THE MASS OF THE CENTRAL BLACK HOLE IN THE SEYFERT GALAXY NGC 4151

KYLE G. METZROTH,1,2 CHRISTOPHER A. ONKEN,1,3 AND BRADLEY M. PETERSON1

Received 2006 January 11; accepted 2006 May 1

ABSTRACT

In order to improve the reverberation-mapping–based estimate of the mass of the central supermassive black hole in the Seyfert 1 galaxy NGC 4151, we have reanalyzed archival ultraviolet monitoring spectra from two campaigns undertaken with the International Ultraviolet Explorer. We measure emission-line time delays for four lines, C iv λ1549, He ii λ1640, C iii] λ1909, and Mg ii λ2798, from both campaigns. We combine these measurements with the dispersion of the variable part of each respective emission line to obtain the mass of the central object. Despite the problematic nature of some of the data, we are able to measure a mass of $(4.14 \pm 0.73) \times 10^7 M_\odot$, although this, like all reverberation-based masses, is probably systematically uncertain by a factor of 3–4.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — quasars: emission lines — ultraviolet: galaxies

1. INTRODUCTION

Reverberation mapping (Blandford & McKee 1982; Peterson 1993) of active galactic nuclei (AGNs) is used to characterize the size of the broad-line region (BLR) in these objects by measuring the time delay between continuum changes and the response of the emission lines. By combining the reverberation time delay, or lag, with the width of the variable part of the emission line, it is possible to estimate the mass of the central object, presumably a supermassive black hole, under the assumption that the dynamics of the BLR gas is dominated by gravity. In this case, the mass is given by

$$M_{\text{BH}} = \frac{f \tau \Delta V^2}{G},$$

(1)

where the size of the BLR is given by the light-travel time $c\tau$, $\tau$ is the emission-line time delay, $\Delta V$ is the width of the emission line, $G$ is the gravitational constant, and $f$ is a factor of order unity that depends on the geometry, kinematics, and inclination of the BLR. Two lines of evidence argue that the reverberation-based mass estimates have some veracity:

1. Different emission lines have different response times, and these are inversely correlated with line width in a manner consistent with a virialized BLR, i.e., $\tau \propto \Delta V^{-2}$ (Peterson & Wandel 1999, 2000; Onken & Peterson 2002; Kollatschny 2003). Moreover, at least in the particularly well-studied case of the Hβ line in NGC 5548, the lag and line width change over time in response to luminosity changes, and the virial relationship seems to be preserved (Peterson et al. 2004; Cackett & Horne 2006).

2. There is a relationship between the reverberation-based black hole mass $M_{\text{BH}}$ and host-galaxy bulge velocity dispersion $\sigma_*$, that is consistent with the same correlation, the $M_{\text{BH}}-\sigma_*$ relation, that is observed in quiescent galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000a, 2000b; Ferrarese et al. 2001; Tremaine et al. 2002; Onken et al. 2003, 2004; Nelson et al. 2004).

With respect to the second point, the consistency of the $M_{\text{BH}}-\sigma_*$ relationship between AGNs and quiescent galaxies allows us to calibrate the reverberation-based mass scale to that of quiescent galaxies by determining a statistical mean value for the scaling constant $f$ in equation (1), as was done by Onken et al. (2004).

Reverberation results also show that there is a simple relationship between the size of the BLR $R = c\tau$ and luminosity, $L$, of the form $R \propto L^\alpha$, where $\alpha \approx 0.5$, but depends somewhat on the luminosity measure and also, presumably, the particular emission line for which $R$ is measured (Kaspi et al. 2000, 2005; Bentz et al. 2006a). This is an especially important result, since the mass of the black hole in any AGN can then be estimated through a single measurement of luminosity and line width, thus enabling mass estimates for large populations of AGNs (Wandel et al. 1999; Vestergaard 2002, 2004; McLure & Jarvis 2002; Kollmeier et al. 2006; Vestergaard & Peterson 2006).

Reverberation mapping is currently the only broadly applicable method by which we can directly measure AGN black hole masses, and it holds promise because it is the only direct method of black hole mass measurement that does not depend on angular resolution. Moreover, reverberation-based mass measurements anchor the calibration for masses based on radius–luminosity scaling relationships. Thus, given the importance of the reverberation results, we have undertaken a variety of programs designed to improve the reverberation measurements from existing data, in addition to carrying out new reverberation-mapping experiments. These efforts have included compilation and consistent reanalysis of most existing reverberation data (Peterson et al. 2004). In the particular case of NGC 3783, we completely re-measured and reanalyzed the data obtained with the International Ultraviolet Explorer (IUE) using improved spectral extractions (Onken & Peterson 2002), which resulted in a remarkable improvement in the precision of the central black hole mass. In this contribution, we undertake a similar reanalysis of the IUE spectra of NGC 4151, motivated at least in part by the fact that NGC 4151 is one of the few AGNs in which measurement of the black hole mass by other means is plausible, which would thus enable a direct comparison between masses measured by reverberation and those measured by other direct methods.

In this contribution, we reexamine spectra from two ultraviolet monitoring campaigns undertaken with IUE in 1988 (Clavel et al. 1990) and in 1991 (Ulrich & Horne 1996) and compare the results with those from two ground-based optical monitoring programs.
that were reanalyzed by Peterson et al. (2004). A third ultraviolet monitoring program on NGC 4151 in 1993 (Crenshaw et al. 1996) is not revisited here because the program was too short (9.3 days) to yield meaningful results on the emission-line responses. In § 2, we describe the processing and measurement of the ultraviolet spectra. Our reverberation analysis is described in § 3, and in § 4 we discuss our measurement of the black hole mass. Our conclusions appear in § 5.

2. THE ULTRAVIOLET SPECTRA

The databases for both IUE monitoring programs consist of multiple observations made with the Short Wavelength Prime (SWP) and Long Wavelength Prime (LWP) cameras in the low-dispersion mode with a large (10′′ × 20′′) oval aperture. The SWP spectra cover the wavelength range 1150–2000 Å, while the LWP spectra cover the range 1800–3300 Å, although the LWP spectra are nearly worthless shortward of about 2200 Å. The first data set that we examine was obtained during the period 1988 November 29–1989 January 30 and is composed of 33 SWP and 22 LWP spectra (Clavel et al. 1990). The second set was obtained between 1991 November 9 and 1991 December 15 and is composed of 44 SWP and 37 LWP spectra (Ulrich & Horne 1996). The original spectral images were processed with the New Spectral Image Processing System (NEWSIPS), replacing the older IUE Spectral Image Processing System (UESIPS) extractions that were used in the original analysis. Compared to the UESIPS spectra, the NEWSIPS spectra have improved photometric accuracy and have higher signal-to-noise ratio (S/N); AGN spectra processed with NEWSIPS show a 10%–50% increase in S/N (Onken & Peterson [2002] and references therein).

Measurements were made of each of the SWP and LWP spectra. The continuum flux was measured in the SWP spectra over a 30 Å bandpass centered on 1355 Å in the observed frame. Emission-line fluxes were measured by defining nominally line-free regions bracketing the lines, fitting a linear continuum between these regions, and measuring the flux above the interpolated continuum. The wavelengths of the continuum-fitting regions and the limits of the line integration are given in Table 1 for four emission lines, C iv λ1549, He ii λ1640, C iii] λ1909, and Mg ii λ2798. We did not include measurements of the Lyα λ1215+N v λ1240 complex because this spectral region is hopelessly contaminated by geocoronal Lyα emission. We also attempted to measure the flux in the Si iv λ1400 feature, but the results were very poor because the line is so weak. These measurements were discarded. There were a few spectra in which the measured fluxes deviated strongly from more plausible values obtained from redundant spectra obtained at the same epoch (i.e., during the same 8 hr observing shift). We are not always able to identify specific causes of these deviant points; some effects, such as grazing-incidence cosmic rays, are notoriously difficult to remove from IUE spectra through the standard pipeline processing methods such as NEWSIPS. We elected to simply remove the strongly deviant values from the light curves before processing. The measurements of the continuum and emission-line fluxes used in this analysis are given in Tables 2–5.

Multiple measurements that were obtained within a single 8 hr IUE observing shift were compared to determine uncertainties in the fluxes on the assumption that no real detectable variability occurred on such short timescales. Following this, data points obtained in a single shift were replaced by a weighted average to form the final light curves shown in Figures 1 (left) and 2 (left) and which were used as the basis for the time series analysis described in § 3.1. The statistical properties of these light curves are summarized in Table 6. Column (1) identifies the spectral feature, and column (2) gives the total number of measurements in the time series. The average and median intervals between individual data points are given in columns (3) and (4), respectively. The mean flux and its standard deviation appear in column (5). The mean fractional error, based on comparison of closely spaced observations, is given in column (6). Column (7) gives the “excess variance” for each light curve, computed as

\[ F_{\text{var}} = \frac{\sqrt{\sigma^2 - \delta^2}}{\langle f \rangle} \,, \tag{2} \]

where \(\sigma^2\) is the variance of all of the fluxes, \(\delta^2\) is the mean square uncertainty of the fluxes, and \(\langle f \rangle\) is the mean flux for all observations. Also listed in column (8) is \(R_{\text{max}}\), the ratio of the maximum and minimum fluxes for each time series.

3. DATA ANALYSIS

3.1. Time Series Analysis

To find the time delay between the continuum and emission-line variations, we cross-correlate each of the emission-line light curves with that of the 1355 Å continuum. The methodology we employ is the interpolation correlation function method described by White & Peterson (1994). The cross-correlation functions (CCFs) for the emission lines are shown in Figures 1 (right) and 2 (right). In order to assess uncertainties in the time delay measurements, we employ the model-independent Monte Carlo FR/RSS method described by Peterson et al. (1998), with some modifications introduced by Peterson et al. (2004), which works as follows. For a single realization, a light curve of \(N\) data points is
sampled $N$ times without regard to whether or not any given point has been previously selected; this is called "random subset sampling," or RSS. Any data point that is selected.

The values so computed for these data sets are given

The subset of these points, sampled and altered by the FR/RSS algorithm, are then cross-correlated as though they were real data. This yields a CCF like those seen in Figures 1 and 2. We locate the peak value $r_{\text{max}}$ of the CCF, which occurs at a time lag $T_{\text{peak}}$. We also compute the centroid of the CCF, $\tau_{\text{crr}}$, based on those points near the peak with values $r \geq 0.8r_{\text{max}}$. A large number of such Monte Carlo realizations builds up a cross-correlation peak distribution (CCPD) for $T_{\text{peak}}$ and a cross-correlation centroid distribution (CCCD) for $\tau_{\text{crr}}$. As argued elsewhere, $\tau_{\text{crr}}$ is more repeatable and has a clearer physical interpretation, so we prefer it to $T_{\text{peak}}$. We thus take the average values of the CCCD and CCDP to be $\tau_{\text{crr}}$ and $T_{\text{peak}}$, respectively. The uncertainties $\Delta T_{\text{upper}}$ and $\Delta T_{\text{lower}}$ are computed such that 15.87% of the CCCD realizations have values $\tau < \tau_{\text{crr}} - \Delta T_{\text{lower}}$ and 15.87% of the CCCD realizations have values $\tau > \tau_{\text{crr}} + \Delta T_{\text{upper}}$, with the errors in $T_{\text{peak}}$ defined similarly. These uncertainties correspond to $\pm 1 \sigma$ for a Gaussian distribution. The values so computed for these data sets are given in Table 7. Note that the errors are generally asymmetric, but usually not strongly so. It should be noted that formally these

| Image Name | Julian Date ($\sim 246,000$) | $F_\lambda (1355 \, \AA)$ (10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) | C iv $\lambda 1549$ (10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | He ii $\lambda 1640$ (10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$) | C iv $\lambda 1909$ (10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$) |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SWP34845   | 7497.562        | 227.48 ± 10.20  | 53.17 ± 6.62    | 34.56 ± 2.78    |
| SWP34868   | 7499.549        | 229.65 ± 10.29  | 52.57 ± 6.54    | 35.83 ± 2.89    |
| SWP34869   | 7506.123        | 184.00 ± 8.25   | 33.00 ± 4.11    | 34.42 ± 2.77    |
| SWP35028   | 7510.174        | 181.19 ± 8.12   | 33.89 ± 4.22    | 37.16 ± 2.99    |
| SWP35058   | 7513.273        | 164.41 ± 7.37   | 26.95 ± 3.35    | 34.42 ± 2.77    |
| SWP35059   | 7513.305        | 177.79 ± 7.97   | 31.98 ± 3.98    | 37.16 ± 2.99    |
| SWP35090   | 7516.165        | 140.97 ± 6.32   | 25.55 ± 3.18    | 32.76 ± 2.64    |
| SWP35098   | 7518.066        | 131.98 ± 5.92   | 24.39 ± 3.04    | 37.02 ± 2.98    |
| SWP35099   | 7518.135        | 129.10 ± 5.79   | 20.99 ± 2.61    | 38.33 ± 3.09    |
| SWP35123   | 7520.111        | 107.59 ± 4.82   | 12.30 ± 1.53    | 33.28 ± 2.68    |
| SWP35124   | 7520.166        | 121.40 ± 5.44   | 15.95 ± 1.99    | 35.30 ± 2.84    |
| SWP35171   | 7524.109        | 114.64 ± 5.14   | 17.60 ± 2.19    | 32.87 ± 2.65    |
| SWP35172   | 7524.171        | 106.29 ± 4.76   | 16.64 ± 2.07    | 31.69 ± 2.55    |
| SWP35210   | 7527.075        | 100.50 ± 4.51   | 13.06 ± 1.63    | 27.38 ± 2.21    |
| SWP35211   | 7527.143        | 101.39 ± 4.55   | 17.84 ± 2.22    | 31.76 ± 2.56    |
| SWP35264   | 7532.083        | 105.06 ± 4.71   | 21.22 ± 2.64    | 30.93 ± 2.49    |
| SWP35297   | 7536.019        | 153.93 ± 6.90   | 21.15 ± 2.63    | 31.92 ± 2.57    |
| SWP35298   | 7536.075        | 160.55 ± 7.20   | 25.25 ± 3.14    | 32.40 ± 2.61    |
| SWP35330   | 7540.032        | 160.04 ± 7.17   | 25.96 ± 3.23    | 36.94 ± 2.98    |
| SWP35331   | 7540.091        | 155.24 ± 6.56   | 24.67 ± 3.07    | 32.93 ± 2.65    |
| SWP35374   | 7544.004        | 163.48 ± 7.33   | 28.77 ± 3.58    | 39.64 ± 3.19    |
| SWP35375   | 7544.070        | 170.93 ± 7.66   | 32.32 ± 4.02    | 35.22 ± 2.84    |
| SWP35388   | 7547.998        | 175.48 ± 7.87   | 33.62 ± 4.18    | 34.70 ± 2.80    |
| SWP35389   | 7548.059        | 171.56 ± 7.69   | 32.38 ± 4.03    | 36.17 ± 2.91    |
| SWP35403   | 7551.842        | 172.33 ± 7.72   | 24.95 ± 3.11    | 39.66 ± 3.20    |
| SWP35404   | 7551.901        | 151.81 ± 6.81   | 27.76 ± 3.45    | 34.32 ± 2.77    |
| SWP35417   | 7553.270        | 153.76 ± 6.89   | 32.38 ± 4.15    | 31.19 ± 2.51    |
| SWP35428   | 7554.177        | 142.02 ± 6.37   | 19.38 ± 2.45    | 37.88 ± 3.05    |
| SWP35429   | 7554.232        | 139.96 ± 6.27   | 21.38 ± 2.66    | 31.65 ± 2.55    |
| SWP35457   | 7556.842        | 139.96 ± 6.27   | 21.38 ± 2.66    | 31.65 ± 2.55    |
| SWP35458   | 7556.908        | 139.51 ± 6.25   | 26.34 ± 3.28    | 33.77 ± 2.72    |
and LWP images from 1988 and 1991, respectively.

Figures 3 and 4, we show the mean and rms spectra for the SWP mean spectrum and a root mean square (rms) spectrum; the rms spectra obtained during the observing campaign to construct a emission line, specifically avoiding contaminating nonvariable NGC 4151 is

\[
\frac{z}{d} = \frac{1}{1 + \frac{z}{d}}
\]

observed-frame measurements need to be corrected for time dilation by division by \(1 + z\), where the systemic redshift of NGC 4151 is \(z = 0.00332\).

### 3.2. Line Width Measurement

To obtain the black hole mass, we also need to measure the width of each emission line. Indeed, we wish to measure the line-of-sight velocity distribution for the variable part of the emission line, specifically avoiding contaminating nonvariable (on reverberation timescales) components, such as a contribution from the much larger narrow-line region. We use all of the spectra obtained during the observing campaign to construct a mean spectrum and a root mean square (rms) spectrum; the rms spectrum isolates the variable part of the emission lines. In Figures 3 and 4, we show the mean and rms spectra for the SWP and LWP images from 1988 and 1991, respectively.

To measure the emission-line widths, we first interpolate the rms continuum under the emission lines by fitting a linear continuum in the continuum windows given in Table 1. We then characterize the line width in two ways, by its full width at half-maximum (FWHM) and by the second moment of the line profile, i.e., the line dispersion, \(\sigma_{\text{line}}\) as described by Peterson et al. (2004). To evaluate the uncertainties in these measurements, we follow the procedure described by Peterson et al. (2004), which is similar in spirit to that used to evaluate uncertainties in the time delays. For a sample of \(N\) spectra, we select \(N\) spectra at random, in each case without regard to whether or not a particular spectrum has been previously selected. These \(N\) random spectra are used to construct mean and rms spectra, and both line width measurements are made for each emission line. This constitutes one Monte Carlo realization. A large number of similar realizations yields a mean and standard deviation for each
line width measure. Line width measurements and associated uncertainties for each of the emission lines are given in Table 8. The emission-line widths here have been converted to the rest frame of NGC 4151 and have been adjusted as described by Peterson et al. (2004), based on data originally published by Maoz et al. (1991) and Kaspi et al. (1996). There is considerable scatter in the emission-line fluxes for He \(\alpha\) \(\lambda 1640\), C iv \(\lambda 1549\), C iii \(\lambda 1909\), and Mg ii \(\lambda 2798\), as listed in Tables 2 and 3. The continuum flux is plotted in units of \(10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\), and the emission-line fluxes are in units of \(10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\). Right: Result of cross-correlating each of these light curves with the 1355 \AA\ continuum light curve. The top is thus the continuum autocorrelation function.

Two obvious difficulties are apparent on inspection of Figures 3 and 4. The first of these is that the core of the C iv emission line is strongly self-absorbed. This is very apparent in the rms spectra and is especially strong in the 1991 data. It is impossible to correct for this absorption, since we do not know the intrinsic unabsorbed C iv profile. However, we can try to assess the severity of the systematic uncertainty by modeling the intrinsic profile in a variety of ways to see how much the line width measurement might change. We experimented with various means of accounting for the effects of the absorption, and the largest change in line width was obtained by fitting the unabsorbed wings of the emission line with a Gaussian. The Gaussian so constructed had a value of \(\sigma_{\text{line}}\) that was about 10% smaller than that obtained in our direct measurement, and the value of the FWHM, which is more sensitive to the flux at line center, decreased by more than 20%. We can regard our measurement of the C iv line width as an upper limit that is probably not a terrible overestimate of the true unabsorbed value of \(\sigma_{\text{line}}\). In any case, the effect on the black hole mass estimate is quite insignificant, given the level of accuracy that we can currently achieve in black hole mass measurement. We also note that the Mg ii line is self-absorbed, but the absorption is much weaker, and the emission line in the rms spectrum is too noisy for the absorption feature to be apparent.

A second difficulty is that the C iv and He \(\alpha\) emission lines are strongly blended in their wings. Since these cannot be uniquely deblended, we assume that the both lines are approximately symmetric about line center and use the unblended half of each line (the short-wavelength side for C iv and the long-wavelength side for He \(\alpha\)) to determine the width. These are the values of the line widths that appear in Table 8.

### 4. THE BLACK HOLE MASS

As noted earlier and as observed in other sources, we expect that if the dynamics of the BLR is dominated by the gravitational force of the central black hole, we should see a virial relationship between emission-line widths and time lags of the form \(\Delta V \propto \tau^{-1/2}\). To test this for NGC 4151, we plot the emission-line line widths from the rms spectra (Table 8) versus the measured time delays (Table 7) in Figure 5. We supplement the UV data with measurements of the H\(\alpha\) and H\(\beta\) line widths and lags from Peterson et al. (2004), based on data originally published by Maoz et al. (1991) and Kaspi et al. (1996). There is considerable scatter in Figure 5, but with the exception of the H\(\alpha\) and H\(\beta\) measurements based on the Kaspi et al. (1996) monitoring program, the

---

**TABLE 5**

| Image Name | Julian Date (-2,440,000) | Mg ii \(\lambda 2798\) |
|------------|--------------------------|-----------------------|
| LWP21671   | 8570.530                 | 54.45 ± 1.56          |
| LWP21681   | 8571.520                 | 58.60 ± 1.70          |
| LWP21750   | 8577.500                 | 57.02 ± 1.65          |
| LWP21751   | 8577.570                 | 56.87 ± 1.64          |
| LWP21752   | 8577.620                 | 60.61 ± 1.75          |
| LWP21764   | 8578.480                 | 58.65 ± 1.70          |
| LWP21765   | 8578.530                 | 57.92 ± 1.68          |
| LWP21774   | 8579.560                 | 56.47 ± 1.63          |
| LWP21775   | 8579.610                 | 57.10 ± 1.65          |
| LWP21785   | 8580.750                 | 54.26 ± 1.57          |
| LWP21791   | 8581.570                 | 54.56 ± 1.58          |
| LWP21792   | 8581.620                 | 53.27 ± 1.54          |
| LWP21798   | 8582.570                 | 52.71 ± 1.52          |
| LWP21827   | 8584.560                 | 51.87 ± 1.50          |
| LWP21835   | 8585.540                 | 48.67 ± 1.41          |
| LWP21836   | 8585.610                 | 50.59 ± 1.46          |
| LWP21845   | 8586.550                 | 50.20 ± 1.45          |
| LWP21854   | 8587.550                 | 45.81 ± 1.33          |
| LWP21855   | 8587.610                 | 44.98 ± 1.30          |
| LWP21863   | 8588.560                 | 52.89 ± 1.53          |
| LWP21872   | 8589.560                 | 49.81 ± 1.44          |
| LWP21873   | 8589.630                 | 48.52 ± 1.40          |
| LWP21893   | 8591.460                 | 46.38 ± 1.34          |
| LWP21894   | 8591.570                 | 43.59 ± 1.26          |
| LWP21904   | 8592.550                 | 46.45 ± 1.34          |
| LWP21905   | 8592.660                 | 49.40 ± 1.43          |
| LWP21930   | 8595.460                 | 47.18 ± 1.36          |
| LWP21931   | 8595.530                 | 46.71 ± 1.35          |
| LWP21943   | 8596.590                 | 43.65 ± 1.26          |
| LWP21956   | 8597.630                 | 42.06 ± 1.22          |
| LWP21965   | 8598.460                 | 49.16 ± 1.42          |
The only UV line not affected by self-absorption or blending is the effect of which is apparent in its flat-topped CCF (Fig. 2). somewhat short, especially in the case of the Mg undersampled, and the duration of the 1991 experiment was they appear to be. Neither of the two UV monitoring data sets on Petson et al. 2004) the range of lags is nearly a factor of 15. of 3, whereas in the similar plot for NGC 5548 (see Fig. 3 of 2004). The range of lags in this diagram is less than a factor scatter is similar to that seen in other sources (see Peterson et al. 2004). The range of lags in this diagram is less than a factor of 3, whereas in the similar plot for NGC 5548 (see Fig. 3 of Peterson et al. 2004) the range of lags is nearly a factor of 15. Moreover, given the limited quality of the monitoring data on NGC 4151, it is perhaps surprising that the results are as good as they appear to be. Neither of the two UV monitoring data sets on NGC 4151 is remarkably good; the 1988 IUE data are slightly undersampled, and the duration of the 1991 experiment was somewhat short, especially in the case of the Mg ii observations, the effect of which is apparent in its flat-topped CCF (Fig. 2). The only UV line not affected by self-absorption or blending is C iii, for which the variations are comparatively weak.

![Fig. 2.—Light curves and cross-correlation functions based on the 1991 IUE observations of NGC 4151, as listed in Tables 4 and 5 and plotted as in Fig. 1.](image)

The two existing optical data sets are even more problematic. In the case of the 1988 data from Maoz et al. (1991), the emission-line lags appear to be well determined, but it is difficult to measure the width of the broad-line component in these spectra reliably. In NGC 4151, the narrow-line components are much stronger relative to the broad-line components than they are in most type 1 AGNs. The spectra from this campaign are of rather low resolution, so the [O iii] lines are partially blended with one another. Moreover, the line-spread function appears to vary among the spectra, possibly as a result of drift in the large aperture that was used to ensure an accurate flux calibration. The combination of these factors makes it hard to isolate the broad-line component and determine their widths with great confidence. Nevertheless, the Hα and Hβ lags and line widths plotted in Figure 5 are reasonably consistent with the virial relationship derived from the UV lines in this object.

On the other hand, the optical data described by Kaspi et al. (1996) present some serious difficulties for a virial interpretation. However, in this particular case, the nature of the variations during this campaign was not favorable for reverberation analysis—both the continuum and emission lines showed nearly monotonically increasing flux throughout the monitoring period, and the amplitude of variation was relatively low. Without a strong change in the sign of the first derivative of the light curves, as seen in the light curves in Figures 1 and 2, it is difficult to obtain a highly reliable reverberation lag. In an attempt to mitigate the unfavorable effects of a monotonic rise, we experimented as seen in the light curves in Figures 1 and 2, it is difficult to obtain a highly reliable reverberation lag. In an attempt to mitigate the unfavorable effects of a monotonic rise, we experimented with removing the long-term trend in these data prior to cross-correlating the time series (i.e., “detrending” the data; see Welsh

**TABLE 6**

| TIME SERIES (1) | N (2) | (T) (3) | Tmedian (4) | MEAN FLUX (5) | MEAN FRACTIONAL ERROR | Fvar (6) | Rmax (7) |
|-----------------|------|--------|------------|--------------|----------------------|---------|---------|
| 1988 1355 Å...... | 18   | 3.4    | 3.8        | 58.1 ± 17.3  | 0.046                | 0.293   | 2.65 ± 0.15 |
| 1988 C iv........ | 19   | 3.3    | 3.6        | 154.2 ± 35.6 | 0.036                | 0.228   | 2.28 ± 0.13 |
| 1988 He ii........ | 19   | 3.3    | 3.5        | 27.7 ± 10.7  | 0.100                | 0.369   | 3.89 ± 0.60 |
| 1988 C iii....... | 19   | 3.3    | 3.6        | 34.2 ± 2.4   | 0.066                | 0.018   | 1.29 ± 0.10 |
| 1988 Mg ii....... | 14   | 4.4    | 4.0        | 25.9 ± 2.6   | 0.050                | 0.088   | 1.36 ± 0.12 |
| 1991 1355 Å...... | 22   | 1.7    | 1.0        | 140.0 ± 56.1 | 0.039                | 0.390   | 3.38 ± 0.17 |
| 1991 C iv........ | 22   | 1.7    | 1.0        | 283.6 ± 73.7 | 0.024                | 0.259   | 2.17 ± 0.06 |
| 1991 He ii........ | 22   | 1.7    | 1.0        | 53.6 ± 15.3  | 0.070                | 0.275   | 2.58 ± 0.23 |
| 1991 C iii....... | 22   | 1.7    | 1.0        | 54.8 ± 6.0   | 0.027                | 0.106   | 1.50 ± 0.043 |
| 1991 Mg ii....... | 20   | 1.5    | 1.0        | 51.0 ± 5.0   | 0.025                | 0.094   | 1.39 ± 0.06 |

1 Continuum and emission-line fluxes are in the same units as used in Tables 2–5.
Fig. 3.—Mean and rms spectra based on the 1988 IUE observations of NGC 4151, showing the mean (top left) and rms (bottom left) spectra formed from the SWP data and the mean (top right) and rms (bottom right) spectra formed from the LWP data. Fluxes are in units of $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, and the spectra are plotted in the observed frame.

Fig. 4.—Mean and rms spectra based on the 1991 IUE observations of NGC 4151, showing the mean (top left) and rms (bottom left) spectra formed from the SWP data and the mean (top right) and rms (bottom right) spectra formed from the LWP data. Fluxes are in units of $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, and the spectra are plotted in the observed frame.
This had the effect of moving the already small lag even closer to zero. Our suspicion is that this lag measurement is spurious. It seems likely that at such a low level of variability there are correlated errors between the continuum and emission-line measurements, which manifest themselves as a correlated signal at zero lag. We have not been able to demonstrate this conclusively and thus need to keep in mind the possibility that these measurements represent an actual deviation from the virial relationship. However, given the unfavorable nature of the observed variations, we are more inclined at the present time to simply disregard this particular data set.

The best-fit slope to all of the data points in Figure 5 is $-1.52 \pm 0.84$, which differs from the virial slope of $-0.5$ by only $1.2 \sigma$. Obviously, additional, better data will be required to determine whether or not the virial relationship between lag and line widths holds in the case of NGC 4151.

Setting aside this difficulty, we nevertheless proceed with an estimate of the mass of the central black hole by using equation (1) with the scaling factor $f = 5.5$, as determined by Onken et al. (2004) by normalizing the AGN $M_{\text{BH}}$-$\sigma$ relationship to that for quiescent galaxies. We use $\tau_{\text{opt}}$ for the time delay and $\sigma_{\text{line}}$ to characterize the line width. If we use all of the data in Figure 5, we find a black hole mass of $M_{\text{BH}} = (2.58 \pm 0.35) \times 10^7 M_\odot$, based on a weighted average of the individual mass estimates for each line. If we restrict the mass estimates to the UV data points from the present work, we obtain a mass estimate of $M_{\text{BH}} = (8.55 \pm 1.26) \times 10^7 M_\odot$. Our preferred estimate is obtained by eliminating the most problematic data, leaving only $\mbox{C m}\alpha$, $\mbox{He II}$, and $\mbox{Mg II}$ from the two UV campaigns. The resulting mass estimate is $M_{\text{BH}} = (4.14 \pm 0.73) \times 10^7 M_\odot$. We remind the reader, however, that due to unquantified systematic uncertainties (as embodied in the scale factor $f$ in eq. [1]), this is probably uncertain by a factor of 3–4 (Onken et al. 2004), as are all reverberation-based mass estimates.

5. CONCLUSIONS

In this contribution, we have examined archival $IUE$ spectra that have been reprocessed with the NEWSIPS software. For two separate monitoring programs, we were able to obtain emission-

| Line                  | $\sigma_{\text{line}}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|-----------------------|-------------------------------------|--------------------|
| 1988 C IV $\lambda 1549$ | $5698 \pm 245$                     | $6697 \pm 543$    |
| 1988 He II $\lambda 1640$ | $5013 \pm 323$                     | $5356 \pm 1270$  |
| 1988 C III $\lambda 1909$ | $2553 \pm 307$                     | $2646 \pm 745$   |
| 1988 Mg II $\lambda 2798$ | $2581 \pm 179$                     | $4823 \pm 1105$  |
| 1991 C IV $\lambda 1549$ | $5140 \pm 113$                     | $4858 \pm 149$   |
| 1991 He II $\lambda 1640$ | $4530 \pm 92$                      | $4597 \pm 659$   |
| 1991 C III $\lambda 1909$ | $2817 \pm 81$                      | $6997 \pm 1366$  |
| 1991 Mg II $\lambda 2798$ | $2721 \pm 141$                     | $4658 \pm 1850$  |

1 Based on the shortward side of the line only.

2 Based on the longward side of the line only.

REFERENCES

Bentz, M. C., Peterson, B. M., Pogge, R. W., Vestergaard, M., & Onken, C. A. 2006a, ApJ, 644, 133
Bentz, M. C., et al. 2006b, ApJ, in press
Blandford, R. D., & McKee, C. F. 1982, ApJ, 255, 419
Cackett, E. M., & Horne, K. 2006, MNRAS, 365, 1180
Clavel, J., et al. 1990, MNRAS, 246, 668
Crenshaw, D. M., et al. 1996, ApJ, 470, 322

We are grateful for support of this program by the NSF through grant AST 02-05964 and by NASA through grant HST GO-09849 from the Space Telescope Science Institute.
Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631
Kaspi, S., et al. 1996, ApJ, 470, 336
Kollatschny, W. 2003, A&A, 407, 461
Kollmeier, J. A., et al. 2006, ApJ, in press (astro-ph/0508657)
Maoz, D., et al. 1991, ApJ, 367, 493
McLure, R. J., & Jarvis, M. J. 2002, MNRAS, 337, 109
Nelson, C. H., Green, R. F., Bower, G., Gebhardt, K., & Weistrop, D. 2004, ApJ, 615, 652
Onken, C. A., Ferrarese, L., Merritt, D., Peterson, B. M., Pogge, R. W., Vestergaard, M., & Wandel, A. 2004, ApJ, 615, 645
Onken, C. A., & Peterson, B. M. 2002, ApJ, 572, 746
Onken, C. A., Peterson, B. M., Dietrich, M., Robinson, A., & Salamanca, I. M. 2003, ApJ, 585, 121
Peterson, B. M. 1993, PASP, 105, 247
Peterson, B. M., & Wandel, A. 1999, ApJ, 521, L95
———. 2000, ApJ, 540, L13
Peterson, B. M., Wanders, I., Horne, K., Collier, S., Alexander, T., & Kaspi, S. 1998, PASP, 110, 660
Peterson, B. M., et al. 2004, ApJ, 613, 682
Tremaine, S., et al. 2002, ApJ, 574, 740
Ulrich, M.-H., & Horne, K. 1996, MNRAS, 283, 748
Vestergaard, M. 2002, ApJ, 571, 733
———. 2004, ApJ, 601, 676
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Welsh, W. F. 1999, PASP, 111, 1347
White, R. J., & Peterson, B. M. 1994, PASP, 106, 879