THE MASS OF THE CENTRAL BLACK HOLE IN THE SEYFERT GALAXY NGC 3783

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ABSTRACT

Improved analysis of ultraviolet and optical monitoring data on the Seyfert 1 galaxy NGC 3783 provides evidence for the existence of a supermassive, \((8.7 \pm 1.1) \times 10^6 \, M_\odot\) black hole in this galaxy. By using recalibrated spectra from the International Ultraviolet Explorer satellite and ground-based optical data, as well as refined techniques of reverberation mapping analysis, we have reduced the statistical uncertainties in the response of the emission lines to variations in the ionizing continuum. The different time lags in the emission-line responses indicate a stratification in the ionization structure of the broad-line region and are consistent with the virial relationship suggested by the analysis of similar active galaxies.

Subject headings: galaxies: active — galaxies: individual (NGC 3783) — galaxies: nuclei — galaxies: Seyfert — ultraviolet: galaxies

On-line material: machine-readable tables

1. INTRODUCTION

The primary model that has emerged over the last few decades for the radiation source of an active galactic nucleus (AGN) is accretion onto a supermassive black hole (SMBH). Variations in the ionizing continuum have been seen to influence the strength of emission lines arising from the broad-line region (BLR). Cross-correlation of the continuum and emission-line light curves yields a characteristic time lag with which each line echoes the continuum fluctuations (Blandford & McKee 1982). This reverberation mapping technique has been used to measure the sizes of BLRs for a growing number of AGNs (see Wandel, Peterson, & Malkan 1999; Kaspi et al. 2000).

In addition to the BLR size, reverberation analysis can be used to estimate the mass of the SMBH. The reliability of these reverberation masses has been debated because of the uncertainty surrounding the common assumption of virialized BLR gas motions. The detailed kinematics and structure of the BLR is an unresolved issue and could lead to systematic errors on the order of a factor of a few or perhaps more (see Fromerth & Melia 2001; Krolik 2001). However, the excellent agreement between the black hole mass–bulge velocity dispersion \((M-\sigma)\) relationships for reverberation-mapped AGNs and normal galaxies (Ferrarese et al. 2001) suggests that the systematic discrepancy introduced in reverberation mapping is small. Additionally, AGNs for which multiple emission lines have been mapped (NGC 5548, 3C 390.3, NGC 7469) show an inverse relationship between the time lag and the emission-line width, consistent with the gas motions being dominated by the gravity of the SMBH (Peterson & Wandel 1999, 2000).

A combined optical and ultraviolet (UV) monitoring campaign was carried out on the Seyfert 1 galaxy NGC 3783 by the International AGN Watch consortium, making use of the International Ultraviolet Explorer (IUE), the Hubble Space Telescope (HST), and a host of ground-based observatories over a period of 7 months in 1991–1992. The results of that work have been published by Reichert et al. (1994), Stirpe et al. (1994), and Alloin et al. (1995). Compared to the consortium’s earlier study of another Seyfert galaxy, NGC 5548 (see Clavel et al. 1991; Peterson et al. 1991; Dietrich et al. 1993), the emission-line time lags were relatively uncertain, too poorly constrained in fact to reveal any possible virial relationship between line width and time lag.

The continued rarity of such campaigns, however, makes it clearly desirable to learn as much as possible from the extant data sets. This provides the motivation for our current study.

With the release of an updated processing pipeline and calibration for IUE data, the possibility arose to reanalyze the spectra of NGC 3783 and reduce the uncertainties of the emission-line time lags. In addition, the techniques of reverberation analysis have matured in the years since the original data were published, now providing more consistent methodology for cross-correlation and error estimation. Thus, we have reexamined the data, deriving more precise results for the emission-line reverberation and revising the previous estimates of the reverberation mass.

Section 2 describes the observations and how the data were reduced. In § 3, we explain the analysis procedure and give our cross-correlation results. Section 4 discusses the results and the SMBH mass determination, and our conclusions are summarized in § 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. UV Data

The IUE observations of NGC 3783 were conducted in 69 separate epochs with two sampling rates. The first interval (of 45 epochs) had an average spacing of 4.0 days, while the final 24 epochs observed the AGN with an average spacing of 2.0 days. A more complete description of the UV observing program is provided by Reichert et al. (1994).

In addition to the original IUE Spectral Image Processing System (UESIPS), Reichert et al. (1994) used a Gaussian extraction method (GEX; see Clavel et al. 1991) to obtain the spectra of NGC 3783. After the original data had been taken, a new standard processing pipeline was introduced. The main advantages of the New Spectral Image Processing System (NEWSIPS; Nichols et al. 1993) with respect to the older IUESIPS are the improved photometric accuracy and
higher signal-to-noise ratio (S/N) of the spectra; these characteristics have been achieved by introducing a new method of raw data science registration (which both reduces the fixed pattern noise in the images and improves the photometric corrections), a weighted slit extraction method, and rederived absolute flux calibrations. NEWSIPS also includes corrections for nonlinearity that might have affected previous studies. Overall, NEWSIPS-processed spectra show average S/N increases of 10%–50% over IUE-SIPS data (Nichols & Linsky 1996).

We retrieved the NEWSIPS-extracted short-wavelength prime camera (SWP; Harris & Sonneborn 1987) spectra from the IUE Final Archive.1 While Reichert et al. (1994) analyzed data from both the SWP and long-wavelength prime cameras, we have limited our study to observations made with the SWP instrument, which has a wavelength range of 1150–1975 Å in the low-dispersion mode (Newmark et al. 1992).

Each spectrum was examined and several types of problems led to spectra being removed from further consideration: (1) low S/N (determined by inspection, but corresponding roughly to a continuum S/N limit of 10); (2) unusual spectral features (possibly due to grazing cosmic-ray impacts); and (3) short exposure times (when longer exposure data were available from the same epoch and the line-flux data were discrepant). Some anomalous features were checked against the GEX frames, from which cosmic-ray impacts were carefully removed. Problems with the spectra were ignored in cases where they occurred in spectral regions outside those used in computing line and continuum fluxes. Continuum and emission-line flux values were measured using the wavelength limits listed in Table 1.

The continuum was defined by a linear fit through four spectral regions (1340–1370, 1440–1480, 1710–1730, and 1840–1860 Å). An alternate fit through the first three of these regions produced consistent results. Wavelength-specific problems in two cases (SWP 45150 and SWP 45206) led us to substitute the alternate continuum fit for these spectra.

We have estimated the flux uncertainties by considering instances in which multiple independent exposures were obtained at the same epoch (i.e., a single pointing toward the target). Flux ratios between pairs of points within each epoch were calculated, and the standard deviation of the flux ratios was taken as the fractional uncertainty for all observations. This analysis was conducted independently for each emission line and continuum band. As noted above, however, highly discrepant data were removed prior to this analysis. In spite of our use of an edited data set, the large number of data pairs contributing to our error estimate (about 35) justifies our continued use of these values in the analysis. The final UV data set is given in Table 2 for the continuum measurements and in Table 3 for the emission lines.

The velocity width desired for the reverberation mass calculation is related to the emission-line velocity full width at half-maximum ($V_{\text{FWHM}}$) by

$$\sigma = \frac{\sqrt{3} V_{\text{FWHM}}}{2},$$

where the factor of $3^{1/2}/2$ is used to maintain consistency with previous work (e.g., Wandel et al. 1999; Kaspi et al. 2000) and assumes isotropic gas motion.

An rms spectrum was created from the data to isolate the varying parts of the emission lines, and it was from this spectrum that the primary $V_{\text{FWHM}}$ values for the emission lines were measured. The $V_{\text{FWHM}}$ data were constructed by considering the extreme flux values within the continuum regions, fitting two continuum slopes (to the highest flux levels and lowest flux levels), and averaging the measures of $V_{\text{FWHM}}$ derived from the two continuum determinations. Finally, the data were converted to their rest-frame widths using $z = 0.009730 \pm 0.000007$ (Theureau et al. 1998). Previous work examining the difference between using the mean and rms spectra have not produced significantly different results (e.g., Kaspi et al. 2000), but in principle the rms spectrum should better trace the gas with which we are concerned. We have measured line widths from both spectra (Fig. 1) and report the results of our mean and rms $V_{\text{FWHM}}$ measurements in Table 4. Geocoronal $Ly\alpha$ emission blended into the $Ly\alpha$ spectral region precludes $V_{\text{FWHM}}$ measurement for this line and thus also prevents $Ly\alpha$ contribu-

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1 See http://ines.laeff.esa.es/ines.

| Line/Band | Wavelength Range (Å) |
|-----------|----------------------|
| 1355 Å continuum .................. | 1340–1370 |
| 1460 Å continuum .................. | 1445–1475 |
| 1835 Å continuum .................. | 1820–1850 |
| 5150 Å continuum .................. | 5140–5160 |
| Lyα ........................................... | 1225–1280 |
| Si iv λ1400 + O iv/λ1402 ........... | 1355–1460 |
| C iv λ1549 .............................. | 1460–1624 |
| He II λ1640 + O iii/λ1663 ........... | 1624–1710 |
| Si iii λ1892 + C iii/λ1909 ........... | 1890–1948 |
| Hβ ........................................... | 4830–4985 |

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FIG. 1.—Top: rms UV spectrum. Bottom: Mean UV spectrum. Wavelengths delineated above the spectrum indicate emission-line ranges, while those below the spectrum mark ranges of continuum flux measurement.
were scaled to a constant flux by using the spectral scal-
timescales these data are probing. Thus, the individual spec-
ations for further analysis.

that were excessively noisy or contained other anomalies
set possible for the cross-correlation analysis and
(CTIO) 1.0 m telescope to ensure the most homogene-
data gathered at the Cerro Tololo Inter-American Observa-
Stirpe et al. (1994). We have limited our investigation to the
sis is still feasible by excluding the contaminated portion of
m determination, but cross-correlation analy-

### 2.2. Optical Data

Ground-based optical spectroscopy was conducted over
the same time period as the IUE observations. The optical
data analyzed here were retrieved from the AGN Watch
site, and details of the observations are described by
Stirpe et al. (1994). We have limited our investigation to the
data gathered at the Cerro Tololo Inter-American Observa-
tory (CTIO) 1.0 m telescope to ensure the most homogene-
ous data set possible for the cross-correlation analysis and
for the construction of the mean and rms spectra. Spectra
that were excessively noisy or contained other anomalies
were discarded from consideration, leaving 37 CTIO observ-
ations for further analysis.

Narrow spectral lines are assumed to not vary over the
timescales these data are probing. Thus, the individual spec-
tra were scaled to a constant flux by using the spectral scal-

![RMS Optical Spectrum](image_url)

**Fig. 2.** Top: rms optical spectrum. Bottom: Mean optical spectrum. Wavelength indications same as in Fig. 1.

### Table 2

| Image Name     | Julian Date (2,440,000+) | $F(\lambda 1355)$ | $F(\lambda 1460)$ | $F(\lambda 1835)$ |
|---------------|-------------------------|------------------|------------------|------------------|
| SWP 43438.....| 8611.948                | 60.811 ± 2.432   | 57.899 ± 2.142   | 52.244 ± 1.776   |
| SWP 43439.....| 8612.031                | 57.353 ± 2.294   | 57.395 ± 2.124   | 50.582 ± 1.720   |
| SWP 43472.....| 8615.949                | 51.984 ± 2.079   | 50.204 ± 1.858   | 47.259 ± 1.607   |
| SWP 43473.....| 8616.029                | 51.979 ± 2.079   | 45.407 ± 1.680   | 45.024 ± 1.531   |
| SWP 43485.....| 8618.118                | 47.391 ± 1.896   | 47.043 ± 1.741   | 44.713 ± 1.520   |

**Note.**—Continuum fluxes are given in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

### Table 3

| Image Name     | Julian Date (2,440,000+) | He ii $\lambda 1640 +$ O iii $\lambda 1663$ | Si iv $\lambda 1400 +$ O iv $\lambda 1402$ | Ly$\alpha$ | C iv $\lambda 1549$ | Si iii $\lambda 1892 +$ C iii $\lambda 1909$ |
|---------------|-------------------------|------------------------------------------|------------------------------------------|-----------|----------------|------------------------------------------|
| SWP 43438.....| 8611.948                | 17.051 ± 1.705                           | 12.769 ± 1.430                           | 41.751 ± 1.837 | 76.614 ± 2.988 | 9.707 ± 1.175                           |
| SWP 43439.....| 8612.031                | 14.790 ± 1.479                           | 10.856 ± 1.216                           | 41.387 ± 1.821 | 74.662 ± 2.912 | 9.180 ± 1.111                           |
| SWP 43472.....| 8615.949                | 15.837 ± 1.584                           | 10.362 ± 1.161                           | 38.720 ± 1.704 | 69.633 ± 2.716 | 8.968 ± 1.085                           |
| SWP 43473.....| 8616.029                | 15.365 ± 1.536                           | 11.732 ± 1.314                           | 39.614 ± 1.743 | 71.235 ± 2.778 | 13.764 ± 1.665                           |
| SWP 43485.....| 8618.118                | 13.188 ± 1.319                           | 8.559 ± 0.959                            | 37.369 ± 1.644 | 73.775 ± 2.877 | 10.270 ± 1.243                           |

**Note.**—Emission-line fluxes are in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

### Table 4

| Emission Line     | $V_{\text{FWHM}}^\text{rms}$ (rms) | $V_{\text{FWHM}}^\text{mean}$ (mean) |
|------------------|-----------------------------------|--------------------------------------|
| He ii $\lambda 1640 +$ O iii $\lambda 1663$.....| 6.34 ± 0.90 | 4.74 ± 0.69 |
| Si iv $\lambda 1400 +$ O iv $\lambda 1402$.....| 5.73 ± 2.71 | 4.81 ± 0.50 |
| Ly$\alpha$........| .......................... | .......................... |
| C iv $\lambda 1549$..........................| 3.55 ± 0.59 | 3.03 ± 0.07 |
| Si iii $\lambda 1892 +$ C iii $\lambda 1909$.....| 2.61 ± 0.16 | 2.82 ± 0.31 |

**Note.**—Velocity data are in units of $10^3$ km s$^{-1}$. 

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2 See http://www.astronomy.ohio-state.edu/~agnwatch.
between 5028 and 5090 Å) to less than 2.5%. Additional iterations failed to produce any light curves with smaller scatter. The mean [O III] λ5007 flux was normalized to $8.44 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, the value derived by the careful analysis of Stirpe et al. (1994).

Following the calibration of the spectra, the Hβ line was measured between 4830 and 4985 Å (with the continuum set by a linear fit between 4800–4820 and 5130–5150 Å). The flux uncertainties were measured in the same way as for the UV data (§ 2.1), and the results are given in Table 5. Because of the smaller optical data set, the flux errors for Hβ and the 5150 Å continuum rely on only seven data pairs. To be cautious, we have been more conservative in our estimation of the optical flux uncertainties. The method for measuring $\gamma_{\text{FWHM}}$ was also applied to the optical data and yielded values of (2.91 ± 0.19) $\times 10^3$ km s$^{-1}$ for the rms spectrum and (2.65 ± 0.02) $\times 10^3$ km s$^{-1}$ for the mean optical spectrum.

### 3. LIGHT-CURVE ANALYSIS

In Table 6, we compare the sampling characteristics of our data with the previously published light curves. When we bin the data in each epoch, the variability parameters of the old and new UV data sets appear nearly identical. The “excess variance” $F_{\text{var}}$ represents the mean fractional variation of each data set (see Rodrigues-Pascual et al. 1997); $R_{\text{max}}$ is the ratio of maximum to minimum flux levels. The updated optical data set is much more sparse than the previously published data because of our desire for the most homogeneous data set possible.

Figure 3 shows the light curves for each of the UV and optical emission lines and continuum bands. Applying the techniques described by Peterson et al. (1998), we generated cross-correlation functions (CCFs) relating the various emission-line light curves to the 1355 Å continuum flux. We report both peak ($\tau_{\text{peak}}$) and centroid ($\tau_{\text{cent}}$) cross-correlation lags. However, the reader should be warned that “lags” in the text will hereafter refer to centroids unless otherwise noted and that such lags do not represent a simple phase shift between the light curves.

As Koratkar & Gaskell (1991a) noted for NGC 3783 (and other reverberation-mapped AGNs), the choice of what threshold to use for the centroid calculation can significantly affect the resulting time lag. Figure 4 shows that some lines tend toward larger lags and others toward smaller values as the centroid becomes increasingly dominated by the peak value. For the interpolated CCF (ICCF; Gaskell & Peterson 1987; White & Peterson 1994), we experimented with different interpolation lengths and different thresholds for the calculation of the lag centroid. Our subsequent analysis uses an interpolation unit of 0.1 days in both light curves (interpolating one data set at a time, with the resulting lags averaged) and a centroid threshold of 80% of the peak correlation coefficient.

In addition to the ICCF, we calculated the discrete correlation function (DCF; Edelson & Krolik 1988) for each continuum band and emission line. While the DCF, which requires binning of the data, is more likely to miss a real correlation than the ICCF under poor sampling conditions, it is also less likely to introduce a spurious relationship (White

### Table 5

| Image Name       | Julian Date (2,440,000+) | F(λ5150) (10$^{-15}$ ergs cm$^{-2}$ Å$^{-1}$) | Hβ (10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) |
|------------------|--------------------------|---------------------------------------------|-----------------------------------------|
| n38607a.......... | 8607.830                 | 11.406 ± 0.605                             | 9.829 ± 0.403                           |
| n38623a.......... | 8623.830                 | 11.707 ± 0.620                             | 10.100 ± 0.414                          |
| n38627a.......... | 8627.830                 | 11.094 ± 0.588                             | 10.272 ± 0.421                          |
| n38631a.......... | 8631.840                 | 10.865 ± 0.576                             | 10.494 ± 0.430                          |
| n38635a.......... | 8635.830                 | 10.781 ± 0.571                             | 10.183 ± 0.418                          |

**Note:** Table 5 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

### Table 6

| Subset                                      | Number | Average | Median | $F_{\text{var}}$ | $R_{\text{max}}$ | Reference |
|----------------------------------------------|--------|---------|--------|-----------------|-----------------|-----------|
| Previous 1460 Å continuum data set...        | 69     | 3.3     | 3.9    | 0.201           | 3.027 ± 0.380   | 1         |
| New UV data set:                             |        |         |        |                 |                 |           |
| Binned by epoch..................................| 69     | 3.3     | 3.9    | 0.203           | 3.119 ± 0.163   | 1         |
| Complete sample..................................| 101    | 2.2     | 2.0    | 0.192           | 2.856 ± 0.162   | 1         |
| 4 day sampling period...........................| 62     | 2.8     | 3.9    | 0.193           | 2.762 ± 0.145   | 1         |
| 2 day sampling period...........................| 40     | 1.3     | 1.7    | 0.140           | 2.043 ± 0.107   | 1         |
| Previous 5150 Å continuum data set...        | 72     | 3.2     | 2.0    | 0.078           | 1.517 ± 0.042   | 2         |
| New optical data set:                        |        |         |        |                 |                 |           |
| Binned by epoch..................................| 35     | 6.6     | 4.0    | 0.065           | 1.516 ± 0.114   | 1         |
| Complete sample..................................| 37     | 6.2     | 4.0    | 0.064           | 1.516 ± 0.114   | 1         |

**Note:** Previously published light curves were collected from the AGN Watch Web site.

**References:** (1) Reichert et al. 1994; (2) Stirpe et al. 1994.
continuum, (plotted are for He $s$ ergs cm$^{-750}$ ONKEN & PETERSON Vol. 572 Si $i$ iii dashed line short-dashed line 1402 (1.4

Fig. 3.—UV and optical light curves: (a) 1355 Å continuum, (b) 1460 Å continuum, (c) 1835 Å continuum, (d) 5150 Å continuum, (e) He $n$ λ1640 + O $m$ λ1663, (f) Si iv λ1400 + O $v$ λ1402, (g) Lyα, (h) C iv λ1549, (i) Si $m$ λ1892 + C $m$ λ1909, and (j) Hβ. Continuum fluxes are in units of 10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$. Emission line fluxes are in units of 10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$. The light curves for each emission line (He $n$ λ1640 + O $m$ λ1663, Si iv λ1400 + O $v$ λ1402, Lyα, C iv λ1549, Si $m$ λ1892 + C $m$ λ1909, and Hβ) were run through the ICCF, DCF, and FR/RSS programs, using the 1355 Å continuum data as the “driving” light curve. The CCFs and CCPDs are shown for each emission line in the panels of Figure 5. The CCPDs are shown to give a graphic indication of the empirical uncertainties and are scaled to the maximum value in each panel.

3.1. Emission Lines

The light curves for each emission line (He $n$ λ1640 + O $m$ λ1663, Si iv λ1400 + O $v$ λ1402, Lyα, C iv λ1549, Si $m$ λ1892 + C $m$ λ1909, and Hβ) were run through the ICCF, DCF, and FR/RSS programs, using the 1355 Å continuum data as the “driving” light curve. The CCFs and CCPDs are shown for each emission line in the panels of Figure 5. The CCPDs are shown to give a graphic indication of the empirical uncertainties and are scaled to the maximum value in each panel.

Each of the emission lines was very well correlated with the continuum flux. The poorest correlation with the continuum was found for Si $m$ λ1892 + C $m$ λ1909, which was found to have a peak ICCF value of $r_{\text{max}} = 0.354$ (i.e., a probability of arising from an uncorrelated parent population of roughly less than 0.001), and we limited the range of computation for this line to ±16 days to avoid aliasing. Table 7 summarizes the previous data and our new results.

Our results for the UV emission lines are generally in agreement with those of Reichert et al. (1994). It should be noted, however, that the peak and centroid lags calculated by Reichert et al. (1994) and Stirpe et al. (1994) used the 1460 Å continuum as the driving light curve. The results quoted here are consistent with those derived from the recalibrated data with the continuum centered at 1460 Å rather than at 1355 Å. Because of the large uncertainties assigned to previous lag values, most of our NEWSIPS lags are within 1 $\sigma$ of the old data. The exceptions are Si $m$ $\lambda$1892 +
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The range of time lags we included in our analysis of Si iv 1892 + C iv 1909 was limited to ±16 days to avoid aliasing.

Table 7: Cross-Correlation Results

| Line/Band      | Previous Results | Current Results |  
|----------------|------------------|-----------------|
|                | $\tau_{peak}$   | $\tau_{cont}$  | $\tau_{peak}$   | $\tau_{cont}$  |
| $F(\lambda 1460)$ | … | … | $-0.1^{+0.3}_{-0.2}$ | $0.0^{+0.2}_{-0.4}$ |
| $F(\lambda 1835)$ | $0.1^{+0.2}_{-0.3}$ | $0.2^{+0.2}_{-0.3}$ | $0.0^{+0.0}_{-0.5}$ | $0.0^{+0.0}_{-0.5}$ |
| $F(\lambda 5150)$ | $1.6^{+1.4}_{-1.6}$ | $1^{+1.4}_{-1.6}$ | $0.4^{+1.4}_{-1.6}$ | $0.7^{+1.4}_{-1.6}$ |
| He ii $\lambda 1640 + O$ $\lambda 1663$ | $0.5^{+0.4}_{-1.6}$ | $1^{+1.4}_{-1.6}$ | $1.5^{+1.4}_{-1.6}$ | $1.4^{+1.4}_{-1.6}$ |
| Si iv $\lambda 1400 + O$ $\lambda 1402$ | $3.9^{+2.6}_{-2.6}$ | $5^{+2.6}_{-2.6}$ | $2.1^{+2.6}_{-2.6}$ | $2.3^{+2.6}_{-2.6}$ |
| Ly$\alpha$       | $3.8^{+0.3}_{-0.3}$ | $4^{+0.3}_{-0.3}$ | $3.6^{+0.3}_{-0.3}$ | $2.2^{+0.3}_{-0.3}$ |
| C iv $\lambda 1549$ | $5.4^{+0.3}_{-0.3}$ | $5^{+0.3}_{-0.3}$ | $3.8^{+0.3}_{-0.3}$ | $4.5^{+0.3}_{-0.3}$ |
| Si iv $\lambda 1892 + C$ $\lambda 1909$ | $15.6^{+2.6}_{-2.6}$ | $9^{+2.6}_{-2.6}$ | $8.5^{+2.6}_{-2.6}$ | $10.2^{+2.6}_{-2.6}$ |
| H$\beta$        | $7.1^{+2.2}_{-2.2}$ | $8^{+2.2}_{-2.2}$ | $10.4^{+2.2}_{-2.2}$ | $9.0^{+2.2}_{-2.2}$ |

Note.—All time lag data are in units of days. The previous results listed here are adapted from the GEX-extracted UV data of Reichert et al. 1994 and from the optical results of Stirpe et al. 1994, both of which used the 1460 A continuum as the driving light curve.

The significant discrepancy between our H$\beta$ results and those of Wandel et al. (1999), 4.5$^{+3.6}_{-1.1}$ days, arises from the double-peaked nature of the CCF. The centroid lag calculated for the 5150 A continuum-H$\beta$ CCF is based on fewer points than the 1355 A continuum-H$\beta$ lag and gives precedence to the peak at smaller lags. We have greater confidence in the results that use the UV continuum data, and those results closely match the UV-H$\beta$ correlation found by Stirpe et al. (1994).

4. IMPLICATIONS FOR THE BLR AND THE SMBH

As the tabular data indicate, the expected pattern of more highly ionized lines having smaller time lags (i.e., originating closer to the ionization source) is reconfirmed by our analysis.

Figure 6 plots $\tau_{\text{rest}}$ FWHM(rms) versus $\tau_{\text{cont}}$ for the five emission lines we measured. The virial assumption predicts a...
The slope of $-0.5$ (in log-log space). Deviation from this relationship would contradict our model, but agreement with the predicted slope cannot rule out other dynamical possibilities (see Krolik 2001, and references therein).

The statistical problem of fitting to intrinsically scattered data with heteroscedastic errors has been addressed with computational methods by Akritas & Bershady (1996). However, our data have the additional difficulty of asymmetric errors in the lags. To account for the asymmetric time lag uncertainties, we first used the larger of the two lag errors and then assessed in which direction the data points differed from the regression. We recalculated the fit using the errors toward the previous regression and confirmed that those were the appropriate choices in the final fit. The slope of the $V_{\text{FWHM}}(\text{rms})-\sigma_{\text{cent}}$ relation derived by the regression software$^3$ was $-0.450 \pm 0.070$, consistent with our expectations for a virial relationship (irrespective of the specific multiplicative factor relating the line widths and $V_{\text{FWHM}}$ values). Hence, we fixed the slope at $-0.5$ and calculated the mass independently for each emission line, applying our previously stated assumption of isotropic BLR gas motion and inserting the appropriate rest-frame values into the following equation:

$$M = \frac{3c\tau V_{\text{FWHM}}^2}{4G}.$$  \hspace{1cm} (2)

Weighting the data by the uncertainty in the direction of the mean (since the lag errors are still asymmetric) yields an average SMBH mass of $(8.7 \pm 1.1) \times 10^6 M_\odot$.

Previous work with IUE archival data having much poorer temporal resolution measured a much larger C IV $\lambda1549$ time lag and derived a mass of $7.3^{+3.5}_{-1.6} \times 10^6 M_\odot$, (Koratkar & Gaskell 1991a, 1991b). Wandel et al. (1999) calculated the H$\beta$ lag with respect to the 5100 Å continuum from the light curves of Stirpe et al. (1994) and then used the rms velocity width to estimate a mass of $1.1^{+1.1}_{-1.0} \times 10^7 M_\odot$.

Applying this method to our version of the optical data yields an SMBH mass of $6.2^{+1.1}_{-0.6} \times 10^6 M_\odot$, within the 1 $\sigma$ error bars for our mass measurement with the full data set. Fromerth & Melia (2000) employed a different means of measuring the velocity dispersion from the data of Reichert et al. (1994) and derived masses of $1.0^{+0.8}_{-0.4} \times 10^7$ and $1.3^{+0.8}_{-0.5} \times 10^7 M_\odot$ from Ly$\alpha$ and C IV $\lambda1549$, respectively. Various disk-accretion models predicting an SMBH mass in the range of $(2.0-7.0) \times 10^7 M_\odot$ were cited by Allon et al. (1995). However, they note the simple nature of these spatially thin, optically thick disk models and the potential for a large discrepancy from the true SMBH mass.

5. SUMMARY

We have conducted reverberation mapping analysis on recalibrated IUE and ground-based optical observations of the Seyfert 1 galaxy NGC 3783 with the goal of revising the mass estimate for the central SMBH. The NEWSIPS spectra confirm the existence of varying time lags for emission lines of different ionization potentials and provide a better constraint on the SMBH mass under the assumption of virial gas motion. The emission line time lags vary from 1.3 to 10.4 days, and analysis of peak and centroid time lags yields similar results for each line. Our mass determination revises the previous values to a mass of $(8.7 \pm 1.1) \times 10^6 M_\odot$.

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