PROPERTIES OF ACTIVE GALAXIES DEDUCED FROM H I OBSERVATIONS

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ABSTRACT

We have completed a new survey for H I emission for a large, well-defined sample of 154 nearby (z \( \leq 0.1 \)) galaxies with type 1 (broad-line) active galactic nuclei (AGNs). We make use of the extensive database of H I and optical parameters, presented in a companion paper, to perform a comprehensive appraisal of the cold gas content in active galaxies and to seek new strategies to investigate the global properties of the host galaxies and their relationship to their central black holes. After excluding objects with kinematically anomalous line profiles, which occur with high frequency in the sample, we show that the black hole mass obeys a strong, roughly linear relation with the host galaxy’s dynamical mass, calculated by combining the H I line width and the optical size of the galaxy. Black hole mass follows a looser, though still highly significant, correlation with the maximum rotation velocity of the galaxy, as expected from the known scaling between rotation velocity and central velocity dispersion. Neither of these H I-based correlations is as tight as the more familiar relations between black hole mass and bulge luminosity or velocity dispersion, but they offer the advantage of being insensitive to the glare of the nucleus and therefore are promising new tools for probing the host galaxies of both nearby and distant AGNs. We present evidence for substantial ongoing black hole growth in the most actively accreting AGNs. In these nearby systems, black hole growth appears to be delayed with respect to the assembly of the host galaxy but otherwise has left no detectable perturbation to its mass-to-light ratio, as judged from the Tully-Fisher relation, or its global gas content. The host galaxies of type 1 AGNs, including those luminous enough to qualify as quasars, are generally gas-rich systems, possessing a cold interstellar medium reservoir at least as abundant as that in inactive galaxies of the same morphological type. This calls into question current implementations of AGN feedback in models of galaxy formation that predict strong cold gas depletion in unobscured AGNs.

Subject headings: galaxies: active — galaxies: bulges — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

Dynamical studies of the central regions of nearby inactive galaxies have revealed that supermassive black holes (BHs; \( M_{BH} \approx 10^6-10^9 M_\odot \)) are ubiquitous and that their masses are strongly coupled to the host galaxy’s bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998) and stellar velocity dispersion (\( M_{BH} \sigma_\star \) relation; Gebhardt et al. 2000a; Ferrarese & Merritt 2000; Tremaine et al. 2002). The occupation fraction of central BHs in bulgeless or very late-type galaxies is poorly constrained, but at least some such systems have been found to contain BHs with masses as low as \( \sim 10^3 M_\odot \) (Filippenko & Ho 2003; Barth et al. 2004; Greene & Ho 2004, 2007b, 2007c) that continue to obey the \( M_{BH} \sigma_\star \) relation (Barth et al. 2005; Greene & Ho 2006b). These empirical correlations, which strongly suggest that BH growth is closely coupled to galaxy formation and evolution, have inspired considerable observational and theoretical attention in the last few years (see, e.g., reviews in Ho 2004a). BH growth, its observational manifestation as nuclear activity, and the consequences of feedback from active galactic nuclei (AGNs) are now widely viewed as unavoidable pieces of the overall puzzle of cosmological structure formation (e.g., Granato et al. 2004; Springel et al. 2005; Hopkins et al. 2006).

The BH-bulge correlations beg several pressing, unanswered questions. Do BHs grow predominantly by radiatively efficient accretion during the luminous (Yu & Tremaine 2002) or obscured (Fabian 1999) quasar phase, by low accretion rates in moderately luminous AGNs at recent times (e.g., Cowie et al. 2003), or by mergers (e.g., Yoo & Miralda-Escudé 2004)? Which came first, BH or galaxy? Must the growth of the BH and its host be finely synchronized so as to preserve the small intrinsic scatter observed in the local BH-host scaling relations?

These issues can be observationally tackled in two steps: first by extending the BH-host scaling relations to active galaxies, wherein the BHs are still growing, and second by probing the evolution of the scaling relations by stepping back in redshift. To this end, two ingredients are needed—BH masses and host galaxy parameters. Fortunately, \( M_{BH} \) can be estimated readily in broad-line (type 1) AGNs, solely from basic spectroscopic data using the mass-luminosity-line width relation (also known as the “virial method”; Kaspi et al. 2000; Greene & Ho 2005b; see Peterson 2007 and references therein). Based on such mass estimates, local AGNs do seem to obey roughly the same BH-host scaling relations as in inactive galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001; McLure & Dunlop 2001; Nelson et al. 2004; Onken et al. 2004; Greene & Ho 2006b; Shen et al. 2008). It is crucial to recognize, however, that at the moment this claim is based on very limited, and possibly biased, data. The bright AGN core renders measurement of bulge luminosity and, in particular, central stellar velocity dispersion extremely challenging (see detailed discussion in Greene & Ho 2006a). Notwithstanding these worries, many people now routinely assume that the BH-host scaling relations can be directly applied to AGNs of arbitrarily high luminosity and redshift.
Here we propose a new angle to investigate the relationship between BH masses and the host galaxies of AGNs. In normal, inactive galaxies, it is well known that the stellar velocity dispersion of the bulge tracks the maximum rotation velocity of the disk, roughly as $v_\text{m} = (\sqrt{2} - \sqrt{3}) \times \sigma_z$ (Whitmore et al. 1979). Although the theoretical underpinnings of this correlation are still murky, and the $v_\text{m}-\sigma_z$ relation is not as tight as has been claimed (Ferrarese 2002; Baes et al. 2003; Pizzella et al. 2005), nevertheless an empirical relation between $v_\text{m}$ and $\sigma_z$ does exist (Courteau et al. 2007; Ho 2007a), which implies that $\sigma_z$ can be estimated from $v_\text{m}$. Now, $v_\text{m}$ can be measured straightforwardly through $\text{H} \, \text{i}$ observations for galaxies that are sufficiently gas-rich. In the absence of a resolved rotation curve, $v_\text{m}$ can be estimated from a single-dish measurement of the $\text{H} \, \text{i}$ profile, provided that we have some constraint on the inclination angle of the disk. With the rotation velocity in hand, we can deduce immediately two physical quantities of interest: the total galaxy luminosity through the Tully-Fisher relation (Tully & Fisher 1977), and, given an estimate of the size of the disk (e.g., from optical imaging), the dynamical mass of the system. The advantages of this approach are clear. Since the $\text{H} \, \text{i}$ is distributed mostly at large radii (e.g., Broeils & Rhee 1997), it should be largely “blind” to the AGN core. This allows us to circumvent the problems encountered in the optical, where attempts to disentangle the bulge from the active nucleus are maximally impacted. Applying this principle, Ho (2007b) has recently used the integrated profile of the rotational CO line to infer certain properties of high-redshift quasar host galaxies.

Apart from dynamical constraints, the $\text{H} \, \text{i}$ observations yield another piece of information of significant interest—a first-order measurement of the cold gas content. As the raw material responsible for fueling not only the growth of the BH but ultimately also the galaxy, one can hardly think of a more fundamental quantity to ascertain. How does the gas content of AGN host galaxies compare with that in inactive galaxies? Depending on one’s view on the evolutionary path of AGNs and the efficacy of gas removal by AGN feedback, active galaxies may be more or less gas-rich than inactive galaxies. Does the gas content scale with the degree of nuclear activity? Does it vary with the nebular properties of the central source? One of the major goals of this paper is to try to address some of these basic questions, which to date have been largely unanswered.

2. THE DATABASE

The analysis in this paper is based on the database presented in the companion paper by Ho et al. (2008), to which the reader is referred for full details. In brief, a comprehensive sample of 154 nearby type 1 (broad-lined) AGNs was assembled, consisting of new Arecibo$^5$ observations of 101 sources with $z \leq 0.11$, mostly selected from the Fourth Data Release of the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006), and a supplementary sample of 53 other nearby sources collected from the literature. In addition to basic $\text{H} \, \text{i}$ properties (line fluxes, line widths, and radial velocities), we also assembled optical data for the AGN (emission-line strengths, line widths, line centroid, nuclear luminosity) and the host galaxy (image, concentration index, size, axial ratio, total magnitude, central stellar velocity dispersion). From this material a number of important physical parameters were derived, including BH mass, Eddington ratio, morphological type, inclination angle, deprojected rotation velocity, $\text{H} \, \text{i}$ mass, dynamical mass, estimated host galaxy luminosity, and certain rudimentary properties of the narrow-line region. Distance-dependent quantities were calculated assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

3. ANALYSIS

3.1. The $v_\text{m}-\sigma_z$ Relation in Active Galaxies

To set the stage of using $v_\text{m}$ as a surrogate dynamical variable to investigate BH-host scaling relations, we first examine the correlation between $v_\text{m}$ and $\sigma_z$ for the active galaxies in our sample. Including all objects that have measurements of both quantities, the scatter is discouragingly large (Fig. 1a). Closer inspection, however, reveals that many of the extreme outliers correspond to objects that have potentially untrustworthy deprojected rotation velocities because of uncertain inclination corrections, as well as a handful of sources whose central stellar velocity dispersions were estimated indirectly from the width of the $[\text{O} \, \text{iii}] \lambda3727$ emission line (following Greene & Ho 2005a). Removing these objects improves the correlation. As further discussed in §3.5, a sizable fraction of the objects in our sample contain nonclassical $\text{H} \, \text{i}$ velocity profiles, which are either single-peaked, highly asymmetric, or both, indicative of strongly perturbed or dynamically unrelaxed $\text{H} \, \text{i}$ distributions. If we further remove these cases—a cut that, unfortunately, drastically reduces the sample to only 40 objects—a much cleaner correlation between $v_\text{m}$ and $\sigma_z$ emerges (Fig. 1b). Because of the small number of objects and their limited dynamic range, the present sample is not well suited to define the $v_\text{m}-\sigma_z$ relation. Nevertheless, the present sample still reveals a statistically significant correlation between $v_\text{m}$ and $\sigma_z$; the Kendall’s $\tau$-correlation coefficient is $r = 0.53$, which rejects the null hypothesis of no correlation with a probability of $P = 98.2\%$. We overplot on the figure the $v_\text{m}-\sigma_z$ relation obtained from the 550 “kinematically normal” inactive spiral galaxies from the study of Ho (2007a). The ordinary least-squares bisector fit for the inactive objects,

$$\log v_\text{m} = (0.80 \pm 0.029) \log \sigma_z + (0.62 \pm 0.062),$$

provides a reasonably good match to the AGN sample. According to the Kolmogorov-Smirnov test, the probability of rejecting the null hypothesis that the AGN and non-AGN samples are drawn from the same parent population is $P = 69.2\%$. We conclude that the two populations are not significantly different. The scatter is still substantial, but recall that the zero point of the $v_\text{m}-\sigma_z$ relation depends on morphological type, such that early-type systems have a lower value of $v_\text{m}/\sigma_z$ than late-type spirals ($v_\text{m}/\sigma_z \approx 1.2$–1.4 for E and S0, compared with $v_\text{m}/\sigma_z \approx 1.6$–1.8 for spirals of type Sc and later; see Ho 2007a). That the zero point for inactive spirals seems to roughly match the current sample of AGNs suggests that their host galaxies are mostly disk galaxies with modest bulge components, consistent with the actual estimated BH masses (median $M_{\text{BH}} = 1.6 \times 10^7 M_\odot$) and morphological types (median $T = 2.5$, corresponding to Sab) of the objects.

Since local AGN host galaxies obey the $M_{\text{BH}}-\sigma_z$ relation, and we have just shown that they roughly follow the same $v_\text{m}-\sigma_z$ relation as in inactive galaxies, we expect $M_{\text{BH}}$ to be correlated with $v_\text{m}$. Not surprisingly, this is confirmed in Figure 2, which additionally reemphasizes that a tighter relation results after removing objects with single-peaked and/or asymmetric $\text{H} \, \text{i}$ profiles.

$^5$ The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.
Fig. 1.—Correlation between the central stellar velocity dispersion and the maximum rotation velocity for the active galaxies in our sample. Panel (a) plots all available data, including those that have uncertain inclination corrections (open circles) and \([\text{O} \text{ii}]\)-based estimates of the central velocity dispersion (open triangles); objects with both reliable rotation velocities and stellar velocity dispersions are plotted as filled circles. No selection has been done with regards to H\(_{\text{i}}\) profile type. Panel (b) excludes all objects with single-peaked and/or asymmetric H\(_{\text{i}}\) profiles, as well as those with uncertain rotation velocities and \([\text{O} \text{ii}]\)-based estimates of the central velocity dispersion. Note the significant reduction in scatter. The dashed line represents the fit to the \(v_m - \sigma_c\) relation for the 550 “kinematically normal” inactive spiral galaxies from the sample of Ho (2007a); see text.

Fig. 2.—Correlation between BH mass and the maximum rotation velocity deduced from H\(_{\text{i}}\) observations. The different panels test for possible dependences on (a) H\(_{\text{i}}\) profile type, (b) inclination angle correction, (c) Hubble type, (d) FWHM of broad H\(_{\alpha}\) or H\(_{\beta}\), and (e) Eddington ratio. In (a), objects with uncertain inclination corrections were removed; in (b)–(e), objects with single and/or asymmetric H\(_{\text{i}}\) profiles were additionally removed. Panel (f) is the same as (e), but the different Hubble types have been adjusted to a common zero point by shifting \(v_m\). The solid line represents the predicted correlation for the whole sample, eq. (2), given the \(M_{\text{BH}} - \sigma_c\) relation of Greene & Ho (2006b) and the \(v_m - \sigma_c\) relation (eq. [1]); the dotted and dashed lines show the zero point offset (in \(M_{\text{BH}}\)) for the objects with \(L_{\text{bol}}/L_{\text{Edd}} \leq 0.1\) and \(L_{\text{bol}}/L_{\text{Edd}} > 0.1\), respectively.
and discussed at length in Ho (2007a), the dominant source of scatter (Fig. 2) Mrk 359 has a highly unusual profile consisting of a narrow peak and a very broad line widths do not seem to be the dominant source of scatter (Fig. 2b). Part of the scatter can be attributed to an effect related to Hubble type. As mentioned above and discussed at length in Ho (2007a), \( v_m / \sigma_v \) varies systematically \( \sigma_v \) with galaxy concentration or morphological type, and because our sample contains a wide range of morphological types (see Ho et al. 2008), we expect the zero point of the \( M_{BH} / v_m \) relation to be smeared by the actual mixture of galaxy types. This is illustrated in Figure 2c, wherein the sample is divided into four broad bins in Hubble type. The small subsamples make it difficult to see the trend in detail, but comparison of the E+S0 galaxies with the later-type spirals clearly shows that the two subgroups are offset from each other, in the sense expected from the variation of \( v_m / \sigma_v \) with morphological type.

Taken at face value, another contribution to the scatter seems to be connected to variations in AGN properties, as shown in Figures 2d and 2e, where we examine possible dependences on broad-line region line width and Eddington ratio. Objects with broad H\( \alpha \) or H\( \beta \) full width at half-maximum (FWHM) <2000 km s\(^{-1}\), commonly designated “narrow-line” Seyfert 1 (NLS1) galaxies, have a slight tendency to be offset toward lower \( M_{BH} \) for a given \( v_m \) (Fig. 2d). Since many NLS1 galaxies tend to have elevated accretion rates (e.g., Collin & Kawaguchi 2004), the weak trend with FWHM may be more clearly discerned by dividing the sample according to Eddington ratio. Indeed, this expectation seems to hold, as shown in Figure 2e, where, within the limited statistics, there appears to be a monotonic decrease of \( M_{BH} / v_m \) with increasing \( L_{bol} / L_{edd} \). The trend with Eddington ratio is stronger than that with luminosity alone (not shown). Could the apparent variation of \( M_{BH} / v_m \) with FWHM and \( L_{bol} / L_{edd} \) be a secondary effect related to the dependence of \( M_{BH} / v_m \) on morphological type? The most active AGNs in the nearby universe live in moderate-mass, relatively late-type disk galaxies (e.g., Heckman et al. 2004; Greene & Ho 2007b); these are precisely the hosts of high-\( L_{bol} / L_{edd} \) systems, such as NLS1s. We attempt to remove the Hubble type dependence by shifting \( v_m \) for the different Hubble type subgroups to a common reference zero point (defined by the entire sample). As expected, the scatter goes down, but, interestingly, the trend with \( L_{bol} / L_{edd} \) persists (Fig. 2f).

3.2. Correlation between \( M_{BH} \) and Galaxy Dynamical Mass

Although our \( H_\alpha \) observations yield no information on the spatial distribution of objects, we can still obtain a rough estimate of the characteristic dynamical mass of the galaxy by combining the deprojected rotation velocity from the \( H_\alpha \) line width with the optical diameter. This approach is justified for the following reason. The size of the \( H_\alpha \) disk in spiral galaxies over a wide range of Hubble types and luminosities tightly scales with the size of the optical disk; within 30%–40%, \( D_{H_\alpha} / D_{25} \approx 1.7 \) (Broeils & Rhee 1997; Noordermeer et al. 2005), where \( D_{25} \) is the optical isophotal diameter at a surface brightness level of \( \mu_B \approx 25 \) mag arcsec\(^{-2}\). Thus, even if the absolute dynamical mass may be uncertain because of our ignorance of the size of the \( H_\alpha \)-emitting disk, the relative masses should be reasonably accurate. Following Casertano & Shostak (1980), Ho et al. (2008) calculated dynamical masses for our AGN sample, which, interestingly, show a fairly strong correlation with BH mass (Fig. 3). In particular, BH mass correlates more strongly with \( M_{dyn} \), which scales as \( D_{25} v_m^2 \), than with \( v_m \) alone. An ordinary least-squares bisector fit to the entire sample, after making the quality cut as above, gives

\[
\log(M_{BH} / M_\odot) = (1.29 \pm 0.11)\log(M_{dyn} / M_\odot) - (6.96 \pm 1.17),
\]  

with an rms scatter of 0.61 dex. The slope is formally steeper than unity, but this result should be regarded as provisional considering that most of the objects span a relatively narrow range of \( M_{dyn} \).

Closer inspection reveals that the zero point of the \( M_{BH} \)-\( M_{dyn} \) correlation also depends on Hubble type (Fig. 3a). At a given \( M_{dyn} \), early-type galaxies have a higher \( M_{BH} \) than late-type galaxies. Relative to the best-fitting line for the whole sample, at a fixed \( M_{dyn} \) the shift in \( M_{BH} \) is \( +0.19, -0.05, -0.10, \) and -0.59 for galaxies of type E/S0, Sa, Sb, and Sc/Sd, respectively. If we adjust the zero point of these groups by their corresponding offsets (in \( M_{dyn} \)), the rms scatter of the resulting correlation decreases to 0.55 dex (Fig. 3b). As in the case of the \( M_{BH} - v_m \) diagram, we find that at a given \( M_{dyn} \) objects with higher \( L_{bol} / L_{edd} \) tend to have smaller \( M_{BH} \).

3.3. The Tully-Fisher Relation for Active Galaxies

The empirical correlation between \( v_m \) and total galaxy luminosity, first introduced by Tully & Fisher (1977), provides yet another avenue to assess potential differences between active and inactive galaxies. As described in Ho et al. (2008), approximate optical host galaxy luminosities can be obtained by comparing the integrated photometry with the nuclear spectroscopy. Figure 4 plots the host galaxy absolute magnitude (after removing the AGN contribution), converted to the B band, versus the maximum rotation velocity; overlaid for comparison is the corresponding Tully-Fisher relation for inactive (spiral) galaxies in the Ursa Major cluster (Verheijen 2001). Considering first the entire sample (Fig. 4a), \( M_B \) host loosely traces \( v_m \), but the scatter is again considerable and the apparent correlation is formally statistically insignificant (\( r = -0.23, P = 93.3\% \)). Pruning, as before, the objects with unreliable inclination corrections and kinematically peculiar profiles filters out most of the egregious outliers, such

\( ^6 \) For the rest of the paper, we have also excluded two objects from the literature sample that have suspiciously low values of \( v_m \) (Mrk 359, \( v_m = 38 \) km s\(^{-1}\); Mrk 493, \( v_m = 24.7 \) km s\(^{-1}\) ). Closer inspection of the original \( H_\alpha \) data shows that Mrk 359 has a highly unusual profile consisting of a narrow peak and a very broad base (Springob et al. 2005); moreover, the inclination angle given in Hyperleda, \( i = 39.5^\circ \), seems inconsistent with the nearly face-on appearance of its Digital Sky Survey image (see Appendix in Ho 2007a for a discussion on the uncertainties associated with inclination angles listed in Hyperleda), suggesting that we have seriously underestimated the inclination correction. Mrk 493 may suffer from the same problem; the optical (SDSS) image of the object appears to be much more face-on than Hyperleda’s value of \( i = 45^\circ \).
that the remaining sample falls mostly within the locus of inactive spirals (Figs. 4b and 4c). The formal correlation between $M_{B,host}$ and $v_m$ is still low ($r = -0.30$) and only marginally significant ($P = 95.0\%$), probably because of the small sample size and limited dynamic range in $v_m$ (90% of the sample has $v_m = 200 \pm 100$ km s$^{-1}$). Apart from the larger scatter exhibited by the active sample, an effect that can be attributed, at least partly, to its broad mixture of Hubble types, the approximate nature in which the host luminosities were estimated, and the sensitivity of the blue bandpass to extinction and stellar population variations (e.g., De Rijk et al. 2007), there are no other gross differences between the Tully-Fisher relation of active and inactive galaxies. Different Hubble types define slightly offset, parallel sequences (Fig. 4b), an effect that has been well documented in the $B$ band. For a given
B-band luminosity, an early-type spiral has a larger characteristic rotation amplitude than a late-type spiral (e.g., Rubin et al. 1985; De Rijcke et al. 2007). To separate out this effect, we applied small corrections to the zero points (in host galaxy luminosity) of each Hubble type bin. The adjusted distribution shows no obvious segregation by AGN properties, such as Eddington ratio (Fig. 4c).

3.4. $H_\text{I}$ Content

We next examine the $H_\text{I}$ content of our sample, with special emphasis on whether AGN hosts differ in any noticeable way from inactive galaxies. In absolute terms, our survey objects are quite gas-rich in neutral atomic hydrogen. The $H_\text{I}$ masses for the detected sources range from $M_{H_\text{I}} \approx 10^9$ to $4 \times 10^{10} M_\odot$ (Ho et al. 2008). Taking into account the upper limits for the nondetections, the Kaplan-Meier product-limit estimator (Feigelson & Nelson 1985) yields a mean of $M_{H_\text{I}} = (7.0 \pm 0.66) \times 10^9 M_\odot$ and a median of $M_{H_\text{I}} = 5.0 \times 10^9 M_\odot$. This is almost identical to the total $H_\text{I}$ mass of the Milky Way (5.5 $\times 10^9 M_\odot$; Hartmann & Burton 1997), and comparable to the average value for Sb spirals (Roberts & Haynes 1994). The above statistics pertain just to the newly surveyed SDSS sources. The literature sample is both heterogeneous and possibly biased because the database from which the $H_\text{I}$ data were compiled, Hyperleda, does not report upper limits. Nonetheless, we confirm that combining both samples does not significantly alter these statistics.

The $H_\text{I}$ content of galaxies varies greatly and systematically across the Hubble sequence (Haynes & Giovanelli 1984; Roberts & Haynes 1994). Thus, in order to conduct a meaningful comparison of the $H_\text{I}$ budget of active and inactive galaxies, we must know their morphological types. Among the 154 sources in our sample that have $H_\text{I}$ detections or meaningful upper limits, 148 have estimates of both their morphological type and host galaxy optical luminosity. Figure 5 shows the distribution of $H_\text{I}$ masses normalized to the $B$-band luminosity of the host galaxy, subdivided into six bins of Hubble types. For reference, we computed the distribution of $M_{H_\text{I}}/L_{B,\text{host}}$ for 13,262 inactive galaxies culled from Hyperleda. These represent all galaxies in the database, reported to be current up to the end of 2003, that have reliable entries of $H_\text{I}$ flux, morphological type, and $B$-band magnitude; known AGNs were excluded, as discussed in Ho et al. (2008, see their Appendix). As previously mentioned, Hyperleda does not record upper limits for $H_\text{I}$ nondetections, so these distributions should be viewed strictly as upper bounds. Since the majority of the galaxies in Hyperleda are relatively bright and nearby, the detection rate of $H_\text{I}$ among the spirals should be very high (~90%; Haynes & Giovanelli 1984), such that the observed distribution can be regarded as being quite close to the true distribution. The situation for early-type galaxies, however, is quite different, because the detection rate is only ~15% for ellipticals (Knapp et al. 1985) and ~30% for S0s (Wardle & Knapp 1986), and so the distributions shown in the figure are highly biased.

Comparison of the active and inactive distributions reveals two interesting points. Among mid- to late-type spirals (Sb and later), the frequency distribution of $M_{H_\text{I}}/L_{B,\text{host}}$ is roughly the same for the two populations. However, for the bulk of the sample, which comprise bulge-dominated Sa spirals and S0s, active galaxies appear to be more gas-rich than their inactive counterparts. The most dramatic manifestation of this effect shows up among the ellipticals, although here we are handicapped somewhat by the small number of sources (9) in the active sample. Note that among the E and S0 subgroups, the difference between the active and inactive samples is far greater than portrayed (although we have no rigorous statistical way to quantify this) because, as mentioned above, the inactive distribution is highly biased by the omission of upper limits. (As noted, the literature data for the active sample are likely biased as well, but we verified that our conclusions are essentially unaffected if we exclude these data from the AGN sample.) The host galaxies of nearby type 1 AGNs across all Hubble types are at least as gas-rich as inactive galaxies, and among early-type systems their gas content appears to be markedly enhanced.

3.5. Environmental Effects

Crude information on the spatial distribution or dynamical state of the gas can be ascertained from the degree to which the observed $H_\text{I}$ line profiles deviate from the classical double-horned signature of an optically thin rotating disk. Experience with nearby galaxies indicates that tidally disturbed systems often exhibit asymmetric, single-peaked, or otherwise highly irregular line profiles (e.g., Gallagher et al. 1981; Haynes et al. 1998). Given the modest signal-to-noise ratio of our data, Ho et al. (2008) decided not to implement a rigorous scheme to quantify the line morphology.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Distribution of $H_\text{I}$ masses normalized to the $B$-band luminosity of the host galaxy, as a function of its Hubble type. The black histograms show the distributions for 13,262 inactive galaxies with $H_\text{I}$ detections listed in Hyperleda. The AGN sample from our study is plotted in red histograms, with upper limits indicated by dotted lines. The entire sample of 154 objects is plotted in the penultimate panel from the bottom, while the top panels show the sample sorted by Hubble type. The number of inactive galaxies in each group is labeled, with the number of active objects shown in parentheses. The bottom-most panel isolates the quasars. The red histograms correspond to objects from the current $H_\text{I}$ sample; the blue histograms correspond to PG quasars observed in CO (Ho 2005a); the green histograms correspond to $z < 0.5$ PG quasars with dust masses (Haas et al. 2003); see text for details.}
\end{figure}
but rather adopted a qualitative classification scheme in which obviously nonclassical profiles were simply labeled as “A” (asymmetric), “S” (single-peaked), or “AS” (combination of both). Among the 66 objects detected in our new survey, eight (12%) are classified as “A,” five (8%) as “S,” and 16 (24%) as “AS,” for an overall frequency of nonclassical profiles of 44%. Ho et al. (2008) performed a systematic census of physical neighbors within a search radius of 7.5′ around each object. There seems to be no clear association between profile peculiarity and the presence of nearby neighbors. While some objects with single-peaked and/or asymmetric profiles have plausible nearby companions, many do not; at the same time, a number of objects with apparent companions exhibit seemingly regular line profiles. The presence or absence of kinematic irregularity also appears to be uncorrelated with any of the global or AGN parameters that we have at our disposal. We searched for possible differences in the following quantities but found none that was statistically significant: morphology type, galaxy luminosity, total and relative H i mass, AGN luminosity, broad-line region FWHM, BH mass, and Eddington ratio.

3.6. Connections with AGN Properties

The availability of optical data affords us an opportunity to explore possible connections between the H i and AGN properties of our sample. Concentrating on the SDSS objects, for which we have homogeneous optical spectroscopic measurements, we find that their narrow emission-line ratios place the majority of them in the territory of Seyfert nuclei (Fig. 6). This is not surprising, since most of the SDSS-selected type 1 AGNs tend to have relatively high accretion rates (Greene & Ho 2007b), which generally correspond to high-ionization sources (Ho 2004b). The objects detected in H i do not stand out in any noticeable way from the nondetections. The same holds for the electron densities of the narrow-line region, as can be inferred from the line ratio [S ii] 6716/[S ii] 6731: the H i detections are statistically indistinguishable from the H i nondetections (Fig. 7). Next, we searched for a possible dependence of AGN luminosity or Eddington ratio on H i content, either in absolute ($M_{\text{BH}}$) or relative ($M_{\text{BH}}/L_{\text{B, host}}$) terms, but again found none (Fig. 8). There is, at best, a mild trend of increasing H i luminosity with increasing H i mass (Fig. 8a), but given the mutual dependence of the two quantities on distance, we regard this result as highly suspect.

4. DISCUSSION

4.1. Black Hole–Host Galaxy Scaling Relations

The relative ease with which integrated H i emission can be detected in nearby AGNs opens up the possibility of using the global H i line width as a new dynamical variable to investigate the scaling between BH mass and host galaxy potential. A quantity that can be readily measured from single-dish spectra, the H i line width has been widely used in a variety of extragalactic contexts as an effective shortcut to estimate $v_m$, the maximum rotation velocity of galaxy disks. If $v_m$ correlates with bulge velocity dispersion, $\sigma_b$, as originally suggested by Whitmore et al. (1979), $v_m$ can be used in place of $\sigma_b$ to define a $M_{\text{BH}}-v_m$ relation to substitute for the more traditional $M_{\text{BH}}-\sigma_b$ relation. A number of authors have suggested that galaxies over a wide range in morphological types obey a tight correlation between $v_m$ and $\sigma_b$, to the point that $v_m$ and $\sigma_b$ can actually replace, and perhaps should be regarded as more fundamental than, $\sigma_b$ (Ferrarese 2002; Baes et al. 2003; Pizzella et al. 2005). This result has been challenged by Courteau et al. (2007) and Ho (2007a), who found, using much larger samples, that the ratio $v_m/\sigma_b$ shows significant intrinsic
scatter and systematic variation across the Hubble sequence. Nevertheless, a $v_m-C27/C3$ relation does exist, at least statistically, and in circumstances when $C27/C3$ is difficult or impossible to measure (e.g., in very bright or very distant AGNs), $v_m$ may offer the best or possibly the only means of constraining the host galaxy. Such was the motivation behind the recent study of Ho (2007b; see also Shields et al. 2006), who used the width of the rotational CO line, locally calibrated against H $i$, to infer the masses of the host galaxies of high-redshift quasars. The line width method, however, can prove to be useful even under less extreme conditions. As discussed at length in Greene & Ho (2006a), a variety of factors conspire to make measurement of $C27/C3$ very challenging in galaxies containing bright AGNs, regardless of their redshift. To bypass this difficulty, many studies resort to using gas velocity dispersions measured from narrow nebular lines, but this shortcut has its own set of complications (Greene & Ho 2005a). Others skip the kinematical route altogether and instead use the host galaxy (or bulge, if available) luminosity as the variable to relate to the BH mass. However, cleanly decomposing the underlying galaxy, much less its bulge, in the presence of a bright AGN core is often a nontrivial task, even under the most ideal conditions (e.g., Kim et al. 2007).

Within this backdrop, we explored the correlation between BH mass and $v_m$. As expected, a loose correlation exists between these two quantities, but the scatter is enormous, $\sim$1 dex (Fig. 2a). Many of the extreme outliers correspond to objects with single-peaked and/or clearly asymmetric H $i$ profiles, while others have especially questionable inclination corrections; removing these produces a cleaner correlation. Note that apart from being inefficient (roughly 40% of the sample was rejected), this step imposes no serious complication, since classical double-horned line profiles are easy to recognize. Nonetheless, even after this filtering, the scatter is still substantial (0.9 dex; Fig. 2b). We identified a number of parameters associated with the AGN that seem to contribute to the scatter (FWHM of the broad emission lines, nuclear luminosity, and Eddington ratio), but an important contribution comes from the morphological type variation within the sample (Fig. 2c). As discussed in Courteau et al. (2007) and Ho (2007a), the zero point of the $v_m-C27/C3$ relation varies systematically with galaxy concentration (which is loosely related to galaxy morphology or bulge-to-disk ratio). If we arbitrarily shift the zero points of the different Hubble type bins to the average relation for all Hubble types, the scatter decreases somewhat to $\sim$0.7 dex (Fig. 2f).

Fig. 8.—Variation of nuclear H $\alpha$ luminosity (a, b) and Eddington ratio (c, d) with H $i$ content. Objects detected in H $i$ are plotted as filled symbols, while the nondetections are marked as open symbols with arrows.
More promising still seems to be the correlation between BH mass and galaxy dynamical mass, which requires knowledge of one additional parameter—namely, the galaxy’s optical diameter. Retaining, as before, only the objects with robust inclination corrections and kinematically normal H I profiles, the \( M_{\text{BH}} \)-\( M_{\text{dyn}} \) relation has an rms scatter of 0.61 dex, which further improves to 0.55 dex after shifting the different Hubble types to a common reference point (Fig. 3). While this scatter is larger than that of the local AGN \( M_{\text{BH}} \)-\( \sigma \) relation (0.4 dex; Greene & Ho 2006b), our estimates of the dynamical masses leave much room for improvement, both in terms of getting higher signal-to-noise ratio line profiles and deeper optical images, which will allow more accurate measurements of inclination angles and isophotal diameters and better estimates of morphological types.

### 4.2. The Chicken or the Egg

One of the most intriguing results from our analysis is the tentative detection, both in the \( M_{\text{BH}} \)-\( v_{\text{m}} \) (Fig. 2f) and \( M_{\text{BH}} \)-\( M_{\text{dyn}} \) (Fig. 3b) diagrams, of differential growth between the central BH and the host galaxy. For a given host galaxy potential (\( v_{\text{m}} \) or \( M_{\text{dyn}} \)), AGNs with higher accretion rates (Eddington ratios) have systematically less massive BHs, implying that in these systems the central BH, still vigorously accreting near its maximum rate, has yet to reach its final mass, which, from observations of inactive systems, we know to be a well-defined constant fraction of the total bulge luminosity or mass (Kormendy & Richstone 1995; Magorrian et al. 1998; Häring & Rix 2004). Many (but not all) of the objects with still-growing BHs turn out to have narrower broad Balmer lines (FWHM \( \lesssim 2000 \) km s\(^{-1}\)) because NLS1 galaxies tend to have higher accretion rates. At a fixed \( v_{\text{m}} \), the AGNs in our sample with \( L_{\text{bol}}/L_{\text{Edd}} \geq 0.1 \) on average have BHs 0.19 dex (factor of 1.5) less massive than those with \( L_{\text{bol}}/L_{\text{Edd}} \lesssim 0.1 \); in terms of fixed \( M_{\text{dyn}} \), the difference in BH masses between the low- and high-accretion rate subgroups is ~0.41 dex (factor of 2.6). In their study of type 1 AGNs with stellar velocity dispersion measurements, Greene & Ho (2006a) also noticed that the best-fitting \( M_{\text{BH}} \)-\( \sigma \) relation for AGNs has a small zero point offset of ~0.17 dex relative to Tremaine et al.’s (2002) fit of the \( M_{\text{BH}} \)-\( \sigma \) relation for inactive galaxies. A result similar to that of Greene & Ho (2006a) has been reported by Shen et al. (2008), who additionally note that the amplitude of the \( M_{\text{BH}} \)-\( \sigma \) relation for AGNs depends on Eddington ratio, in the same sense that we find in our study. The overall qualitative agreement among the three independent studies lends credence to the idea that the most highly accreting BHs are still actively growing.

Mathur et al. (2001; see also Grupe & Mathur 2004; Mathur & Grupe 2005), using the width of the [O iii] \( \lambda 5007 \) line as a substitute for \( \sigma \), a shortcut that allows large numbers of AGNs to be placed on the \( M_{\text{BH}} \)-\( \sigma \) relation, proposed that NLS1s contain BHs that are undermassive with respect to their bulges, by as much as 0.55 dex after shifting the different Hubble types to a common reference point (Fig. 3). While this scatter is larger than that of the local AGN \( M_{\text{BH}} \)-\( \sigma \) relation (0.4 dex; Greene & Ho 2006b), our estimates of the dynamical masses leave much room for improvement, both in terms of getting higher signal-to-noise ratio line profiles and deeper optical images, which will allow more accurate measurements of inclination angles and isophotal diameters and better estimates of morphological types.
relatively faint AGNs, preferentially make it into a magnitude-limited survey such as SDSS if they reside in more luminous (more massive) galaxies.

4.3. Host Galaxies and Environment

Even though most sizable nearby galaxies harbor central BHs, they exhibit very feeble traces of nuclear activity (Ho et al. 1997b). Only a tiny fraction of the local galaxy population accrete at rates high enough to qualify them as respectable AGNs (Ho 2004b; Greene & Ho 2007b). Why is this? The low space density of luminous AGNs in the local universe surely reflects some combination of the overall reduced gas supply in present-day galaxies as well as their more placid dynamical environments, but precisely which physical parameters—internal or external to the system—act as actual trigger for the onset of nuclear activity in any given galaxy remains largely an unsolved problem (Ho et al. 1997c, 2003; Ho 2004b). In a similar vein, and especially given the recent discussion of the purported link between BH and galaxy growth, it is of interest to know what impact AGN activity actually has on the properties of the host galaxy.

Our new H i survey offers an opportunity to examine these issues from some fresh angles. Despite the limited quality of the data, our visual examination of the optical images do not give the impression that the galaxies or their immediate environments are particularly unusual. Some clear cases of interacting or binary systems exist within a separation of 50 kpc (Ho et al. 2008; see Fig. 3g, SDSS J165601.61+211241.2; Fig. 4b, SDSS J130241.53 + 040738.6), but overall the optical morphologies of the hosts appear undisturbed and large (i.e., nearly equal-mass) physical companions are rare. There are also no discernible differences between the objects detected and undetected in H i (compare Fig. 3 vs. Fig. 4 in Ho et al. 2008).

Excluding the objects with anomalous H i profiles, the rest of the sample is not just morphologically normal but also dynamically normal. We draw this inference from our analysis of the Tully-Fisher relation for the active galaxies, which, besides the anticipated larger scatter due to various measurement uncertainties, reveals no striking differences compared to regular disk galaxies (Fig. 4). As an aside, it is worth making an obvious point: the fact that our objects obey the Tully-Fisher relation implies that the H i must be roughly regularly distributed, at least regular enough so that its integrated line width traces the flat part of the galaxy rotation curve. Hutchings et al. (1987) and Hutchings (1989) previously failed to see a clean Tully-Fisher relation for their sample of AGNs because of the high frequency of asymmetric H i profiles. By contrast, the more extensive study by Whittle (1992) found that Seyfert galaxies do define a Tully-Fisher relation, but one that is offset toward lower velocities compared to normal spiral galaxies. He interpreted this as an indication that Seyfert galaxies have lower mass-to-light ratios (by a factor of 1.5−2), possibly as a result of enhanced star formation. Our results do not agree with Whittle’s. We have verified that the discrepancy between the two studies does not stem from the different fiducial relations chosen for inactive spirals. While Whittle’s reference Tully-Fisher relation has a much steeper slope than the one we adopted (from Verheijen 2001), the two zero points are very similar.

We speculate, but cannot prove, that the low-velocity offset seen by Whittle may be caused by contamination from objects with kinematically peculiar, preferentially narrow H i profiles. Inspection of our data (Fig. 4) reveals that prior to excluding the objects with asymmetric or single-peaked profiles our sample also has a mild excess of low-velocity points. Indeed, a non-negligible fraction of all galaxies, irrespective of their level of nuclear activity, show this behavior, which Ho (2007a) attributes to dynamically unrelaxed gas acquired either through minor mergers or primordial accretion.

Enhanced star formation frequently seems to precede nuclear activity (Kauffmann et al. 2003; see discussion in Ho 2005b), but at least for the AGN luminosities probed in this study, the extent of the young stellar population has left no visible imprint on the mass-to-light ratio of host galaxies, insofar as we can gauge from the Tully-Fisher relation.

Do AGN host galaxies possess a higher fraction of kinematically anomalous H i profiles than inactive galaxies? Our study, as in previous ones (Mirabel & Wilson 1984; Hutchings et al. 1987), tentatively suggests that the answer is yes, but a quantitative comparison is difficult. Single-dish surveys of isolated, (mostly) inactive disk galaxies also report frequent detections of asymmetric H i line profiles (e.g., Baldwin et al. 1980; Lewis et al. 1985; Matthews et al. 1998), which are attributed to noncircular motions, unresolved companions, or genuine perturbations in the spatial distribution of the gas. Richter & Sancisi (1994) and Haynes et al. (1998), for example, find asymmetric profiles in roughly 50% of the spiral galaxies they surveyed. Similarly, Lewis (1987) studied a large sample of face-on spiral galaxies and found narrow H i profiles to be rare. He interprets this result to imply that a substantial fraction of the galaxies must have distorted H i distributions, whose large-scale motion is misaligned with respect to the plane of the stellar disk. Thus, in absolute terms the frequency of nonclassical H i profiles in our sample (44%; § 3.5) is very similar to the frequency reported for inactive galaxies, but we are wary to draw any firm conclusions from this because the signal-to-noise ratio of our spectra is generally much lower than those of the control samples and because of the qualitative nature of our profile classification.

The kinematically anomalous objects account for 17% of the 792 galaxies studied by Ho (2007a), but this fraction depends on Hubble type, being more common among early-type systems. Among S0 galaxies, the fraction reaches 40% (Ho 2007a), nearly identical to the frequency found among the active systems studied here, which, although strictly not all S0 galaxies, nonetheless tend to be bulge-dominated disk galaxies. As in the case of inactive galaxies (Ho 2007a), the kinematic peculiarity for the AGN sample cannot be attributed to tidal interactions or comparable-sized nearby neighbors.

4.4. Gas Content and Implications for AGN Feedback Models

Insofar as their H i content is concerned, the host galaxies of the AGNs in our sample are endowed with plenty of gas. The most meaningful metric is the specific rather than the absolute gas mass, and because this quantity spans a wide range across the Hubble sequence (Roberts & Haynes 1994), we can sharpen the comparison even further by specifying the morphological type of the galaxy. This exercise (Fig. 5) convinces us that type 1 AGNs are at least as gas-rich as inactive galaxies, and among early-type hosts, beginning with Sa spirals and certainly by the time we reach S0s and Es, AGN hosts appear to be even more gas-rich than their inactive counterparts. For example, the sensitive survey of 12 inactive E and S0 galaxies by Morganti et al. (2006) detected H i emission in nine objects, of which only one has $M_{HI}/L_B^{host} > 0.1$. By contrast, among the 30 active E and S0 galaxies in our survey that were detected in H i, 26 (87%) have $M_{HI}/L_B^{host} > 0.1$. Our results are qualitatively consistent with those of Bieging & Biermann (1983) and Mirabel & Wilson (1984). Because of the nature of the control sample of inactive objects (only detections are available), we hesitate to be more specific, but E and S0 galaxies hosting AGNs may be overabundant in H i by as much as an order of magnitude. Previous studies of
nearby elliptical and S0 galaxies have hinted of a possible statistical connection between H\textsc{i}-richness and radio activity (Dressel et al. 1982; Jenkins 1983; Morganti et al. 2006), two well-known examples being the low-power radio galaxies NGC 1052 (Knapp et al. 1978) and NGC 4278 (Raimond et al. 1981). The validity of our conclusion, of course, critically depends on the accuracy of the morphological types. However, to bring the average $M_{\text{H}\text{i}}/L_{\text{B, host}}$ ratios of the E and S0 subgroups to conform to the average values of inactive galaxies, we would have to shift the morphological types to as late as Sb or even Sc spirals. It seems unlikely that the morphologies could be so blatantly wrong. Alternatively, perhaps we have grossly miscalculated the host galaxy optical luminosities. Without improved optical imaging (§ 5), however, these alternative explanations remain purely hypothetical.

The global gas content bears no relationship to the level of AGN activity, either in terms of absolute luminosity or Eddington ratio (Fig. 8). Ho et al. (2003) had come to the same conclusion for nearby LINERs and Seyferts, but now the same holds for AGNs on average 2–3 orders of magnitude more luminous. Whether H\textsc{i} is detected or not also makes no impact whatsoever on the optical spectrum (Figs. 6 and 7). Perhaps none of this should come as a surprise. The H\textsc{i} data, after all, probe spatial scales vastly disproportionate to those relevant for the AGN central engine. Moreover, the accretion rates required to power the observed activity are quite modest. The H\alpha luminosities of our sample range from $10^{40}$ to $10^{44}$ erg s$^{-1}$, with a median value of $4 \times 10^{43}$ erg s$^{-1}$. Adopting the H\alpha bolometric correction given in Greene & Ho (2007b) and a radiative efficiency of 0.1, this corresponds to a mass accretion rate of merely $2 \times 10^{-2} M_{\odot}$ yr$^{-1}$.

Many current models of galaxy formation envision AGN feedback to play a pivotal role in controlling the joint evolution of central BHs and their host galaxies. During the major merger of two gas-rich galaxies, each initially seeded with its own BH, gravitational torques drive a large fraction of the cold gas toward the central region of the resulting merger remnant. Most of the gas forms stars with high efficiency in a nuclear starburst, at the same time feeding the central BH at an Eddington-limited rate. This process consumes a large amount of the original cold gas reservoir. The combined energy generated from supernova explosions and the central engine wrecks havoc on the rest of the interstellar medium in the galaxy, shocking it to high temperatures and redistributing it to large scales, thereby shutting off further star formation and accretion. While the specific formulation of the problem and the methodology for solving it may vary from study to study (e.g., Granato et al. 2004; Springel et al. 2005; Croton et al. 2006; Hopkins et al. 2006; Hopkins & Hernquist 2006; Sijacki et al. 2007; Di Matteo et al. 2008), one generic prediction runs constant: the onset of nuclear activity, especially during the peak phase of accretion when the central object unveils itself as an optically visible AGN, in concert with supernova feedback from the accompanying starburst, liberates so much energy on such a short timescale that the bulk of the cold gas gets expelled from the galaxy. None of the existing models makes very precise predictions about the cold gas content during the evolution of the system, but it seems clear, regardless of the details, that during the optically visible (unobscured) phase of the AGN the host galaxy should be deficient in cold gas. This expectation is inescapable if AGN feedback is to have as dramatic an effect on the evolution of the host galaxy as has been suggested.

Our observations present a challenge to the framework of AGN feedback just outlined. Far from being gas-deficient, the host galaxies of optically selected type 1 AGNs are, if anything, unusually gas-rich, and at the very least we can state with confidence that their gas content is normal. To be fair, the vast majority of our sample consists of Seyfert galaxies. They are hosted in disk (S0 and spiral) galaxies, which probably never experienced many major mergers, and their nuclei fall far short of luminosity threshold of quasars, which, although rare, dominate the BH mass density in the universe (e.g., Yu & Tremaine 2002). These objects probably fall outside of the purview of major merger-driven models (Hopkins & Hernquist 2006). Our sample, on the other hand, does contain seven objects that formally satisfy the luminosity criterion of quasars, of which four (PG 0844+349, PG 1426 + 015, PG 2130+099, and RX J0608.0+3058) are detected in H\textsc{i}. All four are very gas-rich, with H\textsc{i} masses ranging from $M_{\text{H}\text{i}} = 5 \times 10^{9}$ to $2 \times 10^{10} M_{\odot}$ and $M_{\text{H}\text{i}}/L_{\text{B, host}}$ values that are not obviously low.

Beyond the present set of observations, two other lines of evidence contradict the notion that optically selected quasars are gas-deficient. Scoville et al. (2003) performed an unbiased search for CO emission from all $z < 0.1$ quasars from the ultraviolet-selected sample of Palomar-Green (PG) sources (Schmidt & Green 1983), finding that the majority of them ($\sim 75\%$) contain abundant molecular gas, ranging from $M_{\text{H}_2} \approx 10^9$ to $10^{10} M_{\odot}$; those that were undetected have upper limits consistent with the detections. Bertram et al. (2007) report very similar statistics from their recent CO study of low-luminosity quasars selected from the Hamburg/ESO survey. These molecular gas masses are comparable to, if not greater than, those typically found in mid to late-type spirals. Ho’s (2005a) compilation of CO observations of other PG quasars further reinforces this point, and even more extreme molecular gas masses ($M_{\text{H}_2} \approx 10^{10} - 10^{11} M_{\odot}$) have been detected in high-redshift quasars (Solomon & Vanden Bout 2005 and references therein). The Milky Way, for reference, has $M_{\text{H}_2} = 2 \times 10^9 M_{\odot}$ (Scoville & Good 1989). Of the three PG quasars that overlap with our H\textsc{i} sample, for instance, PG 1426 + 015 has $M_{\text{H}_2} = 6.5 \times 10^9 M_{\odot}$, PG 2130+099 has $M_{\text{H}_2} = 3 \times 10^9 M_{\odot}$, and PG 0844+349 has an upper limit of $M_{\text{H}_2} = 1 \times 10^9 M_{\odot}$. Combining this with the H\textsc{i} masses, all three objects have a total (H\textsc{i} + H\textsc{2}) neutral gas mass in excess of $10^9 M_{\odot}$. Yet another way to recognize that PG quasars have plenty of cold gas comes from noting that substantial amounts of dust have been detected in them. Haas et al. (2003) appraised the dust content in a sample of 51 PG quasars by combining far-infrared continuum observations along with millimeter and submillimeter data. Their derived dust masses range from $M_{\text{dust}} \approx 7 \times 10^8$ to $3 \times 10^9 M_{\odot}$, with a median value of $8.8 \times 10^8 M_{\odot}$. For a Galactic molecular gas-to-dust ratio of 150, this corresponds to $M_{\text{H}_2} \approx 1.3 \times 10^9 M_{\odot}$; for a higher gas-to-dust ratio of 600 (Young & Scoville 1991), $M_{\text{H}_2} \approx 5.3 \times 10^9 M_{\odot}$. These indirect estimates of molecular gas mass are consistent with those derived from CO observations.

To graphically compare the gas masses of PG quasars side-by-side with those of the lower luminosity AGNs in our sample, we converted the molecular and dust masses into approximate H\textsc{i} masses. We adopt, for the sake of illustration, $M_{\text{H}_2}/M_{\text{H}\text{i}} = 3$, a value characteristic of early-type spirals (Young & Scoville 1991), and $M_{\text{H}_2}/M_{\text{dust}} = 600$. We calculated BH masses for the sources using the H\beta line widths from Bororan & Green (1992) and optical continuum luminosities from the spectrophotometry of Neugebauer et al. (1987), and then inferred $B$-band host galaxy luminosities using the correlation between BH mass and bulge luminosity given in Kormendy & Gebhardt (2001), for simplicity assigning all the luminosity to the bulge. As summarized in the bottom panel of Figure 5, PG quasars span almost 4 orders of magnitude in $M_{\text{H}\text{i}}/L_{\text{B, host}}$, from objects as gas-poor as the most extreme ellipticals to as gas-rich as the most gas-dominated dwarf irregulars. Although this exercise becomes progressively...
more uncertain for high-redshift objects, we can attempt a similar order-of-magnitude calculation for the nine high-redshift quasars listed in Ho (2007b), using BH masses listed therein and the molecular gas masses given in Solomon & Vanden Bout (2005). Under the same assumptions adopted for the PG quasars, we find an average value of $\log \left( \frac{M_{\text{HI}}}{L_{\text{B bulge}}} \right) \approx -0.9$, in the middle of the range observed for PG quasars (Fig. 5). In fact, this estimate, which assumes a local value for the ratio of BH mass to bulge luminosity, is most likely a lower limit because high-redshift quasars in general (Peng et al. 2006a, 2006b) and this subset of objects in particular (Shields et al. 2006; Ho 2007b) seem to exhibit a higher ratio (by a factor of a few) of BH mass to host galaxy mass.

Given the lack of specific theoretical predictions, we cannot attempt a quantitative comparison of our results with AGN feedback models. Nonetheless, we wish to stress that the typical unobscured quasar possesses a gas reservoir normal for its stellar content and does not appear to be depleted in cold gas. Whether this poses a difficulty or not for AGN feedback models deserves further consideration.

5. FUTURE DIRECTIONS

The pilot study presented here can be improved and extended in several ways. A number of the $\text{H}i$ observations would benefit from longer integrations. Roughly one-third of our sample was undetected in the current experiment, and the upper limits on their $\text{H}i$ masses remain relatively high; nearly half of the non-detections have limits above $M_{\text{HI}} = 10^{10} M_\odot$. It would be useful to improve these limits by a factor of a few, down to $M_{\text{HI}} \approx 5 \times 10^9 M_\odot$, the scale of the Milky Way. Higher signal-to-noise ratio spectra of the detected sources would allow us to better study the $\text{H}i$ line profiles, especially to quantify the apparent excess in line asymmetry and its implications for the dynamical state of the gas and the circumgalactic environment of the host. In terms of new observations, it would be particularly worthwhile to observe a larger sample of high-Eddington ratio systems in order to verify the trends with Eddington ratio identified in this study. This can be easily accomplished using the current SDSS database (Greene & Ho 2007b, 2007c). To put more stringent constraints on AGN feedback scenarios, it would be highly desirable to increase the number of high-luminosity AGNs (quasars) in the surveys. Given the rarity of nearby quasars and the redshift limit of Arecibo, this will be a difficult task, but some progress can still be made.

The current project represents a major initiative in characterizing the cold gas content in type 1 AGNs. We have demonstrated that $\text{H}i$ observations can yield many useful insights into the nature of AGNs, BHs, and their host galaxies. This tool should be applied to other classes of AGNs. A useful extension of this program would be to observe a well-matched sample of type 2 (narrow-line) AGNs in order to test their relationship to type 1 objects. Kim et al. (2006; see also Ho 2005b and Lal & Ho 2007), for example, have argued that type 2 quasars are the evolutionary precursors, as opposed to simply misoriented counterparts, of type 1 quasars. If true, type 2 sources are likely to be more gas-rich than their type 1 counterparts, or perhaps their interstellar medium might be less dynamically relaxed, differences that can potentially be discerned through $\text{H}i$ observations.

The analysis presented here critically depends on a number of quantities derived from optical images of the host galaxy, namely its inclination angle, isophotal diameter, luminosity, morphological type, and, to a lesser extent, local environment. All of these measurements can be greatly improved with the help of better optical imaging. In many instances, the SDSS images (Ho et al. 2008) simply lack the necessary depth or resolution to yield clear-cut measurements of these parameters. High-resolution (e.g., Hubble Space Telescope) images would be particularly valuable, as they would simultaneously yield a reliable decomposition of the AGN core from the host galaxy, as well as a quantitative measurement of the bulge component. All of the correlations presented in this study should be reexamined once such data become available, to see if their scatter can be reduced.

We have stressed the utility of $\text{H}i$ observations, but, of course, a full inventory of the cold interstellar medium should include the molecular component as well, which, depending on the galaxy type, can dominate over the atomic component. A systematic CO survey of the objects in our $\text{H}i$ program would be highly desirable, not only to complete the gas inventory but also to bootstrap the kinematical analysis to the CO line width. Unlike the current limitations of $\text{H}i$ observations, the rotational transitions of CO can be observed to almost arbitrarily high redshifts (Solomon & Vanden Bout 2005), a necessary ingredient to access AGN host galaxies at early epochs. Ho (2007b) discusses the use of the CO Tully-Fisher relation as a powerful tool to investigate the host galaxies of high-redshift quasars.

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