SPATIALLY RESOLVED NARROW-LINE REGION KINEMATICS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We have analyzed Hubble Space Telescope spectroscopy of 24 nearby active galactic nuclei (AGNs) to investigate spatially resolved gas kinematics in the narrow-line region (NLR). These observations effectively isolate the nuclear line profiles from less than 100 pc scales and are used to investigate the origin of the substantial scatter between the widths of strong NLR lines and the stellar velocity dispersion $\sigma_s$ of the host galaxy, a quantity that relates with substantially less scatter to the mass of the central, supermassive black hole and more generally characterize variations in the NLR velocity field with radius. We find that line widths measured with STIS at a range of spatial scales systematically underestimate both $\sigma_s$ and the line width measured from ground-based observations, although they do have comparably large scatter to the relation between ground-based NLR line width and $\sigma_s$. There are no obvious trends in the residuals when compared with a range of host galaxy and nuclear properties. The widths and asymmetries of [O III] $\lambda$5007 and [S II] $\lambda$6716, 6731 as a function of radius exhibit a wide range of behavior. Some of the most common phenomena are substantial width increases from the STIS to the large-scale, ground-based aperture and almost no change in line profile between the unresolved nuclear spectrum and ground-based measurements. We identify asymmetries in a surprisingly large fraction of low-ionization [S II] line profiles and several examples of substantial red asymmetries in both [O III] and [S II]. These results underscore the complexity of the circumnuclear material that constitutes the NLR and suggest that the scatter in the NLR width and $\sigma_s$ correlation cannot be substantially reduced with a simple set of empirical relations.

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

1. INTRODUCTION

The width of emission lines from the narrow-line region (NLR) in active galactic nuclei (AGNs) has recently received a great deal of interest because it may provide a reasonably accurate, although not precise, estimate of the host galaxy spheroid velocity dispersion $\sigma_s$. The NLR $\sigma_s = \text{FWHM}/2.354$ may therefore be a reasonable “tertiary” black hole mass ($M_*$) estimator based on a series of empirical relations that originate with the $M_*$-$\sigma_s$ relationship between the mass of a galaxy’s central, supermassive black hole and the stellar velocity dispersion of the host galaxy’s spheroid (Ferrarese & Merritt 2000; Gebhardt et al. 2000a) and the relation between $\sigma_s$ and NLR line width from Nelson & Whittle (1996, and earlier work by Whittle 1992b, 1992c). Subsequent measurements and analysis have found that the $M_*$-$\sigma_s$ relationship has an intrinsic scatter of no more than 0.3 dex in log $M_*$ and that this upper limit is due to present measurement uncertainties (Tremaine et al. 2002). Nelson (2000) used this relation and $M_*$ estimates from reverberation-mapping experiments to propose the use of $\sigma_s$ measured from the [O III] $\lambda$5007 line to estimate the black hole mass. Greene & Ho (2005) recently completed a direct comparison of $\sigma_s$ and the gas velocity dispersion $\sigma_v$ for approximately 2000 AGNs from the Sloan Digital Sky Survey (SDSS) and showed that these widths are well correlated, although with considerable scatter. The empirical relation between $\sigma_v$ and $M_*$ is important for a broad range of applications. These applications include estimates of $M_*$ for local AGNs, for AGNs at high redshift, and the cosmic evolution of supermassive black holes. For luminous AGNs with substantial continuum emission, or for AGNs at high redshift, the widths of the narrow emission lines may be the only method to determine $\sigma_s$. In conjunction with measurements of bolometric luminosity $L_{\text{bol}}$, estimates of $M_*$ can also be used to calculate the accretion luminosity of AGNs in terms of the Eddington ratio $L_{\text{bol}}/L_{\text{Edd}}$. At low redshifts, black hole estimates from reverberation mapping have been shown to agree quite well with the slope of the $M_*$-$\sigma_s$ relation (Gebhardt et al. 2000b; Ferrarese et al. 2001; Nelson et al. 2004; Onken et al. 2004) and have been used to calibrate an additional secondary (virial) $M_*$ estimator based on the line width and luminosity of the broad, permitted lines (e.g., Kaspi et al. 2000). Boroson (2003) used this virial relation to show that the [O III] FWHM could be used to estimate $M_*$ to within a factor of 5. The virial and $\sigma_s$ estimates

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of $M_*$ have been used to explore the black hole masses and accretion rates in particular classes of AGNs, most notably the narrow line Seyfert 1 galaxies (Grupe & Mathur 2004), as well as to search for evolution in the $M_*$-$\sigma_*$ relation (Shields et al. 2003). Measurements of evolution in the $M_*$-$\sigma_*$ relation, or skewness in the distribution of the scatter about this relation, could also provide valuable constraints on the formation history of supermassive black holes (Robertson et al. 2005).

The utility of $\sigma_*$ measurements as a proxy for $M_*$ in AGNs is largely limited by the substantial scatter in the relation between $\sigma_*$ and $\sigma_g$. The brightest line for $\sigma_*$ measurements is the [O iii] $\lambda$5007 line, although this line does suffer from substantial blue-aside asymmetries (e.g., Heckman et al. 1981) that dramatically affect the quality of the $\sigma_g$-$\sigma_*$ correlation. Greene & Ho (2005) found that $\sigma_g/\sigma_*=1.34 \pm 0.66$ for the full profile of the [O iii] $\lambda$5007, while after removal of the blue-side asymmetry, the result for the line core is $\sigma_g/\sigma_*=1.00 \pm 0.35$. The other bright NLR lines, [O ii] $\lambda$3727 and [S ii] $\lambda\lambda$6716, 6731, have lower ionization potentials and do not suffer from such substantial asymmetries. The scatter and quality of the $\sigma_g$-$\sigma_*$ relation for these lines is comparable to the core of the [O iii] line. While all of these correlations do strongly confirm the Nelson & Whittle (1996) result that the kinematics of the NLR are dominated by gravity, the origin of the scatter is not clear. One potential origin of this scatter is a nonvirial contribution to the emission line widths. These contributions are clearly present in the blue-asymmetric [O iii] lines, but because these asymmetries are significantly stronger in high-ionization lines like [O iii], compared to lower ionization lines like [S ii] (e.g., de Robertis & Osterbrock 1984), there is good evidence that a range of spatial scales contribute to the observed NLR kinematics. Beyond the gas kinematics that contribute to the [O iii] blue wings, any non-virial contribution to deviations from the $\sigma_g$-$\sigma_*$ correlation is evidently traced equally by the low-ionization [S ii] lines and the core of the higher ionization [O iii] line, since these features show similar scatter.

Other potential origins for the scatter in the $\sigma_g$-$\sigma_*$ relation include the impact of compact radio jets and tidal distortions of the host galaxies. Nelson & Whittle (1996) found that both of these quantities correlate with systematically larger $\sigma_*$ at a given $\sigma_g$, although large-scale radio jets or tidal distortions are not present in most galaxies and therefore cannot be responsible for the bulk of the scatter. Small-scale radio jets may play a more significant role, however, as Ho & Peng (2001) find approximately 60% of Seyfert 1 galaxies qualify as radio loud when the nuclear radio and visible-wavelength flux is isolated from host galaxy emission. Whittle (1992c) showed that the [O iii] lines are significantly broader in Seyfert galaxies with linear radio morphology and high radio luminosity, which suggests that radio jets can affect the NLR velocity field. The spatial distribution of the NLR gas within the bulge may also have a substantial impact on the observed value of $\sigma_*$.

While the NLR gas must approximately trace the spheroid kinematics to produce this correlation, spatially resolved images indicate that the NLR is often approximately confined to a plane (e.g., Pogge et al. 1989b). Whittle (1992b) found that rotation does contribute to the width of the [O iii] emission line, although it does not dominate. Finally, Greene & Ho (2005) investigated whether host galaxy morphology, local environment, star formation rate, AGN luminosity, and Eddington ratio correlated with the observed scatter and only found evidence for systematically larger $\sigma_*$ at higher Eddington ratio. While all of these investigations have determined that tidal disturbances, the presence of a radio source, rotation, and Eddington ratio contribute to the observed scatter, none of them dominate. It would be extremely valuable if the origin of the scatter in the $\sigma_g$-$\sigma_*$ correlation could be identified and substantially reduced, as then $\sigma_*$ and $M_*$ could be estimated more precisely for AGNs.

Further information on the origin of the scatter in the $\sigma_g$-$\sigma_*$ correlation, as well as a more general understanding of the NLR kinematics, may be gained from a high spatial resolution study. Nearly all studies of NLR kinematics to date have employed ground-based, single-aperture measurements with aperture sizes on the order of a few arcseconds. Such aperture sizes correspond to several hundred parsecs in projection and can include most of the NLR. There is good evidence, however, for the presence of stratification in the NLR, such as observations that higher ionization and higher critical density lines tend to be broader (de Robertis & Osterbrock 1986), the presence of a blue, asymmetric wing on the higher ionization [O iii] line and not on other, lower ionization lines such as [S ii], and evidence for modest increases in electron density from recent Hubble Space Telescope (HST) observations (Barth et al. 2001; Shields et al. 2005). The properties of [O ii] led Heckman et al. (1981) to propose that asymmetries in the NLR are due to radial outflow and wind models of the NLR (e.g., Kroll & Vrtilek 1984; Schiano 1986; Smith 1993) are supported by recent, spatially resolved HST Space Telescope Imaging Spectrograph (STIS) kinematics of NGC 4151 (Nelson et al. 2000; Das et al. 2005). These authors find evidence for both a rotational component and two kinematically distinct radial outflow components that appear to decelerate at larger scales.

Crenshaw & Kraemer (2000) similarly studied the central 400 pc of NGC 1068 and found evidence for radial outflow driven by either wind or radiation pressure in the nuclear region, followed by deceleration on larger spatial scales.

In the present paper we analyze spatially resolved spectroscopy of a large sample of nearby AGNs from archival STIS observations and measure the NLR kinematics as a function of aperture size. We investigate the origin of the scatter in the $\sigma_g$-$\sigma_*$ correlation through a range of line width measurements at increasing aperture size, ranging from the limits of HST resolution to an aperture size typical of ground-based studies. We also study line asymmetries as a function of aperture size to investigate the spatial origin of line asymmetries. The sample properties and selection are described next in §2, and the non-standard aspects of the data processing in §3. We describe the line width and asymmetry parameters in §4, along with the results of these measurements for different spatial scales in §5. The implications of this work for the $\sigma_g$-$\sigma_*$ correlation and the kinematics of the NLR are then presented in §6. We summarize our results in the final section.

2. THE SAMPLE

We have adopted the sample of Nelson & Whittle (1995; hereafter NW95) as the parent sample of this investigation of small-scale NLR kinematics because they have obtained high-quality ground-based measurements of many NLR emission features, as well as stellar velocity dispersions, for a wide range of galaxy types. Their sample is largely drawn from the 140 Seyfert galaxies discussed in Whittle (1992a), in which their primary selection criteria were for strong Mg b (~5175 Å) and Ca ii triplet (~8550 Å) absorption features and weak Fe ii emission (which confuses Mg b). With moderate spectral resolution (80–230 km s$^{-1}$ FWHM), they measured the redshift, stellar kinematics ($V_c$ and $\sigma_*$), and a variety of characteristics for the [O iii] $\lambda$5007 and [S ii] $\lambda$9096 lines (see §4). These high-quality ground-based data are a critical point of comparison for our study of the small-scale kinematics.
We searched the HST archive and found 24 AGNs from the NW95 sample with moderate-resolution spectroscopy of either the \([\text{O} \text{iii}]\) or \([\text{S} \text{ii}]\) emission lines (G430M and G750M gratings, respectively) through either a 0'1 or 0'2 wide slit. The spectral resolution of the G750L and G430L gratings (~500 km s\(^{-1}\)) is not high enough to resolve line width changes in nearly all of these sources, while, in contrast, the instrumental resolution is substantially higher for G430M and G750M. The 0'1 and 0'2 slit widths have a spectral resolution of ~1.5 pixels FWHM for point sources, and the G430M and G750M gratings have dispersions of 0.28 and 0.56 \(\text{Å}\) pixel\(^{-1}\). The instrumental velocity resolution FWHM is therefore 25 and 40 km s\(^{-1}\), respectively. The resolution is approximately a factor of ~2.7 times larger for an unresolved source that uniformly fills the 0'2 slit and a factor of ~1.7 times larger for the 0'1 slit. The STIS plate scale is 0'05078 pixel\(^{-1}\) and the slit length is 50''. The details of our sample, including host galaxy properties, program identification, and observing mode, are provided in Table 1. Of the 24 galaxies, only NGC 2110 has observations with both the G430M and G750M settings.

3. DATA REDUCTION

Our sample is drawn from many different STIS observing programs, and thus the objects were obtained with many different observing sequences. The reduction steps therefore vary from galaxy to galaxy depending on the number of dithered exposures, the number of CR-SPLIT frames, and whether the observations were obtained prior to the primary (side 1) STIS electronics failure on 2001 May 16. We found that the reduced spectra taken directly out of the CALSTIS pipeline are not of optimum quality for any of our galaxies. In this section we discuss our modifications to the CALSTIS pipeline for the various observing sequences employed to obtain these archival data.

3.1. Multiple Dithered Exposures

Twelve of our 24 galaxies (those obtained for proposals 7361, 8055, and 9143) include multiple exposures of the nucleus and employed integer pixel dithering along the slit. These exposures had only one CR-SPLIT frame, and thus the CALSTIS pipeline reduction did not include cosmic-ray correction. To account for the cosmic rays, we broke out of the CALSTIS pipeline after the dark subtraction, bias subtraction, and flat fielding for each exposure (using the \_flt.fits calibration file). After aligning the exposures, we used the Laplacian cosmic-ray identification IRAF routine (lacosmic; van Dokkum 2001) to create a bad pixel map for each two-dimensional spectrum. The pixels flagged as cosmic rays by lacosmic were then rejected when the multiple spectra were combined. The lacosmic routine occasionally mistook spectral features for cosmic rays, leaving emission lines blank in the final combined image. In these cases we replaced the empty pixels with the corresponding values from the original \_flt image. Once the cosmic-ray cleaning was complete, we reinserted this combined, cosmic-ray-rejected file into the CALSTIS pipeline for the final wavelength and flux calibrations.

3.2. Multiple CR Splits

When multiple images were obtained at the same pointing, the exposures could be combined with the ocrreject step in the CALSTIS pipeline to produce a cosmic-ray-corrected image. We have run the spectra from galaxies with multiple CR splits listed in Table 1 up through this cosmic-ray rejection step in the CALSTIS pipeline. However, even with multiple CR splits, the pipeline output most often is still peppered with cosmic rays. We thus used lacosmic to zap the remaining rays in the ocrreject output (\_crj.fits image) before reinserting the spectra into the pipeline for the wavelength and flux calibrations.

3.3. Side 2 STIS Electronics Correction

The 10 data sets for proposal 9143 were obtained after 2001 May 16, when the side 1 STIS electronics failed. The side 2 electronics do not have closed-loop temperature control of the CCD, and this results in a dark rate that varies with temperature. Thus, the dark calibration image is a poor approximation to the real dark rates for hot pixels, and the outputs of the CALSTIS pipeline have many strongly negative pixels after the dark-subtraction step. Unfortunately, even the dithering scheme employed for this proposal did not easily remove the negative “holes” created in the images.

To correct for these negative pixels, we roughly followed the method outlined by R. W. Pogge et al. (2005, in preparation). From the combined, cosmic-ray-rejected image for each galaxy (see § 3.1), we created a list of pixels that fell more than 3 \(\sigma\) below the background median, which we fed into a custom IRAF script that replaced each negative pixel with the mean of its surrounding 3 \(\times\) 3 pixel box. We then reinserted this corrected image into the CALSTIS pipeline. For images obtained prior to the side 1 electronics failure, hot pixels that remained after the dark correction were eliminated as part of the cosmic-ray-cleaning step.

4. DATA ANALYSIS

Once these steps were complete, we extracted one-dimensional spectra of different aperture sizes from the two-dimensional spectra using the CALSTIS x1d routine, which performs a geometric rectification and background subtraction. For each galaxy we extracted spectra with apertures of integer pixel sizes from 2–50 centered on the nucleus, corresponding to angular sizes of 0'10–2'54. We chose to integrate progressively wider apertures, rather than attempt to measure the differential line profiles as a function of radius, because one of the main goals of our study is to characterize the transition between NLR profiles on very small scales and the ground-based apertures used in previous work.

Figure 1 presents three one-dimensional spectra for each of the 24 galaxies in the sample. The leftmost column of panels plots each galaxy’s spectrum summed over an 0'2 aperture, which approximately represents the nuclear emission unresolved by STIS. The middle column of panels plots the sum of a 1'' aperture centered on the nucleus. The 1'' aperture was chosen as a compromise between the resolution of previous ground-based studies and the angular extent over which emission lines are detectable in most of the STIS spectra. Finally, the rightmost column of panels shows the difference of the middle and leftmost panels. The difference spectra in these panels thus illustrate the line profiles outside of the nucleus and are discussed below in the context of line widths and asymmetries outside of the nuclear region.

We applied a scalar throughput correction to the flux-calibrated 0'2 spectra (4 pixel extraction box height) produced by x1d because the default throughput correction table (referenced by the PCTAB keyword) does not include an entry for a 4 pixel extraction box height. When a 4 pixel extraction box height is requested, the throughput value for a 3 pixel box height is employed instead of default, although the throughput is approximately 10% larger for a 4 pixel box compared to a 3 pixel box. The default behavior of x1d therefore overestimates the flux in a 4 pixel box when it assumes the lower throughput appropriate
| Name             | Class | $cz$ (km s\(^{-1}\)) | Distance (Mpc) | $D$ (arcsec) | Morphology (T) | $\log L_{1.4\text{GHz}}$ (W/Hz) | ID     | Mode | CR-SPLIT | Apertures (arcsec) | Refs. Dist. | Refs. $D$ | Refs. Morph. |
|------------------|-------|----------------------|---------------|-------------|--------------|-------------------------------|--------|------|-----------|-------------------|-------------|-----------|-------------|
| Mrk 270          | 2     | 3137                 | 38.1          | 65.8        | -2           | 21.51                         | 9143   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| Mrk 573          | 2     | 5166                 | 68.9          | 101.9       | -1           | 21.56                         | 9143   | G750M| 1         | 52X0.2            | 4           | 6         | 7           |
| Mrk 686          | 2     | 4251                 | 56.7          | 90.8        | 5            | 22.51                         | 9143   | G750M| 1         | 52X0.2            | 4           | 6         | 5           |
| NGC 788          | 2     | 4061                 | 54.1          | 77.3        | 0            | ...                           | 9143   | G750M| 1         | 52X0.2            | 4           | 6         | 7           |
| NGC 1052         | 2     | 1307                 | 18.0          | 77.3        | -5           | ...                           | 7403   | G750M| 3         | 52X0.2            | 2           | 5         | 7           |
| NGC 1358         | 2     | 4008                 | 53.4          | 119.7       | 0            | ...                           | 9143   | G750M| 1         | 52X0.2            | 4           | 5         | 7           |
| NGC 1667         | 2     | 4547                 | 60.6          | 53.5        | 5            | ...                           | 9143   | G750M| 1         | 52X0.2            | 2           | 5         | 7           |
| NGC 2110         | 2     | 2249                 | 30.0          | 42.5        | -3           | ...                           | 8610   | G750M| 6         | 52X0.2            | 4           | 6         | 7           |
| NGC 2273         | 2     | 1929                 | 27.6          | 203.3       | 5            | 21.84                         | 9143   | G750M| 1         | 52X0.2            | 1           | 5         | 5           |
| NGC 3031         | 1.8   | -39                  | 1.4           | 1439.3      | 3            | 20.81                         | 7351   | G750M| 2         | 52X0.1            | 1           | 5         | 7           |
| NGC 3227         | 1.5   | 1024                 | 20.6          | 119.7       | 1            | 21.84                         | 7403   | G750M| 2         | 52X0.2            | 1           | 5         | 7           |
| NGC 3516         | 1.5   | 2503                 | 38.9          | 137.5       | -2           | 21.85                         | 8055   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| NGC 3982         | 2     | 1155                 | 17.0          | 109.2       | 3            | 21.54                         | 7361   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| NGC 4051         | 1.5   | 622                  | 17.0          | 361.5       | 4            | 21.35                         | 8228   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| NGC 4579         | 1.9   | 1334                 | 19.1          | 378.6       | 3            | 21.34                         | 7403   | G750M| 3         | 52X0.2            | 3           | 5         | 7           |
| NGC 5347         | 2     | 2295                 | 31.1          | 101.9       | 2            | 21.07                         | 9143   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| NGC 5427         | 2     | 2733                 | 33.2          | 181.2       | 5            | ...                           | 9143   | G750M| 1         | 52X0.2            | 1           | 5         | 7           |
| NGC 7682         | 2     | 5109                 | 68.1          | 65.8        | 2            | 22.59                         | 9143   | G750M| 1         | 52X0.2            | 4           | 5         | 7           |
| Mrk 348          | 2     | 4505                 | 60.1          | 75.5        | 0            | 22.17                         | 8253   | G430M| 2         | 52X0.2            | 4           | 6         | 7           |
| Mrk 1066         | 2     | 3523                 | 47.0          | 72.1        | -5           | 23.16                         | 8253   | G430M| 2         | 52X0.2            | 4           | 6         | 7           |
| NGC 2110         | 2     | 2249                 | 30.0          | 42.5        | -3           | ...                           | 8253   | G430M| 2         | 52X0.2            | 4           | 6         | 7           |
| NGC 4151         | 1.5   | 966                  | 20.3          | 424.8       | 2            | 22.25                         | 8473   | G430M| 3         | 52X0.2            | 1           | 5         | 7           |
| NGC 5194         | 2     | 461                  | 7.7           | 534.8       | 4            | 22.20                         | 7574   | G430M| 2         | 52X0.2            | 1           | 5         | 7           |
| NGC 5929         | 2     | 2250                 | 38.5          | 65.8        | 2            | 22.22                         | 8253   | G430M| 2         | 52X0.2            | 1           | 5         | 7           |
| NGC 7674         | 2     | 8673                 | 115.6         | 60.0        | 4            | 23.63                         | 8259   | G430M| 2         | 52X0.2            | 4           | 5         | 7           |

**Notes.**—Col. (1): galaxy name. Several common aliases are Mrk 270 = NGC 5283, Mrk 686 = NGC 5695, NGC 3031 = M81, and NGC 5194 = M51a. Col. (2): AGN type, where type 1 AGN exhibit broad permitted lines and type 2 AGN have narrow permitted lines. Col. (3): $\delta$ profile median redshift from Nelson & Whittle (1995) ([O\text{III}] C80 or [S\text{II}] C80 redshifts used for galaxies with no [O\text{III}] median redshift given). Col. (4): distance. Col. (5): angular diameter in arcseconds of the 25 mag arcsec\(^{-2}\) isophote. Col. (6): morphological type (de Vaucouleurs numerical type). Col. (7): radio luminosity ($\log L_{1.4\text{GHz}}$ of the absolute spectral luminosity at 1.4 GHz) from Condon et al. (2002). Col. (8): HST proposal ID for data used. Col. (9): STIS grating. Col. (10): number of CR-SPLIT exposures. Col. (11): STIS aperture. Cols. (12)–(14): references to published distances, sizes, and morphologies.

**References.**—(1) Tully 1988; (2) Jensen et al. 2003; (3) Solanes et al. 2002; (4) $H_0 = 75$ km s\(^{-1}\) Mpc\(^{-1}\) (adopted for consistency with Tully 1988); (5) Nilson 1973; (6) Vorontsov-Velyaminov & Arkipova 1974; (7) de Vaucouleurs et al. 1991.
Fig. 1.—Profiles for the [S ii] λ6717, 6731 or [O iii] λ5007 lines for our sample presented at aperture sizes of 0″2 (left) and 1″ (center), as well as for 1″–0″2 (right). The best-fit Gaussian profiles are shown as dark, solid lines, while the individual components are shown as gray lines. Residuals are plotted below each fit. The vertical dashed line represents the position of the centroid of each line profile in the 1″ aperture. A polynomial fit to the AGN continuum has been subtracted from NGC 3227, NGC 3516, NGC 4051, and NGC 4579. All other profiles have only had a constant subtracted. The profiles have been plotted in rest wavelengths using the $cz$-values from in Table 1. Note that a Gaussian profile was not fit to NGC 7682 because the STIS G750M grating was centered too far to the blue and the broad, red wing of the [S ii] λ6731 line did not fall on the detector.
Fig. 1.—Continued
for a 3 pixel box. To properly correct the 0.2 spectra, we interpolated the throughput values in the correction table to calculate the appropriate quantity for a 4 pixel box height for each instrument configuration and then applied this throughput correction to the x1d output. Also, we note that while the throughput correction in the table was calculated from observations of a point source, the AGNs in this sample are dominated by unresolved nuclear emission and this correction table is a reasonable approximation. This throughput correction is only relevant to the 1–0.2 and 0.2 spectra shown in Figure 1 because the correction is negligible at 1′. The correction also does not affect the width measurements because the spectra are only multiplied by a constant.

We have chosen to characterize the line profiles of the [O III] and [S II] emission lines as a function of aperture size through line widths measured at a range of heights, interpercentile velocity (IPV) widths, and asymmetry measures (e.g., Heckman et al. 1981; Whittle 1985a). The definitions of these parameters,
such that the flux between the line profile (our Gaussian fitting scheme is described in Nelson & Whittle 1995). Figure 2 shows the value of these three quantities as a function of aperture size.

These width measurements are the observed widths and have not been corrected for the instrumental resolution. As noted in § 2, the FWHM velocity resolution of the G430M and G750M gratings is ∼25 and 40 km s⁻¹, respectively, for an unresolved point source and a factor of up to ∼2.5 times higher for a source that fills the slit. The most commonly used method to correct for broadening due to the instrumental resolution is to subtract the width of the instrumental resolution in quadrature. This correction cannot be performed with great accuracy for these observations because there is a substantial difference in resolution between unresolved and resolved emission and both sources of emission likely contribute to the observed emission-line profile. However, we can estimate the magnitude of this effect for the narrowest lines in our sample, which have FWHM ∼ 120 km s⁻¹ (see Table 2) and represent the most affected measurements. If this emission were completely unresolved the correction would be less than 5%, and if it uniformly filled the slit it would be less than 30%. Because the two-dimensional spectra of these sources all indicate that the emission-line gas is centrally peaked, we estimate that the majority of the emission in the smallest aperture is still unresolved. We therefore conclude that instrumental resolution makes at most a small contribution to our reported line widths. For the majority of our sample, the line widths are sufficiently broad that this correction is less than 10% even with the most extreme assumption that the emission uniformly fills the aperture. We also note that the instrumental resolution correction is likely to be more important for the line core (FW80) than at smaller fractions of the peak height (e.g., Whittle 1985a).

In their study of 1749 AGN spectra from the SDSS, Greene & Ho (2005) found that the moments of Gaussian fits to the profiles provide more robust widths than direct measurements from the spectra. However, the SDSS data are typically of lower S/N, and width measurements can be more uncertain in the low-S/N regime. The STIS spectra used for our sample generally have sufficient S/N and resolution that we can confidently measure emission-line widths without assuming any model for the line shape. Also, because the majority of the line profiles have a blue or redshifted wing and/or a broad central component, measuring widths directly from the data allows us to avoid approximating single values of the moments from a combination of multiple Gaussian components.

The dominant uncertainty in direct measurement of the line widths is the continuum level, because these lines have high S/N. As noted in § 4.1, we fit the continuum by either a constant or a power law. The line width measurement uncertainty depends on both the uncertainty in the continuum level and the line profile shape, as, for example, a given continuum uncertainty will produce a smaller width uncertainty in a broad line than a narrow line. We estimate that the uncertainties in our direct width measurements are less than 5%. The width measurements that required Gaussian fits have a formal uncertainty of approximately 5% (Greene & Ho 2005), although this is only a true estimate if the lines can be correctly represented by Gaussians. Those cases in which the fitting routine varied between direct width measurements and Gaussians (the switch between black and gray symbols in Fig. 3) indicate that the uncertainties are at most 10%. The lack of substantial stellar continuum emission in the extremely narrow STIS slit removes a potentially significant source of the uncertainty in width measurements derived from ground-based

Fig. 2.—Sample [O iii] λ5007 profile (0.2 aperture) with definitions of the width parameters FW20, FWHM, FW80, IPV10, and IPV20, and the asymmetry parameters A10 and A20. Note the broad wings and blue asymmetry typically seen in AGN [O iii] profiles.
| Name         | $\sigma_v$ (km s$^{-1}$) | Line Width Measurements | Aperture = 0$''$2 | Aperture = 1$''$ |
|--------------|--------------------------|-------------------------|------------------|----------------|
| Mrk 270      | 148 [O iii]              | [S ii] 396 620          | [S ii] 100 223 457 | [O ii] 135 254 494 |
| Mrk 573      | 123 [S ii]               | [S ii] 290 540          | [S ii] 81 176 280 | [S ii] 5.7 56 |
| Mrk 680      | 124 [O iii]              | [S ii] 359 609          | [S ii] 97 192 313 | [O ii] 9.6 43 |
| NGC 788      | 140 [O iii]              | [S ii] 190 295          | [S ii] 7 140 247 | [O iii] 14 56 |
| NGC 1052     | 207 [O iii]              | [S ii] 770 1085         | [S ii] 314 592 966 | [O ii] 3.4 26 |
| NGC 1358     | 173 [O iii]              | [S ii] 220 410          | [S ii] 117 361 574 | [O iii] 3.4 26 |
| NGC 1667     | 173 [O iii]              | [S ii] 275 410          | [S ii] 43 337 462 | [O iii] 6.1 0.9 |
| NGC 2110     | 220 [O iii]              | [S ii] 295 645          | [S ii] 284 584 1005 | [O iii] 27 31 |
| NGC 2273     | 124 [S ii]               | [S ii] 158 348          | [S ii] 52 102 317 | [O iii] 3.4 26 |
| NGC 3031     | 167 [O iii]              | [S ii] 335 ...          | [S ii] 238 388 614 | [O iii] 15 56 |
| NGC 3227     | 144 [S ii]               | [S ii] 536 1151         | [S ii] 59 225 473 | [O iii] 36.3 8.5 |
| NGC 3516     | 235 [O iii]              | [S ii] 250 550          | [S ii] 37 171 263 | [O iii] 6.3 4.6 |
| NGC 3982     | 62 [O iii]               | [S ii] 203 358          | [S ii] 95 184 335 | [O iii] 96 36 |
| NGC 4051     | 88 [S ii]                | [S ii] 208 353          | [S ii] 56 126 248 | [O iii] 58 36 |
| NGC 4579     | 170 [O iii]              | [S ii] 653 1278         | [S ii] 156 497 847 | [O iii] 3.4 26 |
| NGC 5347     | 93 [O iii]               | [S ii] 392 677          | [S ii] 73 159 393 | [O iii] 2.0 1.9 |
| NGC 5427     | 74 [O iii]               | [S ii] 264 620          | [S ii] 103 282 614 | [O ii] 15 56 |
| NGC 7682     | 123 [S ii]               | [S ii] 239 363          | [S ii] 66 155 431 | [O ii] 15 56 |
| Mrk 348      | 118 [O iii]              | [O iii] 363 660         | [O iii] 89 195 448 | [O iii] 15 56 |
| Mrk 1066     | 105 [O iii]              | [O iii] 417 714         | [O iii] 124 265 463 | [O iii] 15 56 |
| NGC 2110     | 220 [O iii]              | [S ii] 295 645          | [O iii] 161 575 1546 | [O iii] 15 56 |
| NGC 4151     | 178 [S ii]               | [O iii] 233 575         | [O iii] 118 246 403 | [O iii] 15 56 |
| NGC 5194     | 102 [S ii]               | [O iii] 195 364         | [O iii] 75 120 291 | [O iii] 15 56 |
| NGC 5929     | 121 [O iii]              | [O iii] 405 576         | [O iii] 62 123 230 | [O iii] 15 56 |
| NGC 7674     | 144 [O iii]              | [O iii] 350 960         | [O iii] 133 298 566 | [O iii] 15 56 |

**Notes.**—Col. (1): galaxy name. Col. (2): stellar velocity dispersion measurement from NW95. Col. (3): line used for width measurements in NW95. Cols. (4)–(5): FWHM and FW20 values from NW95. Col. (6): line used for our width measurements. Cols. (7)–(9): our FW80, FWHM, and FW20 measurements in an 0$''$2 aperture (the G superscript denotes measurements obtained from a Gaussian model of the line profile). Cols. (10)–(12): FW80, FWHM, and FW20 values measured in a 1$''$ aperture. Col. (13): percent change in FWHM between the 0$''$2 to 1$''$ aperture sizes. Col. (14): percent change between our 1$''$ aperture measurement and the NW95 value.

observations, which may be particularly relevant for fainter emission lines, such as [S ii].

### 4.3. Area and Asymmetry Measurements

Whittle (1985a) advocates the use of area measurements to define line width parameters, rather than simple cuts at varying heights, because they have an integral nature and are thus smoothly defined and less sensitive to the presence of noise or the effects of instrument resolution. His definitions of the interpercentile velocity widths (IPV10 and IPV20) and asymmetries (A10 and A20) are also illustrated in Figure 2. The median is the wavelength that denotes the center of area for the profile, and the lengths marked “a,” “b,” “c,” and “d” represent the separation between the median and the profile’s 10%, 90%, 20%, and 80% area values, respectively. The IPV10 parameter characterizes the base and wings of the profile, much as did the FW20 width suggested by Heckman et al. (1981), while the IPV20 parameter and higher percentage areas characterize the line core. The A10 and A20 values serve to clearly quantify the profile’s red or blue asymmetry.

We have chosen to measure our area parameters from Gaussian fits to the line profiles, rather than directly from the data as discussed in Whittle (1985a). This choice was driven by the [S ii] lines, which are mildly to severely blended in all of our sources. Because these lines are blended, we could not measure the interpercentile markers in the same manner as Whittle (1985a) for the more isolated [O iii] 5007 line. We experimented with taking the 10th and 20th percentile markers of the total [S ii] doublet area from the blue wing of the 6717 Å line and the 80th and 90th percentile markers from the red wing of the 6731 Å line and then scaling the widths a, b, c, and d by the relative widths of the [S ii] lines, but the potentially variable line ratio of the [S ii] doublet made this approach uncertain. In the end, we found that the Gaussian profiles provided more robust measurements of the area parameters, as we were able to isolate the separate contributions to the line profile from each of the [S ii] lines. Also, the Gaussian fits allowed us to avoid the subtleties in treating fractional wavelength increments discussed by Whittle (1985a).

Very few of these galaxies are well fit by a single Gaussian. The [O iii] line often has an asymmetric blue wing in addition to a broad central component, and so we allow for up to three Gaussian components in our fitting routines. With the exception of the sources with bright AGN continua, we fit a constant continuum term. We fit the [O iii] $\lambda\lambda4959$ and $\lambda5007$ lines simultaneously with their wavelength separation and relative strengths fixed to the theoretical ratio of 3:1 determined by atomic physics. For the [S ii] doublet we also fit the two lines simultaneously and with a fixed separation, although we allow their relative line strengths to vary because the [S ii] $\lambda6717/\lambda6731$ ratio is sensitive to electron density. In principle, the line widths of the 6717 and 6731 Å lines may be different due to stratification in the NLR, so we initially allowed the widths of the two lines to vary in our fitting routine. However, we found that the widths of the two lines differed by less than 3%, which is within the error of the Gaussian fit parameters described in the previous section. We therefore fixed the widths of these two lines in the fitting routine.
Fig. 3.—Line width parameters FW20 (diamonds), FWHM (squares), and FW80 (crosses) plotted against aperture size in units of physical distance (below) and angular size (above) for each galaxy in our sample. The NW95 measurements for FW20 (dashed lines), FWHM (dotted), and 2.354 $\times\sigma$ (dash-dotted) are plotted as horizontal lines. Black symbols denote measured widths, while gray symbols denote values obtained from a Gaussian model of the line profile.
The fitting routine employed here was adopted from Greene & Ho (2005). The first step is to fit a single Gaussian to the profile, and then we allow a second central component centered between $-5$ and $+5$ Å of the line peak (although occasionally the component was best fit outside these limits). We keep this second component if the $\chi^2$ value for the fit improves by at least 20%. For [O iii] we experimented with a third, blue component that was generally centered between $-20$ and 0 Å of the central component. Again we kept this component when $\chi^2$ improved by at least 20%. For the [S ii] lines we only allowed for one additional component between $-10$ and $+10$ Å of the line peak. The best fits from our Gaussian routine for each forbidden line profile are shown in Figure 1, and the fit residuals are plotted below the spectrum in each panel. The IPV widths at 0.2 and 1″ are provided in Table 3 and plotted as a function of aperture size in Figure 4, while the asymmetry measurements are listed in Table 4 and shown in Figure 5. Unlike the width measurements, the IPV area-defined parameters are relatively insensitive to instrumental resolution (Whittle 1985a).

5. RESULTS

All but 3 of the 24 galaxies in the sample have measurable emission outside of a central, 0.2 aperture, where 0.2 corresponds to 8–115 pc for this sample (excluding the very nearby NGC 3031). The three galaxies that lack detectable emission outside of 0.2 (Mrk 686, NGC 3516, and NGC 5427) were observed with G750M and not G430M. The brighter [O iii] line is always detectable outside of the central 0.2. The presence of significant emission outside of 0.2 is illustrated in the rightmost columns of Figure 1, which displays the difference between the
sum of a 1” and 0”2 aperture centered on the nucleus. In addition to the three galaxies that do not exhibit detectable emission outside of 0”2, nine additional galaxies with [S ii] observations have weak emission on larger scales and six have substantial emission. However, even emission lines that are quite weak outside of 0”2 can contribute to the line profiles in larger, integrated apertures.

5.1. Line Widths versus Aperture Size

The line width and IPV values as a function of aperture size are shown in Figures 3 and 4, respectively. Figure 3 plots the radial dependence of FW20, FWHM, and FW80 for each galaxy, while Figure 4 shows IPV10 and IPV20. The figures also include the ground-based measurements from NW95 (horizontal lines), unless the values measured in the ground-based aperture fall outside the range of the vertical axes. Our measurements in 0”2 and 1” apertures, along with the NW95 data, are listed in Tables 2 and 3. For nearly all of the galaxies there are substantial differences between the values in the nuclear region and the maximum STIS aperture size, as well as between the maximum STIS aperture size and the NW95 measurements. These differences between the STIS apertures and the ground-based measurements could be due to uncertain resolution corrections in the narrowest lines, although galaxies with narrow emission lines are not systematically different than galaxies with well-resolved lines. An alternate explanation is that these measurements fall below those from NW95 because the STIS slit only subdues a fraction of the NLR. We will discuss this point further in § 6.

Figure 3 shows that the line profile widths almost always increase or remain approximately constant. The FWHM for 10 galaxies increases by greater than 10%, while for an additional 11 the FWHM changes by less than 10%. Only three galaxies decrease by greater than 10% from the 0”2 to 1” aperture (NGC 1358, NGC 5427, and NGC 2110 in both emission lines). Two galaxies (NGC 1358 [S ii], NGC 2110 [O iii]) decrease by more than 30% and are interesting cases because a decrease requires both significant emission at larger spatial scales and a velocity width that is substantially narrower at larger scales than in the nuclear region. Comparison of the 0”2 and 1” apertures clearly indicates that the profiles are substantially broader in the central region. IPV variations with aperture size are particularly sensitive to changes in the base and wings of the lines, which may probe the acceleration or deceleration of winds. For example, an increase corresponds to more high velocity emission-line gas outside of the nuclear region than in the nucleus. While 11 of these galaxies have IPV20 variations of less than 10% between the 0”2 and 1” STIS apertures, several exhibit substantial variations. IPV20 increases by over 30% from 0”2 to 1” in both Mrk 573 and NGC 3227, while it decreases by over 30% for NGC 2110 [O iii] (and nearly this amount in [S ii]). In contrast, our FW20 measurements for these galaxies only increase moderately with aperture size, if at all, which implies that the IPV width measurements are indeed more sensitive to behavior in the wings, as suggested by Whittle (1985a). The substantial IPV decreases with radius in NGC 1358 and NGC 2110 provide good evidence

### Table 3

| Name          | Line  | IPV20 (km s⁻¹) | IPV10 (km s⁻¹) | Line  | IPV20 (km s⁻¹) | IPV10 (km s⁻¹) | IPV20 (%) | IPV20 (%) |
|---------------|-------|----------------|----------------|-------|----------------|----------------|-----------|-----------|
|               |       | (1)            | (2)            | (3)   | (4)            | (5)            | (6)       | (7)       |
| Mkn 270       | [O iii] | 472            | 637            | [S ii] | 238            | 371            | 5.0       | 89        |
| Mkn 573       | [S ii] | 423            | 572            | [S ii] | 132            | 211            | 48        | 120       |
| Mkn 686       | [O iii] | 454            | 593            | [S ii] | 153            | 273            | 25        | 140       |
| NGC 788       | [O iii] | 225            | 305            | [S ii] | 104            | 182            | 17        | 39        |
| NGC 1052      | [S ii] | 810            | 1075           | [S ii] | 700            | 961            | 19        | 33        |
| NGC 1358      | [O iii] | 355            | 505            | [S ii] | 339            | 477            | 24        | 40        |
| NGC 1667      | [O ii] | 365            | 525            | [S ii] | 549            | 714            | 23        | 14        |
| NGC 2110      | [S ii] | 655            | 950            | [S ii] | 766            | 1010           | 12        | 3         |
| NGC 2273      | [S ii] | 254            | 325            | [S ii] | 160            | 288            | 18        | 34        |
| NGC 3031      | [O iii] | ...            | ...            | [S ii] | 441            | 567            | ...       | ...       |
| NGC 3227      | [S ii] | 775            | 994            | [S ii] | 394            | 526            | 39        | 42        |
| NGC 3516      | [O ii] | 490            | 665            | [S ii] | 202            | 258            | 9.4       | 120       |
| NGC 3982      | [O ii] | 452            | 452            | [S ii] | 189            | 324            | 4.8       | 130       |
| NGC 4051      | [O ii] | 293            | 405            | [S ii] | 224            | 293            | 22        | 7         |
| NGC 4579      | [S ii] | 920            | 1143           | [S ii] | 586            | 750            | 6.7       | 68        |
| NGC 5347      | [S ii] | 513            | 679            | [S ii] | 236            | 392            | 1.3       | 120       |
| NGC 5427      | [S ii] | 659            | 956            | [S ii] | 299            | 554            | 7.0       | 140       |
| NGC 7682      | [S ii] | 266            | 330            | [S ii] | 774            | 1102           | 1.3       | 66        |
| Mrk 348       | [O ii] | 543            | 770            | [O iii] | 669            | 991            | 6.6       | 13        |
| Mrk 1066      | [O iii] | 640            | 902            | [O iii] | 445            | 596            | 22        | 17        |
| NGC 2110      | [O iii] | 655            | 950            | [O iii] | 1670           | 2199           | 33        | 41        |
| NGC 4515      | [S ii] | 536            | 774            | [S ii] | 441            | 721            | 21        | 0.6       |
| NGC 5194      | ...   | ...            | ...            | ...   | 299            | 422            | -22       | ...       |
| NGC 5929      | [O iii] | 412            | 514            | [O iii] | 254            | 409            | 2.8       | 58        |
| NGC 7674      | [O iii] | 1255           | 1640           | [O iii] | 1524           | 1836           | -5.2      | -13       |

Notes.—Col. (1): galaxy name. Col. (2): line used for width measurements in NW95. Cols. (3)–(4): IPV20 and IPV10 values given by NW95. Col. (5): line used for our width measurements. Cols. (6)–(7): IPV20 and IPV10 values for our sample with a 0”2 aperture. Cols. (8)–(9): IPV20 and IPV10 values for our sample with a 1” aperture. Col. (10): percent change in IPV20 from 0”2 to 1” aperture sizes. Col. (11): percent difference between our IPV20 measurement within 1” and the NW95 IPV20 value.
Fig. 4.—IPV10 (crosses) and IPV20 (diamonds) measurements obtained from the Gaussian fits to the line profiles plotted against aperture size as in Fig. 3. The Nelson & Whittle (1995) measurements for IPV10 (dotted) and IPV20 (dashed) are plotted as horizontal lines. NGC 7682 is not shown because the red wing of the [S ii] line did not fall on the STIS CCD.
radiation-driven winds that decelerate at larger scales, as has already been noted for NGC 4151 by Nelson et al. (2000).

We note that several IPV profiles in Figure 4 exhibit pronounced jumps in IPV value with radius between neighboring data values. These jumps are either due to instances where our Gaussian fitting routine switched between a single-component fit and a multiple-component fit (or vice versa), or the presence of knots of line-emitting gas outside of the nuclear region.

5.2. Asymmetries

Figures 3 and 4 described above indicate that markedly different velocity components contribute to the emission-line profiles in the nucleus and at larger scales in approximately half of the sample. In addition to this information on the widths of these velocity components, the presence or absence of asymmetries can provide information on the origin of the line-emitting material along the line of sight, particularly in the presence of significant gas and dust in the NLR.

As noted previously, the [O III] line is quite often reported to have significant, typically blue, asymmetries, while asymmetries are rarely observed in lower excitation lines (Heckman et al. 1981; de Robertis & Osterbrock 1984; Whittle 1985b). Our measurements of the Whittle (1985b) asymmetry parameters listed in Table 4 confirm that asymmetries are more common in [O III], and these values are illustrated in Figure 5. Within the 0′′.2 aperture we find that 6/7 galaxies with [O III] observations have \(|A_{20}| > 0.1\), while 9/18 galaxies with [S II] observations have such asymmetries. While we observe asymmetries less frequently in [S II] than [O III], we still measure asymmetries in a substantially larger fraction of galaxies than typically observed in ground-based observations and we discuss this point further below. Two particularly extreme cases of asymmetries are NGC 1667 [S II] and NGC 5194 [O III]. The asymmetries are less pronounced in the larger 1′′ aperture, where only 7/18 galaxies in the [S II] sample and 5/7 in the [O III] sample have such significant asymmetries.

Several of these galaxies exhibit rather unusual asymmetries. While most have blue asymmetries, several have significant red asymmetries. One peculiar case is Mrk 573, which is more asymmetric on larger scales and this larger-scale asymmetry is red: \(A_{20} = -0.22\) in the 1′′ aperture. Inspection of HST images of Mrk 573 (Martini et al. 2003) reveals that the strong red asymmetry outside of the nucleus is due to the chance intersection of the STIS slit with an individual NLR cloud. Mrk 270 [S II], NGC 1667 [S II], and NGC 5194 [O III] also exhibit significant red asymmetries in the 0′′.2 aperture spectra, although they are less asymmetric on larger scales. The red-asymmetric component in these cases is broader than the core.

Blue asymmetries in [O III] were suggested by Heckman et al. (1981) to be due to a combination of radial outflow from the nuclear region and gas and dust that obscures the redshifted emission from the far side of the galaxy. The blue asymmetries...
have pronounced asymmetries on larger scales as well and indicate blue asymmetries, negative $A_{20}$ values indicate red asymmetries, and (see Fig. 1). For these two galaxies Mrk 348 agree well with this interpretation. NGC 7682 and Mrk confined to the nuclear region in NGC 4051, NGC 5347, and NGC 3031, NGC 5347, and spectra are the difference between the spectrum of each galaxy with the spectra shown in the rightmost panels of Figure 1. These sample at aperture sizes of 0''.

Fig. 5.—$A_{20}$ measurements for the $[\text{S} \text{ii}]$ and $[\text{O} \text{iii}]$ emission lines in our sample at aperture sizes of 0'' (crosses) and 1'' (diamonds). Positive $A_{20}$ values indicate blue asymmetries, negative $A_{20}$ values indicate red asymmetries, and near-zero values indicate symmetric profiles. The average $A_{20}$ values for $[\text{S} \text{ii}]$ and $[\text{O} \text{iii}]$ at each aperture are shown.

summed with a 1'' aperture and a 0'' aperture and therefore effectively isolate the emission-line component due to material outside of the nuclear region. The two vertical lines in each panel for a given galaxy correspond to the line peak of the emission lines in the 1'' aperture. The line profiles in the rightmost panels relative to these vertical lines therefore illustrate the extent to which emitting material outside of 0'' contributes to any asymmetries in the line profiles. To characterize the line asymmetry outside of the nuclear, 0'' aperture, we calculated the fraction of the total 1''-0'' line flux on the blue side of the line centroid in the 1'' aperture. A fraction greater than 0.5 corresponds to a blue asymmetry, while less than 0.5 corresponds to a red asymmetry. These values are listed in the last column of Table 4. Eight galaxies have strong blue asymmetries outside of 0'' (fraction > 0.6), 2 have strong red asymmetries (fraction < 0.4), and the remaining 14 are either relatively symmetric (10) or have little flux outside of 0'' (5) in the STIS aperture. The significant asymmetry in NGC 2110 is only seen in $[\text{O} \text{iii}]$.

6. DISCUSSION

The changes in the NLR velocity field in the STIS aperture have revealed pronounced differences between the unresolved, nuclear kinematics and the NLR on larger scales, yet these larger scale kinematics still sub tend only a fraction of the NLR for many galaxies because of the narrow STIS slit. Even the line characteristics measured from the integrated STIS slit may therefore differ from ground-based flux measurements. We estimated the fraction of the NLR observed with these observations through a comparison of the total flux in the STIS aperture and the value reported in the ground-based measurements from Whittle

| Name       | Line | $A_{10}$ (0''2) | $A_{20}$ (0''2) | $A_{10}$ (1'') | $A_{20}$ (1'') | Blue Area (1''-0''2) |
|------------|------|----------------|----------------|---------------|---------------|---------------------|
| Mrk 270    | [S ii] | -0.17          | -0.20          | -0.12         | -0.14         | 0.43                |
| Mrk 573    | [S ii] | 0.00           | -0.01          | -0.21         | -0.22         | 0.24                |
| Mrk 686    | [S ii] | -0.3           | -0.03          | 0.00          | 0.00          | ...                 |
| NGC 788    | [S ii] | 0.13           | 0.11           | 0.03          | 0.03          | 0.76                |
| NGC 1052   | [S ii] | -0.09          | -0.09          | -0.05         | -0.06         | 0.35                |
| NGC 1358   | [S ii] | 0.01           | 0.03           | 0.01          | 0.01          | ...                 |
| NGC 1667   | [S ii] | -0.23          | -0.21          | 0.03          | 0.04          | 0.46                |
| NGC 2110   | [S ii] | -0.09          | -0.10          | 0.00          | 0.00          | 0.48                |
| NGC 2273   | [S ii] | 0.34           | 0.42           | 0.34          | 0.39          | 0.76                |
| NGC 3031   | [S ii] | 0.00           | 0.01           | 0.00          | -0.01         | 0.77                |
| NGC 3227   | [S ii] | 0.09           | 0.12           | 0.10          | 0.13          | 1.00                |
| NGC 3516   | [S ii] | 0.00           | 0.01           | 0.00          | 0.01          | ...                 |
| NGC 3982   | [S ii] | 0.26           | 0.25           | 0.24          | 0.22          | ...                 |
| NGC 4051   | [S ii] | 0.29           | 0.31           | 0.25          | 0.25          | 0.82                |
| NGC 4579   | [S ii] | -0.06          | -0.07          | -0.08         | -0.09         | 0.59                |
| NGC 5347   | [S ii] | 0.35           | 0.37           | 0.32          | 0.34          | 0.56                |
| NGC 5427   | [S ii] | -0.02          | -0.02          | -0.02         | -0.02         | ...                 |
| NGC 7682   | [S ii] | ...            | ...            | ...           | ...           | 0.52                |
| Mrk 348    | [O ii] | 0.36           | 0.38           | 0.28          | 0.29          | 0.56                |
| Mrk 1066   | [O ii] | 0.41           | 0.33           | 0.31          | 0.29          | 0.46                |
| NGC 2110   | [O ii] | 0.15           | 0.12           | 0.11          | 0.14          | 0.78                |
| NGC 4151   | [O ii] | -0.02          | -0.02          | 0.14          | 0.12          | 0.42                |
| NGC 5194   | [O ii] | -0.13          | -0.18          | 0.03          | 0.06          | 0.52                |
| NGC 5929   | [O ii] | -0.13          | -0.17          | -0.08         | -0.06         | 0.70                |
| NGC 7674   | [O ii] | 0.46           | 0.44           | 0.45          | 0.45          | 0.75                |

Notes.—Col. (1): galaxy name. Col. (2): emission line used in STIS data analysis. Col. (3)–(4): $A_{20}$ and $A_{10}$ asymmetry measurement within a 0'' aperture. Col. (5)–(6): $A_{20}$ and $A_{10}$ measurement within a 1'' aperture. Col. (7): fraction of the 1''-0''2 profile area that lies blueward of the 1'' line centroid.
This comparison demonstrated that the STIS aperture includes between 25% and 90% of the [O\textsc{iii}] flux measured by Whittle (1992a) for the seven galaxies with STIS [O\textsc{iii}] measurements. The velocity field sampled by the STIS apertures also may depend on the orientation of the spectroscopic slit relative to the major axis of the host galaxies, as there is evidence that rotation is partly responsible for the NLR widths (Whittle 1992b), or the orientation relative to the NLR and radio jet axis, which are known to be unrelated to the host galaxy semimajor axis (Ulvestad & Wilson 1984; Schmitt et al. 2003). However, the orientation for most of these observations was not specified in order to reduce scheduling constraints.

6.1. Comparison with Ground-based Measurements

One striking characteristic of Figures 3 and 4 is how poorly the line profile measurements agree with the ground-based values on even the largest scales (see also Fig. 6). Of the 24 galaxies with measured FWHM in the 1\arcsec aperture, the FWHM of only 6 (NGC 1358, NGC 3031, NGC 3982, NGC 4051, NGC 4151, and NGC 7674) is within 10% of the ground-based value (see Table 2), while 12 are discrepant by greater than 30%—comparable to the observed scatter in the $\sigma_\gamma$-$\sigma_\delta$ correlation. Surprisingly, 1 of these 12 measurements (NGC 2110 [S\textsc{ii}]) is actually >30% larger in the STIS aperture than in the ground-based measurement. This broad, nuclear component is quite obvious in Figure 1. For NGC 3516 the difference between the STIS and NW95 measurements can be attributed to the slit orientation, as this galaxy is known to have a large, extended NLR (Pogge et al. 1989a), yet we detect little emission in our slit outside of the nuclear region.

For the seven galaxies with [O\textsc{iii}] measurements, we examined the difference between the FWHM in our 1\arcsec aperture and the ground-based value as a function of the fraction of the
flux within the 1″ STIS aperture. The STIS flux measurement for NGC 7674 includes 90% of the ground-based value reported by Whittle (1992a), and our measured FWHM is within 10% of his value. This confirms that when most of the ground-based flux falls within our much narrower aperture we measure the same kinematics. For the other six galaxies these data miss a larger fraction of the total flux and the line widths are quite different in some instances. The most notable is the STIS measurement of Mrk 348, which includes 60% of the ground-based value and is 60% narrower. The STIS measurements of the remaining five galaxies include only 30% of the flux in the Whittle (1992a) aperture and the differences in width between the two aperture sizes range between none (NGC 4151) and 150% (NGC 5929).

The disagreement between widths measured in our 1″ aperture and the ground-based aperture is more striking for IPV20 (see also Table 3) than for line widths, as only two galaxies (NGC 4051 and NGC 4151) have STIS 1″ and NW95 measurements that agree within 10%. The majority (15/24) have NW95 values >30% larger than the STIS measurements and 2/24 (NGC 7682 and NGC 2110 [O iii]) are less than 30% of the ground-based measurements. However, we note that most differences in IPV20 between the STIS 1″ and NW95 are comparisons between STIS [S ii] and NW95 [O iii] measurements and they may therefore partly reflect more pronounced wings in the [O iii] line relative to [S ii]. For example, NGC 2110 has a 1″ IPV20 = 423 km s\(^{-1}\) for [S ii] and IPV20 = 1105 km s\(^{-1}\) for [O iii]. NW95 measured 655 km s\(^{-1}\) for [O iii].

As described in § 5.2, there are also substantial differences between the fraction of AGNs with asymmetries in the low-excitation [S ii] line in these data and ground-based measurements. This change may be due to the dilution of nuclear asymmetries by larger scale emission from host galaxy starlight or more symmetric emission from the NLR on larger scales. Host galaxy dilution may in particular explain why we detect significant asymmetries in such a large fraction of the [S ii] profiles compared to expectations from ground-based programs (Filippenko & Halpern 1984; de Robertis & Osterbrock 1984; Greene & Ho 2005). This result implies that the asymmetries are primarily due to nuclear line-emitting gas, rather than material more evenly distributed throughout the NLR on larger scales.

This comparison of width and IPV values suggest that measurements within the STIS aperture are generally smaller than the ground-based values. A quantitative comparison demonstrates that this is the case, relative to both ground-based NLR width measurements and \(\sigma_2\) (see Table 5 and Fig. 6). Comparison of the STIS FWHM measurements in the 0″2, 1″, 100 pc, and 200 pc apertures (divided by 2.354 to approximate a Gaussian \(\sigma_g\)) to \(\sigma_2\) show that the STIS measurements systematically underestimate \(\sigma_2\) by 10%–20%. The STIS measurements similarly underestimate the ground-based NW95 FWHM measurements. Figure 6 does not show any significant evidence for differences between [S ii] and [O iii]. The scatter between STIS and \(\sigma_2\) measurements is slightly worse (30%–40%) than the scatter between STIS and NW95 FWHM measurements (20%–40%). In contrast, Figure 7 indicates that STIS measurements at 0″2 and 1″ are significantly more similar in value and have substantially less scatter (10%–20%); see also Table 5). The smaller measured widths in the STIS slit is likely due to the collisional nature of gas, which will therefore tend to reside at least partially in a disk. A narrow slit at a random orientation will then sample a smaller fraction of the full radial velocity field than a larger aperture slit and therefore measure a smaller width.

The comparable number of galaxies with red and blue asymmetries on larger scales, and more importantly that these asymmetries are in general substantially weaker than those in the 0″2 aperture, suggest that asymmetries measured in large (including ground based) apertures originate on small scales, or less than ~100 pc based on the spatial resolution of these observations.

### 6.2. Correlations with Global Properties

In addition to the quality of the correlations between line widths measured in various apertures and \(\sigma_2\), we also searched for systematic trends between the residuals and the properties of the galaxies. We specifically investigated the residuals between the measurements in the 1″ aperture and \(\sigma_2\) as a function of distance, Hubble type, fraction of the galaxy in a 1″ aperture, and radio power. Significant residuals as a function of galaxy distance, Hubble type, and fraction of the angular size of the galaxy subtended by the spectroscopic slit would indicate very useful information about the origin of the scatter in the \(\sigma_2-\sigma_2\) relation, and these quantities could potentially be used to empirically determine corrections to reduce scatter, as well as provide insight into its origin. For example, the NLR measured
Fig. 7.—Comparison of our [S II] (diamonds) and [O III] (stars) FWHM measurements in different apertures. (a) Width measured in a 1'' aperture plotted against the width measured in an 0.2'' aperture. (b) Width measured in a 200 pc aperture plotted against the width measured in a 100 pc aperture. The dashed line in each frame represents a 1:1 correspondence between the quantities plotted.

Fig. 8.—Comparison of residuals between gas and stellar kinematics and various global properties. The four panels show (a) distance, (b) Hubble T type, (c) fraction of the galaxy size (2'' divided by the angular size provided in Table 1), and (d) radio power. The points to the left of the dashed line do not have a measured radio flux and are only shown to indicate the ordinate values.
exactly within the host bulge’s effective radius might prove to be the best tracer of $\sigma$. Some evidence for such a relation might be revealed in the residuals plotted against these three parameters; however, as shown in Figure 8, there is no evidence that the residuals are correlated with any of these parameters.

Whittle (1992c) found evidence that Seyfert galaxies with linear radio morphology and high luminosity tend to have broader lines. We do not see significant correlation between residuals in $\sigma$ and $\sigma$ in our data, although only three galaxies in our sample are above his radio luminosity threshold of $L_{1415} \geq 10^{22.5}$ W Hz$^{-1}$. Other parameters mentioned in § 4 that correlate with systematically broader emission-line widths include $L/L_{\text{Edd}}$ (Greene & Ho 2005) and disturbed morphologies (Whittle 1992b); however, this sample does not contain a sufficient number of objects with either high accretion rates or significantly disturbed morphologies to investigate these quantities. Boroson (2005) also recently noted that strongly blueshifted [O iii] lines (relative to the host galaxy) were systematically broader than similar objects that were not blueshifted. These objects tended to be those with large $L/L_{\text{Edd}}$. None of the seven galaxies in our [O iii] sample have substantial blueshifts.

7. SUMMARY

We have conducted a detailed analysis of spatially resolved [O iii] and [S ii] NLR emission from 24 well-studied, nearby AGNs. These observations have detected considerable emission outside of the unresolved nucleus (0′/2 or 10–100 pc) and this emission often contributes significantly to the measured line profiles at larger scales. We have characterized the spatial dependence of this emission with a range of width, area, and asymmetry measurements and shown that there are not only substantial changes from 0′/2 to 1′ (typical of ground-based observations) but also from a 1′ long STIS aperture (with either a 0′/1 or 0′/2 width) and the approximately 1′ × 1′ or larger aperture used for ground-based measurements of these galaxies. In particular, the large variations in line profiles as a function of aperture size demonstrate that the profile of the NLR lines are set by the kinematics of the gas in the NLR itself and not just radiatively driven winds from the nucleus.

The spatial scale(s) responsible for the NLR emission lines has received substantial recent attention because the widths of the NLR lines may be used to estimate the stellar velocity dispersion $\sigma$, which in turn can be used as a proxy for the black hole mass $M_\bullet$. Our analysis shows that even at the largest spatial scales observed with STIS, the line widths are systematically smaller by 10%–20% than ground-based width measurements (as well as $\sigma$). As we estimate that the STIS slit may include as little as 25% of the NLR flux, emission on larger scales or outside of the narrow STIS slit width must broaden the line profiles.

While the line profile measurements from the STIS data are systematically less than the ground-based NLR and $\sigma$ values, the scatter is comparable. The substantial scatter in the $\sigma$ relation therefore appears to be due to a sufficiently complex set of parameters that it is effectively stochastic, at least to the extent that the scatter cannot be reduced to the magnitude of the scatter in the $M_\bullet-\sigma$ relation. In addition to rotation, Eddington ratio, and compact radio jets, the list of parameters that increase the scatter should include the clumpiness of the NLR, the orientation of the NLR with respect to the host galaxy semimajor axis, and the amount and distribution of dust in the NLR. If the NLR were as isotropic as the stellar distribution, the scatter would be comparable to the $M_\bullet-\sigma$ relation; yet because the gas is collisional, and also clumpy, it cannot be as good a tracer of the bulge potential.

This interpretation is supported by the substantial and diverse types of width variations observed in these spatially resolved measurements. Specifically, the most common types of line width variation are <30% changes between the 0′/2, 1′, and NW95 apertures (nine galaxies) and relatively little width increase in the STIS aperture, but a substantial increase (>30%) between the 1′ STIS and NW95 measurements (also nine galaxies). The remaining types of variations observed are greater than 30% width changes on the STIS scales only (four) and on all scales (two). Two of the four galaxies with only substantial profiles changes on the STIS scale have substantially broader emission in the 0′/2 than in the 1′ aperture. These large nuclear velocities may be due to radiatively driven winds that decelerate or simply do not extend to larger scales. However, neither of these nuclear line profiles exhibit substantial asymmetries, which suggests that if this emission is due to a uniform outflow, there is not substantial dust in the nuclear region.

Both red and blue asymmetries are observed in the [S ii] and [O iii] line profiles. These observations are unusual in two respects. First, asymmetries in [S ii] are reported far less frequently than in [O iii], yet we observe [S ii] asymmetries with nearly comparable frequency. The low frequency of observed [S ii] asymmetries in ground-based observations has been ascribed to the fact that [S ii] is a lower ionization line. Our observations suggest that asymmetries are commonly present in [S ii], but the weaker [S ii] emission is more easily diluted by host galaxy starlight and not as readily observed in the larger ground-based apertures. Second, we observe several examples of galaxies with red asymmetries in either [S ii] or [O iii]. For the cases in which the red asymmetries are largely confined to the unresolved nuclear spectrum, these observations do not agree well with outflow models that produce blue asymmetries through invocation of obscuration of the far side of the galaxy. These red asymmetries may be due to the patchy nature of the ISM on very small scales, which may produce uneven illumination of NLR clouds and a patchy line-of-sight velocity distribution for the NLR clouds. Such variations within the NLR may be responsible for the bulk of the scatter in the $\sigma$ relation.

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