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Circumnuclear Dust in Nearby Active and Inactive Galaxies. II. Bars, Nuclear Spirals, and the Fueling of Active Galactic Nuclei[1]

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ABSTRACT

We present a detailed study of the relation between circumnuclear dust morphology, host galaxy properties, and nuclear activity in nearby galaxies. We use our sample of 123 nearby galaxies with visible–near-infrared colormaps from the *Hubble Space Telescope* to create well-matched, "paired" samples of 28 active and 28 inactive galaxies, as well as 19 barred and 19 unbarred galaxies, that have the same host galaxy properties. Comparison of the barred and unbarred galaxies shows that grand design nuclear dust spirals are only found in galaxies with a large-scale bar. These nuclear dust spirals, which are present in approximately a third of all barred galaxies, also appear to be connected to the dust lanes along the leading edges of the large-scale bars. Grand design nuclear spirals are more common than inner rings, which are present in only a small minority of the barred galaxies. Tightly wound nuclear dust spirals, in contrast, show a strong tendency to avoid galaxies with large-scale bars. Comparison of the AGN and inactive samples shows that nuclear dust spirals, which may trace shocks and angular momentum dissipation in the ISM, occur with comparable frequency in both active and inactive galaxies. The only difference between the active and inactive galaxies is that several inactive galaxies appear to completely lack dust

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structure in their circumnuclear region, while none of the AGN lack this structure. The comparable frequency of nuclear spirals in active and inactive galaxies, combined with previous work that finds no significant differences in the frequency of bars or interactions between well-matched active and inactive galaxies, suggests that no *universal* fueling mechanism for low-luminosity AGN operates at spatial scales greater than ~ 100 pc radius from the galactic nuclei. The similarities of the circumnuclear environments of active and inactive galaxies suggests that the lifetime of nuclear activity is less than the characteristic inflow time from these spatial scales. An order-of-magnitude estimate of this inflow time is the dynamical timescale. This sets an upper limit of several million years to the lifetime of an individual episode of nuclear activity.

Subject headings: galaxies: active – galaxies: Seyfert – galaxies: nuclei – galaxies: ISM – ISM: structure – dust, extinction

1. Introduction

Many observational programs over the past few years have led to the proposition that all galaxies with a substantial spheroid component contain supermassive black holes, irrespective of the presence or absence of nuclear activity (e.g. Richstone et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). Since black holes grow via the accretion of matter and this accretion leads to detectable nuclear activity, these results imply that all galaxies must go through an accretion phase, yet the mechanism which triggers nuclear activity in "currently" active galaxies remains unknown. In order to fuel active galactic nuclei (AGN), essentially all of the angular momentum must be removed from some fraction of the host galaxy's interstellar medium (ISM). Low-luminosity AGN, which dominate the local population, require accretion rates of $0.01 - 0.1 M_{\odot}$ yr^{-1}, assuming typical radiative efficiencies.

Studies of AGN and inactive control samples have investigated the frequency of several mechanisms for angular momentum transport to determine their viability. Interactions between galaxies is one good candidate (Toomre & Toomre 1972) as theoretical simulations of mergers show significant accretion into the central regions of the merger remnant (e.g. Hernquist 1989; Barnes & Hernquist 1991; Mihos & Hernquist 1996). Interactions may be responsible for triggering AGN activity in the more luminous quasars (Hutchings & Neff 1997; Bahcall et al. 1997), yet detailed studies of interacting pairs have not found a statistically significant excess of the lower-luminosity Seyfert galaxies in interacting systems (Fuentes-Williams & Stocke 1988). Large-scale bars have also been proposed as a mechanism to fuel nuclear activity (Simkin, Su, & Schwarz 1980; Schwarz 1981). The nonaxisymmetric potential due to a large-scale bar leads to the formation of a shock front along the bar's leading edges (Prendergast 1983; Athanassoula 1992) and material has been observed flowing into the central regions of several barred galaxies (Quillen et al. 1995; Regan, Vogel, & Teuben 1997; Jogee, Kenney, & Smith 1999). However, detailed near-infrared (NIR) studies of large samples of active and inactive galaxies have shown either no, or at most a marginal (2.5σ), excess of large-scale bars in active samples (Mulchaey & Regan 1997; Knapen, Shlosman, & Peletier 2000). These studies of interacting and barred galaxies pushed the effective spatial resolution limit of ground-based observations for large samples of AGN, yet the typical spatial resolution of these investigations remain many hundreds of parsecs.

Several *HST* programs over the past few years have targeted the circumnuclear morphology of large active galaxy samples to search for signatures of AGN fueling (e.g. Malkan, Gorjian, & Tam 1998; Regan & Mulchaey 1999; Martini & Pogge 1999). One of the main goals of these programs was to investigate the fraction of Seyferts with nuclear bars (bars with semimajor axis lengths typically less than a kiloparsec), which could be comprised of gas or stars (Shlosman, Frank, & Begelman 1989; Pfenniger & Norman 1990) and cause the transport of matter from approximately a kiloparsec to tens of parsecs. However, these studies have found nuclear bars in only $\sim 25\%$ of all Seyferts (Regan & Mulchaey 1999; Martini et al. 2001) and studies of Seyfert and control samples have found similar fractions of double bars in samples of active and inactive galaxies with large-scale bars (Márquez et al. 2000; Laine et al. 2002; Erwin & Sparke 2002). The comparable fractions of nuclear bars in active and inactive galaxies, combined with the apparent absence of them in the majority of all active galaxies, suggests that some other mechanism is needed to fuel nuclear activity in many active galaxies.

One new candidate that arose from the *HST* studies is nuclear dust spirals (Regan & Mulchaey 1999; Quillen et al. 1999; Martini & Pogge 1999; Pogge & Martini 2002). Visible–NIR color maps of the majority of the active galaxies in these surveys showed nuclear spirals, with a wide range of coherence, that extend from approximately a kiloparsec down to tens of parsecs (the limiting spatial resolution of the nearest subsample). These nuclear spirals are distinct from the spiral arms in the main disks of these galaxies as they appear to have density contrasts of only a factor of a few above the ambient ISM and no associated star formation. Nuclear spirals are a promising fueling mechanism not only by virtue of their frequency, but also because they may mark the location of shock fronts or turbulence in the central, circumnuclear gaseous disks and therefore trace the sites of angular momentum dissipation. The possibility of shock-driven inflow, as traced by nuclear spiral structure, has been the subject of a number of recent theoretical studies (Fukuda et al. 1998; Montenegro, Yuan, & Elmegreen 1999; Wada & Norman 2001; Maciejewski et al. 2002; Wada, Meurer, & Norman 2002).

While most of the observational programs to date have targeted the circumnuclear region of active galaxies, nuclear dust spirals have also been observed in a small number of inactive galaxies with single-bandpass observations (Phillips et al. 1996; Carollo, Stiavelli, & Mack 1998). In *HST* Cycle 9 we began a program (SN8597, PI Regan) to obtain WFPC2 images of galaxies with prior NICMOS observations (from SN7330, PI Mulchaey and GO7867, PI Pogge) in order to quantify the frequency of nuclear spiral structure in inactive galaxies. We present the observations of our final sample of 123 galaxies, along with a description of the sample, survey design, and classification system for circumnuclear dust structure, in Martini et al. (2002, hereafter Paper I). Our nuclear dust classification has six types, including four for nuclear dust spirals: grand design, tightly wound, loosely wound, and chaotic spirals. We placed galaxies with dust structures but without evidence for nuclear spirals in a fifth, "chaotic" class, and galaxies with no detected circumnuclear dust structure into a sixth, "no structure" class. The final dataset presented in Paper I, in spite of the initial effort to create a well-match active and control sample, is relatively heterogeneous due to both the vagarious *HST* snapshot scheduling and our attempt to augment the sample with additional nearby galaxies of interest.

In the present paper we create well-matched subsamples of the full dataset presented in Paper I in order to measure the relative frequency of nuclear dust spirals in active and inactive galaxies. This sample creation, described in the next section, draws unique pairs of active/inactive or barred/unbarred galaxies that otherwise have all of the same host galaxy properties and are at the same distance, while also maximizing the total size of the subsample drawn from the full dataset. In §§3 and 4 we describe the trends for circumnuclear dust morphology for the active/inactive and barred/unbarred samples, respectively. The implications of these results for the fueling of nuclear activity are described in §5 and our results are summarized in §6.

2. Paired Sample Selection

To construct the best-matched sample given the available observations, we have developed an algorithm to identify a unique inactive, control galaxy for each active galaxy and maximize the number of pairs of active and inactive galaxies. The host galaxy properties used to identify possible control galaxies for each active galaxy were the four properties used to define the original RSA control sample: Hubble type (T), blue luminosity (M_B), heliocentric velocity (v), and inclination (R_{25}), along with a fifth property: the angular size of the host. This fifth property is expressed as the fraction ($frac_{20}$) of the angular extent (D_{25}) of the host galaxy within the 20″ field of view of the color maps shown in Figure 1 of Paper I.

The constraints on these parameters are: $\Delta T < 1$, $\Delta M_B < 0.5$ mag, $\Delta v < 1000\,\mathrm{km\,s^{-1}}$, $\Delta R_{25} < 0.1$, and $\Delta frac_{20} < 0.1$. These constraints were applied to the subsample of 86 (out of 123) galaxies with $v < 5000\,\mathrm{km\,s^{-1}}$ and $R_{25} < 0.30$. These two cuts were chosen to avoid distant galaxies, where the *HST* spatial resolution is comparable to ground-based observations of nearby galaxies, and highly inclined systems, where we found our morphological classifications were less reliable (see Paper I).

The algorithm first identifies all possible control galaxies for each active galaxy through measurement of the absolute difference between each of the host galaxy parameters. As there are more active than inactive galaxies in the final dataset, the number of inactive galaxies is the main constraint on the final number of matched pairs. The first step in the algorithm is therefore to identify each inactive galaxy that has only one active galaxy match. These unique galaxy pairs are placed into the output catalog and the active galaxies in these pairs are then removed from the list of possible matches for the remaining inactive galaxies. This procedure is then repeated until no potential matched pairs remain. For the case where there are no inactive galaxies with a unique active galaxy match, the control galaxy with the fewest number of active galaxy matches was picked and matched with the active galaxy with the smallest number of other control galaxy matches.

This method successfully found a unique active galaxy match for each inactive galaxy with $v < 5000\,\mathrm{km\,s^{-1}}$, $R_{25} < 0.30$, and at least one possible pair: the best possible outcome. For other parameter constraints described below it was either equally successful or at worst would fail to match only one or two control galaxies. This process yielded a final, matched sample of 28 active galaxies and 28 inactive galaxies. The distribution of nuclear classifications and host galaxy properties for this sample is shown in Figure 1. The galaxies in this active and inactive sample are listed in Table 1 and their host galaxy properties are provided in Paper I. The mean (and rms) differences between the pairs for each of these properties are: $\Delta M_B = -0.03(0.29)$ mag, $\Delta T = 0.11(0.72)$, $\Delta v_h = -218(553)\,\mathrm{km\,s^{-1}}$, $R_{25} = -0.01(0.04)$, and $frac_{20} = -0.01(0.04)$. If we increased the size of the constraints, such as from 0.5 to 1 mag in M_B, the sample size would only increase by three pairs, which we decided did not justify the chance this would increase systematic biases. The top left panel of the figure shows the relative distribution of active and inactive galaxies in each of the six nuclear classes. The remaining panels show the distribution of host galaxy properties.

We did not include the presence or absence of a large-scale bar in this sample selection, as this additional constraint would have further reduced the sample size. The sample listed in Table 1 has more unbarred inactive galaxies (ten) than unbarred active galaxies (four). As we show next, nuclear spiral structure appears to be present in barred and unbarred galaxies with equal frequency, so this should not affect our results, although the distribution of barred and unbarred galaxies into the nuclear spiral classes is different.

We created matched samples of barred and unbarred galaxies in the same manner as for the active and inactive galaxies. The goal of this investigation was to measure the frequency of nuclear spiral structure in barred and unbarred galaxies, as well as to verify the two results noted in Paper I: the existence of grand design nuclear spirals only in barred galaxies and the strong tendency for tightly wound nuclear spirals to avoid barred galaxies. Due to the small number of unbarred galaxies (25 or 86) in this sample, only 19 pairs of barred and unbarred galaxies were identified. These galaxies are listed in Table 2. Figure 2 shows the distribution of these galaxies in each of the morphological classes for circumnuclear dust, along with the distributions of their host galaxy properties. The mean differences between the pairs of barred and unbarred galaxies in each of the parameters are: $\Delta M_B = -0.01(0.27)$ mag, $\Delta T = 0.19(0.59)$, $\Delta v_h = -68(528)\,\mathrm{km\,s^{-1}}$, $R_{25} = 0.01(0.05)$, and $frac_{20} = 0.00(0.04)$. The barred and unbarred pairs were not required to have the same nuclear activity, although as eleven of 19 barred galaxies and eight of 19 unbarred galaxies were active, the comparison below should not be biased by any differences between active and inactive galaxies.

3. Results for Active Galaxies

3.1. Frequency of nuclear spiral structure in active galaxies

The main result of Figure 1 is that nuclear spiral structure is found with comparable frequency in active and inactive galaxies for a sample well-matched by host galaxy properties. When all four nuclear spiral classes are summed together, 21 of the 28 active galaxies (75%) have nuclear dust spirals compared to 17 of the 28 (61%) inactive galaxies. The significance of this result can be estimated with a binomial distribution as each galaxiy either has a nuclear spiral or does not, these outcomes are statistically independent, and each galaxy has the same probability of having a nuclear spiral. The variances of the active and inactive samples are $\sigma_a^2 = 28 \times 0.75 \times 0.25 = 5.25$ and $\sigma_i^2 = 28 \times 0.61 \times 0.39 = 6.66$, respectively, and the variance of the difference is $\sigma^2 = \sigma_a^2 + \sigma_i^2 = 11.91$. Thus, the observed spiral frequencies formally differ by only 1.2σ, which is not statistically significant.

Of the four types of nuclear spirals, there are approximately equal numbers of active and inactive galaxies in the grand design, tightly wound, and chaotic spiral classes. The active galaxies with loosely wound nuclear spirals outnumber inactive galaxies with similar circumnuclear morphologies by a factor of three to one, although this excess has less than 2σ significance. The main result from this figure is that nuclear spirals are found with comparable frequency in active and inactive galaxies.

3.2. Frequency of circumnuclear dust structures in active galaxies

Another interesting result from Figure 1 is that 25% (seven) of the inactive galaxies have no obvious circumnuclear dust structure at all, whereas all of the active galaxies have some structure in their circumnuclear dust distribution. These galaxies must either have no circumnuclear dust, or this dust must be smoothly distributed. Employment of the binomial distribution estimate shows that this difference has a formal significance of 3σ. These galaxies include four S0s, an Sa, an Sab, and an Sbc, and therefore it is not Hubble type alone which drives the absence of circumnuclear dust structure. Spatial resolution is important to identify dust structures in the centers of galaxies, as color maps are most sensitive to dust structure with an angular size comparable to the PSF. We are therefore progressively less sensitive to small-scale dust structure in the more distant galaxies. However, as we have an equal number of active and inactive galaxies at each distance, there is no bias against the detection of dust structures in one sample relative to the other. Therefore spatial resolution will not effect the relative frequency of dust structure in active and inactive galaxies, although it may effect the number of galaxies with detected dust structure,

The full sample from Paper I includes these same seven inactive galaxies with no circumnuclear dust structure: NGC 357, NGC 628, NGC 1398, NGC 1638, NGC 3300, NGC 3458, and NGC 7096, along with one active galaxy: NGC 3362. This AGN was excluded from the discussion in the present paper because it has a heliocentric velocity greater than 5000 km s^{-1} ($v \sim 8300$). The lack of circumnuclear dust structure in this AGN may be due to poor spatial resolution, or contamination by light from the central point source. The presence of some emission line gas in the central region of NGC 3362 indicates that it does have some circumnuclear gas, even though no dust structure is apparent in the colormap. The fact that the only AGN in this class in the full sample is at a large distance, and in any case shows emission line structure in the circumnuclear region, further supports our result that inactive galaxies have a strong tendency to lack circumnuclear dust structure relative to active galaxies.

4. Results for all Galaxies

4.1. Grand-design nuclear spirals in barred galaxies

The upper left panel of Figure 2 shows the distribution of the barred and unbarred galaxies into each nuclear class. While the sample is smaller than shown in Figure 1, the differences appear more striking. The first column confirms the result from Paper I that grand design nuclear spiral structure is only found in galaxies with large-scale bars. Seven grand design nuclear spirals are found in barred galaxies, whereas none are found in unbarred galaxies. This result has 3σ formal significance. In Paper I we found 19 barred galaxies with grand design structure and no unbarred galaxies in this class. Grand design nuclear spiral structure is therefore only found in galaxies with large-scale bars. Furthermore, these grand design nuclear dust spirals always appear to connect with dust lanes along the leading edges of the large-scale bar. If the barred galaxies in this sample and in the full sample discussed in Paper I are representative of the population of barred galaxies, grand design nuclear spirals are present in approximately a third of all barred galaxies (27% of the full sample from Paper I, 37% of the present, smaller sample). These grand design nuclear spirals are therefore more common than inner rings, which were only found in a small minority of barred galaxies in Paper I. Only three of the 19 barred galaxies listed in Table 2 show evidence for inner rings in the *HST* observations presented in Paper I.

The morphology of these dust lanes is in good agreement with the predictions of hydrodynamic simulations of gas morphology in the circumnuclear regions of barred galaxies (Englmaier & Shlosman 2000; Maciejewski et al. 2002; Wada, Meurer, & Norman 2002). The observations clearly show the shock fronts in large-scale bars continues into the circumnuclear region to the limit of our angular resolution, which corresponds to tens of parsecs from the nucleus. The inflow of matter due to large-scale bars can lead to the secular evolution of galaxies, fuel circumnuclear star formation, accretion, and may eventually lead to the dissolution of the large-scale bar (Kormendy 1993; Friedli & Benz 1993). The fact that inner rings are only found in a small minority of barred galaxies, and are less common than grand design spirals, shows that the "pile up" of bar-driven inflow into a ring is a rare occurence.

4.2. Tightly wound nuclear spirals in unbarred galaxies

In the full sample described in Paper I there were three barred galaxies (out of 70) with tightly wound nuclear dust spirals compared with eight (of 31) unbarred galaxies. Two of those barred galaxies with tightly wound nuclear dust spirals were excluded from this analysis because of distance or because there was not an unbarred galaxy with comparable host galaxy properties. The matched sample shown in Figure 2 has seven unbarred galaxies with tightly wound nuclear spirals and only one barred galaxy with a tightly wound nuclear spiral. This difference has a formal significance of 2.5σ and therefore may represent a second real difference in the circumnuclear structure of barred galaxies. As there are a small number of barred galaxies with tightly wound nuclear dust spirals, the connection between tightly wound nuclear spirals and the absence of a large-scale bar is not as strong as the connection between grand design nuclear spirals and large-scale bars. Nevertheless, given the fact that barred galaxies far outnumber unbarred galaxies in the full sample, and there is an even stronger trend in the full sample, there may be a physical connection between the absence of a large-scale bar and the presence of a tightly wound nuclear dust spiral. The tendency for tightly wound nuclear spirals to be present in unbarred galaxies could be confirmed (improved to 3σ significance) with an additional sample of on order ten unbarred galaxies that are well-matched to our existing barred galaxy sample.

4.3. Correlations with host galaxy properties

To investigate any additional correlations between host galaxy properties and circumnuclear dust structure, we have examined the mean host galaxy properties of all of the galaxies in Paper I with $R_{25} < 0.30$ and $v < 5000\,\mathrm{km\,s^{-1}}$. The mean Hubble type of this sample is only slightly later than Sab. This is also the case for all of the individual nuclear classes except for the loosely wound spiral class, which has an earlier mean Hubble type between S0/a and Sa. The similar mean Hubble types for each nuclear class suggests that there is not a strong relationship between galaxy type and the morphology of the circumnuclear dust. The fact that the loosely wound spirals are more common in galaxies whose large-scale spiral arms are more tightly wound may be due to the relative importance of the bulge and disk in the circumnuclear and large-scale morphology. However, Rubin et al. (1985) showed that the rotation curves of galaxies are more dependent on luminosity than on Hubble type.

A difference in luminosity, parametrized here as M_B, could therefore explain the variations in circumnuclear dust structure if the amount of differential rotation is the primary factor in the pitch angle of the nuclear spirals. In general, there are no large differences in the average M_B from class to class. The mean M_B for the entire sample is -20.3 mag and the mean value for each class deviates at most by little over half a magnitude from this value. The deviation is largest between the tightly wound nuclear spirals, which have $M_B = -20.9$ mag and the loosely wound nuclear spirals, which have $M_B = -20.1$ mag. Therefore it appears that the tightly wound nuclear spirals are found in more luminous galaxies. As Rubin et al. (1985) found that more luminous galaxies have larger central velocity gradients, tightly wound nuclear spirals may therefore be found in more luminous galaxies if these galaxies also deviate more strongly from solid-body rotation. An alternate explanation is that the tightly wound spirals have been undisturbed for a longer period of time and have had more time to wind. Kinematic observations are necessary to determine if the circumnuclear rotation curve is the primary driver of nuclear spiral pitch angle.

Two additional parameters that describe the morphology of these galaxies, but are not included in our paired sample matching, are the presence of a ring or pseudo ring and whether or not a galaxy is classified as peculiar. We have used the RC3 classifications listed in Table 3 of Paper I to compute the relative frequency of ringlike and peculiar morphology as a function of nuclear classification and found that the relative frequencies of these classifications are consistent with each other across the six circumnuclear dust classes. This consistency is not very significant, however, as the quality of the RC3 classifications is difficult to quantify for the full sample. A larger number of well-matched galaxy pairs would provide an improved basis for investigation of correlations between circumnuclear morphology and host galaxy properties.

All of the mechanisms proposed to fuel nuclear activity in galaxies are also methods that can trigger circumnuclear star formation and may lead to secular evolution. Recent work on a direct connection between Seyferts and starbursts by Storchi-Bergmann et al. (2001) has investigated connections between the circumnuclear dust morphology and star formation. These authors studied the relationship between the Malkan, Gorjian, & Tam (1998) "inner Hubble type" classification and the presence of circumnuclear star formation and found that most Seyferts with circumnuclear star formation were classified as late-type inner spirals, or loosely wound spirals in our classification system. If there is more star formation in galaxies with high pitch angle nuclear spirals, this could help to explain the slightly brighter M_B of the loosely wound nuclear spirals relative to the other three nuclear spiral classes. Inspection of the images and colormaps shown in Figure 1 of Paper I shows some observational support for the results of Storchi-Bergmann et al. (2001), namely the star formation in NGC 1672, NGC 4314, NGC 5427, and NGC 6951. We note, however, that our sample was not designed to carry out a well-defined study of star formation.

5. Discussion

Although our analysis based on matched pairs of either active/inactive or barred/unbarred galaxies minimizes sample biases, there are nevertheless several to consider. The first is that the bar and active galaxy classifications are nonuniform. As described in Paper I, several of the allegedly inactive galaxies designated as controls for the RSA Seyfert Sample were later reclassified as active galaxies by the Palomar Survey (Ho, Filippenko, & Sargent 1997). While many of the inactive galaxies in this sample were part of the Palomar survey, the other galaxies were observed as part of less sensitive surveys that may be biased against the detection of very low-luminosity AGN. This reflects a problem inherent in the view of galaxies as either active or inactive, when in reality the intensity of nuclear activity varies along a continuum over many orders of magnitude. Proper inclusion of, for example, bins of L_{bol}/L_{Edd} or accretion rate, would require considerably larger samples. For the current investigation it is very nevertheless unlikely that at least any bright Seyfert 1 galaxies were included in our inactive sample due to the fact that there are no bright, unresolved point sources at the centers of their visible or near-infrared *HST* images. Several quite faint active galaxies from the Palomar Survey do not have distinct nuclei, so the possibility remains that there are very low-luminosity active galaxies in the inactive sample. The vast majority of these misclassified active galaxies would have to be in the dust-free or chaotic classes to significantly change our results on active galaxies.

A second potential selection effect is that the brightness of the nuclear point source in the active galaxies may increase the M_B used to match the active and inactive samples. While this is a concern for comparisons of luminous AGN, it is unlikely to affect this study because most of the bona fide AGN are still relatively low luminosity nuclei and only make a minor contribution to the total galaxy+AGN luminosity. To test this we have artificially decreased the M_B value by half a magnitude and rematched the pairs of active and control samples. There was no significant difference in either the frequency of nuclear spiral structure or the result that the total absence of circumnuclear dust was only found in the inactive galaxies.

A related uncertainty to the first point above is that the sample matching process is only as reliable as the host galaxy properties that are used to create the samples. Fortunately, all of the host galaxy properties were obtained from the RC3 catalog (de Vaucouleurs et al. 1991) and therefore were extracted from a homogeneous dataset. While it is more difficult to obtain accurate galaxy classifications for more distant or less luminous galaxies, the fact that the galaxy samples were matched based on both of these properties simultaneously should account for distance- and brightness-dependent errors in the measurement of the host galaxy properties. A more serious problem is the bar classifications. While all of these galaxies have bar classifications in the RC3 catalog, it is now well known that NIR observations often identify bars in galaxies considered unbarred at visible wavelengths (e.g. Mulchaey, Regan, & Kundu 1997) and several of the unbarred galaxies lack NIR data. If some of the unbarred galaxies were later found to be barred based on NIR observations, that would not change our result that grand design nuclear spirals are only found in galaxies with large-scale bars, although this could effect the result that small pitch angle nuclear spirals (the TW class) are preferentially found in unbarred galaxies.

A final uncertainty is the quality of our own nuclear classifications. As discussed in Paper I, the classifications for many galaxies were initially disputed. However, most of these disputes were between the different nuclear spiral classes and would not affect our result on the relative frequency of nuclear spirals in active and inactive galaxies. The main uncertainty that could affect this result is the misclassification between the chaotic spiral and chaotic dust classes. However, half (three) of the active galaxies classified as chaotic would have to have spiral structure and half (also three) of the inactive galaxies classified as chaotic spirals would have to lack spiral structure in order produce a 3σ difference between active and inactive galaxies. The probability of both circumstances is quite low.

5.1. Matter inflow in barred galaxies

Approximately a third of the barred galaxies in this sample show curved dust lanes which start at the leading edges of their large-scale bars, have a grand design morphology in the circumnuclear region and then extend into the unresolved nuclear region. The apparent extension of the shock fronts in these galaxies into the circumnuclear region presents a strong case for the bar-driven inflow of matter to the nucleus in at least some barred galaxies. While single color maps do not provide a direct measure of the matter surface density in these dust lanes due to uncertainties caused by the unknown dust geometry and optical depth effects, a lower limit of a few $M_{\odot}$ pc^{-2} is reasonable (Regan & Mulchaey 1999; Martini & Pogge 1999). In simulations of dust lanes in barred galaxies the maximal inflow rates are as high as $\sim 100\,\mathrm{km\,s^{-1}}$ (Athanassoula 1992), similar to measurements of the maximum gas velocity parallel to the dust lanes for several galaxies (Regan, Vogel, & Teuben 1997; Reynaud & Downes 1998). The mean inflow in the simulations is a few $\mathrm{km\,s^{-1}}$.

Sakamoto et al. (1999) derive a lower limit of $0.1 - 1$ $\mathrm{M_{\odot}\ yr^{-1}}$ for the accretion rate into the central kiloparsec of barred galaxies from their CO data. This amount of matter inflow from bars is sufficient to explain the enhanced molecular gas content at the centers of barred galaxies (Sakamoto et al. 1999; Regan, Sheth, & Vogel 1999) and trigger circumnuclear star formation. There may also be sufficient matter inflow to fuel low-luminosity nuclear activity. However, this material must still travel from tens of parsecs, the best spatial resolution of these observations, to scales of less than a parsec in order to come within range of the central black hole's gravitational potential.

5.2. Do nuclear dust spirals fuel nuclear activity?

The presence of grand design spiral shocks demonstrates the presence of a mechanism for matter inflow to the centers of barred galaxies, yet this symmetric spiral structure is only found in a minority of active and inactive galaxies. The majority of nuclear dust spirals take less symmetric forms with a range in pitch angle, or even have a chaotic appearance that may just exhibit some shear due to differential rotation. These forms of nuclear spiral structure are probably not formed by large-scale forces in the host galaxy, such as a bar, and instead are probably created *in situ*. Turbulence, either due to pressure or gravitational forces, may create structures that are then sheared into a spiral form due to differential rotation (Elmegreen et al. 1998; Montenegro, Yuan, & Elmegreen 1999; Wada 2001). The characteristics of density contrasts formed by acoustic turbulence include low density enhancements over the ambient ISM, a lack of associated star formation due to their low density, an increase in contrast at smaller radii, and that they should completely fill the circumnuclear disks in which they propagate (Elmegreen, Elmegreen, & Eberwein 2002).

As the turbulence which leads to these spirals produces shocks in the ISM, and shocks dissipate energy and angular momentum, these spirals trace the sites of angular momentum transfer that can lead to the fueling of nuclear activity. In a test of this scenario by Elmegreen, Elmegreen, & Eberwein (2002), analysis of nuclear dust spirals in the LINERs NGC 4450 and NGC 4736 show that the azimuthal Fourier power spectrum of these spirals has a slope of $-5/3$, indicative of turbulence. The tightly wound, loosely wound, and chaotic nuclear spirals have similar morphologies to the nuclear spirals studied by Elmegreen et al. (1998) and Elmegreen, Elmegreen, & Eberwein (2002), which suggests that most nuclear spirals are caused by a turbulent process.

While morphological arguments suggests that nuclear spirals are formed by turbulence and shocks, the question remains: Does sufficient angular momentum transfer occur to fuel nuclear accretion? The presence of an insignificant excess of nuclear spirals in active galaxies over inactive galaxies does not support this scenario. This is not to say that matter inflow is ruled out, only that it stops short of the central black hole. Kinematic evidence for inflow associated with these spirals, as well as emission-line signatures of shocks, would provide more compelling evidence that nuclear spiral structure can produce the accretion rates required to fuel low-luminosity AGN.

5.3. Constraints on the duty cycle of nuclear activity

Bars and interactions are mechanisms that can remove angular momentum and fuel nuclear activity. Nuclear spirals could be another possibility, provided that they trace sufficiently strong shocks in the circumnuclear ISM. However, all three of these proposed fueling mechanisms are found with approximately equal frequency in both active and inactive galaxies. This naturally prompts the question: If these mechanisms are responsible for fueling AGN, why are AGN not found in the otherwise indistinguishable inactive galaxies? These observations of nuclear dust spirals, as well as previous work on other similarities in the host galaxies of low-luminosity AGN on larger scales, show that there are not clear differences between active and inactive galaxies on any scales greater than approximately a hundred parsecs, the smallest scales probed by the present work.

The absence of clear differences between active and inactive galaxies to within approximately 100 pc radius of their galactic nuclei, combined with the presumption that all of these galaxies possess supermassive black holes, suggests that the characteristic inflow timescale from this radius is an upper limit on the lifetime of nuclear activity. A plausible estimate of this inflow timescale is the dynamical timescale. At a hundred parsecs, the dynamical timescale is several million years in a typical galaxy. If the structures responsible for AGN fueling exist at hundreds of parsec scales, but they are equally common in inactive galaxies, this suggests that the lifetime for an individual episode of nuclear activity is less than several million years. In our proposed scenario, where the structures responsible for AGN fueling are present in essentially all galaxies, all galaxies periodically go through a short-lived AGN phase.

6. Conclusions

The cold ISM in the circumnuclear region of nearly all spiral galaxies exhibits a wealth of structure. This structure often takes the form of nuclear dust spirals, which demonstrates that some differential rotation is present in the circumnuclear region of most spiral galaxies.

A comparison of a well-matched sample of 19 barred and 19 unbarred galaxies has confirmed our previous result (Paper I) that grand design nuclear dust spirals are only found in galaxies with large-scale bars. Grand design spirals are present in approximately a third of all barred galaxies and these circumnuclear spirals connect to the relatively straight dust lanes associated with the large-scale bar. The dust lanes therefore form essentially contiguous structures from many kiloparsec scales to within tens of parsecs of galactic centers. These nuclear spirals are also more common than inner rings, which are found in only a minority of all barred galaxies. The fact that most barred galaxies do not have rings inside the bar suggests that bar-driven inflow does not commonly stall in a circumnuclear ring. Our comparison of barred and unbarred galaxies also shows that there is a marginally significant tendency for tightly wound nuclear dust spirals to be found in galaxies that lack large-scale bars. The low pitch angle of these spirals may be due to an increased time for winding or greater differential rotation.

To test for differences in the circumnuclear dust distribution in active and inactive galaxies, we have created a well-matched sample of 28 active and 28 inactive galaxies by identifying pairs with all of the same host galaxy properties. This analysis finds only a statistically insignificant excess of nuclear spirals in active galaxies over the inactive control sample and that nuclear spiral structure is present in the majority of both types. A perhaps more surprising result was that although all of the active galaxies have some discernible dust structure, seven of the 28 inactive galaxies have no circumnuclear dust structure. These galaxies either have an extremely smooth dust distribution or no cold component to their ISM in the circumnuclear region. The comparable frequency of nuclear dust spirals in a well-matched sample of active and inactive galaxies, when combined with similar results for the frequency of bars or interactions from previous work, suggests that there is no universal fueling mechanism for low-luminosity AGN at scales greater than 100 pc from galactic nuclei.

We have shown that the circumnuclear dust morphologies of most active and inactive galaxies are indistinguishable. All of these galaxies are assumed to contain supermassive black holes and therefore the main difference between them is whether or not that central black hole is currently fueled. If the structures responsible for fueling nuclear activity are not present on the hundreds of parsec scales probed by these observations, or are present with equal frequency in active and inactive galaxies, then the timescale for nuclear activity must be less than the timescale for matter inflow from these spatial scales. If the dynamical timescale on these spatial scales is an approximate measure of the characteristic inflow time, this suggests an upper limit to the lifetime of an individual episode of nuclear activity is several million years.

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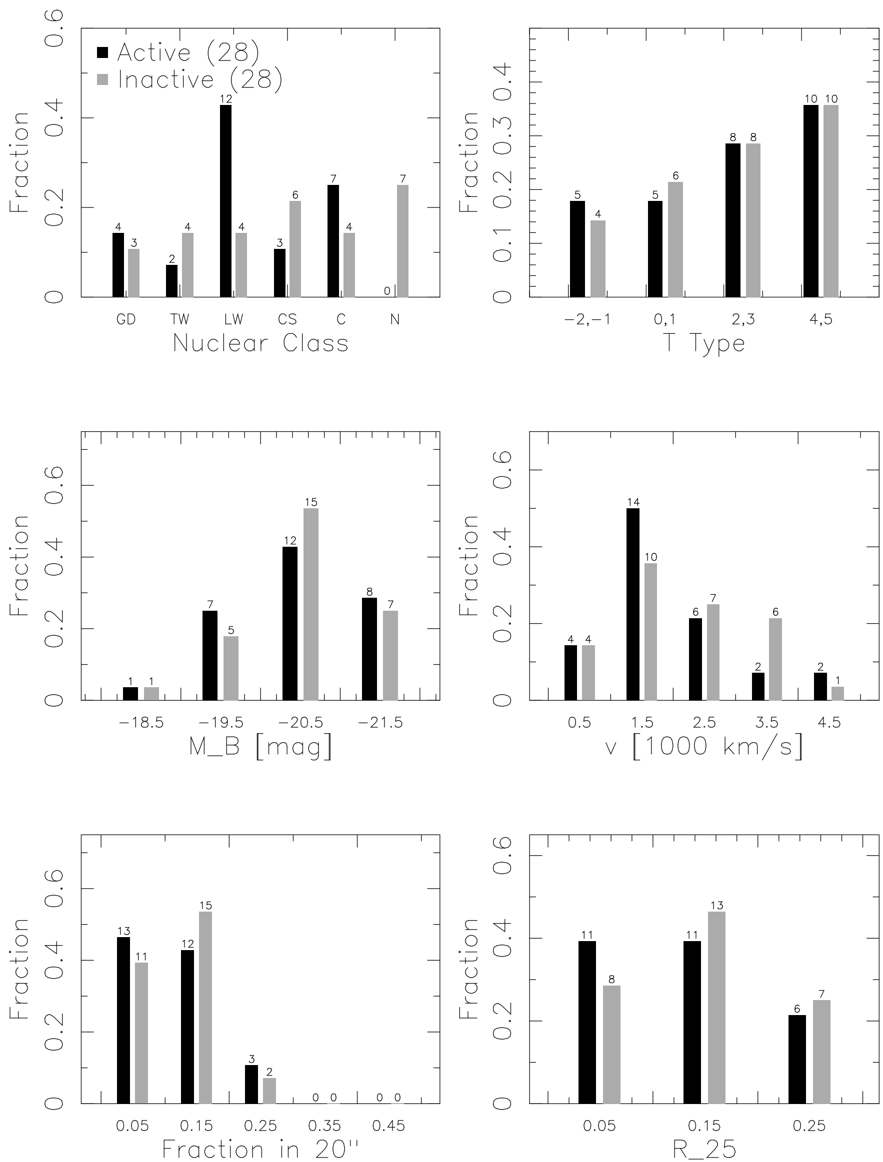

Fig. 1.— Distribution of the matched sample of 28 active and 28 inactive galaxies listed in Table 1 and described in §2. The upper left histogram shows the distribution of these galaxies into the six nuclear classes defined in Paper I. These classes are: GD: grand design nuclear dust spiral; TW: tightly wound nuclear spiral; LW: loosely wound nuclear spiral; CS: chaotic spiral; C: chaotic dust structure; N: no dust structure present. The histogram bars are normalized to the total number of galaxies in each class and the number of galaxies in each class is given above the histogram bar. The remaining five histograms show the distribution of the Hubble type, B luminosity, heliocentric velocity, size, and inclination of the active and inactive galaxies. The seven inactive galaxies with no circumnuclear dust structure, as opposed to no similar active galaxies, has a formal significance of 3σ. There are also three times as many active galaxies with loosely wound spirals as inactive galaxies, although this is not formally significant. The remaining panels show the close correspondence of the active and inactive galaxies in each of these five host galaxy properties.

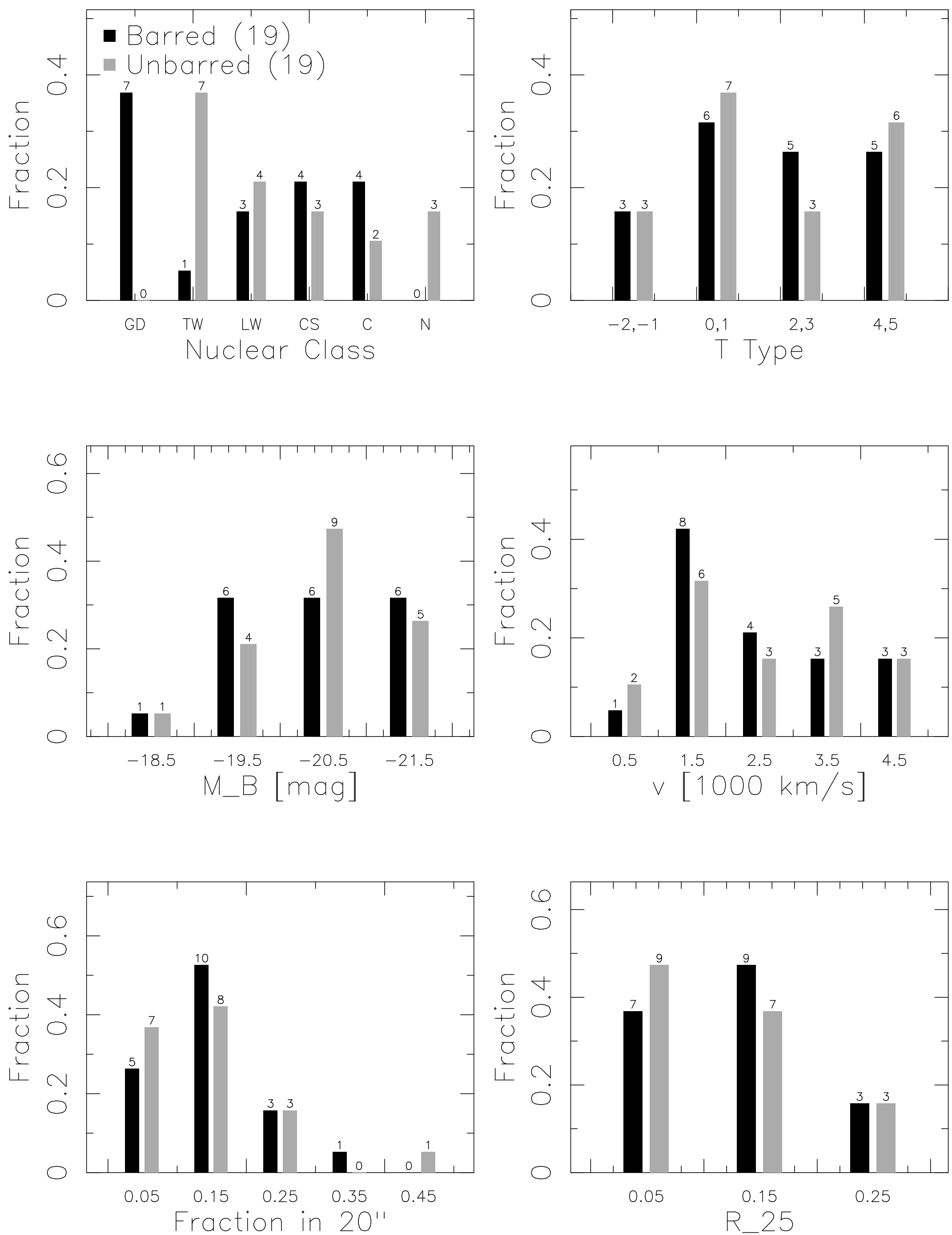

Fig. 2.— Same as Figure 1 for the matched sample of 19 barred and 19 unbarred galaxies listed in Table 2 and described in §2. Grand design nuclear spirals are only found in barred galaxies, while there is a marginally significant tendency for tightly wound nuclear spirals to be present in unbarred galaxies. The remaining panels show the similar host galaxy properties of the barred and unbarred galaxies.

Table 1. Matched active and inactive sample

Active Galaxy	Inactive Galaxy
IC2560	NGC7392
MRK1066	NGC3300
NGC1068	NGC1398
NGC1667	NGC0214
NGC1672	NGC5383
NGC2273	NGC5691
NGC2336	NGC1530
NGC3227	IC5267
NGC3486	NGC1300
NGC3516	NGC1638
NGC3786	NGC2179
NGC4143	NGC3458
NGC4151	NGC2146
NGC4303	NGC4254
NGC4725	NGC2985
NGC4939	NGC3145
NGC5273	NGC3032
NGC5347	NGC7096
NGC5427	NGC2276
NGC5643	NGC4030
NGC5953	NGC2460
NGC6300	NGC3368
NGC6744	NGC5054
NGC6814	NGC0628
NGC6951	NGC5970
NGC7469	NGC5614
NGC7496	NGC7716
NGC7743	NGC0357

Note. — The sample of active galaxies (Col. 1) and the corresponding inactive, control for each (Col. 2). Each control galaxy has approximately the same host galaxy type, absolute blue luminosity, heliocentric velocity, size, and inclination as the active galaxy in the same row of the Table (see §2). The distribution of their nuclear classifications and host galaxy properties are shown in Figure 1.

Table 2. Matched barred and unbarred sample

Barred Galaxy	Unbarred Galaxy
MARK1066	IC5063
NGC1530	NGC5054
NGC2273	IC5267
NGC2276	NGC5427
NGC2460	NGC5953
NGC3032	NGC5273
NGC3145	NGC4939
NGC3351	NGC4380
NGC3516	NGC1638
NGC4253	MARK1210
NGC4303	NGC4254
NGC4725	NGC2985
NGC5135	NGC5614
NGC5347	NGC7096
NGC5643	NGC4030
NGC5691	NGC2179
NGC6412	NGC0628
NGC7130	NGC0788
NGC7469	NGC5548

Note. — Same as Table 1 for the barred and unbarred galaxy sample described in the text and shown in Figure 2.