric system employed by SDSS can be found in Gunn et al. (1998), Lupton et al. (2002), and Fukugita et al. (1996) and Smith et al. (2002), respectively. Hogg et al. (2001) describe the photometric monitor, Pier et al. (2003) present the astrometric calibration, and Eisenstein et al. (2001), Strauss et al. (2002), and Blanton et al. (2003) discuss the selection of the galaxy spectroscopic tiling. An overview of the SDSS can be found in York et al. (2000).

The following subsections summarize the method of identifying void and wall galaxies, and their general properties. We present them in terms of emission-line activity and their classification in various species that reflect various degree of contribution from nuclear accretion and star formation. Our spectral analysis uses measurements of absorption and emission-line fluxes and equivalent widths (EWs) drawn from a catalog built by the MPA/JHU collaboration.\(^1\) In this data set, the line-emission component is separated and subtracted from the total galaxy spectrum based on fits of stellar population synthesis templates (Tremonti et al. 2004). To relate the central BH accretion activity to the host properties, we also use in this analysis stellar masses of galaxies and two stellar absorption-line indices, the 4000 Å break strength and the H\(\delta_a\) Balmer absorption-line index, as calculated by Kauffmann et al. (2003c). A detailed analysis of many of these properties, and their relation to the AGN phenomenon in particular, is presented in Kauffmann et al. (2004).

2.1. The Void Galaxy Sample

Voids galaxies were identified using a nearest neighbor analysis to find galaxies that reside in regions of density contrast with \( \delta \rho/\rho < -0.6 \) as measured on a scale of \( 7 \, h^{-1} \, \text{Mpc} \). Wall galaxies are then those objects for which \( \delta \rho/\rho \geq -0.6 \). The void galaxy selection procedure is described in detail in Rojas et al. (2004). Briefly, this method uses a volume-limited sample and defines the density field that traces the distribution of voids. From the flux-limited sample that extends to this \( z \) max, the galaxies within a sphere of radius \( 7 \, h^{-1} \, \text{Mpc} \), are flagged as belonging to voids while the rest of them are classified as wall galaxies. This procedure yields a sample of 1010 void galaxies and 12,732 wall galaxie...
galaxies. Objects that lie close to the edge of the survey have been discarded, as it is impossible to accurately count the neighbors if they are not observed.

Note that the density around void galaxies ($\rho_{\text{void}}$) is higher than the mean density of a void ($\bar{\rho}_{\text{void}}$) because galaxies are clustered and the few void galaxies tend to lie close to the edges of the voids. Our choice of density contrast and nomenclature is consistent with studies of voids in other three-dimensional samples (Hoyle & Vogeley 2002, 2004) where individual void structures were identified using an objective voidfinder algorithm that fill 40% of the universe and have a mean density $\bar{\rho}/\rho < -0.9$. The average density around the few galaxies in voids is typically $\delta \rho/\rho < -0.6$ when measured on a scale of $7 h^{-1}$ Mpc (the typical underdensity for voids is $\delta \rho/\rho \approx -0.78$). Tests of such void-finding methods with cold dark matter simulations and semianalytic models (Benson et al. 2003) indicate that such identifications and the locations of true voids are accurate in the distributions of both galaxies and mass.

### 2.2. The Spectral Classification

We identify and classify accretion sources and other types of active systems in the void and wall galaxy samples based their emission-line properties. Following, for example, Baldwin et al. (1981), Veilleux & Osterbrock (1987), and Constantin & Vogeley (2006), we employ a set of four line flux ratios to distinguish between systems in which ionization is dominated by accretion and/or starlight: $[\text{O iii}] \lambda 5007/\text{H}\beta$, $[\text{N ii}] \lambda 6583/\text{H}\alpha$, $[\text{S ii}] \lambda 6716,6731/\text{H}\alpha$, and $[\text{O i}] \lambda 6300/\text{H}\alpha$. Thus, we select from the parent sample of galaxies a subset of strong emission-line sources that show significant emission in all six lines used in the type classification ($\text{H}\alpha$, $\text{H}\beta$, $[\text{O iii}]$, $[\text{N ii}]$, $[\text{S ii}]$, and $[\text{O i}]$), and a set of passive objects that show insignificant, if any, line-emission activity. An emission feature is considered to be significant if its line flux is positive and is measured with at least 2 $\sigma$ confidence.

To classify the actively line emitting objects we employ the criteria proposed by Kewley et al. (2006). Through their semiempirical nature, the Kewley et al. (2006) separation lines match well with objects’ locations in three diagnostic diagrams which combine pairs of the six lines mentioned above. Figure 1 illustrates these definitions for cases where the line fluxes are constrained to $>2 \sigma$ accuracy, separately in voids and walls. The galaxies that show strong star-formation activity, the $H$ $\Pi$ galaxies, are those that lie below the Kauffmann et al. (2003c) curve (dashed line) in the $[\text{O iii}]$/H$\beta$ versus $[\text{N ii}]/\text{H}\alpha$ diagram, and remain confined to the left wing of the point distribution in the other two diagrams as well. Objects situated above this curve but below the Kewley et al. (2001) theoretical “maximum star formation” line (solid blue line) are defined as transition objects (Ts, or composites). Galaxies whose line flux ratios place them above the Kewley et al. (2001) curves are those where the AGN component is considered to be dominant. The AGNs are separated into Seyferts (Ss) and LINERs (Ls) by a diagonal (solid blue line) that represents the best fit to the location of the minimum of the distributions in pairs of line ratios defining the $[\text{O iii}]$/H$\beta$ versus $[\text{S ii}]/\text{H}\alpha$ and $[\text{O iii}]$/H$\beta$ versus $[\text{O i}]/\text{H}\alpha$ diagrams (Kewley et al. 2006).
Even though we consider these criteria as the best basis for categorizing the line-emitters, we test our results with respect to the Ho et al. (1997) definition, for the sake of comparison with previous works. Figure 1 shows the Ho et al. (1997) separation lines as (green) dotted lines. There are some important differences between these two classification methods, some of which are briefly discussed by Kewley et al. (2006). Although the LINER samples remain at least 90% consistent in these two different definitions, a significant number of Seyferts and transition objects change class. The Kewley et al. criteria classify quite a few Seyferts that would be defined by Ho et al. either as H II galaxies or Ts based on their low ionization level, gauged by their [O III]/Hβ ratio. The number of objects classified as Ts significantly increases with the Kewley et al. (2006) method. However, many of these systems are clearly dominated by starlight, even if their emission embodies a possible accretion component. Constantin & Vogele (2006) show that a large fraction of Ts defined based on the [N II]/Hα diagram heavily populate the H II locus in the other two diagrams. The [S II]/Hα and [O I]/Hα line flux ratios are more sensitive to the type of ionization than [N II]/Hα, and therefore are better discriminators between accretion- and stellar-dominated excitation processes; hence, the AGN definitions based on the [O III]/Hβ versus [N II]/Hα diagram should be regarded with caution. For the void galaxy sample, however, the separation between LINERs and Seyferts is practically independent of the chosen classification method; the sample is very small in size, and the fraction of border-line objects is relatively low.

We note here that LINERs are not unambiguously considered to be AGNs. Mechanisms alternative to accretion onto a black hole, like photoionization by hot, young stars (Filippenko & Terlevich 1992; Shields 1992; Barth & Shields 2000), clusters of planetary nebula nuclei (Taniguchi et al. 2000), or shocks (Dopita & Sutherland 1995), have proved relatively successful in explaining the optical spectra of these sources. Particularly ambiguous in their interpretation are the transition sources. It is not clear whether these objects are a “composite,” with a LINER/Seyfert nucleus surrounded by star-forming regions, or not. Shields et al. (2007) and Constantin et al. (2007) show examples where this model does not work. Thus, we consider that among the narrow-line-emitting objects only Seyferts are bona fide AGNs, and advise more caution in generalizing the term AGN.

3. INCIDENCE OF AGN ACTIVITY

We present here the results of a comparative analysis of both photometric and spectroscopic properties of the void and wall galaxies. We consider separately various types of emission-line activity, whether dominated by star formation, accretion, or a mix of them. In this section in particular, we compare the rate of occurrence/detection of different types of emission-line activity in voids and walls, both globally and at fixed host properties.

3.1. Global Frequencies

We present in Table 1 the percentages of strong line-emitters (all six lines are detected) and subclasses of objects relative to the whole void and wall galaxy samples. We list these numbers for definitions involving strictly high statistical significance in the line flux measurements (greater than 2σ level). We find that strong line-emission activity is clearly more common in voids than in walls. This difference seems to be accounted for by the difference in the rate of occurrence of H II-type emission. Objects of other types of spectral activity show equal or lower frequency in the most underdense regions relative to the crowded ones. That the fraction of H II galaxies in the void regions (32.8%) is significantly higher than in walls (20.8%) is consistent with previous spectroscopic studies of void galaxies, indicating that their specific star formation rates are higher than in their wall counterparts (Rojas et al. 2005), and with the finding that the H II galaxies are less clustered than other galaxies (Constantin & Vogele 2006).

The systems whose spectra indicate the presence of an accreting black hole as an ionization source show a somewhat mixed behavior. While Seyferts seem to be equally represented in voids and walls (1.5%), their weaker counterparts, the LINERs, are present to a significantly smaller fraction in voids (2%) than in walls (4.1%). Although the samples of objects involved in this comparison are small, with only 20 LINERs in voids and 510 LINERs in walls, the difference is significant at more than 3σ. Constantin & Vogele (2006) show that LINERs cluster more strongly than Seyferts, so the weaker representation of LINERs in the void regions is not surprising, and supports these results.

The transition objects show an intermediate behavior between LINERs and Seyferts, being slightly less common in voids than in walls. These trends are somewhat expected based on their clustering properties as well, although the significance of this comparison is only at the 1.5σ level.

It is important to note that these trends are nearly independent of the classification criteria. The drop in the fraction of LINERs from walls to voids is only slightly larger using the Ho et al. (1997) classification, from 1.8% (18 out of 996 void galaxies) to 4.4% (552 out of 12,153 wall galaxies), thus confirming that this type of activity is not frequent in the lowest density regions. Even for the transition objects, whose definition varies the most between Ho et al. (1997) and Kewley et al. (2006), with the latter allowing for more objects that are either classified as H II galaxies or remain unclassified by the first method, the fractions show the same trend, being higher in walls, and do not change by more than 5%. Thus, the results are consistent with those based on the Kewley et al. (2006) definition, and show that AGN activity is generally less common in voids than in walls.

3.2. Frequencies at Fixed Host Properties

Because void and wall galaxies are characterized by quite different distributions in their morphologies and luminosities (Rojas et al. 2004), any possible variation in the AGN properties, including the frequency of their occurrence, could be related to such morphological differences. To examine these issues for our particular samples, we present in Table 2 the median values for host r-band absolute magnitudes (Mr) and host concentration indices (C2 as a proxy for the morphological type) for void and wall galaxies.

\[ C = \frac{R_{200}}{R_{50}} \]

where \( R_{200} \) and \( R_{50} \) are the radii from the center of a galaxy containing 50% and 90% of the Petrosian flux measured in the r band.
line-emitting objects of different spectral types. Void hosts are clearly less luminous than their wall counterparts, by $\approx 0.5$ mag, although their morphologies are quite similar. There is no evidence for more late type systems (smaller $C$ values) hosting actively line-emitting galaxies in voids than in walls. We thus emphasize here a comparison of various emission properties at fixed host brightness.

Figure 2 illustrates the fractions in which Seyferts, Ls, Ts, and H II galaxies are detected in systems characterized by different $M_r$ and $C$ values. We also show here how $C$ and the stellar mass of objects ($log M_*/M_\odot$) are distributed as a function of $M_r$ for all these kinds of objects. Note that the stellar mass and the intrinsic brightness of galaxies correlate very well in both voids and walls. Thus, our investigation of AGN fractions and other emission-line properties at fixed brightness apply as well to the corresponding bin in stellar mass. Throughout the paper, we interchangeably characterize galaxies by stellar mass or absolute magnitude. The distribution of $C$ as a function of $M_r$ is generally flat given the errors, and there is no significant difference in the $C$ values of void and wall systems at any given brightness. LINERs are an exception: the ones in walls show earlier type hosts at larger brightness, while the ones in voids exhibit the opposite trend, giving rise to significant differences in $C$ between void and wall systems of a given $M_r$.

When fractions are compared at fixed luminosity and fixed concentration index some interesting trends stand out. The most striking feature is that the objects that show signs of AGN activity, i.e., the Seyferts, Ls, and Ts, are clearly underrepresented among the most luminous or massive ($M_r < -20$, log $M_*/M_\odot > 10.5$) hosts in voids. Among moderately bright, medium-mass galaxies ($M_r \approx -20.5$, log $M_*/M_\odot \approx 10.5$), Seyferts appear more frequently in voids than in walls, while Ls and Ts are equally common in these different environs. For H II galaxies, their frequencies among void galaxies are clearly higher than in wall galaxies, at almost all host brightnesses and morphologies. This result agrees well with previous findings of higher specific star formation rates in void galaxies relative to their wall counterparts (Rojas et al. 2005), with the general tendency of actively star-forming systems to be more common in the most underdense regions than in other environs, and in particular with the fact that H II galaxies are less clustered than other galaxies (Constantin & Vogele 2006).

It is noteworthy that Seyferts appear to favor different kinds of hosts in voids and walls. In voids, they concentrate almost exclusively in galaxies with $M_r \approx -20$, spanning not more than an order of magnitude in their luminosities ($-19.5 \approx M_r \approx -20.5$). In walls, Seyferts prefer generally bright hosts. While the fraction of Seyferts in luminous wall systems increases at least 3 times relative to that in fainter hosts, there are no detected void Seyferts at $M_r \approx -20.5$. On the other hand, where void and wall Seyfert galaxies overlap in brightness, Seyfert-like activity is more frequent in underdense regions than in more crowded environments.

![Fig. 2](https://example.com/figure2.png)

**Fig. 2:** Left: Fractions of void and wall galaxies that are spectroscopically classified as Seyferts, LINERs, transition objects, and H II galaxies as a function of their $r$-band absolute magnitude ($M_r$) and their concentration indices ($C$). Right: Median values for $C$ and (dust-corrected) stellar mass ($log M_*/M_\odot$) in bins of 0.5 mag of $M_r$, separately in voids (black) and walls (gray). Error bars are shown only for bins that include at least two objects.
Finally, void Seyferts seem to prefer earlier type galaxies than those living in walls (there are no void Seyferts in galaxies with $C \leq 2.25$).

LINERs and Ts are peculiar as well; while their fractions among faint and moderately bright hosts are quite similar in voids and walls, they basically disappear among the bright void galaxies. The spike at $M_r \approx -22$ corresponds to the only void galaxy that exhibits this level of brightness. Thus, the large difference in the total fraction of LINERs between voids and walls is explained solely by the strong deficiency of such systems in luminous hosts in underdense regions. A similar trend in the occurrence rate at fixed brightness is present among Ts; however, they seem to show peculiarities as a function of in their morphological type as well. Void Ts hosted by earlier type galaxies ($C \approx 3$) seem more frequent than the wall ones, but they are similarly common in void and wall hosts of late-type morphologies. This is interesting given that void emission-line systems are generally absent among early-type hosts.

There are only three actively line-emitting void galaxies at $M_r \approx -21$. One object is spectrally classified as a T, while the other two remain unclassified because they do not comply simultaneously to the Seyfert-LINER separation criteria in the diagrams involving [S ii] and [O i], and thus have properties that are somewhat intermediate between a Seyfert and a LINER. Even if these two objects are both Seyferts or both Ls, there is no statistically significant rise in the fractions of void AGNs corresponding to this brightness range. The error bars of these fractions remain rather large; with either two Ls or two Seyferts in this absolute magnitude range, their fraction in voids would be $0.3\% \pm 0.3\%$. Thus, among bright galaxies, the relative fraction of accretion-dominated systems in voids and walls remains unconstrained. Moderately and less luminous void galaxies are, however, clearly more prone to hosting AGNs than their wall counterparts.

### 3.3. Frequencies and the Strength of Accretion Activity

That void and wall galaxies host accretion activity to a different degree should not come as a surprise. Kauffmann et al. (2004) showed that at fixed galaxy mass, the low-density regions host twice as many AGNs as the high-density ones. We find here, however, that such a trend extends to voids only for galaxies that are moderately bright and moderately massive ($M_r \approx -20, 10 < \log M_r/M_\odot < 10.5$). Figure 2 shows that, while the fraction of galaxies containing strong AGNs increases with brightness, and therefore with $M_*$, in both voids and walls, it is clear that there is no statistically significant surplus of any type of AGN in the most massive void galaxies relative to their wall counterparts.

For a more direct comparison with the Kauffmann et al. (2004) results, we also examine the fractions in which void and wall galaxies of a given stellar mass host AGNs. Using the exact definition of AGN samples employed by Kauffmann et al. (2004), we show these fractions in Figure 3, separately for strong and weak [O iii] line emitters. It is readily apparent that AGN activity at all levels is equally frequent among massive void and wall galaxies ($\log M_*/M_\odot > 10.5$), while at lower mass ($\log M_*/M_\odot < 10.5$) both strong and weak AGNs are generally more frequent in voids than in walls. The total fraction of massive (log $M_*/M_\odot > 10.5$) galaxies with strong lines ($L_{[OIII]} > 10^{39}$ erg s$^{-1}$) is 9% in walls and only 11% in voids, which is far from the 100% difference found by Kauffmann et al. (2004). On the other hand, for the log $M_*/M_\odot < 10.5$ galaxies the fraction of strong-lined AGNs in

![Figure 3](#)
voids (2.8%) is twice as high as that in walls (1.4%). Figure 3 also shows the distributions of [O iii] luminosities in objects of high and medium stellar mass ranges, separately for void and wall galaxies. Among the massive galaxies, only the low-accretion (log $L_{\text{[O iii]}}$ erg s$^{-1}$ ≈ 37) systems appear marginally more frequent in voids than in walls, while all levels of AGN activity seem more common in voids than in walls among less massive hosts.

To summarize, the environmental dependence of the rate of occurrence of the AGN phenomenon varies with the properties spanned by their hosts. Our comparative analysis conducted at fixed host properties shows clearly that nuclear accretion is more frequent in voids than in walls among moderately massive and luminous ($M_r \sim -2.0$, log $M_*/L_{\text{[O iii]}} < 10.5$) hosts while it remains similarly common among massive, luminous ($M_r \leq -2.0$ and log $M_*/L_{\text{[O iii]}} > 10.5$) void and wall galaxies. These results show that accounting for host galaxy properties, i.e., luminosity and mass, is essential for understanding the environmental behavior of AGN activity; previous findings of roughly constant fraction of galaxies hosting AGN across a wide range of environments (Miller et al. 2003) are justified because they are based on investigations of bright galaxies ($M_r \leq -2.0$) only.

3.4. Incidence of Radio Activity

Scrutiny of potential differences in radio activity between wall and void galaxies is of great interest for understanding the environmental dependence of accretion activity as radio observations overcome obscuration. The Faint Images of the Radio Sky at Twenty cm survey (FIRST; Becker et al. 1995) offers the advantage of providing high angular resolution and sensitivity, and therefore is well suited for extracting information regarding galactic nuclear activity.

We cross-matched the SDSS void and wall galaxy samples described in § 2 with the FIRST catalog of sources with flux densities exceeding 1 mJy at 1.4 GHz. The global census of SDSS void and wall galaxies that show radio activity at this level is surprisingly different in voids and walls. Table 3 lists the results of cross-matching statistics and a comparison of the $\nu L_{\nu}(1.4 \text{ GHz})$ measurements per galaxy type. Only 16 (1.6%) of void galaxies are brighter than 1 mJy at 1.4 GHz, and they are all strong line emitters. Within walls, the fraction of objects with flux densities exceeding this limit is significantly higher: 308 objects (or 2.5%), about 80% of them showing line-emission activity. These calculations indicate at greater than 2 $\sigma$ that radio activity in the centers of galaxies is less common in voids than in denser environments.

This trend is not equally shared by galaxies of different spectral properties. We note that none of the void Ls are detected in FIRST, while a fraction as high as 7% of the wall Ls appear as FIRST sources. Seyferts and Ts show similar, if not identical, detection rates in FIRST in voids and walls; their corresponding fractions of FIRST detections account for 15%–20% and 9%, respectively. Radio-active H ii galaxies are slightly more common in walls than in voids. While the difference in the FIRST detection rate between all void and wall galaxies is statistically significant, the variation of radio activity per spectral type remains ambiguous, particularly for the void AGNs where the number statistics remain low. If a single void LINER were detected in FIRST, the fractions of void and wall Ls with radio activity would become indistinguishable within the errors (5% within voids vs. 7% within walls). The level of radio activity also shows differences between the void and wall systems, with the wall ones being clearly more luminous at 1.4 GHz. A per-type comparison remains, however, pointless because of the very small number of void galaxies with measurable nuclear radio emission. We present, for reference, the $\nu L_{\nu}(1.4 \text{ GHz})$ luminosities in Table 3 as well. Note also that none of the void galaxies considered here would be considered radio-loud; the highest radio luminosity among void galaxies is $\nu L_{\nu}(1.4 \text{ GHz}) = 1.7 \times 10^{38}$ erg s$^{-1}$, or $L_{\nu}(1.4 \text{ GHz}) = 3 \times 10^{22}$ W Hz$^{-1}$.

These measurements are consistent with previous investigations of the large-scale structure of radio sources, but reveal potential new features as well. In particular, the fact that radio activity is enhanced in wall regions relative to voids is in line with evidence that radio-loud galaxies are locally restricted to the supergalactic plane, avoiding the voids (e.g., Shaver & Pierre 1989). However, that the radio-emitting Hii systems are less common, and probably weaker in voids than in denser regions, is at odds with previous indications of a diminution in the star-forming activity with increasing local density, for both radio and optically selected star-forming galaxies (e.g., Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Christlein & Zabludoff 2005; Best 2004; Doyle & Drinkwater 2006). Note that while these studies examine the overall star formation activity within galaxies, either through galaxy colors or Hα equivalent widths, our comparison refers to this kind of activity in the centers of galaxies only. Thus, taken at face value, the discrepancy shown by our measurements might indicate that core star formation activity shows somewhat opposite environmental dependence trends relative to that occurring in the envelope; in lower density regions, star formation activity seems weaker in the core but stronger in the envelope of galaxies. That color gradients might also depend on galaxy density, probably as strongly as the star formation rate does, in the sense that galaxies in rarefied regions exhibit bluer envelopes than those in crowded environs (Park et al. 2007), appears to support this idea.

A possible explanation for this difference may be that the radio emission associated with nuclear star formation activity is not entirely due to stellar activity, but it includes an additional component. A possible such contribution may be an AGN that is heavily obscured, or its emission-line characteristics are swamped into the light of the host galaxy or the circumnuclear star-forming regions; note that the definition of the Hα class relies on optical line-emission properties, and thus is not sensitive to obscured accretion. That AGNs show possibly stronger radio emission in walls than in voids might thus suggest that the enhanced radio detection and emission in the wall H ii galaxies comes from an accretion source that is heavily obscured. Although not detected in optical wavelengths, such an AGN would be revealed at radio frequencies. This picture seems supported by other studies; e.g., hydrodynamical simulations of galaxy evolution processes, through merger events, predict that for a large fraction of the accretion time, the AGN (quasar) is heavily obscured, and that the intrinsic quasar luminosity peaks during an early merging phase, but it is completely obscured in optical (e.g., Hopkins et al. 2006), and galaxy spectral analyses indicate that much of the BH growth

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**Table 3: Radio Properties**

| Sample | Void (Fraction) | Wall (Fraction) | $\nu L_{\nu}(1.4 \text{ GHz})$ |
|--------|----------------|----------------|-----------------------------|
| Seyfert | 2 (15%) | 38 (20%) | 0.9 ± 0.1, 4.1 ± 1.8 |
| LINER  | 0 (0%) | 35 (7%) | ... |
| Transition | 5 (9%) | 74 (9%) | 1.6 ± 0.7, 3.7 ± 1.2 |
| H II     | 9 (2%) | 91 (3.4%) | 0.9 ± 0.2, 1.6 ± 0.1 |

*a Counts of sources with FIRST detections at the flux density threshold of 1 mJy at 1.4 GHz.

*b In units of 10^{38} \text{ erg s}^{-1}. Central values are medians and errors are the standard deviation of the median.
occurs in AGNs with high amounts of dust extinction (e.g., Wild et al. 2007). We explore this idea further in the next sections, where we compare accretion rates, obscuration level, and stellar properties of void and wall systems of different optical classifications.

4. NUCLEAR ACTIVITY AND HOST PROPERTIES

We explore here common traits and differences in the relation between nuclear emission-line activity and the host star formation that void and wall galaxies of various spectral types may reveal. We gauge the properties of the void and wall emission-line galaxies by means of nuclear accretion rate, amount of fuel, and properties of their host stellar population. The parameters used in quantifying these characteristics employ emission-line measurements and calculations described by Kauffmann et al. (2003a, 2003b). Our analysis is in some ways similar to that of Kauffmann et al. (2004); however, we concentrate here specifically on the various spectral classifications. It is interesting to note the different accretion powers in the wall and void active galaxies in terms of the most prominent feature, while [O ii] is hardly measurable. The [O i] and [O iii] line fluxes are not simply a scale down (or up) of one another, the [O i]/[O iii] line flux ratio is significantly higher in AGNs than in other line-emitting systems (Heckman 1980).

Thus, particularly for H ii and transition objects, a comparison of the L_{[O ii]}/L_{[O iii]} ratio is one of the most prominent features while [O ii] is hardly measurable. The [O i] and [O iii] line fluxes are not simply a scale down (or up) of one another, the [O i]/[O iii] line flux ratio is significantly higher in AGNs than in other line-emitting systems (Heckman 1980).

![Figure 4](image-url)  
Fig. 4.—Mean values of σ, log L_{[O i]}/σ^4 and log L_{[O ii]}/σ^4 (two proxies for the accretion rate), the Balmer decrement Hα/Hβ, and the [S ii] λ6716/6731 line ratio, measured in bins of 0.5 mag of Mr, for galaxies in voids (black) and walls (gray). The error bars represent the standard deviation of the mean. Data are shown only for bins that include more than two objects. Each row of plots represents a different subclass of objects, as indicated. The line luminosities have been corrected for internal dust attenuation, and are expressed in ergs s^{-1}; the stellar velocity dispersions σ, are in km s^{-1}.

4.1. Accretion and Availability of Fuel

Following Constantin & Vogeley (2006), we investigate the accretion power in the wall and void active galaxies in terms of both L_{[O i]} and L_{[O iii]}. While the [O iii] λ5007 emission is susceptible to stellar contamination, the [O i] λ6300 line appears negligibly affected by this; in systems where star formation dominates the ionization process, i.e., the H ii galaxies, [O iii] is one of the most prominent features while [O ii] is hardly measurable. The [O i] and [O iii] line fluxes are not simply a scale down (or up) of one another, the [O i]/[O iii] line flux ratio is significantly higher in AGNs than in other line-emitting systems (Heckman 1980).
The boost in accretion in the LINERs inhabiting brighter galaxies is an interesting finding, and it is worth investigating its origin. Greater availability of accreting material can surely trigger such behavior. However, the origin of such an enhancement is not obvious, given that their fainter counterparts exhibit the opposite effect. One possibility would be that these systems have more material available for accretion simply because matter is more abundant here. Objects with stronger gravitational potential fields should be more capable of keeping the matter inside, against galactic winds built by the thermal pressure from supernovae, while low-mass systems would eject their gas. Thus, a look at the mass of their inner black holes (\(M_{\text{BH}}\)) should shed some light on this issue. Interestingly, the comparison of their stellar velocity dispersions (\(\sigma_*\)), as a measure of their \(M_{\text{BH}}\) (since \(M_{\text{BH}} \propto \sigma_*\); e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000) shown in Figure 4 reveals that the void LINERs hosted by brighter galaxies have systematically smaller mass BHs than similar wall galaxies. Thus, these particularly active accreting void systems do not have, as conjectured, higher binding energies, and consequently, they are not more powerful in cradling the material available for accretion. Another sensible way to produce the excess of material (i.e., dust) in or around the LINERs hosted by bright void galaxies is star formation. We explore this idea in the next two sections, both by comparing the [O i] and [O iii] line emission and through measures of the age of the stellar population in these sources.

4.2. [O i] versus [O iii]

Because the [O i] and [O iii] line-emission mechanisms are differently affected by star-forming and accretion activities, the differences we see in these parameters between void and wall line-emitting galaxies may suggest some interesting connection between the two sources of ionization. Although [O iii] is a very common emission feature in star-forming galaxies, for the most luminous systems (\(\log L_{\text{[O iii]}}/\text{erg s}^{-1} \geq 40.5\)) this parameter appears to be a good measure of nuclear activity (Kauffmann et al. 2003c; Heckman et al. 2004). However, with the exception of very low \(L_{\text{[O iii]}}\) objects, which are LINERs (Constantin & Vogelezang 2001; Kewley et al. 2006), any other sample characterized by \(\log L_{\text{[O iii]}}/\text{erg s}^{-1} < 40.5\) is heavily contaminated by objects with line flux ratios that better match an H ii–like ionization than an accreting power source (Constantin & Vogelezang 2006). On the other hand, [O i] is extremely weak in systems whose ionization is dominated by star formation, thus [O i] emission is an important indicator of excitation due to accretion. The reason is that the [O i] emission line arises preferentially in a zone of partly ionized hydrogen, which can be quite extended in objects photoionized by a spectrum containing a large fraction of high-energy photons, i.e., originating in accretion, but is nearly absent in galaxies photoionized by young, hot (OB) stars. Therefore, more vigorous star formation activity would cause stronger [O iii] emission, but should barely affect [O i]. Correspondingly, the [O i] emission is expected to be enhanced in systems where accretion is stronger.

Interestingly, the analysis of the [O i] and [O iii] line luminosities that we present in § 4.1 shows that these two parameters compare remarkably well, revealing exactly the same trends: both \(L_{\text{[O i]}}\) and \(L_{\text{[O iii]}}\) are slightly lower in voids than in walls in approximately the same amounts (0.3 dex for Seyferts and 0.5–0.9 dex for fainter Ls). The standard deviation of the mean in \(\log L_{\text{[O iii]}}\) is, however, generally larger than that in [O i], thus diluting the significance of the trends in \(\log L_{\text{[O iii]}}\) with \(M_*\). The larger scatter in \(L_{\text{[O iii]}}\) is probably caused by the contribution of star-forming activity to this line. Such a contribution is expected to be even more enhanced in void galaxies, as they exhibit higher specific star formation rates than their wall cousins (Rojas et al. 2005). Note also that for the LINERs hosted by void bright galaxies, which also show evidence for younger stellar populations (see § 4.3), the enhancement in \(L_{\text{[O iii]}}\) is larger than that in \(L_{\text{[O i]}}\); such a difference signals again contribution by star-forming activity to the [O iii] line emission. Thus, particularly for void galaxies, \(L_{\text{[O iii]}}\) must be used with caution when estimating the accretion rate.

4.3. Relation to Star Formation

A variety of mechanisms have been suggested by which starbursts and AGNs are physically related. An interesting idea is that the collapse of very massive stars can give rise to the seed black hole, which can be fed by stars either directly through tidal capture or indirectly through gas shed via stellar mass loss. Over time, the BH and its host galaxy grow in size, but probably not in lock-step. Because more massive galaxies are less likely to harbor young stars (Kauffmann et al. 2004), and have more massive BHs (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000), it is believed that the mass of the BH might have direct consequences for star birth. Hydrodynamical simulations of galaxy mergers including BH growth and feedback (e.g., Di Matteo et al. 2005; Hopkins et al. 2005; Croton et al. 2006) demonstrate how energetic outflows caused by gas falling onto the central BH might self-regulate both BH growth and star formation in a galaxy by heating the available gas and blowing it out, as previously predicted by, e.g., Silk & Rees (1998), or heating it up to temperatures that suppress clumping and collapsing into stars. Further star formation is therefore repressed as long as \(M_{\text{BH}}\) remains above a critical value (e.g., Schawinski et al. 2006).

The regions least prone to galaxy–galaxy interactions or other disturbing events, the voids, are some of the best test beds of this scenario. We proceed in this section with a comparative analysis of the stellar population ages for various types of actively line-emitting galaxies in voids and walls. The strength of the 4000 Å break (D4000) and the equivalent width of the H ii absorption line (\(\text{H} \alpha\)) provide constraints on the mean stellar age of a galaxy and the fraction of its stellar mass formed in bursts over the past few Gyr (Kauffmann et al. 2003a). For the sake of comparison with previous work (Kauffmann et al. 2003b, 2004; Kewley et al. 2006), we use the measurements of the stellar characteristics derived and described by Kauffmann et al. (2003a) and Brinchmann et al. (2004). Figure 5 shows the results of this comparison, in bins of \(M_*\).

Globally, the void systems exhibit younger collections of stars than those in walls: on average, D4000 is similar or slightly higher in walls than in voids regardless of the types of objects compared; however, \(\text{H} \alpha\) is significantly lower (by ~30% in Seyferts, and ~60% in Ls) in the more crowded environments than in the underdense ones. This comparison supports previous indications of systematically younger galaxies in lower density regions (Kauffmann et al. 2004). Here we find that these trends extend to the most extreme underdense environments as well. We also show here that such differences are due to the different range of host properties spanned by the samples that are compared: the younger mean stellar ages of void systems is a consequence of the general shortage of massive bright galaxies (i.e., the usual hosts of old stellar populations) in the underdense regions. The shift in the void luminosity function toward lower brightness galaxies is nicely documented in Hoyle et al. (2005).

At fixed host brightness, the properties of the central stellar populations of void and wall galaxies are statistically similar; however, there are exceptions. The brightest (\(M_* < -20\)) void hosts of LINERs stand out as interesting peculiarities, as they
Similarly, the fainter (LINERs also show a peculiar boost in both accretion and amount
their wall counterparts (smaller D4000 and larger HδA values), the star formation
histories in void and wall galaxies are very similar.

are clearly associated with younger stellar populations (larger HδA, smaller D4000) than those in walls. Recall that these void LINERs also show a peculiar boost in both accretion and amount of obscuration, which might indicate greater availability of fuel. Similarly, the fainter (M_r < -20) void hosts of LINERs, which show weaker accretion activity and significantly less obscuration, also show signs of older stellar emission (lower HδA values). All these trends indicate that the strength of AGN activity is correlated with the age of the associated stellar population, in the sense that AGN activity is stronger when the surrounding stars are relatively young (few Gyr old, corresponding to D4000 ≤ 1.6 and HδA ≥ 2), while weak AGN activity is associated with mean stellar ages that are invariably older than 10 Gyr (D4000 ≥ 1.8 and HδA ≤ 0). In other words, AGN activity and star formation are somewhat coeval, and it is possible that the same reservoir of fuel is used in igniting these activities. Moreover, that the weak AGNs harbor generally heavier (grown up) BHs and that they are routinely associated with lack of obscuration, low gas densities, and older stellar populations may well be the consequence of the fact that star formation remains suppressed once the BH mass is large enough. Such trends are somewhat apparent among galaxies in general; however, this comparison of the emission-line void and wall galaxies reveals them more explicitly.

5. THE SMALL-SCALE ENVIRONMENT: NEAREST NEIGHBOR STATISTICS

A key point in investigating AGNs in voids is understanding at what scale, if at all, the environment affects accretion activity. As shown by Constantin & Vogele (2006), different types of galactic activity prefer different large-scale structures; LINERs are the most clustered, H II galaxies are the least clustered, and Seyferts and Ts are less clustered than Ls but more clustered than H II galaxies. Dark matter density fluctuations are, however, important at all scales. In fact, because the fractional density fluctuations are largest on the smallest scales, any effect that depends on density will appear to be most strongly correlated with smaller scales than with larger scales. One would thus expect that the small-scale climate also influences the strength and type of accretion or star formation, and even the link between them.

The rate of interaction is supposedly reduced in voids, and thus, an analysis of the effects of small scale environs on galactic activity is particularly instructive. In particular, it is of interest to find out whether objects displaying a certain type of activity are located in the highest or lowest density substructures within the most underdense environs, and whether AGNs are associated or not with small groups within voids. To investigate these issues we measure the distance to the third nearest neighbor (d3nn) as a density indicator, and the distance to the first nearest neighbor (d1nn) as a measure of the probability of having close encounters. We measure d1nn separately for the volume-limited sample, which thus counts only the bright (M_r < -19.5) neighbors, and for the whole (flux limited) sample, which adds fainter galaxies. We note here that a small number of close neighbors are missed due to the 55'' minimum fiber separation; this fiber collision issue is, however, unlikely to affect significantly our comparative analysis of near neighbor statistics of void and wall samples, as the effects should be nearly identical for all samples involved, and thus should cancel out.

Table 4 lists the median values in these parameters for both void and wall systems of various spectral types, and Figure 6 illustrates how these parameters compare at fixed M_r. Because the definition of voids and walls employs d3nn, all void galaxies have larger d3nn than those in walls. As expected, d1nn varies little among void galaxies; the median values are consistent with each other within 1 σ. It is interesting to note, however, an apparent tendency of increasing d1nn with host luminosity (Fig. 6); this suggests that, in voids, more luminous and therefore massive systems are less grouped than the fainter, less massive ones.

Among the wall galaxies, d1nn shows significant differences among objects of different spectral types, and trends that are opposite to those exhibited by void systems: LINERs have the closest third neighbor (with an average of 3.0 ± 0.1 h^{-1} Mpc), and thus the highest density, while the H II galaxies populate less dense regions within walls (their average d3nn ~ 3.6 h^{-1} Mpc). Seyferts and Ts show very similar values (d3nn ~ 3.3 h^{-1} Mpc), which are intermediate between LINERs and H II galaxies. These trends persist even when the samples are split in bins of M_r, and it is pretty clear that d1nn decreases with M_r (Fig. 6). Such findings are consistent with the difference in clustering that Constantin & Vogele (2006) reveal, with LINERs being the most clustered active galaxies, Seyferts showing lower clustering amplitude, and H II galaxies being the systems that are the least clustered. Note, however, that the clustering analysis involves autocorrelations of each type of these emission-line objects, while the nearest-neighbor analysis cross-correlates each type of object with the full population of galaxies.

The distance to the nearest galaxy, d1nn, may be important in assessing whether or not interactions are important in triggering nuclear activity in galaxies. The d1nn measurements generally re-inforce the behavior shown by d3nn but also show some peculiar

\footnote{The fact that we only see small variation in d1nn in voids is not surprising. In these regions, we are measuring distances >7 h^{-1} Mpc, and hence, we are looking at quite large smoothing scales where the rms density fluctuations are smaller than on the scales where d3nn is measured in walls.}
trends. When measured within the volume-limited sample, $d_{1n}$ indicates that, in voids, LINERs, and Seyferts are closer to their bright neighbors than the H ii galaxies, while Ts show a somewhat intermediate behavior. Kolmogorov-Smirnov tests are consistent with clear differences in the distributions of H ii galaxies and LINERs (the probability that the $d_{1n}$ distributions of these two samples share the same parent population is ProbH LINERs $= 0.017$). When fainter neighbors are counted, in the magnitude-limited sample, the likelihood of having close neighbors is very similar for all types of void emission-line systems. In walls, LINERs have the closest neighbors, both faint and bright, while H ii galaxies are the farthest away from any galaxy. These trends suggest that actively star-forming systems prefer the densest subregions in voids and the most rarefied neighborhoods within crowded environments, while the systems in which accretion is strong enough to be detected are generally associated with a grouped small-scale environment.

The comparison of these distances in bins of $M_*$, as shown in Figure 6, may explain these particular trends. For all three measures of density, and in particular for $d_{3n}$, the differences between void and wall galaxies of given brightness is greater for the more luminous objects: the brighter a galaxy is, the more isolated it seems to be in voids, while the most “connected” in walls. Along these trends, H ii galaxies, which are generally fainter than other types of objects, occupy more crowded void subenvironments but more rarefied regions in walls, while LINERs, which inhabit generally bright hosts, are the most isolated in voids and the most grouped in walls.

That more luminous galaxies appear to prefer more crowded regions within walls is consistent with previous results that more luminous systems are more clustered (on large scale). However, their tendency to be more isolated within voids is a new and surprising finding. This observation suggests that while the small-scale environment may influence the intrinsic properties of their inhabitants (e.g., $M_*$), the dynamics that determine the large-scale structure (e.g., expansion vs. contraction) are equally important, as they influence the likelihood for interaction, and thus the type of galactic nuclear activity.

It is important to note that both $d_{1n}$ and $d_{3n}$ address the embedding of the AGN hosts and other galaxies in dark matter halos, however, at different scales: $d_{1n}$, of order 1.5 Mpc $h^{-1}$ in walls and about 3 times higher in voids, examines neighbors that may lie within the same dark matter halo, while $d_{3n}$, which is $\sim 3$ Mpc $h^{-1}$ in walls and $\sim 8.5$ Mpc $h^{-1}$ in voids, measures the large-scale environment traced by multiple halos. Uncertainty in the $d_{1n}$ measure arises because of (1) the fiber collision problem and (2) peculiar velocities along the line of sight. Both effects will tend to increase $d_{1n}$ by removing a few close neighbors and by spreading virialized systems along the line of sight, respectively. Thus, the $d_{1n}$ values in walls, where $d_{1n}$ is small enough to be affected by both systematics, may be overestimates. In voids, these systematic effects go in the same direction; however, they are likely to be smaller, because the density is much lower. The $d_{3n}$ measurements are likely to be affected by these biases in a similar manner, however much less. These arguments thus indicate that our conclusions can in fact be stronger. In particular, the differences in $d_{1n}$ could certainly not be caused by systematic effects, and are generally underestimated. Moreover, the comparison between types of active galaxies in voids and walls should be hardly affected, as the spectral classification and near neighbor statistics are completely independent analyses.

To summarize, the youngest, actively star-forming, fuel-rich systems, i.e., the H ii galaxies, appear in weakly grouped environments, that are the densest regions within voids and the rarefied ones within walls.

On the other hand, the most common type of AGN activity (i.e., LINER-like), which is relatively feeble and associated with old massive evolved hosts, shows a peculiar preference for the
most clustered wall substructures and the emptiest among voids. This trend argues against a major role played by close encounters or mergers in triggering or sustaining their activity. Interestingly, the most active AGNs (Seyferts and Ts) prefer the relatively low density wall subenvironments and the somewhat grouped void ones; this is a behavior that is intermediate between those manifested by LINERs and H \( \text{II} \) galaxies.

6. CONCLUSIONS AND DISCUSSION

6.1. Summary of Results

We use the largest sample of voids and void galaxies yet defined to investigate the galactic nuclear accretion phenomenon in the most underdense regions, in relation to their more populous counterparts. By employing spectroscopic and photometric data based on the SDSS DR2 catalog, and in particular measurements available in the Garching catalog, we conduct a comparative analysis of void and wall systems of different radiative signature.

We find that all types of low-luminosity AGN exist in void regions. However, their occurrence rate and intrinsic properties show variation from their wall counterparts. The differences between the wall and void AGNs seem to be driven by the properties of their hosts, which are correlated with (or governed by) their small-scale environment. Following is a summary of our main results:

1. Among moderately bright or fainter galaxies \([10 < \log(M_\text{d}/M_\odot) < 10.5, M_\text{d} \geq -20]\), the rate of occurrence of AGNs is higher in voids than in walls. The most common accretion activity in voids is of medium power, with \(L_{\text{AGN}} \sim 10^{48} \text{ erg s}^{-1}\). For the more luminous massive hosts, due to small number statistics, the relative prevalence of accretion activity in voids versus walls remains poorly constrained.

2. The majority of void AGNs, which are hosted by \(M_\text{d} \geq -20\) galaxies, have the tendency to accrete at lower rates than in those in walls. This behavior seems related to the fact that the void systems show less obscuration and, perhaps, less dense emitting gas. That the stellar populations associated with void and wall AGNs are similarly aged suggests that fuel might be equally available for accretion in void and wall galaxies of similar properties (i.e., \(M_\text{d}\)), but that fuel is less efficiently driven toward the nucleus in void galaxies.

3. The few void AGNs hosted by bright, massive galaxies \((M_\text{d} < -20, \log(M_\text{d}/M_\odot) > 10.5)\) are LINERs that show peculiarly higher accretion rates, larger amounts of obscuring matter, and more recent star-formation than in their wall counterparts. These particular systems reinforce the general trends other objects show: higher accretion rates are invariably associated with younger stellar populations and higher obscuration. These trends suggest that the amount of obscuration could be a measure of the available fuel for both star formation and accretion.

4. The radio activity of line-emitting galaxies appears both less frequent and weaker in voids than in walls. Were we able to support these differences with statistically significant measurements, they would imply that central radio activity in wall systems, including H \( \text{II} \) galaxies, is more pronounced because it builds on contributions from accretion that remain optically obscured and therefore undetected.

5. Nearest neighbor statistics show that the type of emission-line activity is correlated with the small-scale local environment. The star-forming regions (the H \( \text{II} \) galaxies) populate the most crowded subregions of voids while populating relatively sparse regions in walls; both are environments where low-mass galaxies recently formed. The weakly active galaxies (LINERs) live within the clusters in walls but the most rarefied regions in voids. This finding is puzzling and suggests that these systems, which are generally old, were probably not aware of their environments when they formed. Actively accreting systems (Seyferts and possibly the Ts) inhabit intermediate regions, which are relatively dense galaxy neighborhoods in voids but are of average density in walls.

6. These correlations among the type and strength of galactic nuclear activity, incidence rates of different types, and their small and large scale environments suggest an H \( \text{II} \) → S/T → LINER evolutionary scenario in which interaction is responsible for propelling gas toward the galaxy centers, triggering star formation and feeding the active galactic nucleus.

6.2. The H \( \text{II} \) → S/T → LINER Evolutionary Sequence

Figure 7 illustrates how various intrinsic and host properties of actively line-emitting galaxies follow this H \( \text{II} \) → S/T → LINER sequence. The early stages of such objects manifest themselves as H \( \text{II} \), as the accreting source remains heavily embedded in dust. As the starburst fades in time, the dominance of the Seyfert-like excitation in systems of generally small but actively accreting black holes becomes more evident. Successive evolution reveals aging stellar populations associated with objects spectrally classified as transition objects, that are still showing signs of accretion, followed by LINERs, whose stars are predominantly old and whose accretion onto already grown-up BHs is close to minimal. Note that this H \( \text{II} \) → S/T → LINER progression is very similar in walls and voids. The lower accretion rates and the higher frequency of actively accreting systems in void versus wall galaxies of similar properties indicate a potential delay in the AGN dominance phase within voids. Thus, void AGNs progress through the H \( \text{II} \) → S/T → LINER sequence more slowly, while the sequence is similar for both void and wall galaxies. This picture fits well the observed properties of each type of galaxy nucleus:

1. That H \( \text{II} \) → type of activity is significantly more frequent in voids than in walls suggests that their void-like environments, in which they have closer (both first and third) neighbors than other types of objects have, are essential in triggering their activity. In other words, close encounters that produce either harassment or major and/or minor mergers may be an important cause for igniting both accretion and star formation.

2. Seyferts’ environments in both voids and walls are intermediate between those of H \( \text{II} \) galaxies and LINERs, regardless of their brightness. If the Seyfert-like activity is triggered by interactions, probably the same ones that turn on the H \( \text{II} \) galaxies, there must be a time lag between the onset of the star-burst and when accretion becomes dominant, or simply observable. Such a time interval corresponds to a period of aging of the stellar population (as seen in the differences in \( D4000 \) and H\( \alpha \) between H \( \text{II} \) galaxies and Seyferts), when the poststarburst fuel becomes increasingly available for accretion. Moreover, this progression develops relatively uninterrupted in voids, and therefore, possibly, at a slower pace than it would in walls where close encounters or other types of interactions can either accelerate or terminate it.

3. Void and wall Ts are barely distinguishable in their physical characteristics. In both voids and walls, their nearest neighbor statistics and intrinsic and host properties are intermediate between those of LINERs and H \( \text{II} \) galaxies, for any given range of \( M_\text{d}\). Their BHs are apparently growing (their accretion activity is stronger than that of Ls but weaker than that of Seyferts), their fuel supply seems plentiful (they are found in some of the most obscured systems), and they are associated with (quite massive) stellar populations that are generally younger than those of

\[ M_\text{d} \lesssim 2.0 \times 10^8 \text{ M}_\odot \]
LINERs, but older than the majority of star-forming systems. It is among Ts, however, that the most massive void accreting BHs are observed; this might suggest that, in the proposed H\textsubscript{ii}! S/T! LINER sequence, massive void galaxies reach the low accretion rate (i.e., LINER) phase later than in walls.

4. Whether Seyferts or transition objects are first in this sequence remains ambiguous. Both their intrinsic properties and nearest neighbor statistics are very similar, and remain intermediate between those of H\textsubscript{ii} galaxies and LINERs. The H\alpha/H\beta Balmer decrements and the $d_{195}$ are the only parameters that show a “jump” in the otherwise smooth H\textsubscript{ii}! S! T! LINER evolution manifested by other properties of these systems. Further investigations of these objects should address the differences between them in terms of a possible evolutionary progression.

5. Although we do not provide any quantitative estimates of the time spent in or during the various phases we propose here, this analysis shows that both void and wall galaxies follow the same cycle. The AGN evolution does not affect the gravitational environment. To the contrary, it is the environment that sets the timescale for evolution along such a sequence; it seems to take longer to march through the different phases in voids than in walls, but the physics is the same. The large-scale clustering is consistent with this picture: LINERs are now more clustered because objects in dense regions underwent the H\textsubscript{ii}! S! T! LINER evolution more quickly; the higher rate of galaxy-galaxy interactions speeds up the way AGNs proceed through the sequence. Hosts whose central regions are now in the H\textsubscript{ii} phase will always be less clustered than current LINERs.
Although far from being complete, this proposed evolutionary sequence is engaging and offers a comprehensive picture for the coevolution of AGNs and their host galaxies. The broad idea that mergers trigger star formation and that the AGN appears afterward, in fact shutting off the star formation because of feedback, has been discussed previously in the literature. For example, N-body simulations by Byrd et al. (1987) and Hernquist & Mihos (1995) showed that interactions drive gas toward the nucleus and can produce intense star formation followed by an AGN. More recent state-of-the-art hydrodynamical models (e.g., Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2005, 2006) show that during mergers, the BH accretion peaks considerably after the merger started, and after the star formation rate has peaked. However, whether early bright quasars and later, dimmer AGNs obey similar physics still needs to be addressed. The H\textsc{ii}→S/T→L sequence that this study reveals, based on the smooth alignment of several of their spectral properties, may be the first empirical evidence for an analogous duty cycle in high-redshift bright systems and in nearby galaxies hosting weak quasar-like activity.

This scenario can also accommodate the rather inconclusive findings regarding the role of mergers in activating AGNs: their hosts do not show evidence for bars (e.g., Mulchaey & Regan 1997; Laine et al. 2002) or disturbances caused by galaxy-galaxy effects. The H\textsc{ii} of interactions in the literature could be attributed to selection effects observed by, e.g., Fuentes-Williams & Stocke (1988; Laurikainen & Salo 1995). Dahari (1984; Rafanelli et al. 1995), but not always (Fuentes-Williams & Stocke 1988; Laurikainen & Salo 1995), and pair counting in both optical and IR remains inconclusive, as possible excesses of companions are sometimes found (Dahari 1984; Rafanelli et al. 1995), but not always (Fuentes-Williams & Stocke 1988; Laurikainen & Salo 1995). Moreover, Schmitt (2001, 2004) shows that claims of evidence of interactions in the literature could be attributed to selection effects. The H\textsc{ii}→S/T→LINER cycle suggests that the majority of AGNs might be detected only within a certain period after the interaction, allowing time for the starburst to fade and for the BH accretion to gain strength.

One might argue that that other forms of evolution could also exist for these emission-line galaxies, as opposed to this simple progression. We note that this proposed sequence does not imply that every H\textsc{ii} galaxy at the present epoch must necessarily become a LINER; it is certainly possible that some systems go through H\textsc{ii}-only phases, or L-only phases, which might not be part of the larger progression.

We would, however, like to emphasize that the timescales necessary to transform from one galaxy type to the next are quite reasonable. At a first glance, this is somewhat surprising given the relatively large range in BH masses ($2 \times 10^7 M_\odot$ for H\textsc{ii} galaxies, to $2 \times 10^9 M_\odot$ for LINERs, inferred from $\sigma_z$'s assuming, e.g., Tremaine et al. 2002), and their significantly low accretion rates ($L/L_{\text{Edd}} \leq 0.005$; see Fig. 7, and note that the $L/L_{\text{Edd}} = 0.05$, according to Kewley et al. 2006); apparently, for a canonical value of the accretion efficiency, i.e., 10%, it takes approximately a Hubble time to $\times$-fold in BH mass. The key is in the fact that the low-luminosity AGNs accrete inefficiently, as very little energy generated by accretion is radiated away (the optically thin cooling time of the gas is longer than the infall time). Studies show that, in these cases, the radiative efficiency can be as low as $10^{-6}$ (e.g., Rees et al. 1982; Narayan & Yi 1994; Quataert 2003). With a (not a necessarily extreme) efficiency value of $10^{-5}$ then, the $\times$-folding time in the BH mass is $\approx 4.5 \times 10^7/\text{yr}$, and thus as little as few Myr for, e.g., $L = L/L_{\text{Edd}} = 0.0005$. This (not necessarily extreme) example shows then that such an evolutionary scenario is actually physically possible.

The peculiarity of LINER environments is a new and intriguing result and clearly shows that this type of activity is not controlled by its surrounding environment. Galaxies hosting LINERs could be associated with high initial density peaks in the dark matter distribution, which evolved subject to their large-scale environment. Being generally massive systems to start with, LINERs' hosts would be prone to accreting material around them. In voids, this “cleaning” enterprise would contribute to emptying the already rarefied neighboring space, leaving little or insufficient material for future formation of massive, bright galaxies; they would thus end up in the most underdense void neighborhoods. In walls, and in particular within clusters, the accretion of surrounding material would make a small difference as the matter density is higher. Simulations of dark matter halos and correlations with the properties of their inhabiting galaxies should be able to address these ideas.

Further tests of this H\textsc{ii}→S/T→LINER evolutionary scenario are clearly needed. These tests require larger samples that allow separation into different morphological subsamples, and observables that parameterize the galaxy morphology better than the concentration index. Moreover, we need better constraints on the BH masses and consequently the Eddington rates for the H\textsc{ii} galaxies in particular, or the late-type galaxies in general. When available, analysis of such parameters would shed light on the assumed coevality of star formation and Seyfert-like BH accretion in centers of galaxies, removing ambiguities regarding the initial stages of the H\textsc{ii}→S/T→LINER progression.

Note added in manuscript.—During the review process of this paper, we became aware of another piece of work that introduces the same idea of an evolutionary sequence, “from star formation via nuclear activity to quiescence” (Schawinski et al. 2007). Interestingly, although their general approach, analysis, and samples used are quite different from ours, the measurements on which the evidence for a “star-forming, transition object, Seyfert, LINER” sequence is built share a common set of parameters with those used in our analysis: stellar velocity dispersions, ages of starbursts, and reddening. The global frame in which this evolutionary sequence is presented is, however, definitely different. While Schawinski et al. take a step forward toward understanding this possible time sequence among early-type galaxies and provide an in-depth analysis of the possible timescales involved in this picture, our paper offers a broader perspective on how such an evolutionary sequence constrains the galaxy evolution models, as we provide important links to the environment.

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REFERENCES

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Balogh, M., et al. 2004, MNRAS, 348, 1355
Barth, A., & Shields, J. C. 2000, PASP, 112, 753
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Begelman, M. C., & Nath, B. B. 2005, MNRAS, 361, 1387
Benson, A. J., Hoyle, F., Torres, F., & Vogely, M. S. 2003, MNRAS, 340, 160
Best, P. N. 2004, MNRAS, 351, 70
Blanton, M. R., Lupton, R. H., Maley, F. M., Young, N., Zehavi, I., & Loveday, J. 2003, AJ, 125, 2276
Blanton, M. R., et al. 2005, AJ, 129, 2562
Brinchmann, J., Charlot, S., Heckman, T. M., Kauffmann, G., Tremonti, C., & White, S. D. M. 2004, preprint (astro-ph/0406220)
Byrd, G. G., Seldielus, B., & Valtonen, M. 1987, A&A, 171, 16
Christlein, D., & Blazkobuff, A. I. 2005, ApJ, 621, 201
Constantin, A., & Vogely, M. S. 2004, ApJ, 650, 727
Constantin, A., et al. 2007, ApJ, submitted
Croton, D. J., et al. 2006, MNRAS, 365, 11
Cruzon, S., et al. 2002, AJ, 123, 142
Dahari, O. 1984, AJ, 89, 966
de Robertis, M. M., Hayhoe, K., & Yee, H. K. C. 1998a, ApJS, 115, 163
de Robertis, M. M., Yee, H. K. C., & Hayhoe, K. 1998b, ApJ, 496, 93
Di Matteo, T., et al. 2005, Nature, 433, 604
Dopita, M. A., & Sutherland, R. S. 1995, ApJ, 455, 468
Doyle, M. T., & Drinkwater, M. J. 2006, MNRAS, 372, 977
Einasto, J., Jeeveer, M., & Saar, E. 1990, MNRAS, 193, 353
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Filippenko, A. V., & Terlevich, R. 1992, ApJ, 397, 79L
Fuentes-Williams, T., & Stocke, J. T. 1988, AJ, 96, 1235
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Gebhardt, K., et al. 2000, ApJ, 539, L13
Goldberg, D. M., Jones, T. D., Hoyle, F., Rojas, R. R., Vogely, M. S., & Blanton, M. R. 2005, ApJ, 621, 643
Gomez, P. L., et al. 2003, ApJ, 584, 210
Gunn, J. E., et al. 1998, AJ, 116, 3040
Heckman, T. M. 1980, A&A, 87, 152
Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., Tremonti, C., & White, S. D. M. 2004, ApJ, 613, 109
Henquisit, L., & Milos, J. C. 1995, ApJ, 448, 41
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJS, 112, 315
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Hopkins, P. F., Henquisit, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., & Springel, V. 2005, ApJ, 630, 705
Hopkins, P. F., Henquisit, L., Cox, T. J., Di Matteo, T., Robertson, B., & Springel, V. 2006, ApJS, 163, 1
Hoyle, F., Rojas, R. R., Vogely, M. S., & Brinkmann, J. 2005, ApJ, 620, 618
Hoyle, F., & Vogely, M. S. 2002, ApJ, 566, 641
———. 2004, ApJ, 607, 751
Kauffmann, G., & Haasahnelt, M. 2000, MNRAS, 311, 576
Kauffmann, G., et al. 2003a, MNRAS, 341, 33
———. 2003b, MNRAS, 341, 54
———. 2003c, MNRAS, 346, 1055