BLACK HOLE MASS AND EDDINGTON RATIO DISTRIBUTION FUNCTIONS OF X-RAY-SELECTED BROAD-LINE AGNs AT $z \approx 1.4$ IN THE SUBARU XMM-NEWTON DEEP FIELD

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ABSTRACT

In order to investigate the growth of supermassive black holes (SMBHs), we construct the black hole mass function (BHMF) and Eddington ratio distribution function (ERDF) of X-ray-selected broad-line active galactic nuclei (AGNs) at $z \approx 1.4$ in the Subaru XMM-Newton Deep Survey (SXDS) field. A significant part of the accretion growth of SMBHs is thought to take place in this redshift range. Black hole masses of X-ray-selected broad-line AGNs are estimated using the width of the broad Mg $\text{II}$ line and 3000 Å monochromatic luminosity. We supplement the Mg $\text{II}$ FWHM values with the H$\alpha$ FWHM obtained from our NIR spectroscopic survey. Using the black hole masses of broad-line AGNs at redshifts between 1.18 and 1.68, the binned broad-line AGN BHMFs and ERDFs are calculated using the $V_{\text{max}}$ method. To properly account for selection effects that impact the binned estimates, we derive the corrected broad-line AGN BHMFs and ERDFs by applying the maximum likelihood method, assuming that the ERDF is constant regardless of the black hole mass. We do not correct for the non-negligible uncertainties in virial BH mass estimates. If we compare the corrected broad-line AGN BHMF with that in the local universe, then the corrected BHMF at $z = 1.4$ has a higher number density above $10^8 M_\odot$ but a lower number density below that mass range. The evolution may be indicative of a downsizing trend of accretion activity among the SMBH population. The evolution of broad-line AGN ERDFs from $z = 1.4$ to 0 indicates that the fraction of broad-line AGNs with accretion rates close to the Eddington limit is higher at higher redshifts.

Key words: galaxies: active – galaxies: evolution – galaxies: statistics – quasars: emission lines – quasars: general

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

Since the discovery that supermassive black holes (SMBHs) sit at the centers of most massive galaxies in the local universe (e.g., Kormendy & Richstone 1995), determining their formation history has remained one of the big challenges in astrophysics. It has been further determined that the mass of SMBHs correlates tightly with the physical properties of their host spheroids (e.g., Magorrian et al. 1998; Marconi & Hunt 2003; Gültekin et al. 2009). Such a correlation implies a physical connection between the growth histories of SMBHs and the spheroidal components of galaxies (e.g., Boyle & Terlevich 1998).

Bolometric luminosities of active galactic nuclei (AGNs) reflect the mass accretion rates of their SMBHs; therefore, the luminosity function of AGNs and its cosmological evolution reflects the growth history of SMBHs through accretion (Soltan 1982). The cosmological evolution of AGN luminosity functions has been evaluated using various AGN samples (e.g., Ueda et al. 2003; Silverman et al. 2008; Croom et al. 2009; Aird et al. 2010; Assef et al. 2011; Simpson et al. 2012). The number density evolution of AGNs in different luminosity bins shows that higher-luminosity AGNs, i.e., QSOs, have a peak at higher redshifts, the so-called downsizing trend of the cosmological evolution of AGNs. The total amount of accreted matter estimated by integrating the luminosity functions over luminosity and redshift roughly matches the estimated mass density of SMBHs in the local universe (Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2009); thus, accretion is thought to be the dominant mode of SMBH growth. Applying the continuity equation for the SMBH population, Marconi et al. (2004) evaluated the average growth curves of massive and less-massive SMBHs as a function of redshift. These results imply that SMBHs grow rapidly at redshifts between 1 and 2, and more massive SMBHs grow more than less massive SMBHs in the earlier universe, as

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expected from the “downsizing” trend of the AGN luminosity function.

The luminosity of an AGN does not simply reflect the mass of its SMBH. In calculations of the black hole growth history, the Eddington ratio, i.e., the ratio between the observed accretion rate and the Eddington-limited accretion rate ($\lambda_{\text{Edd}}$), is assumed to be constant in AGNs with different luminosities and redshifts. If a constant Eddington ratio is assumed for AGNs, then their luminosity should directly correspond to the mass of their SMBHs, and the mass-dependent growth history of SMBHs can be calculated. However, recent evaluations of the Eddington-ratio distribution of AGNs in the local universe show that AGNs have a wide range of Eddington-ratios with no preferred value (Kauffmann & Heckman 2009; Schulze & Wisotzki 2010). Therefore, in order to quantitatively understand the accretion growth history of SMBHs, it is necessary to evaluate SMBH masses in any AGN sample for which the cosmological evolution of the luminosity function is evaluated.

Tools are now available for measuring the black hole masses of broad-line AGNs. Reverberation mapping of local broad-line AGNs (e.g., Peterson et al. 2004) reveals the scaling relationship between the 5100 Å monochromatic luminosity ($L_{5100}$) of the broad-line AGN and the size of its broad Hβ-emitting region (Kaspi et al. 2000, 2005). Utilizing this relationship, the black hole masses of a large sample of broad-line AGNs can be estimated from their luminosities and broad Hβ line widths ($\Delta v_{\text{Hβ}}$) (e.g., Vestergaard & Peterson 2006) from the relationship $M_{\text{BH}} = f \Delta v_{\text{Hβ}}^2 L_{5100}^{0.5}$ assuming that the broad-line region is virialized (Peterson & Wandel 1999). The factor $f$ depends on the dynamical structure of the broad-line region, and it is empirically determined by assuming that the black hole mass obtained from the reverberation mapping method and the velocity dispersion of its host bulge follow the $M_{\text{BH}}$ versus $\sigma_{\text{bulge}}$ relation of local non-active galaxies (Onken et al. 2004). This method has been extended to black hole mass estimations using other broad lines, such as Mg II $\lambda\lambda2796, 2803$ (McLure & Jarvis 2002; Vestergaard & Osmer 2009), C iv $\lambda\lambda1548, 1551$ (Vestergaard 2002; Vestergaard & Peterson 2006), and Hα (Greene & Ho 2005), and using luminosities at other wavelengths such as the 3000 Å monochromatic luminosity (McLure & Jarvis 2002), the Hα line luminosity (Greene & Ho 2005), and the hard X-ray luminosity (Greene et al. 2010a). These relationships are calibrated against the black hole mass estimated by the reverberation mapping or that from the single-epoch broad-line width of Hβ and the monochromatic luminosity. Using these extended methods, black hole masses of broad-line AGNs at various redshifts can be estimated from their single-epoch optical spectra.

By applying black hole mass estimates from single-epoch spectra to statistical samples of broad-line AGNs, black hole mass functions (BHMFs) of broad-line AGNs can be evaluated (Wang et al. 2006; Greene & Ho 2007, 2009; Vestergaard et al. 2008; Vestergaard & Osmer 2009; Schulze & Wisotzki 2010; Shen & Kelly 2012; Kelly & Shen 2012). In the local universe, Schulze & Wisotzki (2010) derived the BHMF and Eddington-ratio distribution function (ERDF) of broad-line AGNs detected in the Hamburg/ESO AGN survey. They corrected the effects of the flux limits of their survey in their evaluation of the broad-line AGN BHMF and ERDF, i.e., the fact that the low-mass end of the sample only covers high Eddington ratio AGNs, by assuming that the ERDF is constant regardless of the black hole mass and application of the maximum likelihood method. Hereafter, we label the BHMF and ERDF derived using the $V_{\text{max}}$ method as binned and those corrected for the detection limit using the maximum likelihood method as corrected. The corrected broad-line AGN BHMF covering $M_{\text{BH}}$ values between $10^{6.0} M_\odot$ and $10^{9.5} M_\odot$ and $\lambda_{\text{Edd}}$ down to 0.01 shows a rather steep decrease in number density as a function of mass with no significant break in the mass range covered. The corrected broad-line AGN ERDF shows a steep decline at the Eddington limit and a steep increase in the number density down to $\lambda_{\text{Edd}}$ of 0.01, following a power law with an index of $\sim-1.9$.

The cosmological evolution of the BHMFs of broad-line AGNs has also been examined using large samples of broad-line AGNs from the Sloan Digital Sky Survey (SDSS) using the $V_{\text{max}}$ method (Vestergaard et al. 2008; Vestergaard & Osmer 2009) and a Bayesian approach (Kelly et al. 2010; Shen & Kelly 2012; Kelly & Shen 2012). Kelly et al. (2010), Shen & Kelly (2012), and Kelly & Shen (2012) derive the cosmological evolution of the BHMF of broad-line AGNs in the redshift range between 0.3 and 5 by applying a Bayesian approach (Kelly et al. 2009). Hereafter, we label the BHMF and ERDF derived with the Bayesian approach as estimated. The estimated BHMF of broad-line AGNs shows an increase in number density above $M_{\text{BH}} = 1 \times 10^7 M_\odot$ from $z = 0$ to 2. In contrast, lower mass SMBHs show a relatively flat number density evolution up to $z = 2$. The “downsizing” trend expected from the AGN luminosity function is confirmed by the steeper decrease of active SMBHs in the higher mass range from $z = 2$ to 0. However, it should be noted that broad-line AGNs in the SDSS sample only cover large-$M_{\text{BH}}$ and large-$\lambda_{\text{Edd}}$ AGNs in that redshift range. For example, at $z = 1.5$, the sample is only 30% complete down to $M_{\text{BH}} \sim 10^6 M_\odot$ and $\lambda_{\text{Edd}} \sim 0.6$ (Kelly et al. 2010). Due to the shallow detection limit, the discrepancy between the binned and estimated broad-line AGN BHMFs is as large as two orders of magnitude in the mass range around $M_{\text{BH}} = 10^6 M_\odot$ at $z = 1.4$ (Shen & Kelly 2012). Therefore, in order to examine the cosmological evolution of BHMFs and ERDFs, a sample of broad-line AGNs with fainter detection limits is needed.

In order to reveal accretion onto SMBHs in an era of violent growth, we examine the BHMF and ERDF of broad-line AGNs at $z = 1.4$ using a sample constructed from the X-ray survey of the Subaru XMM-Newton Deep Survey (SXDS) field. As suggested by the SMBH growth curves (Marconi et al. 2004), a significant part of the accretion growth of SMBHs is thought to take place in the redshift range between 1 and 2. Therefore, the direct determination of the BHMF and ERDF in this redshift range is of critical importance. Thanks to the moderately deep detection limit and wide area of the survey, we can construct a large sample of broad-line AGNs that is one order of magnitude fainter than that available from SDSS. Furthermore, the sample covers the flux range around the knee of the X-ray log $N$–log $S$ relation ($1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in the 2–10 keV band; Cowie et al. 2002), and the sample size is several times larger than the deep Chandra surveys in this flux range. The sample represents the population of SMBHs that dominates the accretion growth of the SMBHs.
mass estimates. We then present the detection-limit-corrected broad-line AGN BHMF and ERDF derived using the maximum likelihood method assuming functional shapes of the BHMF and ERDF. In this paper, we do not include the effect of the uncertainties of the virial black hole mass estimate in the BHMF and ERDF determination. In Section 6, the shapes of the corrected broad-line AGN BHMF and ERDF are compared with those in a similar redshift range from SDSS (Shen et al. 2011) and those in the local universe from the ESO/Hamburg survey (Schulze & Wisotzki 2010). The contribution to the binned active BHMF from obscured narrow-line AGNs is also discussed. Throughout this paper, we adopt the following cosmological parameters: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. Magnitudes are given in the AB magnitude system (Oke 1974) unless otherwise noted.

2. SAMPLE

A sample of $z \sim 1.4$ AGNs is constructed from X-ray observations of the SXDS field (Ueda et al. 2008). The field was observed with XMM-Newton covering a central 30' diameter field at a depth of 100 ks exposure and 6 flanking fields with 50 ks exposure time each (Ueda et al. 2008). From summed images of pn, MOS1, and MOS2 detectors, there are 866 and 645 sources detected in the 0.5–2 keV (soft) and 2–10 keV (hard) bands, respectively, with a detection likelihood, which is determined by point-spread function fitting, larger than 7, which corresponds to a confidence level of 99.9%. In this paper, only X-ray sources in the region covered with deep optical imaging data taken with Suprime-Cam on the Subaru telescope (Furusawa et al. 2008) are considered. There are 781 and 584 sources in the soft and hard bands, respectively. Once Galactic stars and clusters of galaxy candidates are removed, 733 (576) sources remain as AGN candidates. Hereafter, we call the former (latter) sample the soft- (hard-) band sample. The detection limit of the survey corresponds to a flux of $6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ ($3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$) in the soft (hard) band. The area covered with the flux limit is 0.05 deg$^2$, and 1.0 deg$^2$ is covered at the flux limit of $4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in the soft band. Considering sources common to both samples, there are 896 unique AGN candidates in total (see Table 1).

In order to identify the X-ray sources spectroscopically, optical observations were conducted with various multi-object spectrographs on 4 m and 8 m class telescopes. The optical spectroscopic observations cover 590 out of the 896 total sources. Even though the observations do not cover the entire sample, they are not heavily biased toward a specific type of object, since we do not use any further discrimination such as color in the target selection in most of the observations. Details of the observations are summarized in M. Akiyama et al. (2012, in preparation).

Additional intensive NIR spectroscopic observations were made with the Fiber Multi-Object Spectrograph (FMOS) on the Subaru telescope (Kimura et al. 2010). This instrument can observe up to 200 objects simultaneously over a 30' diameter field of view in cross-beam switching mode with two spectrographs. The spectrographs cover the wavelength range between 9000 Å and 18000 Å with a spectral resolution of $R \sim 800$ at $\lambda \sim 1.55\mu$m in low-resolution mode. A total of 851 sources were observed with this setup during guaranteed engineering and open-use (S11B-098 Silverman et al. and S11B-048 Yabe et al.) observations. The optical and NIR observations spectroscopically identify 586 out of the 896 sources. The optical and NIR spectra obtained in the identification observations are used for the broad-line width measurements described in the next section.

The remaining 310 sources cannot be identified spectroscopically, mostly because of their faintness. Most of them are fainter than $i = 23.5$ mag. For such objects, photometric redshifts have been estimated using the HyperZ photometric redshift code (Bolzonella et al. 2000) with galaxy and QSO spectral energy distribution (SED) templates. Photometric data in 15 bands covering from 1500 Å to 8.0 μm are used in the estimation. In order to reduce the number of AGNs with a photometric redshift significantly different from the spectroscopic one (“outliers”), we apply two constraints in addition to the $\chi^2$ minimization considering the properties of the spectroscopically identified AGNs. The first is that the objects with stellar morphology in the deep optical images are $z > 1$ broad-line AGNs. Almost all X-ray sources with stellar morphology are identified with broad-line AGNs at $z > 1$ in SXDS. They show a bright nucleus and their observed optical light is dominated by the nuclear component. The second is the absolute magnitude range of the galaxy and QSO templates. Considering the absolute magnitude range of spectroscopically identified broad-line and narrow-line AGNs, we limit the $z$-band absolute magnitude range of the galaxy (QSO) template between $M_\gamma = -20.0$ and 25.0 (mag) ($M_\gamma = -22.0$ and 26.5 (mag)).

The accuracy of the photometric redshifts are examined by comparing them with the spectroscopic redshifts. The median of $\Delta z/(1 + z_{\text{spec}})$ is 0.06 for the entire sample. We further examine the accuracy by the normalized median absolute deviation (NMAD; $\sigma_z$) following Brammer et al. (2008). For the entire sample, $\sigma_z = 0.104$, which is larger than that of the photometric redshift estimations for X-ray-selected AGNs with medium-band filters (Cardamone et al. 2010; Luo et al. 2010). The $\sigma_z$ for broad-line AGNs (0.201) is larger than that for narrow-line AGNs (0.095). This is because there is no strong feature in the SEDs of the broad-line AGNs except for the break below Lyα.

From the photometric redshift determination, not only their photometric redshifts but also their SED types can be

Table 1

| Type                        | $N$  | $N_{\text{soft}}$ | $N_{\text{hard}}$ | Note                                      |
|-----------------------------|------|-------------------|-------------------|-------------------------------------------|
| X-ray sources               | 945  | 781               | 584               | Within deep Suprime-Cam image coverage    |
| AGN candidates              | 896  | 733               | 576               |                                           |
| Optical spec. observed      | 590  | 517               | 396               | Among the 896 AGN candidates              |
| FMOS spec. observed         | 851  | 704               | 548               | Among the 896 AGN candidates              |
| Spec. identified            | 586  | 514               | 397               |                                           |
| Mg II broad line            | 186  | 181               | 137               | $z$ range 0.489–2.329                      |
| Hα broad line               | 81   | 78                | 68                | $z$ range 0.634–1.655                      |
| Mg II and Hα broad line     | 52   | 51                | 44                |                                           |
constrained. For spectroscopically identified AGNs, there is a good correlation between spectral type and best-fit SED type; narrow-line and broad-line AGNs are fitted well with galaxy and QSO templates, respectively. Therefore, we classify objects better fitted with the QSO templates as broad-line AGNs and the others as narrow-line AGNs. Our classification does not perfectly match the spectroscopic classification: in this redshift range, 10 out of 66 (31 out of 118) spectroscopically identified narrow-line (broad-line) AGNs are photometrically classified as broad-line (narrow-line) AGNs. The SEDs of the spectroscopically unidentified objects suggest that most of them are obscured narrow-line AGNs above redshift 1. For six objects, no photometric redshift can be estimated because they are detected only in a few bands. They are faint and are unlikely to be broad-line AGNs in the redshift range between 1.18 and 1.68. Further details of the photometric redshift determination are discussed in M. Akiyama et al. (2012, in preparation).

In this paper, for objects with a spectroscopic identification, we designate them as broad-line AGNs if they show either Mg\textsc{ii} λλ2796, 2803 or Hα emission lines with a width greater than 1000 km s\(^{-1}\). We estimate the black hole mass of the broad-line AGNs with either broad Mg\textsc{ii} or Hα lines. The threshold is narrower than the typical threshold used to discriminate broad-line AGNs (1500 or 2000 km s\(^{-1}\)). We determine the threshold considering the distribution of the FWHM of the broad-line AGNs in the local universe (Hao et al. 2005; Stern & Laor 2012). The broad-line AGNs with the FWHMs close to the threshold correspond to the narrow-line Seyfert 1s. Broad Mg\textsc{ii} and Hα lines are detected for 186 and 81 AGNs, respectively, with redshifts in the range between 0.5 and 2.3. For 52 objects, both broad Mg\textsc{ii} and Hα lines are detected. For 29 objects, a broad line is detected only in Hα. This is mostly due to the lack of optical spectra. Only four AGNs (SXDS0215, SXDS0387, SXDS0527, and SXDS0728) with broad Hα lines show no broad Mg\textsc{ii} line, although their optical spectra cover the Mg\textsc{ii} wavelength region and are deep enough to detect continuum emission. Such AGNs are thought to be moderately affected by dust extinction and we correct for this in the determination of their continuum luminosity for the black hole mass and the intrinsic bolometric luminosity estimates. Details are given in Sections 3 and 4.

For the derivation of the broad-line AGN BHMF, we limit the sample to the redshift range between 1.18 and 1.68. The FMOS H-band observation covers the broad Hα line for AGNs in the redshift range. Considering the typical detection limit for the broad Hα line in this redshift range \((L_{\text{H}\alpha} = 2 \times 10^{42} \text{ (erg s}^{-1}))\), we expect a broad Hα line can be detected for broad-line AGNs brighter than \(L_{2–10 \text{keV}} = 3 \times 10^{43} \text{ (erg s}^{-1})\) if they have a Hα to hard X-ray luminosity ratio typical of broad-line AGNs (Ward et al. 1988). Photometric redshift estimates suggest that 10 of the unidentified sources in this redshift range could be broad-line AGNs. All but one of the 10 candidates have estimated hard X-ray luminosities larger than \(3 \times 10^{43} \text{ (erg s}^{-1})\), but 8 of the 10 broad-line AGN candidates do not show a broad line in the FMOS observations. Considering the uncertainty of the photometric redshift for broad-line AGNs, we expect that these eight objects are broad-line AGNs outside of the redshift range. However, there is a 0.4 dex scatter between the \(L_{2–10 \text{keV}}\) and \(L_{\text{H}\alpha}\) (Ward et al. 1988), and it is still possible that they have weaker broad Hα line than the typical broad-line AGNs. Furthermore, an additional broad-line AGN candidate does not have a broad line in the optical spectroscopy; it may also be a broad-line AGN outside of the redshift range. Considering the non-detection of a broad line in the observed wavelength range, we do not include the 10 photometric candidates of broad-line AGNs in the redshift range in the derivation of the BHMF and ERDF below. The numbers of X-ray-selected AGNs in the redshift range are summarized in Table 2. The median redshift of the sample is 1.43.

The redshift distribution of the sample is shown in Figure 1 for the redshift range 0.5 to 2.5. The thick solid line shows the redshift distribution of the X-ray AGNs with spectroscopic or photometric redshifts. The dashed line shows the distribution of spectroscopically identified AGNs. The thin solid line shows the distribution for broad-line AGNs with spectroscopic redshifts. The dotted line is the distribution for broad-line AGNs that have black hole mass estimates with either broad Mg\textsc{ii} or Hα emission lines.

In Figure 2, the absorption-corrected 2–10 keV luminosity of AGNs is shown as a function of redshift. Following Ueda et al.
with high-energy cutoff hardness ratio and redshift. The intrinsic X-ray spectrum of and estimate the intrinsic column density from the observed 
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distributes between $L$ luminosity is as large as 0.5 dex. 
angle of cos $\pi$, an inclination $\beta$ and cutoff energy $E_c$ of 300 keV are assumed. We calculate the reflection component with the “pexrav” (Magdziarz & Zdziarski 1995) model in the XSPEC package assuming a solid angle of 2$\pi$, a inclination angle of cos $i = 0.5$, and solar abundance of all elements. The strength of the reflection component is about 10% of the direct component just below 7.1 keV. The intrinsic SEDs are modified with intrinsic photoelectric absorption described by a hydrogen column density, $N_H$. The $N_H$ value of each object is evaluated from the observed 0.5–2 keV and 2–4.5 keV hardness ratios. The absorption-corrected luminosity in the 2–10 keV band is derived from the observed 2–10 keV count rate by correcting for the photoelectric absorption. For objects only detected in the 0.5–2 keV band, the count rate in that band is used instead of the 2–10 keV count rate. Most of the broad-line AGNs have a hardness ratio consistent with no significant absorption and the required correction is small. Only 5 out of the 215 broad-line AGNs have log $N_H$ as large as 23; for these, the correction in luminosity is as large as 0.5 dex.

The absorption-corrected 2–10 keV luminosity of AGNs distributes between $L_{2–10\text{keV}} = 10^{43}$ and $10^{45}$ (erg s$^{-1}$) in the redshift range $z = 1–2$. The SXDS AGNs cover the most important part of the accretion growth of the SMBHs. AGNs in the luminosity range dominate the hard X-ray luminosity density of the universe in the redshift range; furthermore, the hard X-ray luminosity density as a function of redshift peaks at $z = 1$ (Aird et al. 2010).

3. LINE WIDTH AND LUMINOSITY MEASUREMENT

3.1. Method for Black Hole Mass Estimation

Assuming that the scaling relationship between luminosity and broad-line region size derived by reverberation mapping for local broad-line AGNs is applicable to broad-line AGNs at high redshifts, black hole masses of broad-line AGNs can be estimated from their continuum luminosities and line widths of the broad lines. We estimate the black hole mass of $\sim 1.4$ broad-line AGNs with Mg $\Pi$ broad-line widths measured in the optical spectra. As the optical spectroscopy does not cover the entire sample, we supplement these with H $\alpha$ broad-line widths measured in the NIR spectra. In this subsection, we first introduce the equation used to estimate the black hole mass.

There are several calibrations available for the black hole mass estimation using the Mg $\Pi$ broad line (McLure & Jarvis 2002; McLure & Dunlop 2004; McGill et al. 2008; Vestergaard & Osmer 2009; Wang et al. 2009; Shen et al. 2011; Rafiee & Hall 2011). We use the black hole mass estimate from the Mg $\Pi$ broad-line FWHM calibrated by broad-line QSOs in the SDSS DR3 (Vestergaard & Osmer 2009). The estimation is consistent to within 0.1 dex of the H $\beta$ and C iv mass estimates with single-epoch spectra. They are calibrated to the black hole mass from the reverberation mapping (Vestergaard & Peterson 2006). It needs to be noted that the black hole mass determined with the single-epoch H $\beta$ spectrum typically has a scatter of 0.4–0.5 dex around that from the reverberation mapping (Vestergaard & Peterson 2006). Park et al. (2012) also estimate the uncertainty of the single-epoch black hole mass to be 0.4–0.5 dex. Furthermore, if AGNs are close to the Eddington limit, then the influence of radiation pressure may cause an underestimation of the black hole mass by 0.5 dex (Marconi et al. 2008).

Because the 3000 Å monochromatic luminosity is available for most of the broad-line AGNs with spectroscopic observations, we use the following equation from Vestergaard & Osmer (2009) incorporating the 3000 Å monochromatic luminosity, $L_{\lambda,3000}$:

$$M_{\text{BH}}[M_\odot] = 10^{6.86} \left( \frac{\text{FWHM}_{\text{Mg} \Pi}}{1000 \text{ km s}^{-1}} \right)^2 \left( \frac{L_{\lambda,3000}}{10^{44} \text{ erg s}^{-1}} \right)^{0.5}.$$

(1)

In this calibration, the FWHM of the broad Mg $\Pi$ line, FWHM$_{\text{Mg} \Pi}$, is measured by fitting multiple Gaussians to the Mg $\Pi$ emission line profile. Vestergaard & Osmer (2009) remove the narrow-line component of Mg $\Pi$ if necessary (Vestergaard et al. 2011). Other calibrations, such as those of McLure & Jarvis (2002) and McLure & Dunlop (2004), fit the Mg $\Pi$ profile with single broad-line and narrow-line components. Rafiee & Hall (2011) use the line dispersion, $\sigma$, of the broad line because $\sigma$ correlates more tightly with the delay observed in reverberation...
mapping, i.e., the size of the broad-line region, than with the FWHM (Peterson et al. 2004).

In Equation (1), the broad-line region size \( R \) is assumed to follow \( L^\alpha \) with an \( \alpha \) of 0.5, which is equivalent to assuming that the broad-line regions of various AGNs can be described as having similar ionization states, ionizing photon spectra, and electron densities. The value of \( \alpha \), based on reverberation mapping results for \( \text{H} \beta \) broad lines, is determined to be 0.47, 0.62 ± 0.14, and 0.518 ± 0.039 (McLure & Jarvis 2002; McLure & Dunlop 2004; Bentz et al. 2006), respectively, all consistent with an \( \alpha \) of 0.5 within the uncertainties.

Regarding the coefficient for the virial product (\( \epsilon \) of \( M_{\text{BH}} = c\sigma_{\text{FWHM}}^2L^{0.5} \) or \( M_{\text{BH}} = f \sigma^2_{\text{FWHM}}L^{0.5} \)), Equation (1) is based on the calibration done by Onken et al. (2004; \( \epsilon \) of 1.4 or \( f \) of 5.5) assuming the estimated \( M_{\text{BH}} \) of local broad-line AGNs from reverberation mapping and their bulge velocity dispersions follow the black hole mass and the bulge velocity dispersion relation of non-active galaxies in the local universe. The coefficient is consistent with that derived with local Seyfert 1 galaxies (\( f = 5.2 \); Woo et al. 2010). Recent calibration shows that broad-line AGNs hosted in barred galaxies are consistent with significantly smaller values (\( f = 2.3 \); Graham et al. 2011), but the range of the black hole mass of the barred galaxies is smaller than that of the current sample, and non-barred galaxies with larger \( M_{\text{BH}} \) are consistent with \( f \sim 5.4 \) (Graham et al. 2011), thus we use Equation (1).

The optical spectroscopic observations do not cover all of the broad-line AGNs at \( z = 1.18–1.68 \); 25 out of 118 spectroscopically identified broad-line AGNs in the redshift range do not have Mg \( \text{II} \) data. Therefore, we also utilize the H\( \alpha \) FWHM in addition to the Mg \( \text{II} \) FWHM; an additional 23 broad-line AGNs have H\( \alpha \) broad-line data. Although the FMOS spectra cover H\( \beta \) in the J band, the strength of the H\( \beta \) broad line is at least three times weaker than the H\( \alpha \) broad line, and the uncertainty of the FWHM of the broad H\( \beta \) is significantly larger than that of the broad H\( \alpha \) line. Therefore, we do not use the H\( \beta \) FWHM. Because the ionization potentials of hydrogen and Mg \( \text{II} \) are similar, Balmer and Mg \( \text{II} \lambda \lambda 2796, 2803 \) broad lines are expected to be emitted in a similar region. A detailed photoionization model calculation indicates that the equivalent widths of H\( \alpha \) and Mg \( \text{II} \) lines have a similar dependency on the cloud density and ionization parameter, i.e., they are emitted from similar broad-line clouds (Korista et al. 1997). Considering this similarity, we use the same black hole mass equation employed for Mg \( \text{II} \) FWHM above for H\( \alpha \) FWHM, after correcting for a small systematic difference between Mg \( \text{II} \) FWHM and H\( \alpha \) FWHM, as detailed below. We do not use the scaling relation calibrated for the H\( \alpha \) broad line (Greene & Ho 2005) in order to be consistent within our sample. The derivation of the 3000 \( \AA \) monochromatic luminosity is discussed in Section 3.4.

3.2. Mg \( \text{II} \) Line Width Measurements with Optical Spectra

Optical spectra of the AGNs were obtained with various instruments on 4–8 m class telescopes such as 2df on the Anglo-Australian Telescope, VIMOS and FORS on the Very Large Telescope, FOCAS on the Subaru telescope, DEIMOS on the Keck telescope, and IMACS on the Magellan telescope. Most of them were obtained with a spectral resolution of \( R \sim 250–500 \). Details of the observations are described in M. Akiyama et al. (2012, in preparation). The optical spectroscopic data were reduced using standard procedures and are corrected for the dependence of the sensitivity on wavelength with standard star observations. We further correct the normalization of the spectra to match the observed \( R \)-band magnitudes in the deep Suprime-Cam images. The optical photometric data are corrected for the Galactic extinction in the SXDS field (\( A_g \) of 0.07 mag). We do not correct the optical spectroscopic data for the wavelength dependence of the Galactic extinction which is negligibly small. This correction does not affect the line width measurement, but affects the continuum flux measurement. The normalization can be affected by the variability of broad-line AGNs between the epochs of the imaging and the spectroscopic observations. Typically, there is a one year gap between the imaging and spectroscopic observations. The structure function of the optical variability of QSOs (Cristiani et al. 1996) suggests that, on average, there can be a 0.2 mag variation during the time lag. Therefore, the uncertainty of \( M_{\text{BH}} \) due to the time-variation of AGNs is expected to be 0.04 dex.

In order to determine the Mg \( \text{II} \) FWHMs of broad-line AGNs, it is necessary to consider Fe \( \text{II} \) emission lines as well as the power-law continuum component in the UV wavelength range. Because there are many broad Fe \( \text{II} \) emission lines in the wavelength range, they look like an additional continuum component to the power-law continuum of broad-line AGNs. We use an Fe \( \text{II} \) template derived from the UV spectrum of the narrow-line Seyfert 1 galaxy, I Zw 1 (Vestergaard & Wilkes 2001). This template covers the rest-frame wavelength range between 1074 Å and 3089 Å. We do not include the Balmer continuum in the fitting because the wavelength coverage is not wide enough to constrain its contribution. The ignorance of the Balmer continuum does not affect the Mg \( \text{II} \) FWHM measurements significantly, but the luminosity of the power-law continuum can be overestimated by 0.12 dex (Shen & Liu 2012).

A fit to the power-law continuum, Fe \( \text{II} \) emission lines, and Mg \( \text{II} \) emission line is carried out as follows. First, we determine the normalization of the Fe \( \text{II} \) and continuum component using a \( \chi^2 \) minimization in the two rest-frame wavelength ranges, 2500–2700 Å and 2900–3000 Å, in which the Mg \( \text{II} \) broad-line component is negligible. These are close to the pure Fe emission windows nos. 9 and 10 in Vestergaard & Wilkes (2001). We vary the line width of the Fe \( \text{II} \) emission lines from 1000 km s\(^{-1}\) to 15000 km s\(^{-1}\) with a step size of 250 km s\(^{-1}\) by convolving a Gaussian profile with the Fe \( \text{II} \) template which has a velocity width of 900 km s\(^{-1}\). We assume a constant line width for all Fe \( \text{II} \) emission lines. The scaling of the Fe \( \text{II} \) emission is changed from 0% to 100% of the observed continuum level with a step size of 0.01%. The continuum component is modeled with a power-law spectrum (\( f_c \propto \nu^{-\gamma} \)). The observed wavelength ranges affected by strong night sky lines (5555–5605 Å and 6270–6320 Å) are removed in the fitting. Because some optical spectra do not have a noise level estimation from the standard reduction method, we estimate the noise level for each spectrum as follows. Considering that the noise level does not vary significantly within the observed wavelength range, we use a constant noise level for the entire wavelength range. In the first stage of the fitting, we use the standard deviation determined within the wavelength range as the noise level. Subsequently, we determine the noise level from the rms of the residual of the first fitting and carry out the final fit for the continuum. The noise level is used for the Mg \( \text{II} \) line profile fitting as well. Examples of continuum fits are shown in the upper panels of Figure 3.

By subtracting the Fe \( \text{II} \) emission and power-law continuum components, the Mg \( \text{II} \) broad-line component is extracted. Then, we measure the FWHM of the Mg \( \text{II} \) broad-emission line after fitting its line profile with multiple Gaussians using a \( \chi^2 \)
minimization. In the fitting, we do not consider the doublet component of $\text{Mg}\ \, \lambda \lambda 2796, \ 2803$ because the separation is small and does not affect the measured width of the broad Mg II line. We use the mpfit package for python to perform the $\chi^2$ minimization (Markwardt 2009). Mpfit uses the Levenberg–Marquardt algorithm to derive the best-fit parameters. For some objects, the Mg II line profile cannot be described with a single Gaussian component. In such cases, we consider up to three broad Gaussians for the broad line. If necessary, we include narrow doublet absorption lines. Sometimes, we also include a narrow Gaussian component to remove artificial spiky noise features. Because no object shows a significant existence of the narrow Mg II line, we do not include a narrow-emission line component in the fitting. No inclusion of the narrow-line component differs from the fitting method used in much of the literature, such as in McClure & Jarvis (2002). Once the pure Mg II broad-line component is fitted with the multiple Gaussian components, the FWHM of the broad Mg II line is measured with the best-fit profile constructed by combining the multiple Gaussians. We do not include absorption lines in the combination. We introduce multiple Gaussian components in order to reproduce the observed Mg II broad-line profile smoothly and here we are not concerned with the physical meaning of the difference from the single Gaussian profile. Examples of the resulting Mg II broad-line fitting are shown in the middle and bottom panels of Figure 3. Because the spectra are obtained with various instruments, the spectral resolution of data varies from object to object. The spectral resolution is evaluated for each spectrum by using the line width of the arc lamp spectrum or night sky emission lines. The measured FWHMs are corrected for the intrinsic spectral resolution.

The uncertainty of the FWHM values for the combined multiple Gaussian profile is not available from the fitting with the mpfit package (the uncertainty is only available for each Gaussian component). Therefore, we evaluate the uncertainty for the FWHM of each object from the rms scatter of FWHMs measured in mock spectra constructed from the best-fit profile of the object. We construct the mock spectra as follows. First, the best-fit multi-Gaussian model is shifted by several pixels in wavelength from its original position. Then, the shifted model profile is combined with the residual of the original fitting. By monotonically increasing the shift and randomly changing the sign of the residual in each pixel, we construct 100 mock spectra. The mock spectra are fitted in the same way as the original data and FWHMs are measured. Finally, the rms scatter of the derived FWHMs is used as the uncertainties of the FWHM measurement. For AGNs whose Mg II broad line is fitted with a single Gaussian component, we compare the uncertainties derived from the $\chi^2$ statistics and from the scatter of the mock measurements. They are consistent with each other, although the rms scatter of the mock measurements is slightly smaller than the uncertainties from the $\chi^2$ statistics. Hereafter, we use the uncertainty derived with the scatter of the mock measurements.

The fitting results are summarized in Table 3. Column 4 of the table describes the model used for each object; “OneBL,” “TwoBL,” and “ThreeBL” indicate fitted with one, two, and three broad lines, respectively. “OneBLOneAbs” indicates a model with one broad and one absorption line.

For the Mg II profile fitting, we also use the specfit software in the stsdas package of IRAF. This package uses the Marquardt algorithm or simplex algorithm to perform the $\chi^2$ minimization. We compare the results obtained with mpfit and specfit for each object. The rms scatter of the difference in FWHMs from the two measurements is 0.06 dex. The resulting uncertainty in $M_{\text{BH}}$ due to the scatter is 0.12 dex. We use the results obtained with mpfit hereafter.

The measured FWHM of the Mg II broad line can be affected by the template used for the Fe II fitting. For the Fe II fitting, we use the empirically derived Fe II template from Vestergaard & Wilkes (2001; VW01 template). There is no Fe II emission in the wavelength range between 2770 Å and 2820 Å in the template. Tsuzuki et al. (2006) also derived the Fe II template (T06 template) from UV and optical spectra of I Zw 1. Utilizing the wide wavelength coverage available, they fit the continuum with a power-law and Balmer continuum and also utilize the Hα line profile to remove the Mg II line component. The important difference between the two templates is the Fe II contribution to the blue wing of the broad Mg II line. In the T06 template,
Figure 4. FWHMs of the broad Mg\(\text{II}\) emission line determined after Fe\(\alpha\) fitting with the VW01 and T06 Fe\(\alpha\) templates. The dashed line shows the equal FWHM line.

The excess wing seen on the blue side of the Mg\(\text{II}\) line of I Zw 1 compared with its H\(\alpha\) line profile is regarded as a contribution from the Fe\(\alpha\) emission line at around 2790 Å. In order to examine the effect of different Fe\(\alpha\) templates on the FWHM measurement, we also apply the Mg\(\text{II}\) emission line fitting process described above using the T06 template for 95 objects whose broad Mg\(\text{II}\) lines are well fitted with one broad-line component with the VW01 template. Figure 4 compares the log FWHM values derived with the two templates. There is a systematic offset of 0.04 dex; the FWHMs derived with the T06 template are systematically smaller than those with the VW01 template. The rms scatter of the difference is 0.05 dex after removing the systematic offset. The resulting systematic uncertainty of \(\Delta M_{\text{FWHM}}\) is 0.08 dex. In order to compare our results with the broad-line AGN BHMFs from the literature, we follow the same fitting procedure using the VW01 template, but we note that the FWHMs can have a systematic uncertainty due to the Fe\(\alpha\) template difference.

3.3. H\(\alpha\) Line Width Measurements from NIR Spectra

The NIR spectra of X-ray sources obtained with FMOS were reduced with the pipeline data reduction software, FIBRE-pac (Iwamuro et al. 2012). The resulting one-dimensional spectra are corrected for atmospheric absorption and sensitivity dependence on wavelength using relatively bright F-G type stars observed simultaneously with the targets. Because we do not use the absolute flux of the continuum component, we do not apply a further correction for normalization based on the photometry. The noise level of each spectrum is also estimated in the pipeline data reduction software.

The profile of the broad H\(\alpha\) line is fitted with mpfit in a manner similar to the broad Mg\(\text{II}\) component. The possible existence of the narrow emission lines of H\(\alpha\) and [N\(\text{II}\)]\(\lambda\lambda 6583, 6548\) makes the fitting more complicated than for the Mg\(\text{II}\) broad line. We include the narrow emission lines in the fitting only if a prominent narrow emission feature, such as the asymmetric profile due to the 1:3 flux ratio of [N\(\text{II}\)] lines, is observed. For the broad H\(\alpha\) component, we use up to two Gaussians to fit the profile. In the fitting process, we assume a constant continuum component because the continuum of the observed NIR spectra does not show a significant tilt in the region around the H\(\alpha\) emission line. Due to the existence of the OH suppression mask, the strength of the narrow emission line can be underestimated even after the sensitivity correction process if the narrow emission line is close to the masked wavelength. We apply the fitting procedure taking into account the underestimation due to the optical masking and the sensitivity correction process. The details of the fitting procedure are described in Yabe et al. (2012). We note that the effect of the OH suppression mask only affects the narrow-emission line and the effects on the broad-emission lines and continuum are negligible. Examples of the H\(\alpha\) fitting are shown in Figure 5.

The uncertainty in the FWHM measurements of the broad H\(\alpha\) emission line is evaluated in the same way as for the broad Mg\(\text{II}\) emission lines. We construct 10 model spectra by adding a shifted best-fit multi-Gaussian model to the residual of the fitting. Then, the same fitting procedure is applied to the model spectra and the rms scatter of the measured FWHMs is used as the uncertainty of the FWHM measurement. In this fitting process, we also take into account the effect of the OH suppression mask.

The resulting FWHM of the broad H\(\alpha\) emission is compared with that of the broad Mg\(\text{II}\) line for broad-line AGNs with FWHM measurements for both lines in Figure 6. We remove the Mg\(\text{II}\) FWHMs of four broad-line AGNs (SXDS0590, SXDS0630, SXDS0790, and SXDS0969) because the

### Table 3

| ID     | \(z\)  | \(\log I_{\text{H}\alpha}/(\text{erg s}^{-1})\) | FWHM \(\text{Mg}\text{II}\) Model | \(\log I_{\text{H}\alpha}/(\text{erg s}^{-1})\) | FWHM \(\text{H}\alpha\) Model |
|--------|--------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0010   | 1.225  | 44.05                           | 5341 ± 12 TwoBL                 | 5135 ± 116 OneBL                |
| 0018   | 1.452  | 44.42                           | ...                             | 5488 ± 92 BLNL                  |
| 0019   | 1.447  | 44.66                           | 4823 ± 312 OneBL                | ...                             |
| 0023   | 1.534  | 44.14                           | ...                             | 5602 ± 112 OneBL                |
| 0027   | 2.067  | 43.75                           | 4136 ± 1499 TwoBL               | ...                             |
| 0034   | 0.952  | 43.55                           | 4286 ± 1005 TwoBL               | 2459 ± 123 TwoBL                |
| 0036   | 0.884  | 44.16                           | 3326 ± 22 TwoBL                 | 2790 ± 50 TwoBL                 |
| 0037   | 1.202  | 43.81                           | 4516 ± 70 TwoBL                 | ...                             |
| 0050   | 1.411  | 44.03                           | 2046 ± 120 OneBL                | 1800 ± 68 OneBL                 |
| 0056   | 1.260  | 44.19                           | ...                             | 8171 ± 456 BLNL                 |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
signal-to-noise ratios of their Mg II spectra are much lower than those of their Hα spectra. Therefore, 48 broad-line AGNs are plotted in the figure. The sample is divided with the absorption-corrected X-ray luminosity. Broad-line AGNs that are brighter (fainter) than $L_{2-10\text{keV}} = 10^{44}$ erg s$^{-1}$ are marked with filled squares (crosses). The measured FWHMs of the broad Mg II and Hα lines roughly follow the equality line. However, there may be a tendency for broad-line AGNs with lower luminosity to have systematically smaller broad Hα FWHMs than broad Mg II lines. The distribution is broadly consistent with those of broad-line AGNs measured in the literature. We show the Mg II and Hα FWHMs of individual broad-line AGNs from Shen & Liu (2012), Greene et al. (2010b), and McGill et al. (2008). The samples of Shen & Liu (2012) and Greene et al. (2010b) are luminous broad-line AGNs with $L_{\text{bol}}$ of $10^{46-48}$ erg s$^{-1}$ at $z=1-2$. By contrast, the McGill et al. (2008) sample covers broad-line AGNs with $L_{\text{bol}}$ of around $10^{45}$ erg s$^{-1}$ at $z \sim 0.3$. The distribution of the former samples is consistent with each other and follows a trend similar to that of the SXDS luminous broad-line AGNs. The latter sample has a systematic offset from the former samples and shows a smaller Hα broad-line FWHM than Mg II FWHM. The trend is similar to that seen in the SXDS less-luminous broad-line AGNs.

We determine the relationship between the Mg II and Hα FWHMs by applying a Bivariate Correlated Error and intrinsic Scatter (BCES) bisector regression analysis (Akritas & Bershady 1996) to the 48 broad-line AGNs including both luminous and less-luminous AGNs. Considering the size of the sample, we do not divide the sample by luminosity in the analysis. The resulting relationship is

$$\log \text{FWHM}_{\text{Mg II}} = (0.795 \pm 0.075) \times \log \text{FWHM}_{\text{Hα}} + (0.771 \pm 0.273).$$  

The rms scatter of log FWHM$\text{Mg II}$ determined with the above relationship using the measured log FWHM$\text{Mg II}$ is 0.11 dex, with a resulting uncertainty for log $M_{\text{BH}}$ of 0.22 dex. The less luminous broad-line AGNs show a systematic offset from the relation of 0.1 dex on average.

The relationship between the FWHMs of the Hβ and Mg II broad lines from McLure & Jarvis (2002; short dashed line), Onken & Kollmeier (2008; thin solid line), Wang et al. (2009; dotted line), and Croom (2011; long dashed line) are shown after converting Hβ FWHM to Hα FWHM.

(A color version of this figure is available in the online journal.)

**Figure 6.** Comparison between FWHMs of Hα and Mg II broad lines for SXDS AGNs. Filled circles and crosses represent broad-line AGNs brighter and fainter than $L_{2-10\text{keV}} = 10^{44}$ erg s$^{-1}$, respectively. The thick solid line represents the BCES bisector fitting result for the SXDS AGNs. Open squares, triangles, and circles are AGNs from Shen & Liu (2012), Greene et al. (2010b), and McGill et al. (2008), respectively. The relationships between the Mg II and Hα FWHMs from McLure & Jarvis (2002; short dashed line), Onken & Kollmeier (2008; thin solid line), Wang et al. (2009; dotted line), and Croom (2011; long dashed line) are shown after converting Hβ FWHM to Hα FWHM.

(A color version of this figure is available in the online journal.)

**Figure 5.** Examples of broad Hα fitting. Upper panels show the observed data (thin solid line) and the best-fit model with each component (thick solid lines). Lower panels show the residual from the fitting (thin solid line). Thick solid lines in the panels enclose the estimated 1σ noise level at each wavelength. Left, SXDS1097 with a single broad line; middle, SXDS0817 with two broad lines; and right, SXDS0018 with a broad line and narrow Hα. (A color version of this figure is available in the online journal.)
of Croom (2011) has a steeper slope than the other relationships and follows the distribution of SXDS broad-line AGNs except for the objects with the largest FWHMs. The relationship of Wang et al. (2009) shows a systematic offset from the other relationships and the distribution of SXDS broad-line AGNs. The origin of the shift is unclear, but it is possible that Wang et al. (2009) use the T06 Fe II template, and the FWHM of Mg II is measured as systematically smaller than other measurements with the VW01 Fe II template (see Section 3.2).

We use the relationship shown in Equation (2) to convert the Hα FWHM to Mg II FWHM and the same black hole mass equation for Mg II FWHM is applied. In total, we use the Hα FWHM measurements for 23 out of 116 broad-line AGNs at redshifts between 1.18 and 1.68.

### 3.4. 3000 Å Monochromatic Luminosities

For most of the objects, we derive a 3000 Å monochromatic luminosity using the best-fit power-law continuum component described in Section 3.2. We do not include the contribution of the Balmer continuum in the fitting; the 3000 Å monochromatic luminosity can be overestimated by 0.12 dex (Shen & Liu 2012). Optical spectra covering the rest-frame 3000 Å are not available for broad-line AGNs that are only covered by the NIR spectroscopic data. We estimate their 3000 Å monochromatic luminosity by interpolating multi-band photometry data. All of the broad-line AGNs are detected in the deep multi-band images obtained with Suprime-Cam. We derive their rest-frame 3000 Å flux by interpolating the photometric measurements in the neighboring two bands around rest-frame 3000 Å. The photometric data can include broad-emission lines and Balmer continuum as well, and the 3000 Å luminosity may thus be affected by the broad-line component. In order to estimate this effect, we compare the 3000 Å luminosity derived from normalized spectra and multi-band photometry for objects with both measurements. They are consistent with each other within the rms of 0.10 dex and the resulting uncertainty of $M_{BH}$ is 0.05 dex. We note that the optical spectra are normalized to match the $R$-band photometry from the imaging observations as described in Section 3.2; therefore, the scatter only reflects the object-to-object variation of the strength of the broad-line components. For the estimation of the 3000 Å monochromatic luminosity with the photometric data, the contribution from the Balmer continuum is not considered. The uncertainty associated with the variability of broad-line AGNs is already described in Section 3.2.

For mildly obscured broad-line AGNs, the 3000 Å luminosity can be affected by dust extinction. Additionally, for low-luminosity broad-line AGNs, the 3000 Å luminosity can be affected by a host galaxy component. In such cases, neither the 3000 Å luminosity derived from the spectra nor the photometry is a good indicator of the intrinsic UV luminosity. In Figure 7, the monochromatic 3000 Å luminosity and absorption-corrected 2–10 keV luminosity of the broad-line AGNs are shown. In this figure, broad-line AGNs with $R−i$ color redder than 0.3 are marked with open circles. Those with an $R−i$ color of 0.3 are redder than the scatter of typical broad-line AGNs in the redshift range observed in SDSS (Richards et al. 2003). Hereafter, we designate broad-line AGNs with $R−i$ redder (blue) than 0.3 as red (blue) broad-line AGNs. In the diagram, blue broad-line AGNs follow the relationship expected from the typical SEDs of broad-line AGNs as a function of intrinsic luminosity, which is shown with the solid line in the figure (Marconi et al. 2004). The dotted line in the figure shows the relationship determined with the BCES bisector analysis for blue broad-line AGNs. In Marconi et al. (2004), the SEDs around 3000 Å are described with a power law with $\alpha = −0.44$ with $L_{\nu} \propto \nu^\alpha$ and a dependence of the optical-to-X-ray flux ratio, $\alpha_{OX}$, on the optical luminosity of broad-line AGNs (Vignali et al. 2003) is considered. The $B$-band luminosity used in Marconi et al. (2004) is converted to a 3000 Å monochromatic luminosity assuming a typical SED of broad-line QSOs $(1.549 \times \lambda_{4360} L_{\lambda_{4360}} = \lambda_{3000} L_{\lambda_{3000}})$; Richards et al. 2006). The consistency of the distribution with this relation suggests that the blue broad-line AGNs have SEDs consistent with the optical-to-X-ray luminosity ratio, $\alpha_{OX}$, dependence on luminosity for typical non-absorbed broad-line AGNs.

On the contrary, most of the red broad-line AGNs have a systematically fainter 3000 Å monochromatic luminosity than the blue broad-line AGNs at the same absorption-corrected 2–10 keV luminosity. The fainter 3000 Å luminosity suggests that the red broad-line AGNs are affected by mild dust absorption, although most of them show a strong Mg II broad line. Additionally, some of the red broad-line AGNs are brighter in their 3000 Å luminosity. Most of them have the lowest absorption-corrected 2–10 keV luminosity and their red colors can be explained by contamination from a host galaxy component in the wavelength range. In both cases, the 3000 Å luminosity is not a good indicator of intrinsic luminosity, thus we use absorption-corrected X-ray luminosity instead of the 3000 Å monochromatic luminosity for the black hole mass estimation. We convert the absorption-corrected hard X-ray luminosity of the red broad-line AGNs to the intrinsic 3000 Å monochromatic luminosity using the relationship derived by Marconi et al. (2004). Considering the scatter of blue broad-line AGNs around the relationship, we estimate that the rms uncertainty of the intrinsic 3000 Å monochromatic luminosity is 0.54 dex, which corresponds to 0.27 dex in the $M_{BH}$ uncertainty. We use the 3000 Å monochromatic luminosity derived from the hard X-ray luminosity of 59 red broad-line AGNs out of the 215 broad-line AGNs for the $M_{BH}$ estimate. There are 26 red broad-line AGNs...
among the 116 broad-line AGNs in the redshift range between 1.18 and 1.68 where the broad-line AGN BHMF and ERDF are derived below.

In summary, 3000 Å monochromatic luminosities are derived in three ways, from the power-law component of the fitting of optical spectra, the optical broadband photometry for broad-line AGNs only with the NIR spectrum, and hard X-ray luminosity for mildly obscured or less-luminous broad-line AGNs. The resulting 3000 Å monochromatic luminosities are summarized in Table 3.

4. BLACK HOLE MASS, BOLOMETRIC LUMINOSITY, AND EDDINGTON RATIO

The distribution of broad-line AGNs in the measured Mg II FWHM versus intrinsic 3000 Å monochromatic luminosity plane is shown in the left panel of Figure 8. Large open squares indicate the FWHMs that are estimated with the broad Hα line and Equation (2). In the panel, the constant $M_{\text{BH}}$ line derived from Equation (1) is shown with solid lines. From bottom to top, the lines correspond to $M_{\text{BH}}$ of $10^6$, $10^7$, $10^8$, $10^9$, $10^{10}$, and $10^{11} M_\odot$. The SXDS broad-line AGNs cover the $M_{\text{BH}}$ range between $10^7 \sim 10^{10} M_\odot$ with a median of $3.2 \times 10^8 M_\odot$.

Although we define broad-line AGNs as having FWHMs above 1000 km s$^{-1}$, a few objects have FWHMs between 1000 and 2000 km s$^{-1}$. In the panel, we compare the distribution with that of broad-line AGNs from SDSS DR5 (filled gray circles; Shen et al. 2008b). The 49,526 SDSS broad-line AGNs, which are selected with broad-line components whose FWHM is larger than 1200 km s$^{-1}$, are distributed between $z = 0.3$ and 2.4. Though there are a far larger number of broad-line AGNs in the SDSS sample than in the SXDS sample, again only a negligible fraction of broad-line AGNs have FWHMs smaller than 2000 km s$^{-1}$. A similar rapid decrease of broad-line AGNs with FWHM smaller than 2000 km s$^{-1}$ is also reported by Hao et al. (2005) and Stern & Laor (2012). They select broad-line AGNs in the local universe from SDSS galaxies as well as quasar samples with broad Hα lines above 1000 km s$^{-1}$.

The distribution of Hα FWHMs shows a rapid decrease in the FWHM range below a few 1000 km s$^{-1}$. The physical origin of the cutoff in the FWHM distribution is unknown.

In the right panel of the figure, only SXDS and SDSS broad-line AGNs at redshifts between 1.18 and 1.68 are plotted. The luminosity limits of the surveys define the left-hand envelopes of the distributions. It can be seen that the SXDS broad-line AGNs cover a 3000 Å monochromatic luminosity down to $10^{43.5}$ erg s$^{-1}$ in the redshift range. This luminosity limit is more than an order of magnitude fainter than that of the SDSS sample in the same redshift range.

We estimate the bolometric luminosity, $L_{\text{bol}}$, from the 3000 Å monochromatic luminosity using a bolometric correction factor of 5.8 for the monochromatic luminosity from Richards et al. (2006), following Vestergaard & Osmer (2009). In Table 4, $M_{\text{BH}}$, $L_{\text{bol}}$, and $\lambda_{\text{Edd}}$ are tabulated. The bolometric luminosities of the SXDS sample are distributed between $L_{\text{bol}} = 10^{45} \sim 10^{46}$ erg s$^{-1}$ with a median of $2.9 \times 10^{45}$ erg s$^{-1}$. The Eddington ratio of each object is calculated as $\lambda_{\text{Edd}} \equiv L_{\text{bol}}/L_{\text{Edd}}$. $L_{\text{Edd}}$ is the Eddington-limited luminosity given by $1.26 \times 10^{38} M_{\text{BH}}$.

Table 4: Black Hole Mass and $\lambda_{\text{Edd}}$ of Broad-line AGNs

| ID  | $z$  | $\log(M_{\text{BH}}/M_\odot)$ | $\log(L_{\text{bol}}/\text{erg s}^{-1})$ | $\log\lambda_{\text{Edd}}$ |
|-----|------|-------------------------------|--------------------------------|-----------------|
| 0010 | 1.225 | 8.8                           | 45.65                          | -1.22           |
| 0018 | 1.452 | 8.9                           | 45.92                          | -1.12           |
| 0019 | 1.447 | 8.9                           | 46.18                          | -0.87           |
| 0023 | 1.534 | 8.9                           | 45.87                          | -1.16           |
| 0027 | 2.067 | 9.0                           | 46.61                          | -0.52           |
| 0034 | 0.952 | 8.5                           | 45.49                          | -1.11           |
| 0036 | 0.884 | 8.5                           | 46.00                          | -0.64           |
| 0037 | 1.202 | 8.4                           | 45.21                          | -1.30           |
| 0050 | 1.411 | 7.9                           | 45.56                          | -0.43           |
| 0056 | 1.260 | 9.0                           | 45.50                          | -1.60           |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
represent constant log $\lambda_{\text{Edd}}$ from $H\alpha$ FWHM are estimated from $H\alpha$ FWHM are marked with large open squares. The dotted line shows the relationship between $\log M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ for a broad-line AGN with $L_{2-10\,\text{keV}} = 10^{43}$ erg s$^{-1}$, corresponding to the faintest object in the sample. The thick solid line indicates the constant Mg$\,$ii FWHM of 1000 km s$^{-1}$. The distribution of the SDSS DR5 sample (Shen et al. 2008b) in the same redshift range is shown with the contours.

(A color version of this figure is available in the online journal.)

Figure 9. Black hole mass vs. Eddington ratio of broad-line AGNs at redshifts between 1.18 and 1.68. Broad-line AGNs whose Mg$\,$ii FWHM are estimated from $H\alpha$ FWHM are marked with large open squares. The dotted line shows the relationship between $\log M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ for a broad-line AGN with $L_{2-10\,\text{keV}} = 10^{43}$ erg s$^{-1}$, corresponding to the faintest object in the sample. The thick solid line indicates the constant Mg$\,$ii FWHM of 1000 km s$^{-1}$. The distribution of the SDSS DR5 sample (Shen et al. 2008b) in the same redshift range is shown with the contours.

5. BLACK HOLE MASS AND EDDINGTON RATIO DISTRIBUTION FUNCTIONS

5.1. Binned Broad-line AGN BHMF and ERDF with the $V_{\text{max}}$ Method

First, we derive the binned BHMF and ERDF for the broad-line AGNs between 1.18 $\leq z \leq$ 1.68 using the $V_{\text{max}}$ method (Avni & Bahcall 1980). Detailed numbers for the sample are shown in Table 2. In the calculations of the binned BHMF and ERDF, we only consider broad-line AGNs with $\lambda_{\text{Edd}}$ larger than 0.01, and remove two broad-line AGNs below the limit. We also remove two broad-line AGNs (SXDS0613 and SXDS0738) with neither Mg$\,$ii nor $H\alpha$ FWHM measurements in the redshift range. We derive the binned broad-line AGN BHMF and ERDF for the soft- and hard-band samples separately.

For the binned broad-line AGN BHMF, we divide the mass range $6.6 \leq \log(M_{\text{BH}}/M_\odot) \leq 10.2$ into nine bins with bin width, $\Delta \log M_{\text{BH}}$, of 0.4 dex. The number density in a bin between ($\log M_{\text{BH}} - \Delta \log M_{\text{BH}}$/2) and ($\log M_{\text{BH}} + \Delta \log M_{\text{BH}}$/2) is given by

$$\Phi_{\text{BH}}(M_{\text{BH}}) \Delta \log M_{\text{BH}} = \sum_{i=1}^{n} \frac{1}{V_{a,i}}. \quad (3)$$

The summation is done for the $n$ broad-line AGNs in the mass bin. Here, $i$ is the index for a broad-line AGN in the mass bin. $V_{a,i}$ is the effective survey volume for the $i$th broad-line AGN in the comoving coordinate and its inverse represents the contribution of the broad-line AGN to the comoving number density of the mass bin. $V_{a,i}$ is given by

$$V_{a,i} = \int_{z_{\text{min}}}^{z_{\text{max}}} \int \frac{\Omega(L_{\text{X'i}}, \log N_{\text{H'i}}, z')}{z' \frac{dz'}{d\Omega}} dV d\Omega d\Omega dz'. \quad (4)$$

Here, $z_{\text{min}}$ and $z_{\text{max}}$ represent the redshift range for the binned broad-line AGN BHMF (1.18 and 1.68, respectively). $\Omega(L_{\text{X'i}}, \log N_{\text{H'i}}, z')$ is the survey area which is calculated assuming that the $i$th broad-line AGN observed at $z_i$ with absorption-corrected luminosity $L_{\text{X'i}}$ and absorption hydrogen column density $N_{\text{H'i}}$ is at redshift $z'$. With an estimated absorption-corrected $L_{\text{X'i}}$ and $N_{\text{H'i}}$ as described in Section 2, we calculate the predicted count rate for each broad-line AGN with $z'$ instead of the observed $z_i$. The same X-ray spectral model of AGNs is used, as explained in Section 2. The survey area for the sample with likelihood larger than seven is determined as a function of count rate for the overlapping region of the X-ray and deep optical surveys (Ueda et al. 2008). The logN–logS relation derived with the area curve for the SXDS X-ray sources is consistent with the relation determined in deeper Chandra surveys (Ueda et al. 2008). The consistency implies the position-dependent detection limit of the X-ray survey is reproduced well in the estimated area curve. If the predicted count rate of an object at a certain redshift $z'$ is below the smallest count-rate limit of the survey, then $\Omega(L_{\text{X'i}}, \log N_{\text{H'i}}, z')$ becomes zero above that redshift. The factor $(1+z')/(1+z_{\text{cen}})$ $^{5}$ corrects for the number density evolution with $(1+z)^{5}$ within the redshift range to determine the corresponding number density at $z_{\text{cen}}$ of 1.43. However, the correction factor is negligible.
Finally, $V_{a,i}$ with even if we introduce a rather strong number density evolution with $k = 4-5$ observed for the X-ray luminosity function of AGNs (Ueda et al. 2003; Hasinger et al. 2005) because the redshift range for this calculation is narrow. Therefore, we neglect this term hereafter and fix the value $k$ at zero for simplicity. Finally, $V_{a,i}$ is obtained by integrating the corresponding survey area for the object at redshift $z_i$ multiplied by the cosmological volume element $(dV/dz^*)dz^*$ of unit solid angle in the redshift range. The uncertainty of the binned broad-line AGN BHMF is estimated using Poisson statistics as

$$\sigma = \left[ \sum_{k=1}^{n} \left( \frac{1}{V_{a,i} \Delta \log M_{BH}} \right)^2 \right]^{1/2}. \quad (5)$$

The resulting binned broad-line AGN BHMFs are shown in Figure 10 and Table 5. The filled and open circles represent the binned BHMFs of soft- and hard-band broad-line AGN samples, respectively. Both of the binned broad-line AGN BHMFs peak at around a $M_{BH}$ of $10^{8.5} M_\odot$. The binned broad-line AGN BHMFs are consistent each other within the $1\sigma$ uncertainty.

The binned broad-line AGN ERDF is derived in the same way for the binned BHMF using the $V_{\text{max}}$ method. We bin the sample in $\lambda_{\text{Edd}}$ by dividing the $\lambda_{\text{Edd}}$ range of $-2.125 < \log \lambda_{\text{Edd}} < 0.375$ into 10 bins with a bin width $\Delta \lambda_{\text{Edd}}$ of 0.25 dex. The number density of a certain Eddington ratio bin between $(\log \lambda_{\text{Edd}}-\Delta \log \lambda_{\text{Edd}}/2)$ and $(\log \lambda_{\text{Edd}}+\Delta \log \lambda_{\text{Edd}}/2)$ is given by

$$\Phi_\lambda(\lambda_{\text{Edd}}) \Delta \log \lambda_{\text{Edd}} = \sum_{i=1}^{n} \frac{1}{V_{a,i}}. \quad (6)$$

Here, $n$ is the number of broad-line AGNs in the Eddington ratio bin. $V_{a,i}$ is the same effective volume for the $i$th broad-line AGN used in the binned BHMF. The uncertainty for each Eddington ratio bin is again given by

$$\sigma = \left[ \sum_{k=1}^{n} \left( \frac{1}{V_{a,i} \Delta \log \lambda_{\text{Edd}}} \right)^2 \right]^{1/2}. \quad (7)$$

The resulting binned ERDF is shown in Figure 11 and tabulated in Table 6. The filled and open circles in the figure are the binned ERDFs for the soft- and hard-band samples, respectively. The binned ERDFs are consistent with each other within the $1\sigma$ uncertainty. In the binned ERDFs, broad-line AGNs in the entire mass range are considered. Due to the flux limit of the survey, the sample covers only broad-line AGNs with larger $M_{BH}$ in the lower $\lambda_{\text{Edd}}$ bins. Therefore, the shape of the binned ERDF can be affected by the flux limit.

In order to examine the $M_{BH}$ dependence of the binned ERDF, in Figure 12, the binned ERDFs derived with the soft-band selected broad-line AGNs in the $M_{BH}$ range between $10^{8.0-8.5} M_\odot$ and that between $10^{8.5-9.0} M_\odot$ are plotted with filled circles and filled diamonds, respectively. The overall shapes of the binned ERDFs do not significantly differ from

### Table 5: Binned Broad-line AGN BHMF

| (log[M_{BH}/M_\odot]) | $\Phi_{\text{soft}}(\log M_{BH})$ | $N_{\text{soft}}$ | $\Phi_{\text{hard}}(\log M_{BH})$ | $N_{\text{hard}}$ |
|------------------------|-----------------------------|-------------|-----------------------------|-------------|
| 7.2                    | $1.65^{+5.80}_{-0.36}$      | 1           | $\cdots$                   | 0           |
| 7.6                    | $5.17 \pm 3.41$             | 4           | $1.50 \pm 1.07$            | 2           |
| 8.0                    | $11.60 \pm 2.43$            | 23          | $27.46 \pm 15.50$          | 17          |
| 8.4                    | $19.90 \pm 3.55$            | 36          | $43.21 \pm 21.54$          | 30          |
| 8.8                    | $18.62 \pm 3.36$            | 34          | $19.93 \pm 5.21$           | 28          |
| 9.2                    | $4.74 \pm 1.50$             | 10          | $4.53 \pm 1.51$            | 9           |
| 9.6                    | $\cdots$                    | 0           | $\cdots$                   | 0           |
| 10.0                   | $0.47^{+1.09}_{-0.39}$      | 1           | $0.47^{+1.09}_{-0.39}$      | 1           |

Notes.

$^a$ The central value of $M_{BH}$ in each bin. The bin size is 0.4 dex and extends ± 0.2 dex from the central value.

$^b$ In units of $10^{-6}[\text{Mpc}^{-3} \Delta \log (M_{BH}/M_\odot)]^{-1}$.

$^c$ The upper and lower limits are determined following Gehrels (1986).
Table 6

| $\log \lambda_{\text{Edd}}$ | $\Phi_{\text{soft}}(\log \lambda_{\text{Edd}})$ | $N_{\text{soft}}$ | $\Phi_{\text{hard}}(\log \lambda_{\text{Edd}})$ | $N_{\text{hard}}$ |
|----------------|-----------------|-----------------|-----------------|-----------------|
| $-2.00$ | $5.79 \pm 2.60$ | $6$ | $6.03 \pm 3.49$ | $4$ |
| $-1.75$ | $5.68 \pm 2.43$ | $6$ | $6.12 \pm 2.89$ | $5$ |
| $-1.50$ | $16.51 \pm 4.11$ | $18$ | $21.29 \pm 7.06$ | $14$ |
| $-1.25$ | $18.36 \pm 4.53$ | $20$ | $20.80 \pm 7.77$ | $15$ |
| $-1.00$ | $18.15 \pm 4.47$ | $20$ | $46.98 \pm 33.71$ | $16$ |
| $-0.75$ | $15.54 \pm 3.77$ | $18$ | $15.23 \pm 4.16$ | $15$ |
| $-0.50$ | $7.12 \pm 2.38$ | $10$ | $3.79 \pm 1.94$ | $5$ |
| $-0.25$ | $3.04 \pm 1.52$ | $4$ | $4.95 \pm 2.28$ | $5$ |
| $0.00$ | $0.76^{+1.75}_{-0.63}$ | $1$ | $2.95 \pm 1.76$ | $3$ |
| $0.25$ | $0.76^{+1.74}_{-0.63}$ | $1$ | $0.76^{+1.74}_{-0.63}$ | $1$ |

Notes.

a The central value of $\lambda_{\text{Edd}}$ in each bin.

b In units of $10^{-6} [\text{Mpc}^{-3} (\Delta \log [\lambda_{\text{Edd}}])^{-1}]$.

c The upper and lower limits are determined following Gehrels (1986).

each other within the uncertainty, except for the lowest log $\lambda_{\text{Edd}}$ range where the lower mass binned ERDF can be affected by the flux limit. Due to the limited number and mass range of the SXDS sample, there is no signature of the dependence of the ERDF on $M_{\text{BH}}$.

5.2. Corrected Broad-line AGN BHMF and ERDF with Maximum Likelihood Method

Both the binned broad-line AGN BHMF and ERDF are affected by the detection limit determined by the X-ray count rate; at the low-mass end of the binned BHMF, the sample covers only high $\lambda_{\text{Edd}}$ broad-line AGNs, and at the low Eddington ratio end of the binned ERDF the sample does not include broad-line AGNs with low $M_{\text{BH}}$. Such detection limits are not corrected for in the calculations of the binned broad-line AGN BHMF and ERDF.

The effects of the detection limit can be corrected through statistical methods assuming the forms of both functions (Kelly et al. 2009, 2010; Schulze & Wisotzki 2010; Shen & Kelly 2012; Kelly & Shen 2012). Schulze & Wisotzki (2010) apply the maximum likelihood method to a sample of low-redshift broad-line AGNs detected in the ESO/Hamburg survey, assuming that the intrinsic ERDF does not depend on $M_{\text{BH}}$. On the other hand, Kelly et al. (2010), Shen & Kelly (2012), and Kelly & Shen (2012) apply a Bayesian approach (Kelly et al. 2009) to SDSS broad-line AGNs. They introduce a dependence of ERDF on the black hole mass. Furthermore, the statistical scatter in the virial black hole mass estimate is considered in the calculations; the scatter can broaden a peak in the intrinsic broad-line AGN BHMF and a steep slope of intrinsic BHMF at the high-mass end can become flatter in the binned BHMF. If the intrinsic BHMF has a peak at a certain black hole mass and there is a turn-over at the low-mass end, then the scatter can also affect the binned BHMF in the low-mass end.

Here, we apply the maximum likelihood method used in Schulze & Wisotzki (2010) for the broad-line AGNs in the soft-band sample. Because there is no significant difference between the binned broad-line AGN ERDFs in the high- and low-mass ranges as shown in Figure 12, we assume that the intrinsic broad-line AGN ERDF is constant regardless of black hole mass. The effect of the scatter of the virial black hole mass estimate is not considered in this paper, because the SXDS sample covers smaller black hole mass and Eddington ratio ranges than the SDSS sample, most of the SXDS broad-line AGNs lie in the mass range below the knee of the BHMF, and in order not to be affected by the uncertainty associated with the modeling of the scatter. The high-mass end of the corrected broad-line AGN BHMF can be affected by flattening due to the scatter.

In this evaluation, we assume the shape of the corrected broad-line AGN BHMF to be either a double-power law or a Schechter function,

$$
\Phi_{\text{BH}}(M_{\text{BH}}) = \frac{M_{\text{BH}}}{\log_{10} e} \phi^* \left( \frac{M_{\text{BH}}}{M^*} \right)^{-\alpha} \left( 1 + \left( \frac{M_{\text{BH}}}{M^*} \right)^{-\beta} \right),
$$

(8)

$$
\Phi_{\text{BH}}(M_{\text{BH}}) = \frac{M_{\text{BH}}}{\log_{10} e} \phi^* \left( \frac{M_{\text{BH}}}{M^*} \right)^{\alpha} \exp \left( -\frac{M_{\text{BH}}}{M^*} \right),
$$

(9)

respectively, with the functions expressed per log $M_{\text{BH}}$. We introduce these two forms because the double power law describes the AGN luminosity function well, and the Schechter function describes the luminosity and mass functions of galaxies. Even though a modified Schechter function describes the non-active BHMF in the local universe (Aller & Richstone 2002; Shankar et al. 2004), we do not implement such a function, since it does not converge and results in a rather small $M^* (10^5-6 M_\odot)$.

For the corrected ERDF, we assume the Schechter function and the log-normal distributions:

$$
\Phi_{\lambda}(\lambda_{\text{Edd}}) = \frac{\lambda_{\text{Edd}}}{\log_{10} e} \phi^* \left( \frac{\lambda_{\text{Edd}}}{\lambda^*} \right)^{\alpha} \exp \left( -\frac{\lambda_{\text{Edd}}}{\lambda^*} \right),
$$

(10)

$$
\Phi_{\lambda}(\lambda_{\text{Edd}}) = \frac{1}{\lambda_{\text{Edd}} \sqrt{2\pi \sigma^2}} \exp \left( -\frac{(\ln \lambda_{\text{Edd}} - \mu)^2}{2\sigma^2} \right).
$$

(11)

We do not consider the $M_{\text{BH}}$ dependence of the ERDF. For both distributions, we define the normalized corrected ERDF with

$$
P_{\lambda}(\lambda_{\text{Edd}}) = \frac{\Phi(\lambda_{\text{Edd}})}{\int_{-2.0}^{1.0} \Phi(\lambda_{\text{Edd}}) d \log \lambda_{\text{Edd}}}. 
$$

(12)
We normalize the corrected ERDF in the range log $\lambda_{\text{Edd}}$ of $-2.0$ and $1.0$. In these functions, $\phi^*$, $\alpha$, $\beta$, and $M^*$ of the corrected BHMF and $\alpha_\lambda$ and $\lambda_{\text{Edd}}^*$ of the corrected ERDF (or $\sigma$ and $\mu$ for log-normal ERDF) are free parameters. We derive the best-fit parameters with the maximum likelihood method (Marshall et al. 1983). The likelihood function is written as

$$S = -2 \sum_{i=1}^{N} \ln p(M_{\text{BH},i}, \lambda_{\text{Edd},i})$$

$$+ \int \int p(M_{\text{BH}}, \lambda_{\text{Edd}}) d\lambda_{\text{Edd}} d\log L_{\text{BH}}$$

(13)

and the model parameters that minimize $S$ are the best-fit parameters (Marshall et al. 1983). The sum of the first term is for the entire $N$ broad-line AGNs in the sample. The term $p(M_{\text{BH}}, \lambda_{\text{Edd}})$ is the expected number of black holes with $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ in units of log $M_{\text{BH}}$ and log $\lambda_{\text{Edd}}$ intervals in the survey redshift range with the assumed $\Phi_{\text{BH}}(M_{\text{BH}})$ and $P_{\lambda}(\lambda_{\text{Edd}})$. $p(M_{\text{BH}}, \lambda_{\text{Edd}})$ is given by

$$p(M_{\text{BH}}, \lambda_{\text{Edd}}) = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \Omega(M_{\text{BH}}, \lambda_{\text{Edd}}, \zeta') dV d\zeta'$$

$$P_{\lambda}(\lambda_{\text{Edd}})\Phi_{\text{BH}}(M_{\text{BH}}) \left( \frac{1 + \zeta'}{1 + \zeta_{\text{cen}}} \right)^k$$

(14)

$\Omega(M_{\text{BH}}, \lambda_{\text{Edd}}, \zeta')$ is the survey area for a broad-line AGN with $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ at $\zeta'$. We calculate the expected count rate for each combination of $M_{\text{BH}}$, $\lambda_{\text{Edd}}$, and $\zeta'$ assuming the same model for the X-ray spectrum of AGNs used in Section 2. We convert the $L_{\text{bol}}$ for a combination of $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ to $L_{2-10\text{keV}}$ with the bolometric correction factor from Marconi et al. (2004). In this calculation, we do not consider the effect of X-ray absorption because the effect is not significant for the sample of broad-line AGNs. In Figure 13, we plot the effective volume

$$V_{\text{eff}} = \int_{\zeta_{\text{min}}}^{\zeta_{\text{max}}} \Omega(M_{\text{BH}}, \lambda_{\text{Edd}}, \zeta') dV d\zeta'$$

(15)

as a function of $L_{2-10\text{keV}}$. We consider log $\lambda_{\text{Edd}}$ down to $-2.0$ and $M_{\text{BH}}$ of $10^6 M_\odot$. Again, we use a $k$ of zero as explained in the previous subsection. We minimize $S$ with the six free parameters with the downhill simplex algorithm (Nelder & Mead 1965). The 1σ uncertainty of the best-fit parameters for each model can be evaluated by the increase of $S$ by one from the minimum value. In order to determine the 1σ uncertainty of each parameter, the parameter is changed from its best value to a different value, and fixing the parameter at the value, the same minimization process is applied for the other parameters and we evaluate the change of the minimum $S$ value from the best-fit value of $S$. The uncertainty of the selected parameter is determined by the change of the minimum of one from the best-fit value. The resulting best-fit parameters are summarized in Table 7.

The resulting corrected broad-line AGN BHMFs and ERDFs are shown in Figures 10 and 11. The corrected ERDFs are normalized by matching the number density in the range $\log L_{\text{bol}} = -2.0$ and that of the corrected BHMF in the range $\log L_{\text{BH}} = 7.0$–$11.0$. The corrected BHMF follows the estimated number density with the $V_{\text{max}}$ method well in the mass range above $10^{9.5}$ $M_\odot$. This is consistent with the limit of the SXDS sample; it extends down to an Eddington ratio of 0.01 in the mass range above $\sim 10^6 M_\odot$. In the lower mass range, the corrected BHMF is slightly larger than the number density derived with the $V_{\text{max}}$ method. The estimated correction is consistent with the corrected ERDF; for $10^{7.5}$ $M_\odot$ black holes, the sample covers an Eddington ratio of $\sim 0.1$, and the ratio below and above this Eddington ratio is 1.7–1.8 from the corrected ERDF. Therefore, the estimated correction is not large. The shape of the corrected ERDF is consistent with that derived in the $10^8$–$10^9$ $M_\odot$ mass range with the $V_{\text{max}}$ method. The correction required for the ERDF is only significant in the low Eddington range, log $\lambda_{\text{Edd}}$ below $-1.5$. Thanks to the coverage for relatively low-luminosity broad-line AGNs, the SXDS sample is rather complete in a wide mass and Eddington ratio range.

The minimum value of the likelihood function does not reflect the goodness of the fit. We evaluate the goodness of the fit by applying the two-dimensional Kolmogorov–Smirnov (2DKS) test on the distribution of the sample in the $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ plane (Fasano & Franceschini 1987). The resulting 2DKS probabilities for the deviation in the plane are shown in Table 7. All of them exceed 20%, and all of the models fit the distribution of objects on the plane well.

In the mass range below $10^{9.5}$ $M_\odot$, the corrected BHMFs show a possible decline to the low-mass end. The mass range is well above the detection limit as shown in Figure 9, but the decline can be affected by the completeness of the broad-line AGN sample. For example, there is a possibility that among objects without spectroscopic identification, low-luminosity broad-line AGNs whose SEDs are dominated by host galaxy components are classified as narrow-line AGNs in the photometric redshift estimation, and they would be missed in the current broad-line AGN sample.

5.3. Constraint from the Hard X-Ray Luminosity Function

The luminosity function of broad-line AGNs is the convolution of their BHMF and ERDF, therefore we can constrain the shapes of broad-line AGN BHMF and ERDF further by using the luminosity function determined from a combination of various AGN samples. In particular, the number density at the bright end of the luminosity function obtained through wider but shallower surveys than SXDS can constrain the shapes of the broad-line AGN BHMF and ERDF in the high $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ range. We note that the fraction of obscured narrow-line AGNs is low in the luminosity range (Hasinger 2008) and the luminous
end of the luminosity function is thought to be dominated by broad-line AGNs.

In Figure 14, we plot the observed hard X-ray luminosity function of AGNs at $z = 1.2−1.6$ based on a combined sample of AGNs from various hard X-ray surveys as filled squares (Y. Ueda et al. 2012, in preparation). The horizontal axis is the absorption-corrected $2−10$ keV luminosity. The hard X-ray luminosity functions of the broad-line + narrow-line AGNs in the SXDS soft-band-selected and hard-band-selected samples are shown as open circles and squares, respectively. The hard-band-selected AGN luminosity function in the SXDS is consistent with that derived from the combined sample. The soft-band-selected AGN luminosity function has a slightly lower number density than the hard-band-selected AGN luminosity function below $L_{2−10\text{keV}} = 10^{44}$ erg s$^{-1}$. The lower number density can be qualitatively explained by the fact that the soft-band-selected sample misses heavily obscured AGNs and the fraction of obscured AGNs is larger for AGNs with lower luminosities.

Because all of the luminosity functions are consistent with each other in the luminosity range above $L_{2−10\text{keV}} = 10^{44}$ erg s$^{-1}$, we use the number density of AGNs at the luminous end of the combined sample as the constraint on the broad-line AGN BHMF and ERDF.

The filled circles represent the hard X-ray luminosity function of broad-line AGNs in the soft-band samples. Again, the hard X-ray luminosity is corrected for intrinsic absorption. The hard X-ray luminosity function shows turnover at $L_{2−10\text{keV}} = 10^{44}$ erg s$^{-1}$. Such turnover is also observed in the broad-line AGN hard X-ray luminosity function at $z = 1−3$ from Chandra surveys (Yencho et al. 2009). At least part of the decrease can be explained by the increasing fraction of obscured narrow-line AGNs in the lower luminosity range as described below. The lines in the figure show the hard X-ray luminosity function derived from the convolution of the corrected broad-line BHMF and ERDF. Solid and dotted lines correspond to luminosity functions with the corrected BHMF of double-power-law and log-normal distributions.

(A color version of this figure is available in the online journal.)

Table 7

| BHMF$^a$ | ERDF$^b$ | $\phi^{c}$ | $\log M^d$ | $\alpha$ | $\beta$ | $\log \lambda_{\text{edd}}^\ast$ | $\sigma_{\text{Edd}}^\ast$ | 2DKS$^e$ | Note$^b$ |
|----------|----------|------------|-----------|---------|-------|------------------|------------------|--------|---------|
| DPL      | SCH      | $19.82 \pm 3.20$ | $8.57 \pm 0.16$ | $-0.05 \pm 0.15$ | $-2.67 \pm 0.28$ | $-0.58 \pm 0.12$ | $-0.74 \pm 0.15$ | 86     |         |
| SCH      | SCH      | $20.80 \pm 3.30$ | $8.77 \pm 0.08$ | $-0.35 \pm 0.15$ | $-0.62 \pm 0.14$ | $...$           | $-0.59 \pm 0.11$ | $-0.74 \pm 0.15$ | 65     | $\times$ |
| DPL      | LOG      | $19.39 \pm 3.20$ | $8.59 \pm 0.15$ | $-0.09 \pm 0.27$ | $-2.70 \pm 0.29$ | $-2.87 \pm 0.16$ | $1.25 \pm 0.14$ | 79     |         |
| SCH      | LOG      | $20.61 \pm 3.20$ | $8.78 \pm 0.08$ | $-0.35 \pm 0.15$ | $...$           | $-2.88 \pm 0.20$ | $1.24 \pm 0.10$  | 62     |         |

Notes.

$^a$ DPL: double-power-law; SCH: Schechter functions.

$^b$ SCH: Schechter; LOG: log-normal distributions.

$^c$ In unit of $10^{-5}$ Mpc$^{-3}$ per unit log $M_{\odot}$ bin.

$^d$ In unit of $M_\odot$.

$^e$ $\mu$ for log-normal distribution.

$^f$ $\sigma$ for log-normal distribution.

$^g$ 2DKS probability in unit of %.

$^h$ Consistency with high-luminosity end of hard X-ray luminosity function. For details, see Section 5.3.
Schechter forms and the thick and thin lines are those derived with Schechter and log-normal ERDF, respectively. The hard X-ray luminosity for each set of $M_{\text{BH}}$ and $\lambda_{\text{Edd}}$ is derived with the bolometric correction for 3000 Å monochromatic luminosity and the relation between $3000L_\lambda$ and $L_{2-10\text{keV}}$ shown with the solid line in Figure 7. Considering the upper limit of the observed $M_{\text{BH}}$ of broad-line AGNs (Vestergaard et al. 2008) and local galaxies (McConnell et al. 2011), we limit the $M_{\text{BH}}$ range to be $10^{6.5}-10^{9.5} M_\odot$ and the log $\lambda_{\text{Edd}}$ range to be $-2$ and 1.

The hard X-ray luminosity functions derived with the double-power-law BHMF or log-normal ERDF can reproduce the observed number density at the high-luminosity end. On the contrary, if both the BHMF and ERDF are modeled with an exponential-cutoff such as the Schechter BHMF with Schechter ERDF (thin dotted line), then the high-luminosity end of the luminosity function cannot be reproduced; the predicted number density is more than one order of magnitude smaller than the observed luminosity function. Therefore, such models are unlikely to represent the BHMF and ERDF of broad-line AGNs at $z \sim 1.4$. Furthermore, if we limit the mass range of BHMF up to $10^{10} M_\odot$, then the predicted luminosity function with a double-power-law BHMF and log-normal ERDF is represented by the dot-dashed line in the figure; the predicted density in the high luminosity end is much lower than the observed one. Thus, in order to reproduce the number density of luminous AGNs, the BHMF needs to be extended up to $10^{10.5} M_\odot$ under the assumption that the ERDF is constant over the wide $M_{\text{BH}}$ range.

In the luminosity range below $L_{2-10\text{keV}} = 10^{44}$ erg s$^{-1}$, the broad-line AGN luminosity function shows decline toward lower luminosity. At least part of the decline can be explained by the increasing fraction of obscured narrow-line AGNs in the lower luminosity range. In Figure 14, we also plot the model luminosity function derived with a double-power-law BHMF and log-normal ERDF after correcting for the fraction of narrow-line AGNs following Hasinger (2008) with the long thin dashed line. In Hasinger (2008), the luminosity dependence of the fraction is derived as a function of redshift. We use the relation derived at $z = 1.2-1.6$. Although the corrected luminosity function still has a lower number density than the broad-line + narrow-line AGN luminosity function, the large fraction of the discrepancy between the broad-line luminosity function and total luminosity function seems to be explained by the obscured fraction down to $L_{2-10\text{keV}} = 10^{43}$ erg s$^{-1}$. The remaining discrepancy can be caused by the possible incompleteness of the broad-line AGN BHMF due to the spectroscopic incompleteness and the difficulties in identifying broad-line AGNs with substantial host contamination. The uncertainty of the fraction of narrow-line AGNs is still large and the sample size of the SXDS is limited. A larger sample is necessary to understand the remaining discrepancy.

6. DISCUSSION

6.1. Broad-line AGN BHMF at $z \sim 1.4$ and Its Evolution to $z = 0$

The binned and corrected broad-line AGN BHMFs from the soft-band sample are compared with the binned and estimated broad-line AGN BHMF from the SDSS sample (Shen & Kelly 2012) in Figure 15. The SXDS binned BHMFs (filled circles) are larger than the binned BHMFs of the SDSS sample (open circles) by one order of magnitude at $10^{8.5} M_\odot$, and by two orders of magnitude at $10^{9} M_\odot$. This is mostly because broad-line AGNs with a lower Eddington ratio are detected in the SXDS sample rather than in the SDSS; the SDSS sample is only 30% complete down to a $M_{\text{BH}}$ of $\sim 10^{6} M_\odot$ and $\lambda_{\text{Edd}}$ of $\sim 0.6$ at $z = 1.4$ (Kelly et al. 2010). Additionally, as discussed in Section 3.4, the SXDS sample covers even mildly obscured broad-line AGNs that may be missed in the SDSS selection of broad-line AGNs due to color and stellarity issues. The thin solid lines in the figure represent the upper and lower envelopes of the estimated broad-line AGN BHMF with a Bayesian approach (Shen & Kelly 2012). The estimated number density at $10^{8} M_\odot$ is consistent with the binned and corrected BHMF of SXDS.

We examine the evolution of the broad-line AGN BHMF from $z = 1.4$ to 0 by comparing the $z \sim 1.4$ corrected BHMF with that in the local universe. The dashed lines in the figure show the corrected local ($z < 0.3$) broad-line AGN BHMF from Schulze & Wisotzki (2010). The binned BHMFs of broad-line AGNs in the local universe of Greene & Ho (2009) and Vestergaard & Osmer (2009) are consistent with the binned BHMF of Schulze & Wisotzki (2010). The corrected BHMF at $z \sim 1.4$ exceeds that of local universe in the mass range above $10^{9} M_\odot$. However, the behavior in the lower mass range is different; the local broad-line AGN BHMF from Schulze & Wisotzki (2010) shows a steep increase with decreasing black hole mass even below the $10^{7} M_\odot$ mass range. On the contrary, the SXDS sample shows a hint of turnover at a mass of $10^{9.5} M_\odot$. The difference in the corrected broad-line AGN BHMF may be indicative of a downsizing trend of accretion activity among the SMBH population. As mentioned in Section 5.2, it should be noted that the identification of broad-line AGNs could be incomplete in the low-mass end.

It is also possible that decline of the activity in the low-mass range from $z = 0$ to 1.4 is caused by luminosity- and redshift-dependent obscuration to the nucleus. Although broad-line AGNs have a wide range of $\lambda_{\text{Edd}}$, the fraction of broad-line AGNs with low-mass SMBHs is higher in the lower luminosity range. A luminosity dependence of the obscured fraction is observed in various AGN samples (e.g., Akiyama et al. 2000; Ueda et al. 2003; Simpson 2005; Brusa et al. 2010); the obscured fraction is higher among lower luminosity AGNs. Recently, based on large samples of X-ray-selected AGNs, it has also...
been suggested that the fraction of obscured AGNs is higher at higher redshifts (e.g., Hasinger 2008; Hiroi et al. 2012). Such redshift- and luminosity-dependent obscuration may hide activity among low-mass SMBHs at high-redshifts. We examine the contribution from obscured narrow-line AGNs to the total active BHMF in Section 6.4.

6.2. Comparison with Total BHMF at $z \sim 6$

In order to examine the growth of SMBHs at higher redshift, we compare binned and corrected broad-line AGN BHMF at $z = 1.4$ with that at $z = 6$. Willott et al. (2010) examined the total BHMF at $z \sim 6$ using the optical luminosity function of broad-line AGNs at that redshift. They derive the total BHMF from the luminosity function using an Eddington ratio distribution derived from a part of their sample. They estimate the total (active + non-active) BHMF by crudely correcting the obscured fraction and duty cycle (active fraction). The resulting best-estimate total BHMF is shown with the thin dotted line in Figure 15. They argue that the total BHMF is constrained down to $10^8 \, M_\odot$. At that mass, the $z = 6$ BHMF has a density of $2.5 \times 10^{-7}$ Mpc$^{-3}$. The number density matches the number density of the $z = 1.4$ corrected BHMF of broad-line AGNs at $10^{0.5} \, M_\odot$. If we naively assume that the $10^8 \, M_\odot$ black holes at $z = 6$ grow to $10^{0.5} \, M_\odot$ black holes at $z = 1.4$ through accretion, then this implies mass growth by a factor of $30$ between $z = 6$ and $1.4$, i.e., in a $3.5$ Gyr period. Such growth implies that the multiplicity of the Eddington ratio and duty cycle has an order of $0.1$ in that period for the massive SMBHs, if we use the rest mass energy to radiation energy conversion efficiency of $0.1$. It should be noted that the high-mass end of the corrected BHMF can be affected by flattening due to the uncertainties in the virial black hole mass estimates; therefore, the effect needs to be corrected before further quantitative evaluation of the growth of SMBHs between $z = 6$ to $1.4$.

6.3. Eddington Ratio Distribution Functions

Both the binned and corrected broad-line AGN ERDFs show a decline at an Eddington ratio of one. Such a distribution suggests that the accretion of X-ray-selected broad-line AGNs is limited by the Eddington luminosity. In Figure 16, we compare the corrected broad-line AGN ERDF with the estimated broad-line AGN ERDF at $z \sim 1.4$ from the SDSS sample (thin solid lines; Shen & Kelly 2012). The shapes of the ERDFs match rather well. It should be noted that there is a possibility that we miss broad-line AGNs accreting at a rate close to the Eddington limit because our X-ray selection is in a relatively high energy range; the energy range of the soft-band sample corresponds to $1.2$–$4.8$ keV at $z = 1.4$. Optical to X-ray SED models of broad-line AGNs predict weak X-ray emission with a steep X-ray spectrum among broad-line AGNs accreting with close to the Eddington limit (Kawaguchi et al. 2001; Done et al. 2012).

In the same figure, we also plot the corrected broad-line AGN ERDF in the local universe from Schulze & Wisotzki (2010). The shape of their binned ERDF in the local universe is consistent with that derived by Kauffmann & Heckman (2009) for a narrow-line AGN sample from SDSS. The shape of the corrected ERDF in the local universe has a knee at an Eddington ratio ($\log \lambda_{\text{Edd}}$ of $-0.6$; Schulze & Wisotzki 2010) similar to that of the corrected ERDF at $z = 1.4$, but shows a steeper increase in the low Eddington ratio range down to $\log \lambda_{\text{Edd}}$ of $-2.0$. The evolution of the corrected broad-line AGN ERDF from $z = 1.4$ to $0$ indicates the fraction of broad-line AGNs with $\lambda_{\text{Edd}}$ close to $1$ is higher at higher redshifts.

6.4. Contribution from Obscured Narrow-line AGNs

Among the X-ray-selected AGNs in the redshift range, more than half are obscured narrow-line AGNs as shown in Table 2. In this subsection, the contribution of these obscured narrow-line AGNs to the binned active BHMF is evaluated using the hard-band sample, which is less biased against obscured AGNs than the soft-band sample. In the calculation of the binned active BHMF, not only spectroscopically identified narrow-line AGNs but also narrow-line AGNs with a photometric redshift are included. Because we use the sample of the hard X-ray-selected AGNs, the contribution from the heavily obscured Compton-thick AGNs are not included. The black hole mass of the obscured narrow-line AGNs cannot be estimated from the FWHM of the broad-line. Here, their black hole mass is estimated assuming that they have the same $\lambda_{\text{Edd}}$ as broad-line AGNs with the same bolometric luminosity.

First, the relation between the Eddington ratio and the bolometric luminosity is determined for the broad-line AGNs in the SXDS sample. The $L_{\text{bol}}$ versus $\lambda_{\text{Edd}}$ distribution of the broad-line AGNs is shown in Figure 17. There is a correlation between the Eddington ratio and the bolometric luminosity. The solid line in the figure represents the relation determined with the least-squares fitting,

$$\log \lambda_{\text{Edd}} = 0.469 \times \log L_{\text{bol}} - 22.46.$$  \hspace{1cm} (16)

The relation is mainly driven by the virial black hole mass estimator used, and the scatter reflects the distribution of the FWHM. The scatter of the $\lambda_{\text{Edd}}$ from the best-fit relation is $0.4$ dex, which is roughly consistent with the width of the distribution of the FWHM. In the figure, the distribution of SDSS (Shen et al. 2008b) and Large Bright Quasar Survey (LBQS; Vestergaard & Osmer 2009) broad-line AGNs are also shown with the contours and crosses. For the SDSS sample, only broad-line AGNs with $M_{\text{BH}}$ from Mg II measurements are shown. All of the broad-line AGNs follow the same trend of increasing $\log \lambda_{\text{Edd}}$ with increasing $L_{\text{bol}}$ as discussed in Croom (2011).

For obscured narrow-line AGNs, their bolometric luminosities are estimated from the absorption-corrected $2$–$10$ keV
luminosity with a bolometric correction factor for the 2–10 keV luminosity (Marconi et al. 2004). We do not use UV or optical luminosities to estimate bolometric luminosity because they severely suffer from dust extinction and contamination from host galaxies. Using the above Eddington ratios for three bolometric luminosity bins, we estimate the black hole mass of each narrow-line AGN as

\[ M_{\text{BH}}[\odot] = \frac{L_{\text{bol}}[\text{erg s}^{-1}]}{1.26 \times 10^{58} \times \lambda_{\text{Edd, median}}} \]  

(17)

The scatter of the \( L_{\text{bol}} \) and \( \lambda_{\text{Edd}} \) relation is large, thus the black hole mass estimation is only valid in the statistical sense. The binned BHMF derived including the narrow-line AGNs is shown in Figure 18 and is tabulated in Table 8. The contribution of the obscured narrow-line AGNs is large in the mass range, log \( M_{\text{BH}} \) \( \lesssim \) 8.5.

In order to examine the fraction of active black holes in the entire SMBH population, we compare the binned active BHMF including narrow-line AGNs with non-active BHMF at intermediate redshifts derived from the galaxy luminosity functions and \( M_{\text{BH}} \) versus \( L_{\text{bulge}} \) relationship (Tamura et al. 2006; Li et al. 2011). Li et al. (2011) estimate the non-active BHMF up to \( z \sim 2 \) from the galaxy \( K \)-band luminosity function, stellar mass function, and their redshift evolution. They assume an evolution of the \( M_{\text{BH}} \) versus \( L_{\text{bulge}} \) relationship as a function of redshift of the form \( M_{\text{BH}}/L_{\text{spheroid, K}} \propto (1 + z)^{1.4} \) following Bennett et al. (2010). They also consider the redshift evolution of the average bulge-to-total luminosity ratio, even though they do not include the luminosity dependence of the ratio. The resulting non-active BHMF is consistent with that estimated in the local universe (Vika et al. 2009). In the figure, the estimated non-active BHMFs at \( z = 0, 1, \) and 2 from Li et al. (2011) are plotted with the solid line, dashed line, and dotted line, respectively. The binned active BHMF including narrow-line AGNs lies between the non-active BHMFs at \( z = 1 \) and 2 in the mass range above \( M_{\text{BH}} = 10^{8.5} \text{ M}_\odot \); a rather high fraction of active SMBHs in the mass range is implied at \( z = 1.4 \). It should be noted that the binned active BHMF is not corrected for the scatter of the virial black hole mass estimate and that of the relation between the log \( L_{\text{bol}} \) and the log \( \lambda_{\text{Edd}} \). Therefore, the number density can be overestimated in the high-mass end due to the contamination from the objects in the lower mass range. In order to discuss the fraction of active SMBHs quantitatively, the scatters needs to be corrected.

### 7. SUMMARY

Black hole masses of X-ray-selected broad-line AGNs detected in the SXDS are estimated from the width of the \( \text{Mg} \\beta \) broad line and the 3000 Å monochromatic luminosity. Because optical spectroscopic observations covering the \( \text{Mg} \\beta \) wavelength range are not complete for the entire X-ray-selected broad-line AGNs, the width of \( \text{H}\alpha \) broad line measured with the NIR spectroscopic survey is also used to provide a supplementary estimate if black hole masses for broad-line AGNs whose \( \text{Mg} \\beta \) broad-line width is not available. The sample of broad-line AGNs is selected using X-ray detection as well as detection of a broad emission line of either \( \text{Mg} \\beta \) in the optical or \( \text{H}\alpha \) in the NIR. Some of the broad-line AGNs have red restframe UV colors, suggesting mild obscuration of their nuclei. For such broad-line AGNs, the hard X-ray luminosity is used to estimate their intrinsic 3000 Å monochromatic luminosity.
assuming a typical optical to X-ray luminosity ratio as a function of bolometric luminosity. In total, black hole masses are estimated for 215 broad-line AGNs at redshifts between 0.5 and 2.3. In the redshift range between 1.18 and 1.68, the black hole mass estimate is highly complete thanks to the supplemental measurements of the H\alpha line width from the NIR spectra.

Using the black hole masses of broad-line AGNs in the redshift range, binned broad-line AGN BHMF and ERDF are initially calculated using the \( V_{\text{max}} \) method. The binned BHMF shows a peak at \( 10^{5.5} M_\odot \). The binned ERDF has a steep decline at \( \lambda_{\text{Edd}} \) of one and a rather flat distribution below the Eddington limit. Because the sample is X-ray-flux-limited, both the binned BHMF and ERDF are affected by the detection limit; the low \( M_{\text{BH}} \) end of the binned BHMF misses the low \( \lambda_{\text{Edd}} \) objects and the low \( \lambda_{\text{Edd}} \) end of the binned ERDF does not include the low \( M_{\text{BH}} \) broad-line AGNs. The effect of the flux limit is corrected by assuming that the ERDF is constant regardless of the black hole mass. Applying the maximum likelihood method with appropriate functional shapes for the broad-line AGN BHMF and ERDF, we determine the corrected BHMF and ERDF. We estimate the black hole masses of 215 broad-line AGNs at redshifts between 0.5 and 2.3. In the redshift range between 1.18 and 1.68, the black hole estimated for 215 broad-line AGNs at redshifts between 0.5 and 2.3.

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**REFERENCES**

Aird, J., Nandra, K., Laird, E. S., et al. 2010, MNRAS, 401, 2531

Akiyama, M., Ohta, K., Yamada, T., et al. 2000, ApJ, 532, 700

Akritas, M. G., & Bershady, M. A. 1996, ApJ, 470, 706

Aller, M. C., & Richstone, D. 2002, AJ, 124, 3035

Assef, R. J., Kochanek, C. S., Ashby, M. K. N., et al. 2011, ApJ, 728, 56

Avni, Y., & Bahcall, J. N. 1980, ApJ, 735, 694

Bennert, V. N., Treu, T., Woo, J.-H., Malkan, M. A., & Bris, A. L. 2010, ApJ, 708, 1507

Bentz, M. C., Peterson, B. M., Pogge, R. W., Vestergaard, M., & Onken, C. A. 2006, ApJ, 644, 133

Bolzonella, M., Miralles, J.-M., & Pello, R. 2000, A&A, 363, 476

Boyle, B. J., & Terlevich, R. 1998, MNRAS, 293, L49

Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503

Brusa, M., Civano, F., Comastri, A., et al. 2010, ApJ, 716, 348

Cardamone, C. N., van Dokkum, P. G., Urry, C. M., et al. 2010, ApJS, 189, 270

Cowie, L. L., Garmire, G. P., Bautz, M. W., et al. 2002, ApJ, 566, L5

Cristiani, S., Trentini, S., La Franca, F., et al. 1996, A&A, 306, 395

Croom, S. M. 2011, ApJ, 736, 161

Croom, S. M., Richards, G. T., Shanks, T., et al. 2009, MNRAS, 399, 1755

Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, MNRAS, 420, 1848

Fasano, G., & Franceschini, A. 1987, MNRAS, 225, 155

Furusawa, H., Koiso, G., Akiyama, M., et al. 2008, ApJS, 176, 1

Gehrels, N. 1986, ApJ, 303, 336

Graham, A. W., Onken, C. A., Athanassoula, E., & Combes, F. 2011, MNRAS, 412, 2211

Greene, J. E., & Ho, L. C. 2005, ApJ, 630, 122

Greene, J. E., & Ho, L. C. 2007, ApJ, 667, 131

Greene, J. E., & Ho, L. C. 2009, ApJ, 704, 1743

Greene, J. E., Hood, C. E., Barth, A. J., et al. 2010a, ApJ, 723, 409

Greene, J. E., Cheng, C. Y., & Ludwig, R. R. 2010b, ApJ, 709, 937

Gültekin, K., Cackett, E. M., Miller, J. M., et al. 2009, ApJ, 698, 198

Hao, L., Strauss, M. A., Tremonti, C. A., et al. 2005, AJ, 129, 1783

Hasinger, G. 2008, A&A, 490, 905

Hasinger, G., Miyaji, T., & Schmidt, M. 2005, A&A, 441, 417

Hiroi, K., Ueda, Y., Akiyama, M., & Watson, M. 2012, ApJ, 758, 49

Iwamuro, F., Moritani, Y., Yabe, K., et al. 2012, PASJ, 64, 59

Kauffmann, G., & Heckman, T. 2009, MNRAS, 397, 135

Kawaguchi, T., Shimura, T., & Mineshige, S. 2001, ApJ, 546, 966

Kelly, B. C., & Shen, Y. 2012, ApJ, submitted (arXiv:1209.0477)

Kelly, B. C., Vestergaard, M., & Fan, X. 2009, ApJ, 692, 1388

Kelly, B. C. Vestergaard, M., Fan, X., et al. 2010, ApJ, 719, 1315

Kimura, M., Maihara, T., Iwamuro, F. et al. 2010, PASJ, 62, 1135

Korista, K., Baldwin, J., Ferland, G., & Verner, D. 1997, ApJS, 108, 401

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

Li, Y.-R., Ho, L. C., & Wang, J.-M. 2011, ApJ, 742, 33

Luo, B., Brandt, W. N., Xue, Y. Q., et al. 2010, ApJS, 187, 560

Magdziarz, P., & Zdzarski, A. A. 1995, MNRAS, 273, 837

Margonari, J., Tremaine, S., Richstone, D. et al. 1998, AJ, 115, 2285

Marconi, A., Axon, D. J., Maiolino, R., Nagao, T., & Pastorini, G. 2008, ApJ, 678, 693

Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21

Marconi, A., Risaliti, G., Gilli, R., et al. 2004, MNRAS, 351, 169

Markwardt, C. B. 2009, in ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems XVIII, ed. D. A. Bohleider, D. Durand, & P. Dowler (San Francisco, CA: ASP), 251

Marshall, H. L., Avni, Y., Tananbaum, H., & Zomarani, G. 1983, ApJ, 269, 35

McConnell, N. J., Ma, C.-P., Gebhardt, K., et al. 2011, Nature, 480, 215

McGill, K. L., Woo, J.-K., Treu, T., & Malkan, M. A. 2008, ApJ, 673, 703

McLure, R. J., & Dunlop, J. S. 2004, MNRAS, 352, 1390

McLure, R. J., & Jarvis, M. J. 2002, MNRAS, 337, 109

Nelder, J. A., & Mead, R. A. 1965, Comput. J., 7, 308

Oke, J. B. 1974, ApJS, 27, 210
Onken, C. A., Ferrarese, L., Merritt, D., et al. 2004, ApJ, 615, 645
Onken, C. A., & Kollmeier, J. A. 2008, ApJ, 689, L13
Park, D., Woo, J.-H., Treu, T., et al. 2012, ApJ, 747, 30
Peterson, B. M., Ferrarese, L., Gilbert, K. M., et al. 2004, ApJ, 613, 682
Peterson, B. M., & Wandel, A. 1999, ApJ, 521, L95
Rafiee, A., & Hall, P. B. 2011, ApJS, 194, 42
Richards, G. T., Hall, P. B., Vanden Berk, D. E., et al. 2003, AJ, 126, 1131
Richards, G. T., Lacy, M., Storrie-Lombardi, L. J., et al. 2006, ApJS, 166, 470
Schulze, A., & Wisotzki, L. 2010, A&A, 516, A87
Shankar, F., Salucci, P., Granato, G. L., De Zotti, G., & Danese, L. 2004, MNRAS, 354, 1020
Shankar, F., Weinberg, D. H., & Miralda-Escude, J. 2009, ApJ, 690, 20
Shen, J., vanden Berk, D. E., Schneider, D. P., & Hall, P. B. 2008a, AJ, 135, 928
Shen, Y., Greene, E., Strauss, M. A., Richards, G. T., & Schneider, D. P. 2008b, ApJ, 680, 169
Shen, Y., & Kelly, B. C. 2012, ApJ, 746, 169
Shen, Y., & Liu, X. 2012, ApJ, 753, 125
Shen, Y., Richards, G. T., Strauss, M. A., et al. 2011, ApJS, 194, 45
Silverman, J. D., Green, P. J., Barkhouse, W. A., et al. 2008, ApJ, 679, 118
Simpson, C. 2005, MNRAS, 360, 565
Simpson, C., Rawlings, S., Ivison, R., et al. 2012, MNRAS, 421, 3060
Soltan, A. 1982, MNRAS, 200, 115
Stern, J., & Laor, A. 2012, MNRAS, 423, 600
Tamura, N., Ohba, K., & Ueda, Y. 2006, MNRAS, 365, 134
Tsuzuki, Y., Kawara, K., Yoshii, Y., et al. 2006, ApJ, 650, 57
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
Ueda, Y., Watson, M. G., Stewart, I. M., Akiyama, M., & Schwope, A. D. 2008, ApJS, 179, 124
Vestergaard, M. 2002, ApJ, 571, 733
Vestergaard, M., Denney, K., Fan, X., et al. 2011, in Proc. Sci., Narrow-Line Seyfert 1 Galaxies and Their Place in the Universe, ed. L. Foschini, M. Colpi, L. Gallo, et al. (Trieste: PoS), 038
Vestergaard, M., Fan, X., Tremonti, C. A., Osmer, P. S., & Richards, G. T. 2008, ApJ, 674, L1
Vestergaard, M., & Osmer, P. S. 2009, ApJ, 699, 800
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Vestergaard, M., & Wilkes, B. J. 2001, ApJS, 134, 1
Vignali, C., Brandt, W. N., & Schneider, D. P. 2003, AJ, 125, 433
Vika, M., Driver, S. P., Graham, A. W., & Liske, J. 2009, MNRAS, 400, 1451
Wang, J.-G., Dong, X.-B., Wang, T.-G., et al. 2009, ApJ, 707, 1334
Wang, J.-M., Chen, Y.-M., & Zhang, F. 2006, ApJ, 647, L17
Ward, M. J., Done, C., Fabian, A. C., Tennant, A. F., & Shafer, R. A. 1988, ApJ, 324, 767
Willott, C. J., Albert, L., Arzoumanian, D., et al. 2010, AJ, 140, 546
Woo, J.-H., Treu, T., Barth, A. J., et al. 2010, ApJ, 716, 269
Yabe, K., Ohta, K., Iwamuro, F., et al. 2012, PASJ, 64, 60
Yencho, B., Barger, A. J., Trouille, L., & Winter, L. M. 2009, ApJ, 698, 380
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965

Yencho, B., Barger, A. J., Trouille, L., & Winter, L. M. 2009, ApJ, 698, 380
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965