UNDERSTANDING THE NUCLEAR GAS DISPERSION IN EARLY-TYPE GALAXIES
IN THE CONTEXT OF BLACK HOLE DEMOGRAPHICS

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ABSTRACT

The majority of nearby early-type galaxies contain detectable amounts of emission-line gas at their centers. The nuclear gas kinematics form a valuable diagnostic of the central black hole (BH) mass. Here we analyze and model Hubble Space Telescope STIS observations of a sample of 27 galaxies; 16 Fanaroff-Riley Type I radio galaxies and 11 (more) normal early-type galaxies. We focus here on what can be learned from the nuclear velocity dispersion (line width) as a complement to the many studies dealing with gas rotation velocities. We find that the dispersion in a STIS aperture of 0.1–0.2 generally exceeds the large-scale stellar velocity dispersion of the galaxy. This is qualitatively consistent with the presence of central BHs but raises the questions of whether the excess gas dispersion is of gravitational or nongravitational origin and whether the implied BH masses are consistent with our current understanding of BH demography (as predicted by the $M$–$\sigma$ relation between BH mass and stellar velocity dispersion). To address this we construct purely gravitational axisymmetric dynamical models for the gas, both thin-disk models and models with more general axis ratios and velocity anisotropies. For the normal galaxies the nuclear gas dispersions are adequately reproduced assuming disks around the BHs with masses that follow the $M$–$\sigma$ relation. In contrast, the gas dispersions observed for the radio galaxies generally exceed those predicted by any of the models. We attribute this to the presence of nongravitational motions in the gas that are similar to or larger than the gravitational motions. The nongravitational motions are presumably driven by the active galactic nucleus (AGN), but we do not find a relation between the radiative output of the AGN and the nongravitational dispersion. Given the uncertainties about the dynamical state of the gas, it is not possible to uniquely determine the BH mass for each galaxy from its nuclear gas dispersion. However, for the sample as a whole the observed dispersions do not provide evidence for significant deviations from the $M$–$\sigma$ relation.

Key words: galaxies: active — galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics — galaxies: nuclei — ISM: kinematics and dynamics

1. INTRODUCTION

The mass of a central black hole (BH) in a galaxy can be directly weighed using gravitational “test particles” moving around it (see, e.g., Kormendy & Richstone 1995). Commonly used test particles are stars, optical emission-line gas, and maser clouds. These move around in the combined potential well of the stellar mass and the central BH mass. A secure direct dynamical measurement of the BH mass requires that the distribution and kinematics of the test particles be measured in the immediate vicinity of the BH, i.e., the BH’s sphere of influence, so that its gravitational potential has a measurable effect on the kinematics in addition to the effect of the stellar mass potential. Ground-based optical telescopes can resolve the BH’s sphere of influence only for very nearby galaxies, with our Milky Way being a spectacular nearby example (e.g., Ghez et al. 2003; Schödel et al. 2003). The Hubble Space Telescope (HST) can provide the required spatial resolution for galaxies with distances up to several tens of megaparsecs (e.g., Kormendy & Gebhardt 2001). The Very Long Baseline Interferometer can in principle probe BH masses out to even larger distances provided that the galaxies display nuclear maser emission. Together these methods have led to direct dynamical measurements of BH masses $M_{\bullet}$ in the range $M_{\bullet} \sim 10^5$–$5 \times 10^9 M_\odot$ in several tens of galaxies in the nearby universe (see, e.g., Tremaine et al. [2002] and Marconi & Hunt [2003] for listings of BH mass measurements). The BH masses are mostly based on dynamical modeling of kinematics of either stars or emission-line gas. The detected BH masses $M_{\bullet}$ correlate well with host spheroid luminosity $L_s$, global stellar velocity dispersion $\sigma$, and spheroid mass (Gerhard et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Marconi & Hunt 2003; Haring & Rix 2004). These correlations roughly represent our current knowledge of the local BH demography. To explore these correlations further, i.e., their scatter and extent in BH mass, dynamical modeling using emission-line gas kinematics in early-type galaxies is convenient and in some respects even crucial. First of all, more than 50% of the early-type galaxies in the nearby universe contain gas at their centers (e.g., Goudfrooij et al. 1994; Ho et al. 1997). Second of all, the most massive BHs currently found (i.e., $M_{\bullet} \gtrsim 10^9 M_\odot$) are often in giant elliptical galaxies. The central stellar surface brightness of these galaxies is typically too low to obtain accurate stellar kinematics with the HST, and maser emission has not been detected (e.g., Barth 2004).

At the centers of galaxies, the collisional gas is expected to settle quickly into a disk, if unperturbed by forces other than gravity (e.g., Habe & Ikeuchi 1985). The frequent detection with the HST of disklke structures in dust and gas in early-type galaxies suggests that settling actually takes place (e.g., van Dokkum & Franx 1995; Tran et al. 2001; Verdoes Kleijn et al.1

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1999; Laine et al. 2003). Therefore, the extended gas velocities in galactic nuclei have been modeled assuming a thin disk in circular rotation. Such models have been successful in explaining the observed gas velocities. However, in the few cases in which both gas velocities and gas dispersions are modeled, it is often found that the nuclear velocity dispersion exceeds the prediction for a thin disk (van der Marel & van den Bosch 1998; Barth et al. 2001; Maciejewski & Binney 2001; Cappellari et al. 2002; Verdoes Kleijn et al. 2002). Many of these targets are active galactic nuclei (AGNs) and display regular disks of dust and gas. The origin of this “excess” velocity dispersion is unknown. Two common ad hoc assumptions are that (1) the excess dispersion is due to nongravitational “turbulent” forces of unknown origin that do not affect the mean circular rotation of the gas (e.g., van der Marel & van den Bosch 1998; Verdoes Kleijn et al. 2002), or (2) the excess dispersion is purely gravitational and affects the rotation of the gas through the asymmetric drift equation (e.g., Barth et al. 2001).

A main aim of this paper is to determine which early-type galaxies do and which do not display an excess in nuclear gas dispersion. If there are galaxies for which the disk remains thin all the way to the nucleus, then any velocity dispersion observed through a nuclear aperture is caused by differential rotation over this aperture. A nuclear aperture samples gas that is much closer to the BH than a series of apertures that sample the extended rotation curve. Hence, the nuclear gas dispersion can be sensitive to much lower BH masses than the rotation curve. This is relevant, as the sensitivity in terms of the minimum detectable BH mass in early-type galaxies with stellar dynamical methods or with gas rotation velocities is typically not much below the values predicted by the correlations between BH mass and spheroid properties. A relevant example in this case is the claim that active spiral galaxies classified as narrow-line Seyfert 1 galaxies harbor BHs with masses smaller than those predicted by the \( M_{\text{BH}} \) relation (e.g., Grue & Mathur 2004).

For galaxies with nuclear gas dispersions in excess of that expected from a thin disk, we want to determine the origin of this excess. On the one hand, if it has a gravitational origin, this implies that the gas should rotate less quickly than the circular speed, and the thin-disk approximation should not hold. The gas might then have a distribution somewhere in the range from a thin disk to a purely spherical distribution. Previous BH mass estimates based on the assumption of thin disks would then be underestimated, and this would affect the observed correlations between BH mass and large-scale spheroid properties. On the other hand, if the excess dispersion has a nongravitational origin, we would like to quantify how it depends on galaxy parameters, such as nuclear activity. This in turn could shed light on the accretion process in these nearby, typically low-luminosity, AGNs.

In summary, this paper studies the nature of the line widths of emission gas in nearby early-type galaxy nuclei and its implications for BH demography and BH accretion processes. A similar study into the line widths of gas for late-type galaxies has been performed by Sarzi et al. (2002). The outline of the paper is as follows. Section 2 describes the sample selection, the data, and the determination of the central gas velocity dispersions. Section 3 compares the observed dispersions to those expected from a thin circular disk. Section 4 compares the observed dispersions to those expected from a gas distribution that is more spheroidal than a disk. Section 5 constrains the direction of the nongravitational dispersion. Section 6 describes the caveats of our modeling. Finally, § 7 provides a discussion of the results and lists the main conclusions of the paper. Throughout the paper we use a Hubble constant \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. SAMPLE AND DATA ANALYSIS

We analyze a sample of 27 galaxies. It consists of galaxies that meet the following requirements: (1) early-type host morphology; (2) distance below 110 Mpc; (3) a large-scale stellar velocity dispersion measurement available from the literature; (4) \( HST \) imaging that shows an identifiable (i.e., relatively unobscured) nucleus; and (5) \( HST \) emission-line spectroscopy for which kinematics and flux profiles have been published (20 galaxies) or are available in the \( HST \) archive (seven galaxies). We excluded galaxies for which the signal-to-noise ratio of the spectrum was very low, complicating a reliable analysis. Sixteen of the galaxies are classified as Fanaroff-Riley Type I (FR I) radio galaxies with jets on scales of tens of kiloparsecs or larger. The other 11 galaxies also have radio emission. Their radio luminosity is typically much lower (see Table 1), and the radio emission originates from a central compact component. We reduced and analyzed the archival data for the seven galaxies similarly to our previous papers (e.g., Noel-Storr et al. 2003; Verdoes Kleijn et al. 2002). The spectra for all galaxies except two were obtained with \( HST \) STIS in combination with the G750M grating. For IC 1459 a \( HST \) STIS spectrum with the G430L grating was obtained, and for NGC 6251 a \( HST \) FOS spectrum with the 0\,′′1 PAIR B aperture. All spectra cover the \( H\alpha + [\text{N}\,\text{II}] \) and \( [\text{S}\,\text{II}] \) \( \lambda \lambda 6716, 6731 \) lines, except for the G430L spectrum of IC 1459. In that case we use the \( H\beta \) line for our analysis. Table 1 lists basic data for the sample galaxies.

The first step is to determine the gas velocity dispersions in the central region of each galaxy. In most cases (both in the literature and in our analysis of the archival spectra) single-Gaussian fits were made to each of the lines of the \( H\alpha + [\text{N}\,\text{II}] \) composite and to the weaker \( [\text{S}\,\text{II}] \) \( \lambda \lambda 6716, 6731 \) lines. Only in NGC 3245 and NGC 4526 are the \( [\text{S}\,\text{II}] \) lines too weak to be fitted. For NGC 6251 we used the fit to the \( H\alpha + [\text{N}\,\text{II}] \) lines available in Ferrarese & Ford (1999). For these narrow components, the \( [\text{N}\,\text{II}] \) \( \lambda 6584 \) was the strongest line in ~85% of the galaxies. In four galaxies (NGC 3245, NGC 3998, NGC 4278, and NGC 6251) a broad emission-line component is clearly present in addition to the narrow \( H\alpha + [\text{N}\,\text{II}] \) components. This is most likely due to a broad \( H\alpha \) component because the broad component is not seen in the \( [\text{S}\,\text{II}] \) forbidden lines, and the forbidden \( [\text{N}\,\text{II}] \) lines originate presumably in the same region as the \( [\text{S}\,\text{II}] \) lines. This broad component was fitted with an additional Gaussian. For the two archival sources with a broad component (NGC 3998 and NGC 4278), we established that the \( [\text{S}\,\text{II}] \) lines provide an important fitting constraint in addition to the \( H\alpha + [\text{N}\,\text{II}] \) region, which is blended heavily due to the broad component. Excluding the \( [\text{S}\,\text{II}] \) doublet from the fit results in ~35% larger (NGC 3998) or smaller (NGC 4278) dispersion. Similarly, Ferrarese & Ford (1999) report for NGC 6251 a width of the \( [\text{S}\,\text{II}] \) lines that is ~37% larger than the \( H\alpha + [\text{N}\,\text{II}] \) lines at the nuclear aperture. For the archival cases with only narrow lines, we determined that the inferred gas dispersion changes by ~10% by excluding the \( [\text{S}\,\text{II}] \) doublet from the fit.

The next step is to find for each galaxy the aperture closest to the nucleus, which we refer to as the “central” aperture. We assume that the dynamical nucleus coincides with the peak in emission-line and continuum flux. The typical dimensions of the STIS apertures are 0\,′′1–0\,′′2 in the spectral direction and 0\,′′05–0\,′′1 in the spatial direction (see Table 2). The exact subpixel location along the slit of the nucleus was determined by fitting a Gaussian to the central few emission-line fluxes. In most cases the peak in velocity dispersion coincides with the flux peak. We indicate in Table 1 the few cases in which the maximum dispersion does not
peak at the central aperture but just outside it. The exact location of the nucleus (i.e., the flux peak under our assumptions) in the direction of the slit width is not known. We assume that it is centrally located in this direction. This seems plausible given that the target acquisition procedure is designed to have the center of the slit located exactly on the brightest continuum point in the galaxy. That this "peak-up" procedure actually succeeded is supported by the steep decline in flux in the parallel slits that are available for many targets. Nevertheless, the effect on our results of a potential offset from this location is discussed in §6. The gas velocity dispersion $\sigma_g$ at the central aperture is listed in Table 1. The typical relative formal measurement error for $\sigma_g$ is $\sim 5\%$.

We also require the unconvolved flux profile for our analysis. The emission-line surface brightness is represented by fitting a double exponential function,

$$I(R) = I_1 \exp(-R/R_1) + I_2 \exp(-R/R_2),$$

(1)
to the narrow emission-line fluxes taking into account the point-spread function (PSF) and disk inclination (see, e.g., Verdoes Kleijn et al. [2002] for a detailed description). The disk inclinations were taken from the literature or determined by us (indicated by an asterisk). A colon indicates galaxies for which a larger dispersion is measured just outside the central aperture (see §2 for details). Col. (8): Black hole masses from detailed dynamical gas disk modeling reported in the literature. Col. (9): Total radio luminosities at 1.4 GHz (assuming a spectral index $\alpha = 0.75$ for $f_{\nu} \propto \nu^{\alpha}$). Col. (10): BH mass and radio emission references.

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**TABLE 1**

**Early-Type Galaxy Sample**

| Galaxy (1) | Type (2) | FR I (3) | $D$ (Mpc) (4) | $M_B$ (mag) (5) | $\sigma_g$ (km s$^{-1}$) (6) | $\sigma_g$ (km s$^{-1}$) (7) | $M_*$ (10$^8$ $M_\odot$) (8) | $L_{\text{radio}}$ [log (W Hz$^{-1}$)] (9) | Reference (10) |
|------------|---------|--------|--------------|----------------|-----------------|----------------|------------------|----------------|------------|
| IC 989     | E       |        | 101          | -20.8          | 176             | 174$^c$         | ...              | 22.74           | r1         |
| IC 1459    | E       |        | 29           | -20.5          | 340$^a$         | 53$\pm$3        | 1.3              | 23.00           | b1, r2     |
| NGC 315    | E       | 1      | 68           | -22.4          | 328             | 528$^b$         | ...              | 24.01           | r3         |
| NGC 383    | E/SO    | 1      | 65           | -22.0          | 267             | 924$^a$         | ...              | 24.42           | r3         |
| NGC 541    | E/SO    | 1      | 73           | -21.5          | 209             | 336             | ...              | 23.85           | r3         |
| NGC 741    | E       | 1      | 70           | -22.5          | 294             | 424             | ...              | 23.76           | r3         |
| NGC 2329   | E/SO    | 1      | 77           | -21.7          | 247             | 301             | ...              | 23.67           | r3         |
| NGC 3078   | E       |        | 35           | -20.9          | 249             | 262$^b$         | ...              | 23.01           | r4         |
| NGC 3245   | SO      |        | 21           | -20.0          | 205$^a$         | 168$^a$         | 2.1              | 20.49           | b2, r5     |
| NGC 3862   | E       | 1      | 84           | -21.5          | 265             | 302             | ...              | 24.66           | r3         |
| NGC 3998   | SO      |        | 14           | -19.8          | 318             | 650$^a$         | ...              | 21.47           | r6         |
| NGC 4278   | E       | 15     | 16           | -19.3          | 260             | 372$^a$         | ...              | 22.08           | r5         |
| NGC 4335   | E       | 1      | 62           | -20.6          | 282$^a$         | 248$^b$         | <1.0             | 23.02           | b3, r3     |
| NGC 4374   | E       | 1      | 15           | -20.9          | 295             | 883             | 3.6              | 23.26           | b4, r3     |
| NGC 4459   | SO      |        | 17           | -20.2          | 186$^a$         | 193$^a$         | 0.7              | 20.01           | b5, r1     |
| NGC 4486   | E       | 1      | 15           | -22.0          | 375$^a$         | 681$^a$         | 29.0             | 24.81           | b6, r3     |
| NGC 4526   | SO      |        | 36           | -19.4          | 260             | 424$^a$         | ...              | 21.36           | r1         |
| NGC 5077   | SO      |        | 36           | -20.9          | 275             | 417$^a$         | ...              | 23.08           | r4         |
| NGC 5127   | E       | 1      | 64           | -20.9          | 189             | 157             | ...              | 23.99           | r3         |
| NGC 5490   | E       | 1      | 69           | -21.4          | 292             | 280$^b$         | ...              | 23.70           | r3         |
| NGC 6251   | E       | 1      | 99           | -21.8          | 290$^a$         | 434$^a$         | 7.8              | 24.49           | b7, r6     |
| NGC 6861   | E/SO    |        | 28           | -21.1          | 382$^a$         | 814$^a$         | ...              | 20.98           | r7         |
| NGC 7052   | E       | 1      | 55           | -21.0          | 266$^a$         | 456             | 3.1              | 22.95           | b8, r3     |
| NGC 7626   | E       | 1      | 47           | -21.6          | 276             | 349$^a$         | ...              | 23.28           | r3         |
| UGC 1841   | E       | 1      | 85           | -21.7          | 348             | 592$^b$         | ...              | 24.85           | r3         |
| UGC 7115   | E       | 1      | 91           | -20.9          | 198             | 545             | ...              | 23.85           | r3         |
| UGC 12064  | E/SO    | 1      | 68           | -20.6          | 255             | 496$^b$         | ...              | 24.29           | r3         |

Notes.—General properties of the galaxy sample. Col. (2): Hubble classification from the LEDA catalog (http://leda.univ-lyon1.fr). Col. (3): Galaxies indicated by a 1 contain large-scale Fanaroff & Riley (1974) type 1 radio jets. Col. (4): Distances from Faber et al. (1989), Tonry et al. (2001), or, if not available, directly from observed recession velocity and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. Col. (5): Absolute blue magnitude from LEDA. Col. (6): Central stellar velocity dispersions typically integrated over an aperture area of several arcsec$^2$. The dispersions are from the LEDA catalog except where noted. See §2 for a discussion of the errors. Col. (7): Gas velocity dispersions of narrow H$\alpha$ + [N $\alpha$] and [S $\alpha$] emission lines as measured from $HST$ spectra at the central aperture. See §2 for a discussion of the errors. These measurements are taken from the literature or obtained by us (indicated by an asterisk). A colon indicates galaxies for which a larger dispersion is measured just outside the central aperture (see §2 for details). Col. (8): Black hole masses from detailed dynamical gas disk modeling reported in the literature. Col. (9): Total radio luminosities at 1.4 GHz (assuming a spectral index $\alpha = 0.75$ for $f_{\nu} \propto \nu^{\alpha}$). Col. (10): BH mass and radio emission references.

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### Notes

- A broad H$\alpha$ line is perhaps present (see §6).
- A broad H$\alpha$ line was fitted in addition to the narrow lines of the H$\alpha$ + [N $\alpha$] complex.
- B Verdoes Kleijn et al. (2002).
- K Korpel & Kleininger (2000).
- BH mass references: (b1) Cappellari et al. 2002; (b2) Barth et al. 2001; (b3) Verdoes Kleijn et al. 2002; (b4) Bower et al. 1998; (b5) Sarzi et al. 2001; (b6) Macchetto et al. 1997; (b7) Ferrarese & Ford 1999; (b8) van der Marel & van den Bosch 1998. Radio emission references: (r1) Dressel & Condon 1978; (r2) Wright & Otrupcek 1990; (r3) Condon & Broderick 1988; (r4) Griffith et al. 1994; (r5) Becker et al. 1995; (r6) White & Becker 1992; (r7) Mauch et al. 2003.
stellar dispersions to estimate BH masses using the $M_\bullet$-σ relation as determined by Tremaine et al. (2002). The relation is calibrated to flux-weighted stellar dispersions σ_e inside an effective radius of the galaxy, which are not available for most of our sample galaxies. However, comparing σ_e and σ_s where possible shows a difference of typically ~7% between σ_e and σ_s. We use this as the typical relative error on our measurement of σ_e in approximation to σ_s. Finally, Table 1 also lists the BH masses obtained from dynamical modeling of central gas disk rotation velocities as published for eight galaxies in the sample.

3. THIN-DISK MODELS

Figure 1 shows the central gas velocity dispersion at small scales (i.e., a typical aperture size of ~0.15 or ~40 pc for a typical galaxy distance of 50 Mpc) versus the large-scale stellar dispersions (tracing the flux-weighted dispersion at kiloparsec scales). The nuclear gas dispersions are almost always larger than the large-scale stellar dispersions, increasingly so for larger stellar dispersions. Given the success rate of BH mass determinations in early-type galaxies, it now seems quite possible that all spheroids harbor a BH at their nucleus. There are two generic ways in which the presence of a BH can contribute to the nuclear gas dispersion. First, gas motions increase at smaller distances from a central BH due to the increase of the gravitational force. Integrating over a finite aperture will lead to a larger observed gas dispersion. We call this the gravitational contribution. An increase will always occur, but its magnitude will depend on the physical structure and orbital distribution of the gas, e.g., a thin rotating disk or a more spherical distribution. The effect is noticeable because for a typical σ_s = 250 km s^{-1} in our sample, the typical central HST aperture is only a factor of 2 larger than the rough measure of the BH radius of influence $r_{\text{BH}} = GM_\bullet/σ_s^2 \sim 20$ pc adopting the $M_\bullet$-σ relation from Tremaine et al. (2002). The relation finds $M_\bullet \sim σ_s^4$ with α = 4. If the gas motions are dominated by gravitation, it is expected that $M_\bullet \sim σ_s^4$ with β = 2, and hence $σ_s \sim σ_e^2$, qualitatively consistent with the increasing ratio of $σ_s$ and $σ_e$ shown in Figure 1. The $M_\bullet$-σ relation also suggests that one should expect a smaller excess gas dispersion in galaxies with smaller $σ_s$ for another reason: galaxies with small $σ_s$ have a smaller BH mass and sphere of influence so that a STIS aperture of fixed size samples more of the gas outside of the BH sphere of influence. A second generic way in which the presence of a BH can contribute to the nuclear gas dispersion is not through its gravitational force but through input of kinetic energy, which perturbs the collisional gas. We call this the hydrodynamic or nongravitational contribution. This energy could be released by processes related to an active BH. As a side remark, it is unlikely that the kinetic energy might be provided by collisions with photons emerging from the active region around the BH. The reason is that the bolometric luminosity of the low-luminosity active nuclei discussed here is
always orders of magnitudes below the Eddington luminosity (e.g., Ho 1999). Shocks, e.g., jet-gas interactions, are a more plausible source of kinetic energy. It could be that the gravitational contribution dominates (e.g., a thin disk of noncolliding gas particles in circular rotation) or that the hydrodynamic contribution dominates (e.g., a fully collisionally driven outflow of gas from the active BH). The well-defined thin dust and gas disks often seen immediately outside the nucleus in these galaxies suggest that the gas might be settled all the way to the nucleus. Therefore, we first determine the answer to the question: In which galaxies can the BH potential account for the observed nuclear gas dispersion assuming that the gas is located in a thin circular disk?

The answer to this question is known already for five galaxies in our sample for which detailed modeling has been performed of both gas velocities and dispersions of the extended gas disk under the assumption of a thin circular disk. In the cases of NGC 7052 (van der Marel & van den Bosch 1998), IC 1459 (Cappellari et al. 2002; Verdoes Kleijn et al. 2000), and NGC 4335 (Verdoes Kleijn et al. 2002), an excess of dispersion by a factor of ~2 or more was observed. For NGC 3245 (Barth et al. 2001), a smaller excess of ~35% was observed. In the case of M87 (Macchetto et al. 1997; Harms et al. 1994), no dispersion excess was observed. The velocity dispersion for this galaxy was accounted for by a model in which the gas resides in an annulus instead of a disk. (This model can also account well for the velocities and peculiarities in the flux distribution.) It is these mixed results on excess gas dispersion that lead us to examine the presence of excess gas dispersion for a larger sample of galaxies.

In the present and following sections (§6–5) we present results of dynamical models of the gas velocity dispersions. Caveats that result from the assumptions in our models are discussed in §6. Performing gas disk kinematical modeling for our complete sample in similar detail as done for the aforementioned few cases is beyond the scope of this paper. Thus, we construct somewhat more simplified thin-disk models. The main simplification is to neglect the stellar mass contribution to the central gravitational potential. The effect of this simplification on the predicted velocity dispersions for the galaxy sample can be estimated as follows. Assume a spherical stellar mass density \( \rho(r) = \rho_0 (r/r_0)^\alpha \) in the nuclear region, where \( r \) is the radius in parsecs and \( \rho_0 \) a scaling constant. According to the LEDA database, the absolute blue magnitude in our sample varies in the range \( M_B = [-19.3, -22.5] \) with a mean \( \langle M_B \rangle = -21.1 \). Assuming a typical galaxy color \( B - V = 0.95 \), this indicates that a typical galaxy in our sample is about 1 mag brighter than the division magnitude at \( M_r \sim -21.0 \) between shallow core and steep core ("power law") galaxies (Gebhardt et al. 1996). Galaxies brighter than this division magnitude typically have \( \alpha \sim -1 \) (while below they have \( \alpha \sim -2 \)). From the study by Gebhardt et al. (1996) we infer a typical \( \rho_0 \lesssim 10^4 M_\odot \text{pc}^{-3} \). With this information we can compute the circular velocity \( v_c = 4\pi G \rho_0 r^{\alpha+1}/(\alpha + 3) \). By comparison, the circular velocity due to the BH is \( v_{\text{BH}}^2 = G M_\bullet / r \). We compute the ratio of these two at \( r = 0.1 \text{ pc} \) from the nucleus assuming a BH mass according to the \( M_\bullet - \sigma \) relation. The value \( r = 0.1 \text{ pc} \) is a typical distance from the galaxy center at which we have measured gas dispersions with HST. The ratio of the circular velocities in quadrature (i.e., equivalent to the ratio in dynamical mass) is always less than 20%. This is much smaller than, e.g., the scatter of ~0.3 dex in the \( M_\bullet - \sigma \) relation (Tremaine et al. 2002). This confirms that the stellar mass contribution in our analysis can be safely neglected, provided that (1) the BH masses are not significantly below the \( M_\bullet - \sigma \) relation, and (2) we are not attempting to model the large-scale rotation of the gas at radii much beyond ~0.1 pc. As an additional check we directly determined the difference in predicted dispersion with and without BH mass for NGC 4335, NGC 7052, and IC 1459. For these galaxies we modeled the stellar mass in previous papers (Verdoes Kleijn et al. 2000, 2002; van der Marel & van den Bosch 1998). These cases confirm the result from the general argument that the difference in predicted dynamical mass is always less than 20% (see also Fig. 2, discussed below).

For a thin circular disk, the velocity dispersion observed in a nuclear aperture is due entirely to differential rotation over the aperture. To calculate this dispersion we used the modeling software described in more detail in van der Marel & van den Bosch (1998) and Verdoes Kleijn et al. (2000, 2002). This modeling takes into account the emission-line flux profile, slit width, and PSF convolution. We first modeled the galaxies for which a BH mass estimate is available in the literature from detailed modeling of the gas rotation velocities. Figure 2 shows the predicted versus observed velocity dispersions for these eight galaxies. Seven galaxies have an observed dispersion in excess of the prediction. The modeling nicely reproduces the aforementioned relative differences in excess dispersion for M87, NGC 3245, NGC 7052, NGC 4335, and IC 1459 known from prior modeling of the rotation velocities in the extended gas disk. To put the complete sample in a similar diagram, we need an estimate of the BH mass for every galaxy. For this we use the \( M_\bullet - \sigma \) relation as calibrated by Tremaine et al. (2002). They derive the relation \( \log (M_\bullet / M_\odot) = 8.13 + 4.02 \log (\sigma/200 \text{ km s}^{-1}) \). The slope of this relation falls between those reported by Gebhardt et al. (2000; slope of 3.75) and Ferrarese & Merritt (2000; slope of 5.27). Figure 3 shows the predicted versus observed dispersion for a thin-disk model, but now assuming for all galaxies a BH mass according to the \( M_\bullet - \sigma \) relation. The observed dispersions in nonradio galaxies scatter around the prediction from the model (except for IC 989; see §7). In fact, the number of nonradio galaxies and their range in observed gas dispersions is large enough that they independently...
Fig. 2.—Observed gas velocity dispersion vs. predicted gas velocity dispersion for a thin-disk model. We use the BH masses and inclinations inferred from detailed models for the gas rotation velocities available in the literature (see Tables 1 and 2). Open symbols indicate FR I–type radio galaxies, while filled symbols indicate galaxies without large-scale radio jets. Circles indicate results from thin-disk models that neglect the contribution of the stellar mass to the gravitational potential. Triangles show the predictions when this simplification is omitted, for the three galaxies for which we published detailed gas modeling previously. The difference between the two model approaches is <10%.

Fig. 3.—Observed gas velocity dispersion $\sigma_g$ as a function of predicted velocity dispersion for an infinitely thin gas disk in circular rotation around a BH with mass $M_\bullet$ according to the $M_\bullet-\sigma$ relation. Radio galaxies are shown as open symbols, and galaxies without large-scale radio jets as filled symbols. Squares indicate galaxies for which the disk inclination is unknown and assumed to be 60°. Galaxies with disk inclination $i < 40°$ are indicated by double circles. The typical measurement errors are indicated in the lower right corner. The dashed and solid lines indicate $\sigma_{\text{model}} = [(1/2)^{1/2} 1, 2^{1/2}]\sigma_{\text{obs}}$, respectively, to facilitate comparison to the $M_\bullet-\sigma$ relation and its ~0.3 dex scatter in BH mass.

Fig. 4.—Ratio of observed and predicted gas dispersions as a function of gas disk inclination. The predicted dispersion is assumed to be caused by the circular rotation in a thin disk around a BH according to the $M_\bullet-\sigma$ relation. The error bars take into account the 0.3 dex intrinsic scatter in the $M_\bullet-\sigma$ relation and typical errors due to aperture differences and dispersion measurement errors. The four arrows indicate where points would move to if disk inclinations were underestimated within the measurement errors for close to face-on disks. Radio galaxies (open symbols) have a systematically larger dispersion ratio than nonradio galaxies (filled symbols). The squares indicate galaxies for which the dust does not provide a constraint on the gas disk inclination (placed at a fiducial inclination of 60°). If the assumed disk inclinations are incorrect, and the observed gas is actually edge-on in all galaxies, then we would have expected the ratios to lie along the solid line, $\sin^{-1} i$. Since many points lie above this line, inclination errors cannot be the (sole) explanation of the observed trend.

confirm the $M_\bullet-\sigma$ relation for the thin-disk model. This is non-trivial because BH masses significantly below the $M_\bullet-\sigma$ relation could have been detected with HST STIS observations. As a measure of the minimally detectable BH mass, we compute the BH mass that causes a gas dispersion that equals that predicted from the combined effect of instrumental broadening and the stellar mass model discussed above. We use again the typical radius of 0.1 and take into account the disk inclination and distance for each galaxy. The resulting masses vary between ~6 × 10$^6$ and ~6 × 10$^7$ $M_\odot$, with a typical value of ~3 × 10$^7$ $M_\odot$. (Exceptions are NGC 3862 and UGC 7115. Their minimally detectable BH masses lie above the $M_\bullet-\sigma$ relation because the instrumental line broadening is larger than the dispersion due to differential gravitational rotation for such close to face-on gas disks.) The BH masses predicted by the $M_\bullet-\sigma$ relation exceed this typical detectable BH mass by a factor of ~2 for the lowest stellar dispersions and by almost 2 orders of magnitude for the highest stellar dispersions in the sample. In conclusion, the gas dispersions in nonradio galaxies support the idea that all early-type galaxies harbor supermassive BHs at their nuclei with masses according to the $M_\bullet-\sigma$ relation.

In contrast to the nonradio galaxies, all radio galaxies have a gas dispersion in excess of that expected from the thin-disk models. About ~50% of those fall above the 1 $\sigma$ scatter from the intrinsic scatter in the $M_\bullet-\sigma$ relation. To explore the origin of this we plot in Figure 4 the ratio $R_{\sigma,\text{d}}$ of observed dispersion and that predicted for the disk model. There is a trend of an increasing ratio
with decreasing disk inclination. In fact, the four largest ratios are all in galaxies with gas disk inclinations \( i < 40^\circ \), i.e., close to face-on disks. This cannot be explained as a result of measurement errors in the dust disk inclinations. The arrows in Figure 4 show by how much \( R_{d,i} \) can decrease due to the known measurement errors. The decreases do not change the overall result that radio galaxies systematically have excess dispersions. A more extreme (and probably unphysical) possibility is to assume that we might have used incorrect inclinations because the measured dust disk inclinations bear no relation to the actual inner gas disk inclinations. However, this would still not provide a satisfactory explanation. If all the gas disks were in reality edge-on and well described by thin-disk models, then we would have expected the points in Figure 4 to fall along the curve \( R_{d,i} = \sin^{-1} \) (solid curve). This still falls below many of the observed dispersion ratios (see Fig. 4). Moreover, an excess gas dispersion is not only seen in radio galaxies with relatively face-on disks. If we exclude systems with disk inclinations \( i < 40^\circ \) from the analysis, the median \( R_{d,i} = 1.32 \) for radio galaxies versus 0.96 for nonradio galaxies. A median test yields a probability of only 0.05 that this difference would occur by chance in the event that the samples were drawn from populations with the same median. Therefore, a solution to account for the excess gas dispersion in radio galaxies probably must be sought in having a significant vertical velocity dispersion component.

Finally, as a sanity check we analyzed the dependence of \( R_{d,i} \) on BH mass and the typical circular velocity of the system, parameterized as \( (GM_*/r_{\text{half}})^{1/2} \), where \( r_{\text{half}} \) is the radius inside which half of the light of the unconvolved emission-line flux distribution is contained. There is no relation between the dispersion ratio and the two measures of the gravitational potential. This confirms that the excess velocity dispersion in the radio galaxies is not somehow an artifact of our gravitational modeling.

### 4. SPHEROIDAL MODELS

Many galaxies in the sample show disks of dust and gas with radii ranging from hundreds of parsecs up to several kiloparsecs. It appears reasonable, but might be wrong, to assume by extrapolation that the nuclear region within the spatial resolution of the observations also has a disk-like geometry. Instead, the gas distribution might be more spheroidal in the vicinity of the BH. In that case the gas moves also out of the plane of the larger scale thin gas disk. This could explain qualitatively the observed increasing ratio of observed versus predicted dispersion for decreasing dust disk inclination. We address next whether such a spheroidal distribution can also quantitatively explain the observed \( \sigma_g \) gravitationally.

Gas in a vertically extended distribution (e.g., a spherical one) tends to collapse quickly to a disk due to hydrodynamic forces. Thus, to maintain a spheroidal structure, one would have to assume that the gas is located in individual clouds that move collisionlessly. As an initial assessment of the plausibility of this we estimate the collision timescale for clouds in a simplistic model: spherical cloulets of ionized hydrogen moving around in a spherical volume. The typical time \( t_{\text{free}} \) between cloulet collisions is estimated as

\[
t_{\text{free}} = \frac{V}{N_{\text{cl}} \sigma_{\text{cl}} v_T},
\]

where \( v_T \) is the typical relative velocity of cloulets, \( V \) is the spherical volume within which the cloulets are contained, \( \sigma_{\text{cl}} \) is the cross section of each cloulet, and \( N_{\text{cl}} \) is the total number of clouds. For \( V \) we take the spherical volume with a radius equal to the half-light radius of the gas distribution as seen projected on the sky. For \( v_T \) we take the circular velocity at half the half-light radius. The number of cloulets \( N_{\text{cl}} \) is computed from

\[
N_{\text{cl}} = \frac{N}{(4/3)\pi R_{\text{cl}}^3 n_e},
\]

where \( N \) is the total number of electrons, \( n_e \) is the electron density, and \( R_{\text{cl}} \) is the radius of each cloudlet. The electron density can be obtained from the relation between the flux ratio \( [S \ {	ext{II}}] \lambda 6716/\lambda 6731 \) and the electron density (Osterbrock 1989).

This flux ratio is only sensitive to electron densities in the range \([10^2, 10^4]\) cm\(^{-3}\). Outside this range the flux ratio becomes constant as a function of \( n_e \). We obtain the flux ratio for 15 of the radio galaxies from Noel-Storr et al. (2003), six of which lead to upper and lower limits on the electron density. The value for \( n_e \) can be estimated as discussed in Osterbrock (1989) assuming case B recombination:

\[
N = \frac{L_{\text{H}\beta}}{n_e \alpha_{\text{eH}\beta} \lambda_{\text{H}\beta}},
\]

where \( \alpha_{\text{eH}\beta} \) is 3.03 \times 10\(^{-14}\) cm\(^{-3}\) is the recombination coefficient (assuming \( T = 10^4 \) K) and \( \lambda_{\text{H}\beta} \) and \( L_{\text{H}\beta} \) are the frequency and luminosity for H\( \beta \). We obtain \( L_{\text{H}\beta} \) from the central H\( \alpha \) + [N \( \text{II} \)] luminosity (Verdoes Kleijn et al. 2002) using the standard \( L_{\text{H}\alpha}/L_{\text{H}\beta} \) ratio of 3.1 and the [N \( \text{II} \)] \( \lambda 6548, 6584/H\beta \) flux ratio determined from our Gaussian line fits. This results in the following equation for the collision time:

\[
t_{\text{free}} \sim \frac{R_{\text{cl}}^3 n_e^2}{\sqrt{M_\ast L_{\text{H}\beta}}},
\]

This increases linearly with the radius of the cloudlets \( R_{\text{cl}} \). If we assume that \( R_{\text{cl}} \) is as large as 1/10 of the half-light radius, then the inferred \( t_{\text{free}} \) varies between \( 10^3 \) and \( 10^{13} \) yr, with a typical value of \( \sim 10^7–10^8 \) yr. Some of the huge scatter is most likely due to the simplicity of the estimate. But either way, it appears unlikely that the gas could remain in a collisionless state for a significant fraction of the Hubble time. Collisions lead to dissipation, loss of energy, and settling onto circular orbits. However, this is only true if there is no energy input into the gas. That may well be incorrect for most of the galaxies in our sample, given that 16 galaxies are FR I radio galaxies, and the remainder have nuclear radio emission. If there is energy input, then the gas can maintain an extended distribution for much longer than the timescale \( t_{\text{free}} \) calculated above. Even though collisions would occur, one might expect the system to evolve through a sequence of states that are all approximately collisionless. Therefore, it is reasonable to study the predictions of collisionless models for the nuclear gas in our sample galaxies.

A major uncertainty in the calculation of collisionless models is the phase-space distribution of the clouds, which is needed to compute the observed velocity dispersion along the line of sight. The phase-space distribution involves a spatial component such as a radial number density profile. We do not know this profile. We only know the flux distribution, which could be quite different. The phase-space distribution also requires knowledge about the nature of the cloud kinematics, for example, anisotropies in the velocity dispersion. These are also unknown. We therefore decided to explore the line-of-sight velocity dispersion (LOSVD) for a plausible range of phase-space distributions. We use the axisymmetric dynamical models presented in de Bruijne et al. (1996). We explore gas clouds with an axisymmetric...
power-law number density distribution with axis ratio \(q\) (i.e., \(\rho(R, z) = \rho_0 [R^2 + (z/q)^2]^{-\gamma/2}\)) in the Kepler potential caused by the BH. The gas clouds are assumed to have a constant velocity dispersion anisotropy \(\beta = 1 - (v_T^2 + v_z^2)/(2v_R^2)\) (i.e., the case II models in de Bruijne et al. [1996]; see Binney [1980], with \([r, \theta, \phi]\) the usual spherical coordinates). Thus, we have four free parameters: the number density scaling constant \(\rho_0\), the axis ratio \(q\), the power-law slope \(\gamma\) of the particle density profile, and the velocity dispersion anisotropy \(\beta\). These models require \(\gamma > \frac{1}{2} + \beta\) to be physical. De Bruijne et al. (1996) evaluated the expected velocity dispersions.

![Graph](image)

**Figure 5.** Ratio of the velocity dispersion for a collisionless spheroid divided by that of a thin disk with identical projected surface density profile, as a function of apparent axis ratio. The small dots indicate spheroid models with varying intrinsic axis ratios, power-law density slopes, and velocity dispersion anisotropies. The ratios of observed velocity dispersions and dispersions predicted by thin-disk models from Fig. 4 are overplotted. Symbols are as in Fig. 4.

We want to know how different the observed velocity dispersion for a spheroid can be compared to the dispersion for a thin disk, for a plausible range of free parameters. Thus, we determined the ratio \(R_{d,i}\) of the velocity dispersions for a spheroid and a thin disk that have the same projected surface density distribution and apparent axis ratio. The latter criterion fixes the ratio of the \(\rho_0\)-values for the two models and implies that \(R_{d,i}\) is independent of \(\rho_0\). We define \(R_{d,i}\) as the ratio of the line-of-sight dispersion weighted by the number density and integrated over an aperture that is typical for the observations. The result depends on power-law slope, axis ratio, and dispersion anisotropy. We explored the parameter ranges \(\gamma = [-1.5, -10], q = [0.1, 0.9],\) and \(\beta = [-\infty, 1]\), which should encompass all plausible models. Figure 5 shows \(R_{d,i}\) as a function of apparent axis ratio for the quoted parameter ranges. Regardless of the choice of parameters, the modeled spheroidal distributions have increased velocity dispersions in comparison to thin disks only for \(q \geq 0.7\) (corresponding to inclinations \(i \leq 45^\circ\) for a thin disk).

As also shown in Figure 4, the nonradio galaxies scatter around \(R_{d,i} = 1\), indicating that their dispersions are consistent with thin disks in circular rotation around BHs that follow the \(M_\ast-\sigma\) relation. By contrast, the radio galaxies have dispersion ratios \(R_{d,i}\) that are systematically larger than 1, and also larger than the \(R_{d,i}\) expected for collisionless spheroidal models. So it seems unlikely that a spheroidal distribution of collisionless gas clouds can account for the nuclear gas velocity dispersions in radio galaxies. We also explored the ratio of the velocity dispersions for an axisymmetric spheroid and a disk at the same inclination instead of the same apparent axis ratio.\(^7\) The reason is that the axis ratio of the gas distribution at the nucleus is not constrained very well by the observations and might deviate from the axis ratio of the larger scale disk. The resulting \(R_{d,i}\) range for spheroid models at a given inclination remains very similar. So this does not alter the conclusions inferred from Figures 4 and 5.

5. THE NONGRAVITATIONAL GAS DISPERSION COMPONENT

The analysis of thin disks and spheroidal models indicates that nongravitational forces might contribute significantly to the observed gas dispersion for radio galaxies. To constrain the minimal relative contribution of a nongravitational dispersion component we plot in Figure 6 (top) the ratio of the observed dispersion and the maximum dispersion predicted by either disk or spheroid models. The minimal ratio is typically between 1 and 2. There is a hint that the minimal ratio increases with axial ratio, i.e., for extended disks that are closer to face-on. This could indicate that the nongravitational dispersion component does not have a random orientation with respect to the extended disk but is oriented preferentially along the spin axis of the extended disk. We explore this idea with two simple models. The models consist

\[^\text{7}\] Note that in this case the disk and spheroid do not have an identical surface density distribution.
of two components: a thin circular rotating disk and a second component of nongravitational motion. We assume equal contribution to the emission light by the two components. In the isotropic model the nongravitational dispersion is isotropic ($\sigma_{\text{iso}}$), and the resulting total dispersion can be written as

$$\sigma_{\text{obs}}^2 = \sigma_{\text{grav}}^2 \sin^2 i + \sigma_{\text{iso}}^2 / 3,$$  \hfill (6)

where $\sigma_{\text{grav}}$ denotes the dispersion due to circular rotation as measured in the plane of the disk and $i$ is the disk inclination. In the perpendicular model the nongravitational dispersion is assumed to be perpendicular to the plane of the disk:

$$\sigma_{\text{obs}}^2 = \sigma_{\text{grav}}^2 \sin^2 i + \sigma_{\text{perp}}^2 \cos^2 i.$$  \hfill (7)

The middle and bottom panels of Figure 6 show the ratios $\sigma_{\text{iso}}/\sigma_{\text{grav}}$ and $\sigma_{\text{perp}}/\sigma_{\text{grav}}$ as functions of the disk axis ratio. The value of $\sigma_{\text{grav}}$ is calculated as before from the thin-disk models, and $\sigma_{\text{iso}}$ and $\sigma_{\text{perp}}$, respectively, are chosen so that $\sigma_{\text{obs}}$ matches the observed value $\sigma_{\phi}$. The perpendicular model shows no trend between the dispersion ratio and disk inclination. The isotropic model shows a weak trend. This would not be expected in an isotropic scenario. On the other hand, the trend in Figure 6 (middle) is dominated by a few galaxies and is not really significant. For some galaxies the implied nongravitational dispersion is larger than $\sqrt{2}\sigma_{\text{grav}}$. In other words, the typical nongravitational motions are larger than $\sqrt{2}$ times the typical circular rotation in those galaxies, which suggests that some of the material might be unbound. However, the models are too simplistic to attach real significance to this result.

The fact that radio galaxies show an excess gas dispersion, while it appears to be absent in nonradio galaxies, possibly points to a link between nongravitational motion and activity.

The AGN could be a source of energy to drive the nongravitational dispersion, e.g., by coherent flows or turbulence. We do not have a direct measure of the kinetic energy output of the AGN to determine its correlation with the amount of nongravitational dispersion present in the gas. Thus, we resort to measures of the radiative energy output of the active nuclei as a proxy. Figure 7 shows $R_{\alpha d}$ as a function of total radio power for both radio and nonradio galaxies. As expected, the difference in excess dispersion for nonradio and radio galaxies is also present as a function of radio luminosity. However, there is no clear indication that larger nongravitational motions occur in more powerful radio galaxies. We examined also the dependence of $R_{\alpha d}$ on radio core and nuclear emission-line luminosity for radio galaxies. No clear trends were found. Similarly, no trends were found between the ratios $\sigma_{\text{iso}}/\sigma_{\text{grav}}$ and $\sigma_{\text{perp}}/\sigma_{\text{grav}}$ with these three indicators of the radiative power of the active nucleus.

6. CAVEATS

Uncertainties in the flux profiles.—For three galaxies in our sample, NGC 3862, NGC 4374, and NGC 4486, we have both the STIS flux profiles and those derived from HST WFPC2 PC chip emission-line images that are available to us. The PC pixel size ($\sim 0.045$) better samples the HST PSF FWHM ($\sim 0.1$) compared to the STIS apertures. From the PC emission-line image, a narrower flux profile is inferred for NGC 3862 and NGC 4374, but a wider profile for NGC 4486, as compared to the flux profiles derived from the STIS data. Using the PC profiles in the thin-disk modeling leads to increases in predicted gas velocity dispersion of $\sim 5\%$, $\sim 50\%$, and $\sim 13\%$ for NGC 3862, NGC 4374, and NGC 4486, respectively. Assuming that similar changes could be expected for the other sample galaxies, this does not change our conclusions.

Another possibility to consider is that we might have systematically overestimated the width of the emission-line flux profiles. If the flux in reality originates closer to the nucleus than in our models, it would naturally explain why the predicted dispersions are lower than observed. Figure 8 shows the radius...
inside which half of the flux from the intrinsic (i.e., unconvolved) flux profile is contained as a function of distance. Figure 8 (top) shows the angular half-light radius. For half-light radii much less than the half-light radius of the HST PSF, i.e., ~0.05, it could well be that the intrinsic flux profile is in fact much narrower. Thus, the profile widths for NGC 2329, NGC 3862, and NGC 6251 should be considered upper limits. This implies that their predicted velocity dispersions should be considered lower limits, as emission-line gas might be rotating closer to the BH than in our models. However, there are two facts that argue against a general overestimate of the width of the flux profiles for all galaxies. First, we find no trend of narrower emission-line flux profiles with increasing dispersion ratios. Second, such a scenario cannot explain the correlation between disk inclination and dispersion ratio. A separate question is whether we are resolving the flux profile at larger distances, as well as nearby. This issue is relevant for comparing the properties of the radio galaxies and nonradio galaxies, since the former sample has a larger average distance. Figure 8 (bottom) suggests that this distance offset is not inducing the difference in excess dispersion, since there is no trend between the physical half-light radius and distance.

Finally, what kind of emission-line flux profile is needed to obtain the observed gas velocity dispersions gravitationally? To first approximation, \( \sigma_g \sim M_\bullet / R_{\text{flux}} \), where \( R_{\text{flux}} \) is the typical radius of the flux profile (e.g., the half-light radius). Figure 4 shows that for radio galaxies, \( R_{\text{flux}} \) needs to decrease by a factor of about 2 up to 100 to have a model with a BH mass according to the \( M_\bullet - \sigma \) relation to account for the observed gas dispersion. Figure 8 shows that the emission-line profile for radio galaxies typically has a half-light radius that is 2 times the radius of the PSF. In conclusion, the emission-line profile for radio galaxies needs to be fully unresolved in general to account for the observed gas velocity dispersion gravitationally. This is ruled out by the observations.

Uncertainties in the location of the BH.—The spatial flux distribution in the direction of the slit length allows us to precisely locate the nucleus along this direction (assuming it coincides with the peak of the emission-line flux; see § 2). But the nucleus was assumed to be at the center of the slit in the direction of the slit width. This is a reasonable assumption (see § 2). We determined that a 0.05 displacement in this direction changes the predicted velocity dispersion by <20% for the thin-disk models. This does not affect our conclusions.

Does the \( M_\bullet - \sigma \) relation underestimate BH masses?—One might account for the excess gas dispersion within the purely gravitational models, seen particularly for radio galaxies, by assuming that the BH mass from the \( M_\bullet - \sigma \) relation underestimates the true BH mass. However, this requires increases in BH masses that are too large to be credible for the following reasons. First, comparison of Figures 2 and 3 shows that detailed estimates of BH masses from gas rotation velocity modeling do not show any indication for BH masses that are systematically larger than those inferred from the \( M_\bullet - \sigma \) relation. (This is a somewhat circular argument, as some of the BH mass measurements from gas were used to determine the \( M_\bullet - \sigma \) relation. Nevertheless, such large BH masses would imply velocity gradients that are larger than observed.) Second, the trend of an increasing \( R_{\text{v,ef}} \) with decreasing disk inclination is not expected if the excess dispersion is due to underestimated BH masses. The dependence of BH mass on stellar dispersion is sometimes claimed to be steeper than used here (e.g., Ferrarese 2000). However, this amounts to at most ~50% larger BH masses, and such uncertainties do not affect our results on excess gas dispersions. Finally, it has been argued that \( M_\bullet \) correlates equally well with host luminosity as with \( \sigma \) (e.g., Marconi & Hunt 2003). This might mean that the \( M_\bullet - \sigma \) relation underestimates \( M_\bullet \) at the high-\( \sigma \) end. The reason is that brightest cluster galaxies (BCGs) fall in this region. BCGs are exceedingly luminous for their stellar dispersion, which is typically above 270 km s\(^{-1}\) (Fisher et al. 1995). If true, it is very unlikely that this will affect our results, because the galaxies in our sample with the largest excess in stellar dispersion compared to gravitational models all have stellar dispersions between 190 and 270 km s\(^{-1}\) (see Fig. 9).

Are thin-disk models plausible?—It was found that for most of the normal galaxies in our sample the nuclear gas dispersions are reasonably well fitted by thin-disk models containing BHs that follow the \( M_\bullet - \sigma \) relation. But the full emission-line shapes contain additional information on the LOSVD and can further constrain the plausibility of the models. We used the thin-disk models to calculate the full LOSVD for the normal galaxies in the sample. Inspection of the data shows a qualitative agreement between predicted and observed LOSVDs. A general property of the LOSVD of thin-disk models is a tendency to be double peaked. In some cases the predicted double-peakness seems slightly too pronounced to be consistent with the data. But it is possible that the predicted peaks have in reality been broadened away by additional velocity dispersion contributions. For example, the gas could be collisionless but orbit in a somewhat more three-dimensional distribution than a disk (as in the models of § 4), or it could have a small additional nongravitational contribution (as in the models of § 5). Overall, the signal-to-noise ratio of the data and the blending of the H\( \alpha \) + [N ii] lines make it difficult to draw strong conclusions from the observed line shapes.

Could an unaccounted-for broad H\( \alpha \) component in radio galaxies influence our results?—The flux from which the velocity dispersions are measured is usually dominated by the flux from the forbidden [N ii] and [S ii] lines, especially the [N ii] \( \lambda 6584 \) line, and not the H\( \alpha \) line. Furthermore, we made sure to correct for the presence of broad H\( \alpha \) if it was clearly detected. This broad component is likely arising from a broad-line region.
located much closer to the nucleus than the narrow component that we model here. Noel-Storr et al. (2003) found tentative indications that a broad line, not readily seen by eye, could be present in eight of the radio galaxies in our sample (Table 1). In these cases they performed fits to the Hα + [N ii], [S ii] complex assuming the permitted Hα line to have both a narrow and a broad component. We redid the thin-disk modeling for these eight galaxies taking into account the tentative broad component in measuring the velocity dispersion and emission-line profile of the narrow component. This resulted in decreases of $R_{e, p}$ by at most 20% and a median decrease of 9%. Thus, these eight galaxies do not change the overall results obtained together with the other radio galaxies. Finally, the dispersion in the extended disk is in many radio galaxies above that expected from instrumental effects and differential rotation over the aperture (e.g., Noel-Storr et al. 2003). This strengthens the idea that the excess dispersions are not due to a nuclear broad line region.

Gaussian fit versus true second velocity moment.—For the thin-disk models we compared the predicted second moment of a Gaussian fit of the full LOSVD to the observed Gaussian fit. By contrast, in the analysis of more spheroidal distributions, $R_{e, p}$ is the ratio of the true second moments. Thus, we assume that the ratio of the true second moments and the ratio of the Gaussian-fit moments do not differ significantly. It is not straightforward to test this assumption quantitatively, since the line profiles are not straightforward to calculate for the spheroidal models. However, we believe that the errors thus introduced are unlikely to exceed several tens of percent (van der Marel & Franx 1993). This is insufficient to affect any of our conclusions. Also, it seems unlikely that a difference in these ratios would affect our main result that there is a systematic difference in nuclear dispersions between radio and nonradio galaxies.

Dependence of the stellar dispersion on inclination.—In our models we have assumed that the BH mass is uniquely determined by the stellar velocity dispersion. However, this can only be approximately true in reality. There must be some intrinsic scatter in the $M$–$\sigma$ relation, if only because the observed velocity dispersion of a galaxy generally depends on the inclination under which the galaxy is viewed, whereas the BH mass does not. This could be important in the context of our results. The four galaxies for which thin-disk models fit the observed gas dispersions most poorly have below-average inclinations, in addition to being radio galaxies (see Fig. 3). It is therefore important to study the relation between stellar velocity dispersion and inclination in some more detail.

To support its shape, an oblate stellar system must on average have more pressure ($\rho\sigma^2$) parallel to the equatorial plane [$\rho\sigma^2 \equiv \rho(v_x^2 + v_z^2)/2$] than perpendicular to it ($\rho\sigma^2 \equiv \rho(v_x^2)\equiv \rho\sigma^2_0$). Therefore, it will generally have a lower LOSVD when viewed face-on than when viewed edge-on. The tensor virial theorem (Binney & Tremaine 1987) gives the ratio of the pressures when integrated over the entire galaxy as

$$\left(\frac{\sigma_0}{\sigma_\perp}\right)^2 = \frac{1}{2} \frac{1}{1 - 1 - \varepsilon^2} \left(\frac{\arcsin e/e}{\arcsin e/e}\right) - 1,$$

where $q_i$ is the intrinsic axial ratio. For example, this gives $\sigma_0/\sigma_\perp \approx 1$ for a spherical galaxy and $\sigma_0/\sigma_\perp \approx 1.34$ for a galaxy with $q = 0.5$. If one were to observe a galaxy with an aperture of infinite size, and if the galaxy had $v_x^2 = v_{\phi}^2$ at all positions in the galaxy, then the ratio of the measured dispersion when viewed edge-on and face-on, respectively, would be equal to $\sigma_0/\sigma_\perp$. However, these requirements are not generally met for real galaxies and real observations. There is no reason why galaxies should have $v_x^2/v_{\phi}^2 = 1$, and observational constraints on this ratio remain scarce (e.g., Gebhardt et al. 2003). Also, velocity dispersion measurements are generally restricted to the central region of the galaxy and/or a specific axis (most often the major axis) and are not integrated over the entire galaxy. So the true dependence of the observed stellar velocity dispersion on the inclination angle can only be addressed with detailed three-integral stellar dynamical models (e.g., Gebhardt et al. 2003; Cappellari et al. 2006), which are outside the scope of the present work. Nonetheless, the tensor virial theorem does provide useful order-of-magnitude guidance. Almost all elliptical galaxies have axial ratios $q > 0.5$ (Franx et al. 1991; Tremblay & Merritt 1995). Therefore, one might expect that inclination effects cause a variation of order $\pm 15\% (\pm 0.06$ dex) in the observed velocity dispersion of galaxies of otherwise identical properties.

An alternative way to constrain the inclination dependence of the velocity dispersion is through the scatter in several well-known relations. The velocity dispersions correlate strongly with galaxy luminosity (the Faber-Jackson relation; e.g., Dressler et al. 1987), with BH mass (the $M_\bullet$–$\sigma$ relation), and with galaxy mass-to-light ratio $M/L$ (Cappellari et al. 2006). None of the latter quantities depends on the viewing angle of the observations, while the velocity dispersion does. Therefore, the observed scatter in these relations sets an upper limit to the rms variation that the inclination might induce in the observed velocity dispersion. The limits are $0.25/3.50 = 0.072$ dex from the Faber-Jackson relation (Dressler et al. 1987), $0.30/0.42 = 0.075$ dex from the $M_\bullet$–$\sigma$ relation (Tremaine et al. 2002), and $0.07/0.82 \approx 0.083$ dex from the relation with $M/L$ (Cappellari et al. 2006). These results are all in reasonable agreement with the expectations from the virial theorem (despite the fact that each of these relations is likely to have other sources of intrinsic scatter as well). Finally, direct estimates of the dispersion anisotropy in giant elliptical galaxies from detailed three-integral stellar dynamical models indicate a change of $\sim 0.05$ dex in stellar dispersion for face-on and edge-on viewing angles (Cappellari et al. 2005). Given that rotational velocities contribute typically less than 10% to the second moment of giant elliptical galaxies, this lends further support to the estimates based on global relations for the dependence of the stellar dispersion on inclination.

To obtain more specific information for the actual galaxies in our sample, we plot their Faber-Jackson relation in Figure 9. The four galaxies with dust/gas disk inclinations $i < 40^\circ$ are indicated with special symbols. If the disks reside in the equatorial plane of the galaxies, then the disk inclinations are identical to the galaxy inclinations. One would then expect the galaxies with $i < 40^\circ$ to have relatively low stellar velocity dispersions for their luminosity. This is exactly what the figure shows. The galaxies with $i < 40^\circ$ seem to lie $\sim 17\% (0.079$ dex) below the average relation between galaxy magnitude and stellar dispersion. This agrees to lowest order with the expectation from the tensor virial theorem and the scatter in well-known correlations.
the $i < 40^\circ$ galaxies in, e.g., Figure 3 somewhat reduces the discrepancy between the observed and predicted gas dispersions for these galaxies. Nonetheless, for all four of the galaxies the observed gas dispersions remain well in excess over those predicted by the thin-disk models. So our conclusion that radio galaxies have a contribution from nongravitational motions in their central gas dynamics remains unaffected.

7. CONCLUSIONS AND DISCUSSION

We have analyzed HST STIS observations of a sample of 27 galaxies. The nuclear velocity dispersion of the gas in a STIS aperture of $\sim0.1^\prime$–$0.2^\prime$ (i.e., scales of tens of parsecs) generally exceeds the large-scale stellar velocity dispersion of the galaxy. This is qualitatively consistent with the presence of central BHs but raises the questions of whether the excess gas dispersion is of gravitational or nongravitational origin and whether the implied BH masses are consistent with our current understanding of BH demography. To address these issues we have constructed purely gravitational axisymmetric dynamical models for the gas, both thin-disk models and models with more general axis ratios and velocity anisotropies. This has yielded the following conclusions:

1. For the normal galaxies in the sample (i.e., without large-scale radio jets) the nuclear gas dispersions are adequately reproduced by models that have purely gravitational motion and BHs that follow the $M_\bullet$–$\sigma$ relation. Among the purely gravitational models we cannot generally discriminate between thin-disk models and vertically extended models. The former might seem preferred theoretically because they represent a longer term equilibrium configuration for the gas. However, in some cases it is unclear if the observed line profiles are consistent with the double-peaked structure that is generally predicted by thin-disk models.

2. The nuclear gas dispersions observed for the radio galaxies generally exceed those predicted by models with only gravitational motions in either a thin disk or a more spheroidal gas distribution. We attribute this to the presence of nongravitational motions in the gas that are similar to or larger than the gravitational motions. The nongravitational dispersion is consistent with being either isotropic or perpendicular to the extended gas and dust disks. The nongravitational motions are presumably driven by the active galactic nucleus (AGN), but we do not find a relation between the radiative output of the AGN and the nongravitational dispersion.

3. Given the uncertainties about the dynamical state of the gas, it is not possible to uniquely determine the BH mass for each galaxy from its nuclear gas dispersion. However, for the sample as a whole the observed dispersions do not provide evidence for significant deviations from the $M_\bullet$–$\sigma$ relation in either active or nonactive elliptical galaxies. In no case is the observed nuclear gas dispersion so low that it puts an upper limit on the BH mass that is significantly below the $M_\bullet$–$\sigma$ relation.

For the normal, i.e., nonradio, galaxies one should note that the success of purely gravitational models does not imply that there are no alternative models that can fit the data. For example, it cannot be ruled out that in reality there is a nongravitational component to the gas motions, and that the BH masses in these galaxies are below the $M$–$\sigma$ relation. Some models in the literature, such as those published for IC 1459 (Cappellari et al. 2002), fall in this category. Nevertheless, if one is willing to assume a priori that the BH masses of all elliptical galaxies follow the $M_\bullet$–$\sigma$ relation, then one can turn the argument around and conclude that normal elliptical galaxies do not have a very significant nongravitational component in their gas motions. The absence of excess dispersion in nonradio galaxies is corroborated by the fact that the BH mass estimates for this sample by itself yield a relation in good agreement with the $M_\bullet$–$\sigma$ relation (e.g., Fig. 3). It is interesting to note in this context that a similarly good correspondence between BH masses from gas dispersions and from the $M_\bullet$–$\sigma$ relation was found for nonactive early-type spiral galaxies by Sarzi et al. (2002).

For the low-luminosity radio galaxies in our sample there is also other evidence, besides the dynamical evidence presented here, for nonflat gas distributions with turbulent motion. The core emission-line luminosity of these galaxies correlates with the radio and optical core luminosity, which are both most likely due to synchrotron emission from the jet (e.g., Chiaberge et al. 1999; Verdoes Kleijn et al. 2002). This correlation could mean that the emission-line luminosity is driven by jet photoionization. It then implies covering factors of $\sim0.3$ and, hence, thick disks (Capetti et al. 2005). Alternatively, the correlation could indicate that the gas is excited by shocks induced by jet–gas interactions.

Although it is mostly the radio galaxies that show significant excess dispersion over a purely gravitational model, there is one normal galaxy for which this is the case too: IC 989. It should be noted, however, that for this particular galaxy the error of 33 km s$^{-1}$ on the stellar dispersion, $\sigma_s = 176 \pm 17$ km s$^{-1}$, is larger than typical for the sample. The predicted gas dispersion can be increased by a factor of $\sim4$ by simply varying $\sigma_s$ within its 1 $\sigma$ confidence range. Also, the predicted gas dispersion could go up by up to a factor of $\sim2$ if the unknown inclination of the purported gas disk is closer to edge-on than the default value of 60$^\circ$ that we assumed. So the evidence for nongravitational gas motions in the normal galaxy IC 989 is not strong.

Finally, we note that it is the sample of relatively close to face-on ($i < 40^\circ$) gas disks that reveal most clearly an excess dispersion compared to a purely gravitational model. Unfortunately, this face-on group only contains radio galaxies. However, a statistically significant difference between the excess dispersion in radio and nonradio galaxies remains when one excludes galaxies with $i < 40^\circ$ gas disks from the analysis. Nevertheless, a good test of the dichotomy found in this paper will be the modeling of gas disks at lower inclinations also in nonradio galaxies. Such data are not available currently.

The evidence for nongravitational gas motions in radio galaxies makes the gas dispersion unsuit for dynamical mass estimates in this class of galaxies. It would be interesting to establish more generally whether dynamical mass estimates from gas velocities, including rotation curves, are robust. This would require comparisons of BH masses from independent indicators (e.g., stellar and gas kinematics) within the same galaxy. Such a comparison has been performed for a radio galaxy (NGC 4335; Verdoes Kleijn et al. 2002) and a nonradio galaxy (Cappellari et al. 2002). Unfortunately, in both cases the stellar dynamical evidence is too inconclusive to reach firm conclusions. But it does appear in both cases that the BH mass implied by thin-disk models for the gas rotation curves is lower than would otherwise have been expected, either from stellar kinematics or from the $M_\bullet$–$\sigma$ relation. This suggests that the gas might be moving slower than the circular velocity, as would be expected, for example, if there were asymmetric drift in the gas. This occurs for gas distributions that are dynamically hotter than a thin disk. More independent BH mass evaluations from gas and other tracers, for both normal and active galaxies, would be quite valuable to shed more light on these issues.
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