THE ACCURACY OF SUPERMASSIVE BLACK HOLE MASSES DETERMINED BY THE SINGLE-EPOCH SPECTRUM (DIBAI) METHOD

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ABSTRACT

The first set of supermassive black hole mass estimates, published from 1977 to 1984 by É. A. Dibai, are shown to be in excellent agreement with recent reverberation-mapping estimates. Comparison of the masses of 17 AGNs covering a mass range from about $10^6$ to $10^9M_\odot$ shows that the Dibai mass estimates agree with reverberation-mapping mass estimates to significantly better than $\pm 0.3$ dex and were, on average, only 0.14 dex ($\sim 40\%$) systematically lower than masses obtained from reverberation mapping. This surprising agreement with the results of over a quarter of a century ago has important implication for the structure and kinematics of AGNs and implies that type-1 AGNs are very similar. Our results give strong support to the use of the single-epoch-spectrum (Dibai) method for investigating the co-evolution of supermassive black holes and their host galaxies.

Subject headings: galaxies:active — galaxies:quasars:general — black holes:masses — galaxies:active:variability

1. INTRODUCTION

It is exactly 100 years this year since the publication of the first evidence of nuclear activity in galaxies (Faith 1908). Over the last half century or so, active galactic nuclei (AGNs) have been the subject of increasingly intensive study which has resulted in tens of thousands of papers being published. Zel’ dovich (1964) and Salpeter (1964) proposed that the huge energy release lasting for millions of years from a typical AGN could be explained by the accretion of matter onto a supermassive black hole. In such accretion, the energy output efficiency may reach 43% of the accreting matter’s rest mass energy. This gave the first estimates of lower limits to the masses of AGNs because the luminosity, $L$, cannot go much above the Eddington limit, $L_{Edd} \sim 1.3 \times 10^{38}(M/M_\odot)$ erg/s, so the mass of the black hole in an AGN has to be of the order of several million to several billion solar masses, depending on the luminosity of the AGN (Zel’dovich & Novikov 1964).

While the Eddington limit gives a lower limit to the mass, $M_{BH}$, of the black hole, the actual mass could be orders of magnitude greater than this. To understand the working of AGNs, $M_{BH}$ needs to be determined observationally, so estimating $M_{BH}$ has always been considered to be a matter of utmost importance in AGN studies. If the motions of gas clouds are dominated by gravity, masses can be estimated in principle from the virial theorem if we know a velocity and an appropriate distance from the center (e.g., Woltjer 1958). The velocity along the line of sight can easily be determined from the Doppler broadening of emission lines, but determining the distance of the emitting material from the central object is difficult.

It was not until the work of Dibai (1977, 1978, 1980, 1984, 1985) that an attempt was made at a consistent spectroscopic determination of the masses of the central objects for a large sample of AGNs. This enabled Dibai to determine black hole masses and Eddington ratios, $L/L_{Edd}$, for dozens of AGNs for the first time (Dibai 1980, 1984), and to begin investigations in what promised to be (and indeed has turned out to be) a very fruitful area: the relationships between these quantities and other AGN parameters (see, for example, Dibai 1984, and Dibai & Zasov 1985). Unfortunately, this work was cut short by Dibai’s premature death, and in the two decades after his 1977 paper there were only a few papers by others using the Dibai method to estimate black hole masses (e.g., Joly et al. 1985, Wandel & Yahi 1985, Padovani & Rafanelli 1988).

In the last decade, however, there has been an enormous growth of interest in determining masses by Dibai’s method because of the close relationship between the masses of black holes and the masses of the bulges of their host galaxies (see Kormendy & Gebhardt 2001 for a review). It is only through the Dibai method that large numbers of black hole masses in AGNs can currently be determined, and the method has already been used in making tens of thousands of mass estimates for AGNs of all redshifts in the Sloan Digital Sky Survey (e.g., McClure & Dunlop 2004, Salviander et al. 2007, Greene & Ho 2007, Shen et al. 2008). It is therefore of interest to revisit the original Dibai mass estimates and see how they compare with more recent independent estimates.

Dibai & Pronik (1967) showed that the emitting regions of the broad and narrow components of AGN optical emission lines (what we now call the BLR and NLR respectively) had to originate in different locations in space, and that the emitting gas, in both cases, had to have a cloudy structure, that is, to fill only a small fraction, $\epsilon$, of the volume of the corresponding region. It has long been recog-
nized (e.g., Bahcall, Kozlovsky, & Salpeter 1972; see also Bochkarev & Pudenko 1973) that BLR variability timescales could be used to estimate the effective distance of the emitting gas from the black hole, and hence to get masses via the virial theorem. Pronik & Chvaček (1972) presented the first long-term Hβ light curve for an AGN. Lyuty & Cherepashchuk (1972) and Cherepashchuk & Lyuty (1973) made narrow-band observations of three AGNs over several months and published the first actual estimates of BLR sizes from the time lag between continuum variability and line variability. Bochkarev & Antokhin (1982), Blandford & McKee (1982), Capriotti, Foltz, & Peterson (1982), and Antokhin & Bochkarev (1983) independently developed methods for recovering information about the BLR from the response of the lines to continuum variations, a subject which has now become known as “reverberation mapping”. Determining BLR sizes became practical and widespread with the introduction of cross-correlation techniques (Gaskell & Spark 1986; Gaskell & Peterson 1987) a few years later.

Once BLR radii were being reliably obtained from cross-correlation studies, the main remaining problem in estimating masses was in establishing that the gas motions were dominated by gravity. The dominant belief from the early days of AGN studies (e.g., Burbidge 1958) was that emission-line gas was outflowing from AGNs, and the virial theorem obviously cannot be applied to an outflowing wind. The idea of determining BLR kinematics diagnostics by line-profile variations was first brought forward by S. N. Fabrika (1980), then Dibai’s graduate student. The first velocity-resolved reverberation mapping (Gaskell 1988; Koratkar & Gaskell 1989; see also Shapovalova et al. 2001a,b) showed that the BLR was not outflowing, but instead showing some net inflow in combination with Keplerian and/or chaotic motion (see Gaskell & Goosmann 2004). This discovery immediately permitted the first reverberation-mapping determinations of black hole masses (Gaskell 1988).

Despite the promising results of the pioneering observations of Lyuty & Cherepashchuk (1972) and Cherepashchuk & Lyuty (1973), it was emphasized by Bochkarev (1984), confirming earlier calculations of Bochkarev & Antokhin (1982) and Antokhin & Bochkarev (1983), that reliable results could only be obtained from long time-sequences of well-sampled, high-accuracy, spectral and photometric observational data obtained through a large-scale international project. The urgent need for starting such collaborations was discussed in detail by Bochkarev (1987a,b).

The following decades saw the progress of the International AGN Watch (I-AW) program (see Clavel et al. 1991; Peterson et al. 1991 et seq.) aimed at determining the BLR size and structure from reverberation mapping. That project proved to be one of the largest global astronomical monitoring programs to date. More than 200 astronomers from 35 countries cooperated for 15 years in accumulating long, densely-sampled, UV, optical, and other wavelength time series for many AGN. As a result of this, and of additional optical monitoring campaigns, reverberation-mapping estimates of the AGN central black hole mass have now been obtained for over 40 AGNs (see Peterson et al. 2004 and Vestergaard & Peterson 2006).

In this paper we make a comparison of AGN central object mass values from reverberation mapping campaigns with the masses obtained by Dibai over a quarter of a century ago. In Section 2 we briefly describe the assumptions made by Dibai. In Section 3 we compare the results yielded by the two methods. Section 4 discusses the implications of the comparison.

2. THE DIBAI METHOD OF ESTIMATING MASSES

In his first (1977) paper Dibai explained the basic principles of his method for estimating the masses of the black holes in AGNs and gave masses for 15 AGNs. In 1980 and 1981 further masses for many more AGNs were published (Dibai 1980, 1981). He then composed a catalogue of the main characteristics of 77 Seyfert 1 nearby galaxies and nearby quasars and of 24 Seyfert 2 galaxies, and used it as the basis for new AGN mass and accretion rate estimates. What were to be the final results were published in Dibai (1984a,b), which did not appear until after the author’s untimely death occurred in November of 1983.1

Dibai estimated the mass of the central region of AGNs under the assumption that the gas clouds responsible for broad emission line formation were moving with more or less parabolic velocities in the gravitational-field of the black hole so that

$$M_{BH} = 1.5Rv^2/G.$$

(1)

Here $M_{BH}$ is the mass of the central object (presumably a black hole), $R$ is the BLR radius, $v$ is the gas velocity (which Dibai determined from the FWHM of the broad component of Hβ), and $G$ is the gravitational constant. To estimate the size of region producing the broad component of Hβ Dibai used the simple relationship:

$$\epsilon(4\pi R^3/3) = L_{H\beta}/E(n, T),$$

(2)

where $\epsilon$ is the BLR gas filling factor; that is, the fraction of the BLR volume filed with the emitting gas. It should be noted that since $L \propto L_{H\beta}$ over many orders of magnitude (Yee 1980; Shuder 1981), Eq(2) means that

$$R \propto L^{1/3}.$$

(3)

Dibai estimated the volume occupied by the emitting gas by assuming that the Hβ line is optically thin and emitted in the low-density approximation (the so-called “coronal approximation”); that is, that the results obtained for classical ionized hydrogen zones may be applied to the line.

On the right-hand side of Eq. (2), $L(H\beta)$ is the luminosity in the Hβ line and $E(n, T) = 1.21 \times 10^{-7}$ erg cm$^{-3}$ s$^{-1}$ is emissivity for H II zones heated up to $T = 10^4$ K with electron number density, $n_e = 10^3$ cm$^{-3}$. Dibai based his estimate of the density on two things. Firstly, the absence of broad components of forbidden spectral lines in AGN spectra leads to a lower limit of $n_e \geq 10^8$ cm$^{-3}$. Secondly, the presence of the semi-forbidden CIII]

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1 It should be mentioned that significant parts of the spectral and photometric data used by Dibai in above the mentioned papers were obtained with Dibai’s personal participation in observations: e.g., see Dibai, Doroshenko, & Postnov (1981) for results of photometry for 27 AGNs and the series of 8 papers by Arakelian, Dibai and Esipov with AGN spectroscopy published in the journal Astrophysics in the period 1970-1973 (see references in Dibai 1984a,b).
**TABLE 1**

| Name       | Dibai | Reverb | ±   | Ref. | Dibai-Reverb |
|------------|-------|--------|-----|------|--------------|
| Mrk 335    | 7.50  | 7.15   | 0.12| 2    | 0.35         |
| PG 0026+129| 8.15  | 8.59   | 0.11| 1    | -0.44        |
| F 9        | 8.00  | 8.41   | 0.10| 2    | -0.41        |
| Mrk 590    | 7.40  | 7.68   | 0.07| 2    | -0.28        |
| 3C 120     | 8.00  | 7.74   | 0.21| 2    | 0.26         |
| Ark 120    | 8.00  | 8.18   | 0.06| 2    | -0.18        |
| Mrk 79     | 7.50  | 7.72   | 0.12| 1    | -0.22        |
| Mrk 110    | 7.20  | 7.40   | 0.11| 2    | -0.20        |
| NGC 3516   | 7.40  | 7.63   | 0.15| 1    | -0.23        |
| NGC 3783   | 7.10  | 7.47   | 0.08| 2    | -0.37        |
| NGC 4515   | 6.00  | 6.28   | 0.19| 1    | -0.28        |
| NGC 4319   | 7.20  | 7.12   | 0.16| 2    | 0.08         |
| 3C 273     | 8.50  | 8.95   | 0.09| 2    | -0.45        |
| Mrk 279    | 7.90  | 7.54   | 0.12| 2    | 0.36         |
| NGC 5548   | 7.70  | 7.83   | 0.02| 2    | -0.13        |
| Mrk 509    | 7.70  | 8.16   | 0.04| 2    | -0.45        |
| NGC 7469   | 7.30  | 7.09   | 0.05| 2    | 0.21         |

Fig. 1.— Comparison of the mass estimates of \[\log M_{\text{Dibai}}\] and \[\log M_{\text{Reverb}}\] with reverberation mapping masses, \[\log M_{\text{Reverb}}\]. The solid line is the OLS-bisector fit and the two dotted lines show regressions of \((X—Y)\) and \((Y—X)\).

\(\Lambda 1909\) line implies an upper limit of \(n_\epsilon \lesssim 10^{10} \text{ cm}^{-3}\). For the filling factor parameter, \(\epsilon\), Dibai adopted a value obtained for the fraction of the volume of the emitting gas in the Crab Nebula, \(\epsilon = 10^{-3}\). With these assumptions Dibai then estimated \(M_{BH}\) for almost 80 type-1 Seyfert galaxies and nearby quasars.

**3. BLACK HOLE MASSES IN AGN: DIBAI (1984B) VS. REVERBERATION MAPPING**

Masses derived from more than 15-years of reverberation mapping of 35 AGN are given in Peterson et al. (2004) and Vestergaard & Peterson (2006). 17 AGNs appear in both these lists and Dibai’s lists. The masses range from \(M_{BH} \sim 10^6 M_\odot\) up to \(~10^9 M_\odot\). The black hole mass estimates for the AGNs in common are shown in Table 1 and plotted in Fig. 1.

As can be seen from Fig. 1, there is obviously a good correlation. Since there are errors in both axes we have performed an ordinary least squares (OLS) bisector regression (see Isobe et al. 1990). This gives the relationship:

\[
\log M_{\text{Reverb}} = 1.14 \log M_{\text{Dibai}} - 0.85. \tag{4}
\]

As can be seen from Fig. 1, there is obviously a good correlation. Monte Carlo simulations show that the error in the slope of the OLS-bisector line is \(\pm 0.18\), so the slope does not differ significantly from unity. The systematic difference in the logarithms of the masses determined by the two methods is

\[
< \log M_{\text{Reverb}} - \log M_{\text{Dibai}} > = -0.14 \pm 0.07. \tag{5}
\]

The systematic difference between the two methods is therefore only 40%.

The scatter in the ratio of masses determined by the two methods is \(\pm 0.28\) dex, but at least some of this must be due to the errors in the reverberation-mapping estimates. The mean of the formal reverberation mass measurement errors quoted by Peterson et al. (2004) and Vestergaard & Peterson (2006) is \(\pm 0.10\) dex. If we make the (unlikely) assumption that these measurement errors are the only source of error in the reverberation mass estimates, then the average error in the Dibai estimates is \(\pm 0.26\) dex. However, this is an approximate upper limit to the errors in the Dibai method because there are other (unknown) errors in the reverberation mapping mass determinations. If we assume that the errors are equally distributed between the Dibai method and the reverberation-mapping method, then the mean of the errors in the Dibai method of black hole mass estimation is \(\pm 0.20\) dex.

\[\text{Denney et al. (2009)}\] have made a detailed examination of the effects of random and systematic observational errors on masses estimated by the Dibai method. They find that with careful treatment of line profiles using high-quality spectra (signal-to-noise ratio \(\geq 20:1\)) it is possible to get errors of \(\leq 0.10\) dex in the mass if the observational uncertainties are the only source of error. Since Dibai did not have the advantage of modern digital spectra, the contribution of observational errors to his mass estimates must have been significantly greater than \(\pm 0.10\) dex. Our comparison thus tells us that under ideal circumstances, the intrinsic accuracy of the Dibai method is potentially quite high.

4. WHAT DOES THE AGREEMENT TELL US?

The surprising agreement of the estimated mass values implies that all the “classical” type-1 AGNs (Seyfert 1 galaxies and nearby quasars) are very much alike in their properties and structure, and that object-to-object differences are smaller than has been hitherto thought. The agreement of the Dibai and reverberation mapping results provides support for the following:

1. BLR gas motions are dominated by gravity, as has been shown by velocity-resolved reverberation mapping (Gaskell 1988; Koratkar & Gaskell 1989, etc.), and as is also strongly supported by the inverse correlation of line widths with the sizes of the emitting regions of different ions, and hence the consistency of mass estimates from these different ions (Krolik et al. 1991; see also Peterson & Wandel 1999, 2000). Thus the emission comes predominantly from gravitationally-bound gas, and not gas flowing away from the nucleus. This is
an assumption in common to both the Dibai and reverberation mapping methods. Dibai recognized from the outset (Dibai 1977) that it had not yet been established that the motions were dominated by gravity. He also noted that outflow velocities in Wolf-Rayet stars only slightly exceed the escape velocity, so his mass estimates could also apply if the BLR was a radiatively-driven outflow.

2. The kinematics of all BLRs are similar. This is again an assumption in common to both the Dibai and reverberation mapping methods.

3. The BLR size scales with optical luminosity as $R \propto L^{\alpha}$. This is supported by reverberation mapping estimates of $R$ (Koratkar & Gaskell 1991; Peterson & Wandel 1993; Bentz et al. 2006). Dibai took $\alpha$ to be $\sim 0.33$ (see Eqs. 2 and 3) while Bentz et al. (2006) get $0.52 \pm 0.04$. While the slope of the line in Fig. 1 ($1.14 \pm 0.18$) is already consistent with unity, if we adopt $\alpha = 1/2$, rather than the $\alpha = 1/3$ Dibai with $L_{H\beta}$ (see Eqs. (2) and (3)), this changes the slope of the line to 0.97.

4. The spectral energy distribution (SED) is very similar in all type-1 AGNs, as has already been argued by Gaskell et al. (2004) and Gaskell & Benker (2008).

5. The “warm” gas has a similar filling factor, $\epsilon \sim 0.001$ for all the type-1 AGNs. This means that the space between BLR clouds is about 10 times bigger than the mean cloud size. Since the BLR is probably flattened (see Gaskell, Klimek, & Nazarova 2008), the average separation between the clouds will be a little smaller.

6. Slow temperature variations of the “warm” ($T \sim 10^4$ K) BLR gas discussed recently by Popović et al. (2008) do not make significant deviations of the average value of BLR gas emissivity $E(n, T)$ in H$\beta$ line for the 17 AGNs considered here from the quantity $1.21 \times 10^{-7}$ erg cm$^{-3}$ s$^{-1}$ adopted by Dibai (1984b).

7. The possible presence of other BLR emission components, such as a BLR component near the jet in radio-loud AGN (see Bochkarev & Shapovalova 2007; Nazarova, Bochkarev, & O’Brien 2007, and Arshakian et al. 2008) in addition to the “standard” BLR associated with the accretion disk does not noticeably affect the average value of the porosity, $\epsilon$, of the gas responsible for the BLR. The contribution of non-standard BLR components to the total BLR emission is thus probably small, at least for the typical BLRs of the 17 AGNs considered here.

The first two of these assumptions are common to both the Dibai method and reverberation mapping, and these two assumptions tell us things about BLR gas flow in AGNs. The next two assumptions are unique to the Dibai method and, in combination with the good agreement of mass estimations we have found, they tell us additional significant things about AGNs. The third assumption is that the physical conditions in the BLR clouds are similar (i.e., similar densities and ionization parameters), and the fourth is that the SEDs are similar. The fifth assumption was only used to get the scale factor or zero point in the original Dibai method. The large number of more recent applications of the Dibai method scale the radii to reverberation mapping radii instead. Nonetheless, the agreement we find between Dibai’s mass scale and that of reverberation mapping implies that Dibai’s assumption of a filling factor of $\epsilon = 0.001$ is a good one. The agreement arises, of course, because of the agreement in estimated radii. Dibai indeed noted at the outset (Dibai 1977) that the estimated radii agreed with the reverberation mapping results of Lyutyi & Cherepashchuk (1972).

Taken together, the apparent correctness of the main assumptions of Dibai’s method reinforces the idea that, despite the wide range of masses of their black holes and the wide range of accretion rates, a large fraction of type-1 AGNs are surprisingly similar. This is an important result which needs to be understood and which requires further study.

The final, obvious, and important conclusion that can be drawn from the good agreement we find between masses estimated by the single-epoch spectrum method pioneered by Dibai (1977) and by the reverberation mapping method (and also the agreement that Peterson et al. 2004 and Vestergaard & Peterson 2006 find between their own single-epoch estimate and reverberation mapping) is that the Dibai method does give reliable black hole mass estimates. This is very important for studying cosmic evolution of black holes and host galaxies because it shows that the long-term, labour-intensive monitoring of reverberation mapping is not necessary to obtain the mass of every single AGN in the sample. The reliability of the Dibai method makes investigations of cosmic AGN evolution, black hole growth, and the links with the properties and evolution of host galaxies considerably easier. The simple comparison we have presented here implies that we can indeed trust this method which has now been used already for obtaining mass estimates of many tens of thousands of AGNs.

The success of the Dibai method certainly does not mean that there is no need for further reverberation mapping studies. Reverberation mapping is needed for testing the reliability of black hole mass determinations for AGNs of extreme types which are not represented in Table 1. For example: high Eddington ratio AGNs (so-called “narrow-line Seyfert 1s”) and very low Eddington ratio AGNs (such as FR1 radio galaxies), which might have non-classical BLRs, are not represented. The good agreement of the Dibai method with reverberation mapping for the 17 AGNs considered here does not reduce the importance of the reverberation mapping in general. The two methods are complimentary and not mutually replaceable.

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