GAS KINEMATICS AND THE BLACK HOLE MASS AT THE CENTER OF THE RADIO GALAXY NGC 4335

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ABSTRACT

We investigate the kinematics of the central gas disk of the radio-loud elliptical galaxy NGC 4335, derived from Hubble Space Telescope (HST) long-slit spectroscopic observations of Hα + [N II] along three parallel slit positions. The observed mean velocities are consistent with a rotating thin disk. We model the gas disk in the customary way, taking into account the combined potential of the galaxy and a putative black hole with mass $M_\bullet$, as well as the influence on the observed kinematics of the point-spread function and finite slit width. This sets a $3 \sigma$ upper limit of $10^8 M_\odot$ on $M_\bullet$. The velocity dispersion at $r \lesssim 0.5$ is in excess of that predicted by the thin rotating disk model. This does not invalidate the model if the excess dispersion is caused by localized turbulent motion in addition to bulk circular rotation. However, if instead the dispersion is caused by the black hole (BH) potential then the thin disk model provides an underestimate of $M_\bullet$. A BH mass $M_\bullet \sim 6 \times 10^8 M_\odot$ is inferred by modeling the central gas dispersion as due to an isotropic spherical distribution of collisionless gas clouds. The stellar kinematics for NGC 4335 are derived from a ground-based (William Herschel Telescope/ISIS) long-slit observation along the galaxy major axis. A two-integral model of the stellar dynamics yields $M_\bullet \gtrsim 3 \times 10^9 M_\odot$. However, there is reason to believe that this model overestimates $M_\bullet$. Reported correlations between black hole mass and inner stellar velocity dispersion $\sigma$ predict $M_\bullet$ to be $\geq 5.4 \times 10^8 M_\odot$ in NGC 4335. If our standard thin disk modeling of the gas kinematics is valid, then NGC 4335 has an unusually low $M_\bullet$ for its velocity dispersion. If, on the other hand, this approach is flawed and provides an underestimate of $M_\bullet$, then black hole masses for other galaxies derived from HST gas kinematics with the same assumptions should be treated with caution. In general, a precise determination of the $M_\bullet-\sigma$ relation and its scatter will benefit from (1) joint measurements of $M_\bullet$ from gas and stellar kinematics in the same galaxies and (2) a better understanding of the physical origin of the excess velocity dispersion commonly observed in nuclear gas disks of elliptical galaxies.

Key words: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 4335) — galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: structure

1. INTRODUCTION

The Hubble Space Telescope (HST) has made it possible to measure the masses of black holes (BHs) in the centers of many nearby active and quiescent galaxies by using stellar and/or gaseous kinematics (for reviews see, e.g., Richstone et al. 1998; van der Marel 1999; Ho 1999; de Zeeuw 2001; Kormendy & Gebhardt 2001). To date, BH masses have been measured in about 40 galaxies, both spirals and ellipticals, and this number continues to increase. The BH masses correlate loosely with host spheroid luminosity (Kormendy & Richstone 1995) and more tightly with inner stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2001). A drawback of this approach is that the gas kinematics might be affected by nongravitational motions. Nevertheless, using the gas kinematics to determine accurate BH masses is an efficient way to determine the central gravitational potential and BH mass (e.g., Harms et al. 1994; Ferrarese, Ford, & Jaffe 1996; Macchetto et al. 1997; van der Marel & van den Bosch 1998; Ferrarese & Ford 1999; Verdoes Kleijn et al. 2000, hereafter VK00; Sarzi et al. 2001; Barth et al. 2001). A better understanding of the physical origin of the excess velocity dispersion commonly observed in nuclear gas disks of elliptical galaxies.

Emission lines are generally much larger than those of the absorption lines in the integrated stellar light, so that measurement of the kinematics of nuclear emission-line gas is an efficient way to determine the central gravitational potential and BH mass (e.g., Harms et al. 1994; Ferrarese, Ford, & Jaffe 1996; Macchetto et al. 1997; van der Marel & van den Bosch 1998; Ferrarese & Ford 1999; Verdoes Kleijn et al. 2000, hereafter VK00; Sarzi et al. 2001; Barth et al. 2001). A more precise determination of the mass-velocity dispersion relation and its scatter will benefit from (1) joint measurements of BH mass from gas and stellar kinematics in the same galaxies and (2) a better understanding of the physical origin of the excess velocity dispersion commonly observed in nuclear gas disks of elliptical galaxies.

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at multiple wavelengths. In particular, we have performed a Space Telescope Imaging System (STIS) spectroscopic survey of the inner gas distributions to measure the kinematics and the physical state of the gas (Noel-Storr et al. 2001).

Here we concentrate on one galaxy from our sample, NGC 4335, which is a relatively unknown isolated giant elliptical (MB = −20.7 mag; Paturel et al. 1997) at 66 Mpc. The gas appears embedded in a well-defined dust disk (diameter ~750 pc) and gas kinematics can be traced sufficiently far out along the three slits to allow detailed gas dynamical modeling. In addition we perform stellar dynamical modeling for NGC 4335 by using the stellar kinematics derived from a William Herschel Telescope (WHT) ISIS long-slit observation.

The paper layout is as follows. Sections 2 and 3 present HST Wide Field Planetary Camera 2 (WFPC2) broad- and narrowband imaging, HST STIS gas emission-line spectroscopy and ground-based WHT ISIS stellar absorption-line spectroscopy, including the basic data reduction and derivation of the gaseous and stellar kinematics. Section 4 describes the modeling of the gas disk flux distribution, the derivation of the stellar mass distribution, and the fits to the observed gaseous kinematics to estimate the BH mass. Section 5 describes two-integral modeling of the WHT stellar kinematics to determine the stellar mass-to-light ratio and to constrain the BH mass independently. Section 6 discusses the implications of the BH mass measurements in NGC 4335 for our understanding of BH demography and for the techniques used to measure black hole masses.

We adopt H0 = 70 km s⁻¹ Mpc⁻¹ throughout this paper. This does not directly influence the data-model comparison for any of our models, but it does set the length, mass and luminosity scales of the models in physical units. Specifically, distances, lengths, and masses scale as H₀⁻¹, while mass-to-light ratios scale as H₀⁰.

## 2. IMAGING

### 2.1. WFPC2 Setup and Data Reduction

We imaged NGC 4335 in the context of HST program GO-6673. We used the WFPC2 instrument (described in, e.g., Trauger 1994; Biretta et al. 1996) on 1997 March 15 to obtain images of NGC 4335 in the F555W (V) and F814W (I) filters and linear ramp filter FR680N, which includes Hα + [N ii]. The observing log is presented in Table 1. The Linear Ramp Filters (LRFs) of the WFPC2 have a central wavelength that varies as a function of position on the detector. The LRF FR680N image (WF CCD) was used as an “on-band” image, with the galaxy position chosen so as to center the filter transmission on the Hα + [N ii] emission lines. A combination of the broadband images F555W and F814W (PC CCDs) was chosen as an “off-band” image and covers primarily stellar continuum. This combination of filters ensures that the effect of dust extinction is the same in the on- and off-band image. The final Hα + [N ii] emission image was obtained by subtracting the stellar continuum, as determined by the off-band image, from the on-band image. The quality of the Hα + [N ii] image is set by the Poisson noise of input images and the uncertainty in the alignment and scaling of the on-band image and off-band image. The stellar surface brightness is steeply rising at the center of NGC 4335. The resulting emission image depends quite sensitively on precise subpixel alignment and scaling. This introduces a ~15% flux error, which is estimated by varying the alignment and scaling within a reasonable range. The V-band and Hα + [N ii] images are shown in Figure 1. Extended Hα + [N ii] emission is present with a roughly elliptical morphology, elongated in the same direction as the dust disk. As described in Section 4.1, the emission-line gas is consistent with being contained in a thin disk, but the uncertainties involved in constructing the image are too large to prove this conclusively. We cannot rule out a more spheroidal distribution, especially toward the nucleus. These data were presented previously in VK99, who also give a more detailed description of the data reduction.

### 2.2. Dust Disk

The central dust detected in NGC 4335 extends to more than 2 kpc from the nucleus. In the outer regions “arms” of dust gradually align with the well-defined central dust disk, which appears as roughly half an ellipse on the west side of the nucleus (see Fig. 1). This is commonly seen in galaxies with inclined nuclear dust disks (e.g., NGC 7052, van der Marel & van den Bosch 1998; NGC 6251, Ferrarese & Ford 1999; 3C 449, Martel et al. 1999). On the east side no dust obscuration is evident in either the V- or I-band image, and its V−I color is typical for dust-free giant elliptical galaxies. We conclude that the eastern half of the dust disk produces negligible obscuration in the optical.

We fitted by eye an elliptical contour to the outline of the dust disk in the V-band image and measured the position angle of the major axis of the dust disk to be P.A. = 156°. This is well aligned with the galaxy major axis just outside the dust disk (see Fig. 1 and VK99). If we assume that the dust disk is thin and intrinsically circular, then the inclination is i = 66° ± 7° (VK99).

The total mass of the kiloparsec-scale dust distribution estimated using the observed color excess is ~5.8 × 10⁵ M☉ if the dust resides in the midplane of the galaxy (VK99). Following the prescription by Goudfrooij & de Jong (1995), the IRAS 60 and 100 μm flux measurements for NGC 4335 from Knapp et al. (1989) indicate a dust mass 2.2 × 10⁶ M☉. This is not inconsistent with the aforementioned result, given that the IRAS measurements cover a much larger area than that occupied by the nuclear dust disk studied with HST. Furthermore, dust mass estimates using color excess are not sensitive to a smoothly distributed dust component, if present (see, for example, Tran et al. 2001).

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| Filter       | λ₀ (Å) | Δλ (Å) | Texp (s) |
|--------------|-------|-------|---------|
| F555W........ | 5473  | 1225  | 460     |
| F814W........ | 8000  | 1459  | 460     |
| LRF............. | 6664  | 83    | 3600    |

Note.—Col. (1): Filter name; cols. (2)-(3): central wavelength of the filter and the FWHM; col. (4): total exposure time, which for the broadband filters and the LRF was divided into two and three back-to-back exposures, respectively.
3. SPECTROSCOPY

3.1. HST STIS Gas Emission-Line Spectroscopy

In the context of GO program 8236, we used STIS (see Kimble et al. 1998) on 1999 September 22 to obtain long-slit spectra of NGC 4335 during two orbits of the HST telescope. We obtained spectra along three adjacent slit positions using a 0°2-wide slit (52/C20.2). The layout of the slits is shown in Figure 1. The G750M grating was used in combination with two-pixel spatial and spectral on-chip rebinning (to obtain a high enough signal-to-noise ratio [S/N] while retaining sufficient spatial and spectral resolution), yielding spectra covering the wavelength range from 6436 to 7100 Å over 511 pixels. Wavelength calibration spectra of the internal arc lamp were obtained at the beginning of the first orbit and at the conclusion of the second orbit.

The slits were aligned along P.A. = 32°44'. This is almost parallel (ΔP.A. = 8°44') to the galaxy major axis (P.A. = 156°). We denote the central slit by C and the adjacent slits on the east and west side by E and W, respectively.

A log of the observations is provided in Table 2. Target acquisition uncertainties and other possible systematic effects could cause the slit positions on the galaxy to differ slightly from those commanded to the telescope. We determined the actual slit positions from the data themselves, using the STIS continuum and emission-line fluxes and the WFPC2 images. We compared the continuum counts as a function of position along the slit for the three STIS slits with the counts in the WFPC2 V and I images at these positions. The STIS continuum was determined blueward of [Sl ii] and redward of [S ii], respectively. This analysis indicates that the positioning errors for the STIS slits with respect to the WFPC2 image are less than 0°05 in both the direction along and perpendicular to the slit. Another estimate of the positioning of the slits with respect to the galaxy nucleus was obtained by interpolation of the central few Hα + [N ii] fluxes, assuming the maximum flux occurs at the galaxy nucleus. This analysis implies that the central slit was properly centered on the nucleus to an accuracy of 0°01. The small slews performed by the telescope between observations to dither the slits and observe the adjacent slits have a nominal positioning error of 0°003.

Most of the necessary data reduction steps were performed by the HST STIS calibration pipeline (CALSTIS version 2.3), including flat-fielding, hot pixel and cosmic-ray removal, absolute sensitivity calibration, and wavelength calibration, which takes into account the Earth’s motion. To facilitate hot pixel and cosmic-ray removal two exposures were taken at each slit position, dithered by 2 pixels in the direction along the slit. The uncertainty in the relative wavelength accuracy is ~0.1 Å or ~5 km s⁻¹ (Diaz-Miller & Goudfrooij 2001).

3.2. Gas Kinematics and Fluxes

The spectra show several emission lines, of which the Hα + [N ii] complex at 6548, 6563, and 6583 Å has sufficiently high S/N for a kinematical analysis. The [S ii]
doublet at 6716 and 6731 Å can be fitted only in the central ~0\degree 2 in the central slit and at a lower S/N. The results for these few points are consistent with the Hα + [N ii] kinematics described below. To quantify the Hα + [N ii] gas kinematics we fitted the spectra, assuming that each emission line is a Gaussian on top of a flat continuum. This yields for each line the total flux, the mean velocity $V$, and the velocity dispersion $\sigma$. We fitted the [N ii] doublet under the assumption that the individual lines have the same $V$ and $\sigma$ and that the ratio of their fluxes equals the ratio of their transition probabilities (i.e., 3; see references in Mendoza 1983). The Hα + [N ii] complex is influenced by blending of the lines, and we made the additional assumptions that Hα and the [N ii] doublet have the same kinematics.

We did the Gaussian fitting using software described in van der Marel & van den Bosch (1998). Prior to the emission-line fit the spectra were rebinned along the slit where necessary to obtain sufficient S/N, hence sufficiently small errors on the gas kinematics (Table 3), to discriminate between the black hole masses in dynamical models discussed in § 4.3 and later. The same Gaussian fitting was performed on modeled emission-line spectra that resulted from the dynamical models. Differences between the velocity profiles (VPs) and the single-Gaussian fits are discussed in § 4.3. The Gaussian fits to the emission lines are shown in Figure 2.

The resulting kinematics are shown in Figure 3 and tabulated in Table 3. The systemic velocity used in Figure 3 and Table 3 was estimated from the HST data themselves, by including it as a free parameter in the dynamical models described below (see § 4.3). This yields $v_{\text{sys}} = 4620 \pm 13$ km s$^{-1}$. This result is consistent with $v_{\text{sys}} = 4615 \pm 22$ km s$^{-1}$ by Huchra et al. (1983) and $v_{\text{sys}} = 4595 \pm 47$ km s$^{-1}$ from the RC3 catalog (de Vaucouleurs et al. 1991).

The mean velocity profiles are smooth functions of position and are indicative of a rotating circular disk of emission

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### TABLE 3

| Slit and Rebin | $x$ (arcsec) | $y$ (arcsec) | $V$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $\Delta \sigma$ (km s$^{-1}$) |
|---------------|-------------|-------------|-----------------|------------------|-----------------|------------------|
| E:            |             |             |                 |                  |                 |                  |
| 2             | 0.347       | -0.254      | 101.00          | 9.68             | 115.71          | 9.44             |
| 1             | 0.196       | -0.232      | 57.01           | 9.58             | 84.86           | 9.34             |
| 1             | 0.096       | -0.217      | 38.39           | 5.65             | 76.64           | 5.62             |
| 1             | -0.005      | -0.202      | -2.00           | 5.48             | 80.75           | 5.47             |
| 1             | -0.105      | -0.187      | -65.27          | 5.88             | 96.18           | 6.03             |
| 1             | -0.205      | -0.171      | -105.18         | 6.50             | 112.63          | 6.26             |
| 2             | -0.356      | -0.149      | -126.46         | 8.49             | 141.02          | 7.98             |
| 2             | -0.556      | -0.119      | -292.72         | 4.77             | 53.30           | 4.62             |
| C:            |             |             |                 |                  |                 |                  |
| 3             | 1.128       | -0.169      | 320.72          | 6.12             | 77.20           | 6.19             |
| 3             | 0.828       | -0.124      | 292.35          | 4.25             | 57.35           | 4.17             |
| 2             | 0.577       | -0.086      | 284.91          | 5.49             | 55.16           | 5.44             |
| 2             | 0.376       | -0.056      | 197.42          | 12.06            | 165.72          | 11.49            |
| 1             | 0.226       | -0.034      | 142.31          | 8.88             | 145.00          | 8.72             |
| 1             | 0.125       | -0.019      | 64.90           | 4.78             | 197.58          | 4.39             |
| 1             | 0.025       | -0.004      | 15.66           | 3.55             | 240.79          | 2.98             |
| 1             | -0.075      | 0.011       | -49.96          | 4.06             | 231.24          | 3.32             |
| 1             | -0.175      | 0.026       | -89.63          | 5.59             | 142.48          | 5.62             |
| 2             | -0.326      | 0.049       | -155.09         | 8.40             | 146.89          | 8.24             |
| W:            |             |             |                 |                  |                 |                  |
| 3             | 1.459       | -0.016      | 364.75          | 3.23             | 49.70           | 3.14             |
| 3             | 1.158       | 0.029       | 354.71          | 6.85             | 82.90           | 6.86             |
| 3             | 0.857       | 0.074       | 310.68          | 5.85             | 92.86           | 5.61             |
| 2             | 0.606       | 0.111       | 315.11          | 5.76             | 87.42           | 5.92             |
| 2             | 0.406       | 0.141       | 312.75          | 5.11             | 92.93           | 5.06             |
| 1             | 0.255       | 0.164       | 209.58          | 11.82            | 147.67          | 11.28            |
| 1             | 0.155       | 0.179       | 105.15          | 8.92             | 179.87          | 8.15             |
| 1             | 0.055       | 0.194       | 28.02           | 5.92             | 163.13          | 5.79             |
| 1             | -0.046      | 0.209       | -12.79          | 6.30             | 159.55          | 6.17             |
| 1             | -0.146      | 0.224       | -68.63          | 8.27             | 128.64          | 8.32             |
| 2             | -0.296      | 0.247       | -120.31         | 5.39             | 87.64           | 5.36             |
| 2             | -0.497      | 0.277       | -155.89         | 9.89             | 113.07          | 9.61             |

**Note.** Kinematics of the Hα + [N ii] emission lines inferred from STIS spectra of NGC 4335 through three parallel slits of 0\degree 197 width. Col. (1): Slit label (see § 3.1 for definition) and number of rebinned pixels of size 0\degree 197 × 0\degree 01042; cols. (2)–(3): position of the aperture center with respect to the major axis (i.e., x-axis) and minor axis (i.e., y-axis). The uncertainties in these positions are ~0\degree 01. The zero point is at the galaxy nucleus; positive x-values lie in the direction of P.A. = 156°. Cols. (4)–(7): Mean gas velocity $V$ and velocity dispersion $\sigma$ and formal random errors as determined from single Gaussian fits to the emission lines.
The rotating disk picture is further supported by the fact that the mean velocities on the minor axis are close to 0 km s\(^{-1}\) in all three slits. The velocity dispersion profiles in all three slits show irregularities. We verified that this result does not depend sensitively on chosen region to fit the continuum and masked deviant pixels during the fit. The velocity dispersion peaks at \(240 \text{ km s}^{-1}\) at the nucleus in the central slit C. In slit W the dispersion peaks near the nucleus. However, in slit E the dispersion actually dips at the position closest to the nucleus. It seems therefore that the kinematics of NGC 4335 are consistent with a rotating gas disk, but with additional turbulent motion.

We also performed single-Gaussian fits to H\(\alpha\) and the [N\(\text{ii}\)] doublet independently. The two resulting flux profiles have very similar shapes. The mean velocities for the two sets of emission lines are very similar as well. The median difference between the mean velocities of the two components is \(20 \text{ km s}^{-1}\). This is slightly larger than the typical formal errors given in Table 3. These formal errors are derived by propagating the spectral flux errors. We will assume 20 km s\(^{-1}\) as a more realistic error estimate for the H\(\alpha\) + [N\(\text{ii}\)] mean velocities. The H\(\alpha\) and [N\(\text{ii}\)] velocity dispersion profiles show very similar behavior, but H\(\alpha\) has systematically lower velocity dispersions by about \(20–70 \text{ km s}^{-1}\). The differences in dispersion could be caused by the fact that (1) the H\(\alpha\) and [N\(\text{ii}\)] have intrinsically different kinematics or (2) the H\(\alpha\) kinematic measurements are affected by stellar H\(\alpha\) absorption. A similar effect of the same magnitude is seen for the gas disk in the S0 galaxy NGC 3245 (Barth et al. 2001).

3.3. WHT ISIS Stellar Absorption-Line Spectroscopy

A long-slit stellar absorption spectrum at P.A. = 148° (i.e., within 10° from the major axis of NGC 4335) was obtained in service mode with the ISIS (blue arm) spec-
trograph on the 4.2 m William Herschel Telescope (WHT) on La Palma on 2001 June 13. A slit width of 1
c0 was used with the R300B grating and the EEV12 CCD detector. The dispersion is 0.86 A pixel
1, and the spatial scale is 0.19 pixel
1. The observed wavelength range was 3430–6900 A. The observations included two
1800 s exposures of NGC 4335, a 60 s exposure of the B2 IVp star BD +33 2642 to facilitate flux calibration,
and standard calibration exposures. The instrumental velocity dispersion \( \sigma_{\text{ins}} \approx 75 \text{ km} \text{s}^{-1} \) was determined from
sky lines and the emission-line widths in the calibration lamp spectra. Both the star and galaxy spectra were
observed with a seeing of FWHM \( \sim 1'' \).

The data reduction was performed in IRAF using the CCDPROC (Version Dec93) and TWODSPEC packages.
The basic data reduction steps include bias subtraction, flat-fielding with dome flats, and cosmic-ray removal. The contribution from dark current is negligible. The wave-
length calibration was done with contemporary CuAr lamp spectra taken directly before and after the observations of NGC 4335. Either 31 or 32 arc lamp emission lines were used to map the wavelength as a function of CCD coordinate. The final residuals per fitted emission line are \( \sim 0.3 \text{ A} \) (or 18 km s
1 at 5000 A). We subsequently performed the wavelength calibration and spatial rectification to align the wavelength direction with the CCD columns in one step. The flux calibration took into account telescope throughput and atmospheric extinction. The Galactic extinction toward NGC 4335 is \( A_B = 0.063 \) (Schlegel, Finkbeiner, & Davis 1998) and hence negligible. As a cross-check for the flux calibration we verified that the broadband flux observed through a 1'' \times 1'' central aperture in the WHT ISIS spectrum and our previously observed HST V-band image (VK99) agreed to
within \( \sim 25\% \), correcting for differences in filter passbands and point-spread function (PSF). This level of agreement

![Fig. 3.—Mean velocity (top row) and velocity dispersion (bottom row) of the ionized gas in NGC 4335, inferred from Gaussian fits to the emission lines in the STIS spectra (as listed in Table 3 and shown in Fig. 2). The abscissa in each plot is the major-axis coordinate of the aperture center. Each column corresponds to the slit position as labeled in the top row.](image)
3.4. Stellar Kinematics

We used the wavelength range ∼5200–5700 Å in the NGC 4335 absorption spectrum to derive the stellar kinematics. This range includes the redshifted Mg b, Fe2, and Fe3 absorption features. To obtain the stellar kinematics we used the pixel space–fitting method of van der Marel (1994), which compares the NGC 4335 spectrum to a stellar “template” spectrum. A suitable template star (spectral type K0 V) was obtained during a different observing run with WHT ISIS in identical setup. To check for template mismatch we also used stellar templates (spectral types K1 III and K2) described in van der Marel & Franx (1993). These data have an instrumental velocity dispersion σ_{inst} ∼ 60 km s⁻¹, i.e., very similar to the σ_{inst} of the NGC 4335 spectrum. The inferred stellar kinematics agree within the errors. The observed stellar kinematics as a function of radius are listed in Table 4 (and also shown in Fig. 12, which is discussed in § 5). Stars and gas rotate in the same direction in the core of NGC 4335. The galaxy spectrum integrated along the slit over the central 25" yields an aperture velocity dispersion σ₀ = 282 ± 15 km s⁻¹. The 25" length corresponds to two effective radii as determined by fitting the surface brightness distribution shown in Figure 6. The listed formal errors include photon noise, uncertainties in the continuum fitting, and the variation in derived σ₀ observed by using different stellar templates. We are not aware of previous determinations of the central velocity dispersion for NGC 4335, but note that the central value σ₀ = 300 ± 60 km s⁻¹ inferred from the Faber & Jackson (1976) relation agrees well with the observations.

### Table 4

| Rebin (1) | x (arcsec) | y (arcsec) | V (km s⁻¹) | ΔV (km s⁻¹) | σ (km s⁻¹) | Δσ (km s⁻¹) |
|-----------|------------|------------|------------|-------------|------------|-------------|
|           |            |            |            |             |            |             |
| 36.-------- | 7.39       | 1.04       | 51         | 10          | 210        | 11          |
| 12.-------- | 3.18       | 0.45       | 95         | 8           | 245        | 9           |
| 5.--------  | 1.65       | 0.23       | 91         | 8           | 297        | 7           |
| 3.--------  | 0.92       | 0.13       | 49         | 7           | 296        | 7           |
| 2.--------  | 0.47       | 0.07       | 34         | 7           | 295        | 7           |
| 2.--------  | 0.09       | 0.01       | 17         | 8           | 314        | 6           |
| 2.--------  | −0.28      | −0.04      | −22        | 7           | 291        | 6           |
| 3.--------  | −0.73      | −0.10      | −46        | 8           | 287        | 7           |
| 6.--------  | −1.54      | −0.22      | −101       | 7           | 258        | 7           |
| 16.-------- | −3.52      | −0.50      | −119       | 8           | 232        | 8           |

Note.—Stellar kinematics inferred from a WHT ISIS long-slit spectrum of NGC 4335 obtained with a slit approximately along the major axis (170" slit width). Col. (1): Number of rebinned pixels of size 170 × 0"19; cols. (2)–(3): position of the aperture center with respect to the major and minor axes (i.e., the x- and y-axes). The coordinate system is identical to that used for the STIS slits in Table 3. Cols. (4)–(7): Mean velocity V and velocity dispersion σ of the stellar absorption lines with the corresponding formal random errors as determined from a fit to the absorption-line spectrum in pixel space (see § 3.4).
Fig. 4.—Comparison between the emission-line fluxes as derived from STIS spectroscopy and WFPC2 imaging. The three plots show for each slit the observed Hα + [N ii] flux density as a function of major-axis position. The open circles denote the STIS Hα + [N ii] fluxes as derived from Gaussian fits (see § 3.2). The filled circles indicate the flux density through the STIS slits as expected from the WFPC2 Hα + [N ii] emission image. The WFPC2 flux errors are discussed in § 4.1. There is a good agreement for slits C and W, but a discrepancy for slit E. Such differences in assumed emission-line flux distribution at more than 0.2 arcsec from the nucleus result in a negligible change in inferred BH mass (see § 4.4).

The WFPC2 flux errors are discussed in § 4.1. The filled circles indicate the flux density through the STIS slits as expected from the WFPC2 Hα + [N ii] emission image. The WFPC2 flux errors are discussed in § 4.1. There is a good agreement for slits C and W, but a discrepancy for slit E. Such differences in assumed emission-line flux distribution at more than 0.2 arcsec from the nucleus result in a negligible change in inferred BH mass (see § 4.4).

the necessary convolutions with the appropriate PSF, pixel size, and aperture size for each setup. The diamonds in Figure 5 show the predictions of the model that best fits all available data simultaneously. This model has parameters $R_1 = 0.0049$, $R_2 = 0.78$ and $I_1/I_{tot} = 0.31$. The absolute calibration gives $I_{tot} = 7.7 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ for Hα + [N ii]. The last panel in Figure 5 shows the intrinsic (i.e., deconvolved) flux distribution as a function of radius.

The thin disk flux model provides a decent fit to the observed STIS fluxes, apart from a slight underprediction of the central fluxes in slit W. The WFPC2 measurements are also reasonably well fitted, although the observed flux profile on the major axis suggests a narrower central flux peak. A second fit was made as well in which we included only the WFPC2 data. This resulted in a considerably narrower intrinsic profile (Fig. 5). However, the two model emission flux distributions result in BH masses that agree to within ~25% as discussed in § 4.4.

4.2. Stellar Luminosity Density

For the purpose of dynamical modeling we parameterize the three-dimensional stellar luminosity density $j$. We assume that $j$ is oblate axisymmetric, that the isoluminosity spheroids have constant flattening $q$ as a function of radius, and that $j$ can be parameterized as

$$j(R, z) = j_0 (m/a)^\alpha [1 + (m/a)^2]^{2/3}, \quad m^2 = R^2 + z^2 q^2.$$ \hspace{1cm} (2)

Here $(R, z)$ are the usual cylindrical coordinates, and $\alpha$, $\beta$, $a$, and $j_0$ are free parameters. When viewed at inclination angle $i$, the projected intensity contours are aligned concentric ellipses with axial ratio $q'$, with $q'^2 = \cos^2 i + q^2 \sin^2 i$. The projected intensity for the luminosity density $j$ is evaluated numerically.

We assume $i = 66^\circ$ as discussed in § 2.2. We take $q' = 0.81$ within a radius of 3″, based on the isophotal analysis of VK99 (their Fig. 2). They determined that the isophotes are very close to elliptical and that $q'$ varies from 0.81 to 0.76 between major-axis radius $R \sim 3''$ and $R \sim 7''$. The isophotal major-axis P.A. = 156° is nearly constant, varying by less than 5° over the same radius range. A model with constant $q$ and P.A. is expected to be adequate in view of the main uncertainties for the BH mass from our dynamical modeling as discussed in § 6. For example, we verified that the variation in ellipticity changes the derived circular velocities by less than 6%, which is small compared with our velocity errors.

We determine the mean flux profile over three rows (corresponding to a width ~0″14) along the unobscured eastern galaxy semimajor axis (see § 2.2). We use the $V$-band fluxes as opposed to $I$-band fluxes because the flux contribution of emission lines is negligible in this wavelength region. The observed surface brightness profile is shown in Figure 6. The projected intensity profile of the best-fit model using the fluxes on the semimajor axis between $r = 0.00$ and $r = 1.00$ is shown by the solid curve. This model has $\alpha = -0.36$, $\beta = -1.02$, $a = 0.35$, and $j_0 = 1.6 \times 10^2 L_\odot$ pc$^{-3}$.

The surface mass density of the dust disk, which is proportional to the optical extinction (see VK99 and references therein), does not show a strong increase toward the center but varies by just about a factor of 2 over the disk (see Fig. 2 in VK00). Taking a Galactic value of the gas-to-dust ratio of 100 (e.g., Bohlin, Savage, & Drake 1978), the total mass of the dust, which extends over a region $r \sim 2.5\arcsec$, is $\sim 5.8 \times 10^7 M_\odot$. The ratio of enclosed disk mass to stellar mass is at most $\sim 6 \times 10^{-4}$ in the range $m = [10 \text{pc}, 1000 \text{pc}]$ (i.e., $m = [0.03, 3']$). Hence we can neglect the gravitational potential exerted by the gas and dust disk.

There is one complication in estimating the stellar mass profile. The central ~0″23 of the galaxy has a color $V-I \sim 1.35$ on both the eastern and western side of the galaxy nucleus. This color is typical of dust-free giant elliptical galaxies. It implies that the dust either does not extend all the way to the center (i.e., has a ring structure) or becomes optically thick toward the center. In the latter case it would hide approximately half the stellar mass in this region as the dust is very close to the center. We discuss this scenario in § 4.4 and find that it requires an unusually low stellar mass-to-light ratio to explain the observed gas kinematics.

4.3. Dynamical Models for a Thin Rotating Gas Disk

Our thin disk models for the gas kinematics are similar to those employed in van der Marel & van den Bosch (1998) and VK00. The galaxy model is axisymmetric, with the stellar luminosity density $j(R, z)$ chosen as in § 4.2 to fit the available surface photometry. The stellar mass density $\rho(R, z)$ follows from the luminosity density upon the assumption of a constant mass-to-light ratio $\mathcal{T}$. The quantity $\mathcal{T}$ is included as a free parameter in the dynamical model. We assume that the gas is in circular motion in an infinitesimally thin disk in the equatorial plane of the galaxy and has the circularly symmetric flux distribution $F(R)$ given in § 4.1; thus the position angle of the gas disk is set by...
the position angle of the galaxy, which is known to an accuracy of $\pm 1^\circ$. The inclination $i$ of the gas disk is assumed to be identical to the dust disk inclination. Below, we will verify P.A. and $i$ also from the two-dimensional gas kinematics independently. The circular velocity $V_c(R)$ is calculated from the combined gravitational potential of the stars and a central BH of mass $M_\bullet$. The line-of-sight velocity profile of the gas at position $(x, y)$ on the sky is a Gaussian with mean $V_c(R)$ and dispersion $\sigma_{\text{gas}}(R)$, where $R = [x^2 + (y/\cos i)^2]^{1/2}$ is the radius in the disk. The velocity dispersion of the gas is assumed to be isotropic, with contributions from thermal and nonthermal motions: $\sigma_{\text{gas}}^2 = \sigma_{\text{th}}^2 + \sigma_{\text{tur}}^2$. For practical reasons, we refer to the nonthermal contribution as “turbulent,” although its origin is not certain (see §4.5). We parameterize $\sigma_{\text{tur}}$ through

$$\sigma_{\text{tur}}(R) = \sigma_{\text{th}} + [\sigma_{\text{tur}} \exp(-R/R_i)]. \quad (3)$$

This functional form is meant merely to provide a fit to the observed dispersion and is not based on an underlying physical mechanism for the turbulence. The temperature of the gas is not an important parameter: the thermal dispersion for $T \approx 10^4$ K is $\sigma_{\text{th}} \approx 10$ km s$^{-1}$ and is negligible with respect to $\sigma_{\text{tur}}$ for all plausible models.

The predicted VP for any given observation is obtained through flux-weighted convolution of the intrinsic VPs with the PSF of the observation and the size of the aperture. The STIS PSF is represented as a sum of five Gaussians (see Table 5). We ignore the effect of “pixel bleeding” for the STIS PSF, since this changes the kinematics predicted by the model by only a few kilometers per second (Barth et al. 2001). The convolutions are described by the semianalytical kernels given in Appendix A of van der Marel (1997) and were performed numerically using Gauss-Legendre integration. A Gaussian is fitted to each predicted VP for comparison with the observed $V$ and $\sigma$. We define a $\chi^2$ quantity that measures the quality of the fit to the kinematical data, and the best-fitting model was found by minimizing $\chi^2$ using a “downhill simplex” minimization routine (Press et al. 1992).

As mentioned, the observed VP and the VP predicted by the dynamical modeling are fitted with a single Gaussian; thus we have to verify that the deviations from a Gaussian are the same in observations and model. Figure 2 shows that
in some spectra, especially near the galaxy nucleus, the emission lines tend to have smaller peaks and broader wings than the Gaussian fit. The same trend is indeed seen in the modeled spectra. We verified that, apart from this difference, there are no systematic differences as a function of radius between the VP and the Gaussian fit. Furthermore, the modeled spectra allow us to determine the difference between the moments of the full VP and the Gaussian fit qualitatively, also for blended Hα + [N II] emission lines, as is the case in many spectra. The representation by single-Gaussian fits turns out to be also quantitatively adequate in the sense that the differences between true and Gaussian v

Fig. 5.—Continued
and $\sigma$ of the VPs are typically within the quoted errors for the observed Gaussian moments.

4.4. Thin Disk Fit to the Gas Mean Velocities

We first analyze the H$\alpha$ + [N II] gas disk mean velocities and defer discussion of the velocity dispersions to § 4.5. We start out with models with no BH in which the gas disk has the orientation as determined from the photometry; thus the gas disk is assumed to have the same inclination $i = 66^\circ$ and position angle P.A. = 156$^\circ$ as the dust disk and galaxy (see § 2.2). This corresponds to an intrinsic axial ratio of $q = 0.77$ for our spheroid model. The STIS long-slit obser-

vations were performed at a small angle $\theta = -8^\circ 44$ to the major axis (see § 3.1).

First we vary the $I$-band mass-to-light ratio $Y_f$ and find that a model with $Y_f = 3$ in solar units fits the observed gas kinematics best (see Fig. 7). We will refer to this model as the “standard model.” There are some differences between the model and observations. For slit W, the model predicts a steeper mean velocity gradient than observed. For slit W, the observed mean velocities around $x \sim 0^\circ 5$ are systematically larger than predicted by the model. The total and reduced $\chi^2$ of this model with one free parameter are 89 and 3, respectively. However, almost 40% of the total $\chi^2$ is contributed by just the two points at $x = 0^\circ 406$ in slit W and at $x = -0^\circ 336$ in slit E. These two large deviations might be caused by local deviations from the model, for instance, local turbulence. In fact, at the latter location the velocity dispersion shows an off-nuclear peak. Discarding these two points, the reduced $\chi^2 = 2$. Thus given the idealization of the model, a rotating disk model with localized turbulence is not too unlikely.

We can estimate $Y_f$ independently from existing empirical correlations between $\Upsilon$ and galaxy optical luminosity. For NGC 4335, $m_B = 13.5$ mag (Paturel et al. 1997), and we assume $B-V = 1.0$, $V-I = 1.3$, and $R-I = 0.45$, which is typical for bright elliptical galaxies and consistent with our WFPC2 observations (see VK99). We derive $Y_f = 2.5$ using the relation between $\Upsilon_R$ and absolute $B$ magnitude determined by van der Marel (1991). The value $Y_f = 3.5$ is found using the correlation between $\Upsilon_V$ and absolute $V$ magnitude as determined by Magorrian et al. (1998). The two values are consistent because both correlations show scatter of a factor $\sim 1.5$ in the observed mass-to-light values at given host luminosity. The value $Y_f = 3.0$ derived from the gas kinematics falls nicely in the expected range $2.5 < \Upsilon < 3.5$.

The inclination of the galaxy and its embedded gas disk are assumed to be similar to the larger scale dust disk. Which $i$ is preferred by the gas disk kinematics alone? To address this question, we derive the stellar mass model and intrinsic emission-line flux model, assuming $i = 40^\circ$ ($q = 0.4$) and $i = 80^\circ$ ($q = 0.8$). The profile shape of our stellar mass model (§ 4.2) does not depend on inclination, but the central stellar mass density changes, i.e., it increases for decreasing inclination. The changes in the intrinsic emission-line flux profile are negligible. For a given $Y_f$, the increase in central stellar density increases the predicted velocities, while the decrease in inclination decreases the line-of-sight component of the predicted velocities. Thus these two effects compete. As Figure 8 shows, compared with the fit for $i = 66^\circ$, the fits are poorer for $i = 40^\circ$ and $i = 80^\circ$, and the best-fit $Y_f \sim 4-5$ is higher than expected from the empirical correlations with host luminosity.

The P.A. of the gas disk is fixed in the model to be identical to that of the galaxy major axis, which is determined to within $\sim 1^\circ$ by the WFPC2 isophotal analysis. We have varied the P.A. of the gas disk major axis by $\pm 20^\circ$ and find that the circular disk model fits best for P.A. = 152$^\circ$, i.e., 3$^\circ$ smaller than the P.A. of the galaxy major axis. The $\chi^2$ increases by more than 40 for P.A. = 152$^\circ$ smaller than the P.A. of the gas disk as preferred by the gas kinematics agrees well with the P.A. derived from the WFPC2 stellar isophotes.

In summary, we see that the kinematics of the gas disk support the disk inclination and P.A. and the mass-to-light ratio $Y_f$ implied by independent methods. The slope

\begin{table}[h]
\centering
\caption{STIS PSF}
\begin{tabular}{ccc}
\hline
\hline
$i$ & $\gamma$ & $\sigma$ (arcsec) \\
\hline
1. & 0.674510 & 0.026922 \\
2. & -0.606168 & 0.045302 \\
3. & 0.798732 & 0.069042 \\
4. & 0.084999 & 0.272356 \\
5. & 0.047927 & 0.860743 \\
\hline
\end{tabular}
\end{table}

Note.—The parameters of the five Gaussians that together represent the STIS PSF as $PSF(r) = \sum_{i=1}^{5} \gamma_i (2\pi\sigma_i^2)^{-1/2} e^{-r^2/(2\sigma_i^2)}$. The parameters were obtained through a fit to the STIS PSF produced with Tiny Tim software by Krist and Hook (see http://www.stsci.edu/software/tinym). Differences between the actual PSF and the analytical fit cause differences in the modeled kinematics that are smaller than the errors in the data.
of the central velocity measurements for each slit are well fitted by this model with no BH. This a posteriori validates our inclusion of the central velocity gradient to determine $M_{\bullet}$ because this gradient is evidently not affected significantly by the central BH mass. It also implies that the data provide an upper limit to the BH mass.

We now determine this BH mass upper limit. The models indicate that only the gradient between the central three points closest in absolute radial distance from the nucleus (i.e., at $|x| < 0.15$ in slit C) are significantly affected by a BH with mass $M_{\bullet} \gtrsim 10^8 M_{\odot}$. We will therefore use these mean velocities to compute the $\chi^2$. Since the model parameters other than $M_{\bullet}$ are optimized to fit the whole velocity profile, the $\chi^2$ from the central three mean velocities is expected to follow approximately a $\chi^2$ probability distribution with $N_{df} = 3-1 = 2$ degrees of freedom (three velocity measurements and one free parameter, $M_{\bullet}$) and hence an expectation value $\langle \chi^2 \rangle = 2$.

In agreement with this the standard model has $\chi^2 = 1.8$. Figure 9 shows the increase in $\chi^2$ as a function of increasing BH mass. From the $\Delta \chi^2$ for the one-parameter model, a $M_{\bullet} > 10^8 M_{\odot}$ is formally ruled out at the 3 $\sigma$ level.
assuming the intrinsic stellar flux inside will be obscured. We determine the stellar mass density opaque. This will alter the assumed stellar mass density, central dust distribution inside \( r \).\n
\[ x/C_{15} \]

\[ x/C_{7} \]

4.4.\n
A more conservative upper limit can be obtained by assuming the gas disk is maximally face-on. This will decrease the inferred intrinsic axis ratio of the galaxy (see \S 4.2). Since no giant elliptical galaxies flatter than E6 are observed, we take \( q = 0.4 \) as the minimum acceptable axis ratio for NGC 4335. This implies a galaxy inclination \( i = 40° \). Figure 9 shows that \( M_\odot \geq 1.8 \times 10^8 \) \( M_\odot \) is ruled out at more than the 3 \( \sigma \) level for \( i = 40° \). Such a model cannot fit the complete velocity curves as well as the standard model for any \( T_f \) (Fig. 8). Moreover, the best fit is provided by \( T_f \approx 5 \) for \( i = 40° \), which is at least 40% larger than expected, as discussed above.

Section 4.1 shows that the WFPC2 flux profile suggests a narrower flux profile than the STIS data. We performed the gas dynamical modeling also with the double-exponential fit to the WFPC2 data only. This results in a \( \sim 25\% \) higher upper limit to the inferred BH mass. The other notable discrepancy between the WFPC2 and STIS fluxes in slit E does not influence the BH mass measurement directly.

In \S 4.2 we discussed the possibility that there might be a central dust distribution inside \( r \approx 0.023 \) that is completely opaque. This will alter the assumed stellar mass density, because inside \( r = 0.023 \) approximately half the galaxy light will be obscured. We determine the stellar mass density assuming the intrinsic stellar flux inside \( r = 0.023 \) is 2 times the observed flux and that the obscuration by dust is negligible outside \( r = 1″ \). The fitted model has \( \alpha = 0.0 \), \( \beta = -1.4 \), \( a = 0.31 \), and \( j_0 = 6.2 \times 10^2 L_\odot \) pc\(^{-3} \). In this case a mass-to-light ratio \( T_f \approx 1.5 \) is needed to obtain a good fit to the galaxy-dominated kinematics. This is an unusually low \( T_f \) and lies well outside the observed scatter of observed absolute magnitude versus \( T_f \) correlations (see \S 4.4). Moreover, the emission-line flux is strongly peaked toward the center, which suggests we have a direct view of the nucleus without significant obscuration by dust. We conclude that NGC 4335 probably does not have an opaque central dust distribution. If, however, it is present, then our upper limit on the BH mass is an overestimate.

In conclusion, there is good agreement between the disk inclination \( i \) and P.A. as determined from gas kinematics and dust morphology and between the mass-to-light ratio \( T_f \) from gas kinematics and from independent methods. These agreements form support for the thin disk model, which indicates \( M_\bullet < 10^8 \) \( M_\odot \). The quantities \( T, i \), and P.A. are mainly constrained by the gas kinematics at \( r > 0.025 \), which is outside the BH radius of influence \( r_{\text{BH}} \) (with \( r_{\text{BH}} = GM_\bullet/\sigma^2 \), and \( \sigma \) the central stellar velocity dispersion). The upper limit to the BH mass is determined from the velocity gradient at \( r < 0.015 \). The inferred BH mass is thus based on the assumption that the thin disk model holds for \( r < 0.015 \). The next section considers whether this assumption is supported by the gas velocity dispersions.

Fig. 8.—\( \chi^2 \) model fit to the mean velocities as a function of \( I \)-band mass-to-light ratio \( T_f \) (in solar units) for three inclinations of the disk, showing models with inclination \( i = 40° \) (dashed curve), \( i = 66° \) (solid curve), and \( i = 80° \) (dotted curve). The most face-on model, with \( i = 40° \), implies an intrinsic galaxy ellipticity \( e = 0.6 \). Models with \( i = 66° \) provide the best fit to the observed mean velocities for \( T = 3 \), which is consistent with stellar dynamical modeling of ground-based observations (see \S 5). An inclination of \( 66° \) is also observed for the central dust disk of NGC 4335. The horizontal dashed lines indicate the 1, 2, and 3 \( \sigma \) level for a two-parameter (i.e., \( T \) and \( i \)) \( \chi^2 \) model. Models with \( i = 80° \) and \( i = 40° \) are formally ruled out at the 2 and 3 \( \sigma \) level and moreover have a best-fitting \( T_f \approx 4 \) and \( T_f \approx 5 \), respectively, which is higher than expected (see \S 4.4).

Fig. 9.—\( \chi^2 \) from the central three H\( \alpha + [N \, v] \) mean velocities in the central slit as a function of BH mass. Only these mean velocities are significantly affected by the BH gravitational field. We have assumed mean velocity errors \( \Delta v = 20 \) km s\(^{-1} \) (see \S 3.2). The model parameters other than BH mass are fixed to the values that best fit the complete mean velocity profile. For the standard model (filled circles and solid line) this is a mass-to-light ratio \( T_f = 3.0 \) and disk inclination \( i = 66° \). The horizontal lines indicate the 1, 2, and 3 \( \sigma \) confidence intervals for this \( \chi^2 \) probability distribution for one free parameter. A black hole mass \( M_\bullet > 10^8 M_\odot \) is excluded at higher than the 3 \( \sigma \) level. Also plotted are the more conservative upper limits for a model with a minimally inclined gas disk of \( i = 40° \), for which \( M_\bullet \geq 2 \times 10^8 M_\odot \) is ruled out at the 3 \( \sigma \) level (dashed line, open circles). However, this inclination does not agree with the dust disk inclination, and the best-fit \( T \approx 4.5 \) is formally ruled out at higher than the 3 \( \sigma \) level (see Fig. 8). See \S 4.4 for a more detailed discussion.
4.5. Gas Velocity Dispersions

The velocity dispersion is only roughly fitted by a model of the form (3) with $\sigma_0 = 50.0$ km s$^{-1}$, $\sigma_I = 200$ km s$^{-1}$, and $R_I = 0.5\arcsec$ (Fig. 10). The observed velocity dispersion varies between $\sigma_{\text{gas}} \sim 50$ km s$^{-1}$ and $\sigma_{\text{gas}} \sim 250$ km s$^{-1}$ (Fig. 10). The value $\sim 50$ km s$^{-1}$ corresponds to the instrumental and thermal line broadening. In the absence of a BH, the induced line broadening due to differential rotation over the apertures increases the predicted dispersion to at most $\sim 70$ km s$^{-1}$. The presence of a BH with mass $10^6 M_\odot$ would affect only the central aperture in each slit, increasing the predicted dispersions to $\sim 100$ km s$^{-1}$. Thus for many apertures, the gas shows a larger velocity dispersion than predicted by the dynamical model of a thin rotating disk. Also a double-Gaussian fit to each emission line, to fit a broad and a narrow component of the emission line, yields a kinematic component in addition to the thin rotating disk. An excess velocity dispersion increasing toward the nucleus, i.e., similar to that seen here, is often observed in other gas disks (e.g., van der Marel & van den Bosch 1998; VK00; Barth et al. 2001), with M87 being a notable exception (Macchetto et al. 1997). Significant excess dispersion is absent only at $r \gtrsim 0.5\arcsec$. These points are well fitted by our model, which is strong evidence that (1) the model of a thin disk in rotation applies at these radii and (2) the model parameters that depend sensitively on these points, i.e., $T_\text{eff}$, P.A., and $i$, are trustworthy regardless of the effects of excess velocity dispersion observed closer to the nucleus. What causes the excess velocity dispersion? Is it gravitational or non-gravitational in origin?

A gravitational origin would imply that the gas rotates at speeds lower than the circular velocity. Only if the excess in velocity dispersion is modest, $\sigma/v \ll 1$, do approximate formulae for this effect of “asymmetric drift” (e.g., Binney & Tremaine 1987) allow the circular velocity to be derived from the observed mean velocity (e.g., Barth et al. 2001). This regime does not apply to the observed kinematics in the central regions if interpreted as asymmetric drift. Unfortunately, the BH mass depends exclusively on these nuclear apertures. It is therefore useful to determine the BH mass in the most extreme case that all dispersion in the central spectrum is gravitational. One option is that the gas forms a spheroidal distribution of collisionless clouddots. To first approximation we can model the gas by assuming a spherical isotropic model and solve the Jeans equations in a similar fashion as done in VK00. A black hole mass $M_\bullet \sim 6 \times 10^6 M_\odot$ is then required to produce the observed $\sigma = 240$ km s$^{-1}$. The model is simplistic and deviations from axisymmetry and isotropy can change the result by factors of a few (de Bruijne, van der Marel, & de Zeeuw 1996). Moreover, the model assumes a constant number density-to-flux density ratio for the emission-line flux. Different ionization mechanisms (e.g., central point source or shocks) quite likely produce quite different relations between number density and emission-line emissivity as a function of radius. A second option is to assume that asymmetric drift is present except at the very center. The central velocity dispersion is then due entirely to differential rotation over the aperture. Also in this case, a $M_\bullet \sim 6 \times 10^6 M_\odot$ is required to produce the central $\sigma = 240$ km s$^{-1}$ for $i = 66^\circ$ and $\Gamma_I = 3$. Thus if the thin disk model breaks down within the
The thin disk model could be a good approximation if the excess velocity dispersion is caused by localized turbulence, which leaves the gas on average in circular rotation. The highly irregular behavior of the velocity dispersion points indeed to a nongravitational origin. The velocity dispersion of the gas peaks toward the nucleus in slit C and W, but dips toward the nucleus for slit E. Interestingly, the location of irregular peaks in the velocity dispersion profile seems to coincide with deviations of the observed mean velocities compared with the model, especially in slit E. The relative flux of [N\textsc{ii}] $\lambda 6583$ and H\textalpha can shed light on the excitation mechanism. Figure 11 shows that the flux ratio [N\textsc{ii}] $\lambda 6583$/H\textalpha roughly peaks toward the nucleus in all slits. This is qualitatively in agreement with the excess dispersion being due to turbulent shocks as they tend to enhance the emission-line ratio (Dopita et al. 1997). Interestingly, the maximum line ratio ([N\textsc{ii}] $\lambda 6583$/H\textalpha $\sim 5$) in fact occurs at the location of the dip in the velocity dispersion in slit E (and a possible dip in slit W). No special feature is detected in the WFPC2 image (Fig. 1) at these locations. However, the spine of the straight radio jet observed at arcsecond-scale resolution with the VLA (P.A. = $79^\circ$; Wrobel, Machalski, & Condon 2002; Xu et al. 2000) passes right through the most conspicuous dip in slit E (between $x = -0\prime 04$ and $x = -0\prime 12$) if it continues straight down to the subarcsecond scales of interest here. Unfortunately, no radio jet emission is detected at VLBA scales (Xu et al. 2000). Surprisingly, the velocity gradient in slit E is regular and only slightly shallower than predicted by our standard model. Thus it seems that the irregular excess in dispersion does not significantly alter the mean rotational velocity.

The irregularity of the velocity dispersion profile and its correspondence to changes in the [N\textsc{ii}] $\lambda 6583$/H\textalpha flux ratio favor a nongravitational origin for the excess velocity dispersion. The irregularities do not correspond to irregularities in the gas mean velocities. Instead, the mean velocities suggest normal rotation. These observations are consistent with a gas disk for which the bulk of the gas orbits at the circular velocity but locally possesses additional kinetic energy in the form of turbulent motions. Testing the viability of such a hydrodynamical model is very interesting but beyond the scope of this paper. This leaves room for an alternative scenario, in which the excess velocity dispersion is predominantly gravitational (despite its irregular behavior), implying $M_\bullet \sim 6 \times 10^6 M_\odot$. The WFPC2 imaging and kinematics cannot rule out such a spherical gas distribution at the very center (§2.1).

5. STELLAR DYNAMICAL MODELS

The WHT ISIS stellar kinematics can place constraints on the mass-to-light ratio $\Upsilon_\ell$ and the BH mass independently of the gas kinematics. We in turn discuss the constraint on $\Upsilon_\ell$ and BH mass. A fully general stellar dynamical modeling of an axisymmetric galaxy requires “three-integral” models in which the phase-space distribution function $f(E, L_z, I)$ depends on the orbital energy, $E$, the angular momentum component parallel to the symmetry axis, $L_z$, and a third, nonclassical integral (e.g., Binney & Tremaine 1987). However, the inferred mass-to-light ratio from ground-based observations is generally insensitive to assumptions about the structure and dynamics of the galaxy. Models with different inclination (van der Marel 1991) or anisotropy (van der Marel 1994, 1999) yield the same value of $\Upsilon$ to within $\sim 20\%$.

Thus, to derive $\Upsilon_\ell$, we constructed axisymmetric two-integral models for NGC 4335 in which the phase-space distribution function $f(E, L_z)$ depends only on the two classical integrals of motion. We use the same galaxy mass model as for the gas kinematics [i.e., $\rho = \Upsilon_\ell \rho$ with $f(R, z)$ as derived in §4.2] and we also include a BH mass. The modeling procedure is the same as used (and described in more detail) by VK00 and similar to applications of models to large samples by, e.g., van der Marel (1991) and Magorrian et al. (1998).
Fig. 12.—Mean stellar velocity (top), velocity dispersion (middle), and root mean square velocities \(v_{\text{rms}} = [V^2 + \sigma^2]^{1/2}\) bottom along the major axis for NGC 4335. The curves are predictions of \((E, L)\) isotropic rotator models with central BH masses of \(M_\bullet = 0, 1.5, 3, \) and \(6 \times 10^9 M_\odot\), respectively, and I-band mass-to-light ratio \(\Upsilon_g = 3.5\) in solar units. This mass-to-light ratio provides a good fit to the stellar velocities for all models and is not inconsistent with, but is 20\% higher than, that inferred from the gaseous kinematics (see § 5 and Fig 8). The two-integral modeling without a BH does not give a good fit to the ground-based stellar velocity dispersions for \(r < 2\prime\) and suggests instead a BH mass \(M_\bullet \sim 3 \times 10^9 M_\odot\). This is at least an order of magnitude higher than that inferred from the gas. As discussed in § 5, two-integral modeling is generally sufficient for an estimate of the mass-to-light ratio \(\Upsilon\) from ground-based data. However, a robust estimate for the BH mass requires both stellar kinematical observations at higher spatial resolution and more general (i.e., three-integral or triaxial) stellar dynamical models.

Figure 12 shows the observed and predicted kinematics as a function of major-axis distance. A value of \(\Upsilon_g \approx 3.5\) in solar units provides a good fit to the stellar mean velocity and velocity dispersion profiles at \(r > 2\prime\). This is 20\% higher than that inferred from the gas. Given the \(\sim 20\%\) uncertainty for \(\Upsilon\), the stellar kinematics out to a radius of \(\sim 5\prime\) are consistent with the mass-to-light ratio inferred by the gas velocity profile in the inner \(\sim 1\prime\).

The two-integral models can reproduce the observed peak in the stellar velocity dispersion in the inner \(\sim 2\prime\) only by invoking a BH of mass \(M_\bullet \gtrsim 3 \times 10^9 M_\odot\). If this BH mass is correct, the \(HST\) gas kinematics are resolving the radius of influence \(r_{\text{BH}} \gtrsim 2\prime\). However, these same gas kinematics firmly rule out such a massive BH. Instead the gas models predict a BH mass that is at least between 5 and 30 times smaller. This is very surprising, because the two gas modeling variants discussed in § 4.5 ascribe all nuclear gas kinetic energy to gravitation. The gas is assumed to be in either a disk or a spherical cloudlet distribution. These two models are expected to bracket the true nuclear gas distribution. However, there are reasons to mistrust the high BH mass from stellar dynamical modeling. If radial anisotropy in the stellar motions is present, the BH mass is overestimated. As an example, Magorrian et al. (1998) determined the BH masses in a sample of 36 galaxies with similar modeling as performed here (i.e., two-integral modeling with ground-based kinematics and \(HST\)-based photometry). They found that for the 15 most nearly spherical galaxies, a spherical model with radial anisotropies removes the need for a BH in all cases (see also van der Marel 1999). It turns out that this degeneracy can be lifted if stellar kinematics at \(HST\) resolution is available (i.e., resolving the sphere of influence of the BH) and the complete parameter space for axisymmetric models is considered with three-integral modeling. Early-type galaxies do indeed harbor BHs, but the masses inferred from two-integral and three-integral axisymmetric modeling differ systematically. We compare nine E and S0 galaxies in Magorrian et al. (1998), which also have three-integral modeling (as listed in Kormendy & Gebhardt 2001). The average ratio of two-integral BH mass over three-integral BH mass is 3.7 with a minimum of 0.41 and a maximum of 10. Thus it is not too unexpected that, if we were to have stellar kinematics at \(HST\) resolution as well, three-integral modeling would indicate a BH mass in better agreement with the value \(M_\bullet = 6.0 \times 10^8 M_\odot\) as derived from the gravitational modeling of the gas velocity dispersion. By contrast, the greater than 30 factor difference in BH mass between the resolved thin disk modeling and the stellar dynamical modeling seems a far stretch. Unfortunately, we cannot expect to obtain a stronger constraint on BH mass with more general axisymmetric three-integral modeling with the current data because we (1) lack stellar kinematics at \(HST\) resolution and hence do not resolve the \(r_{\text{BH}} \approx 0\prime.4\) of a \(M_\bullet = 6 \times 10^8 M_\odot\), and (2) have ground-based stellar kinematics only along the major axis and with reliable measurements of only first- and second-order moments.

6. DISCUSSION AND CONCLUSIONS

Before analyzing the implications of the inferred black hole mass we first discuss the two main differences between our gas disk dynamical modeling and the modeling used for NGC 3245 presented by Barth et al. (2001), which constitutes the current state of the art. First, instead of the observed emission-line flux distribution, we have used a double-exponential fit to the flux distribution. For NGC 3245 the use of an exponential fit changes the inferred \(M_\bullet\) by 30\%. Moreover, it accounted less well for the wiggles in the velocity profile. In our case the deviations of the exponential model from the observed photometric and spectroscopic emission-line fluxes are estimated to have a \(\sim 25\%\) effect on BH mass (see § 4.4). Second, we do not incorporate the velocity shifts due to asymmetric illumination of the slit by the gas disk in the dispersion direction. In other galaxies this could be important to derive the BH mass as they produce surface brightness “caustics” (Maciejewski & Binney 2001). These caustics are not observed in NGC 4335. STIS observations of stars by one of us show that the velocity shift amounts to at most \(\sim 30 \text{ km s}^{-1}\) for a 0″-wide slit in the extreme case of a star at the edge of the slit. Only the (central) apertures in the adjacent slits have an asymmetric flux gradient in the dispersion direction. The kinematics from these apertures are not taken into account in deriving the upper limit to \(M_\bullet\). Hence we conclude that the velocity shift has negligible effect on the derived \(M_\bullet\).

Black hole mass \(M_\bullet\) correlates in general rather tightly with observed velocity dispersion \(\sigma\) in the inner region of galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000). Recently, Tremaine et al. (2002) completed a
detailed analysis of the correlation, and we will use their results in what follows. They find a best-fit correlation of the form \( \log M_\bullet = \alpha + \beta \log(\sigma/\sigma_0) \) with \( \alpha = 8.13 \pm 0.06 \) and \( \beta = 4.02 \pm 0.32 \) for \( \sigma_0 = 200 \) km s\(^{-1}\). The observed spread in the correlation indicates that the intrinsic dispersion in \( \log M_\bullet \) is 0.3 dex (perhaps smaller if observational errors are underestimated). Measuring the central \( \sigma \) in similar fashion as in Tremaine et al. (2002) gives \( \sigma = 282 \) km s\(^{-1}\) for NGC 4335 (see \S 3.4), which corresponds to a predicted \( M_\bullet = 5.4 \times 10^8 \) M\(_\odot\). The 3 \( \sigma \) upper limit \( M_\bullet < 10^8 \) M\(_\odot\) from the thin disk modeling of the gas mean velocities (\S 4.4) falls well below the relation, even when including the reported intrinsic dispersion in \( M_\bullet \). The residuals are \(-0.73\) and \(-0.43\) dex for the upper limit of \( M_\bullet = 1.0 \times 10^8 \) M\(_\odot\) (best-fit model) and \( M_\bullet = 2.0 \times 10^8 \) M\(_\odot\) (for a maximally face-on gas disk), respectively (see Fig. 13). The residuals are even larger if we use the best-fit relation as determined by Ferrarese (2002), who infers a larger \( \beta = 4.58 \). The \( M_\bullet \geq 3 \times 10^9 \) M\(_\odot\) derived from stellar dynamics corresponds to an equally large but positive residual of \( \geq 0.7 \) dex. Finally, the gravitational modeling of the gas velocity dispersions yields \( M_\bullet \sim 6 \times 10^8 \) M\(_\odot\), corresponding to a residual of 0.05 dex, well within the reported intrinsic dispersion of the correlation.

Which BH mass are we to trust? The analysis strongly supports a thin rotating gas disk model at \( r \geq 0.5 \). The model provides a reasonable fit to the gas mean velocities and dispersions, the dust disk morphology and gas disk kinematics indicate the same inclination and P.A., and the \( \Upsilon \) from stellar and gas kinematics is consistent. However, there are doubts about the validity of the model at \( r \leq 0.5 \). The WFPC2 and STIS fluxes are consistent with a thin disk surface brightness profile but the S/N of the WFPC2 image is too low to rule out a more nearly spherical distribution. An excess velocity dispersion with an irregular profile is observed at \( r \leq 0.5 \). Only an ad hoc explanation of localized random motion exists for this excess. It is not clear whether such quasi-stationary turbulence in a thin disk is physically viable (e.g., Wada, Meurer, & Norman 2002; and references therein). If the excess velocity dispersion is (partly) due to gravitational motion around the BH, then the thin disk model understimates the true BH mass. Ascribing all gas kinetic energy, including the excess velocity dispersion, as counterbalancing the gravitational potential in a simple manner of isotropically moving collisionless cloudlets yields a BH mass that agrees well with the \( M_\bullet-\sigma \) correlation (Tremaine et al. 2002). Ascribing the nuclear velocity dispersion to rotational motion from a spatially unresolved disk yields an equally good agreement (\S 4.5). As discussed in more detail in \S 5, it is not too unreasonable to assume that the stellar dynamical modeling overestimates the BH mass by a factor of \( \sim 5 \). This would be due to radial anisotropy (often observed in bright elliptical galaxies such as NGC 4335), which the two-integral modeling does not take into account. In conclusion, the gas spheroidal model infers a BH mass in accordance with the empirical \( M_\bullet-\sigma \) relation but remains very simplistic. If doubts about the validity of the thin disk modeling for \( r \leq 0.5 \) were proved true, its inferred BH mass is expected to be an underestimate, driving the expected true BH mass to higher values, in better agreement with the \( M_\bullet-\sigma \) relation. Similarly, the expected corrections for the stellar dynamical model bring its predicted BH mass in better agreement with the relation.

What are the implications if in reality NGC 4335 indeed harbors a BH with \( M_\bullet \sim 6.0 \times 10^8 \) M\(_\odot\)? Our results then suggest that gas dynamical modeling assuming thin rotating disks cannot be used to derive accurate black hole masses even when all the following are true: (1) the gas mean velocities very clearly suggest rotation; (2) the surrounding dust disk appears regular; (3) the inclination and position angle of the inner gas disk are well constrained due to the use of three adjacent slits and these angles are both indicated by the gas disk kinematics and independent methods; and (4) the derived \( \Upsilon \) from gas and stars agree, ruling out asymmetric drift at \( r \geq 0.5 \). This then would cast doubt on other \( M_\bullet \) values determined from gas kinematics using similar models. Figure 13 shows that these measurements have a large influence on the upper end of the \( M_\bullet \) detections and hence on the slope of the correlation. Moreover, to date all measurements of \( M_\bullet \) in nearby radio galaxies are based on gas kinematics. However, the fact that the inferred BH masses using this method follow the best-fit relation more closely than the stellar dynamical measurements argues against this worry of the validity of the gas dynamical modeling in general. The \( \chi^2 \) per degree of freedom as used in deriving the best-fit relation (see eq. [3] in Tremaine et al. 2002) is 0.27 for the gas dynamical measurements, while for the stellar dynamical measurements it is 1.30 (1.17 if one excludes the

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**Figure 13.**—Measurements of BH mass \( M_\text{BH} \) as a function of the luminosity-weighted velocity dispersion \( \sigma \) within an effective radius for the sample of galaxies compiled by Tremaine et al. (2002) and their linear fit to these data. The BH detections for the entire sample are based on dynamical modeling of observed kinematics from stars (circles), ionized gas (triangles) or masers (squares) in both spiral and early-type galaxies. The filled symbols denote galaxies that have kiloparsec-scale radio jets. Three BH mass measurements for NGC 4335 are plotted as well: the 3 \( \sigma \) upper limit of \( M_\bullet < 10^8 \) M\(_\odot\) from the thin disk modeling of the mean velocities, \( M_\bullet \sim 6 \times 10^8 \) M\(_\odot\) from the gas collisionless cloudlet modeling of the velocity dispersions, and \( M_\bullet \sim 3 \times 10^8 \) M\(_\odot\) from the stellar dynamical axisymmetric two-integral modeling. The validity of these models is discussed in summary in \S 6. The solid line depicts the best-fit relation, which predicts \( M_\bullet = 5.4 \times 10^8 \) M\(_\odot\) for the observed \( \sigma \). The dashed lines depict the estimated 0.3 dex intrinsic dispersion in black hole mass (Tremaine et al. 2002).
Milky Way BH mass measurement, which is obtained from a stellar dynamical model that is completely different from those used for external galaxies. Moreover, the average residual of the gas dynamical BH mass measurements is positive, counter to what is expected if the gas mean velocities systematically underestimate the circular velocity and hence the inferred BH mass.

Independent determinations of $M_*$ in galaxies from gaseous and stellar kinematics observed at high spatial resolution are crucial to address the worries about the gas dynamical modeling. This has been performed for IC 1459 (VK00; Cappellari et al. 2002). Verdoes Kleijn et al. derive from the gaseous kinematics at six Faint Object Spectrograph (FOS) pointings a black hole mass ranging from $M_*=1.5\times10^6\ M_\odot$ (thin disk model) to $6\times10^6\ M_\odot$ (isotropic spheroidal model). However, Cappellari et al. (2002) infer $M_*= (2.6\pm1.1)\times10^9\ M_\odot$, based on three-integral modeling of combined ground-based and HST STIS stellar kinematics. Unfortunately, the HST stellar kinematics cannot be measured accurately inside the sphere of influence for this BH mass. Cappellari et al. also present a more nearly complete view of the gas kinematics from a recent STIS long-slit observation. This indicates that while the data are consistent with the earlier FOS measurements and the inferred BH mass is similar (modeled with independently developed software), the gas mean velocities are rather perturbed in this particular case. Moreover, IC 1459 has an irregular dust distribution. Thus, the gas and dust properties in IC 1459 are quite different from the photometrically and kinematically well-behaved central disk in NGC 4335. An independent $M_*$ measurement based on the stellar kinematics for NGC 4335 at HST resolution and for other galaxies with similar gas disk kinematics would test the validity of the gas dynamical modeling in well-behaved gas disks as opposed to irregular gas disks.

It is similarly crucial to understand the origin of the excess velocity dispersion commonly seen in nuclear gas disks. Presently, it is not clear under which circumstances the thin gas disks become locally turbulent (for example, gravitational or MHD instabilities) and whether they remain globally stable (e.g., Wada et al. 2002, and references therein). A better idea for the origin of the excess is needed to improve on the highly idealized collisionless spherical model discussed in this paper. In this respect, it is also useful to determine the ionization mechanism of the emission-line gas in nuclear disks. If it is shocks, we should be wary about the modeling with unperturbed infinitely thin rotating disks. Furthermore, the disks of gas and dust might perhaps interact with ambient hot X-ray gas, which is often present in the centers of bright elliptical galaxies (e.g., Gunn 1979). The ultimate goal for gas dynamical modeling is thus to explain self-consistently the density, ionization state, and dynamical state of the central gas distributions. This requires high S/N two-dimensional photometry, kinematics and line ratios to determine the dynamics, ionization state, density, and temperature as a function of disk radius. This will provide not only accurate BH masses but also a vast improvement in our understanding of the fueling of BHs.

Kiloparsec-scale radio jets are seen only in early-type galaxies but never in spiral galaxies (with one possible exception known to the authors; Ledlow et al. 2001). For instance, the UGC FR I galaxies all have Hubble types S0 (see VK99). Prior to this study, only BH masses $M_*>2\times10^8\ M_\odot$ were reported in nearby radio galaxies (i.e., M87, NGC 4261, 4374, 5128, 6251, and 7052; see Tremaine et al. 2002 for references). Interestingly, none of the seven galaxies with a Hubble type later than S0 in the sample compiled by Tremaine et al. (2002) have $M_*>1\times10^8\ M_\odot$. We are aware of only one galaxy with a Hubble type later than S0 and $M_*>2\times10^8\ M_\odot$, the Sombrero galaxy (M104, Hubble type Sa), with $M_*=1.0\times10^9\ M_\odot$, but this measurement is based on models less general than three-integral stellar dynamical models. By contrast, all BH mass upper limits and detections in a sample of 16 mostly early-type disk galaxies (Hubble type S0–Sb; Sarzi et al. 2001) are below $2\times10^8\ M_\odot$. These results suggest that the differences in BH mass might be the underlying factor for this host preference of radio jets. However, if our determination of a $3\sigma$ upper limit of $M_*<10^9\ M_\odot$ on the BH mass of NGC 4335 is correct, then NGC 4335 would illustrate that BHs with $M_*<10^8\ M_\odot$ are also capable of producing FR I radio jets. This would argue against BH mass being the (only) parameter underlying the host morphology preference of radio galaxies.

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