ACCRETION PROPERTIES OF A SAMPLE OF HARD X-RAY (≤60 keV) SELECTED SEYFERT 1 GALAXIES

J. Wang, Y. F. Mao, and J. Y. Wei
National Astronomical Observatories, Chinese Academy of Science, 20A Datun Road, Chaoyang District, Beijing, China; wj@bao.ac.cn

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ABSTRACT

We examine the accretion properties in a sample of 42 hard (3–60 keV) X-ray selected nearby broad-line active galactic nuclei (AGNs). The energy range in the sample is harder than that usually used in similar previous studies. These AGNs are mainly compiled from the RXTE All Sky Survey, and complemented by the released INTEGRAL AGN catalog. The black hole masses, bolometric luminosities of AGN, and Eddington ratios are derived from their optical spectra in terms of the broad Hβ emission line. The tight correlation between the hard X-ray (3–20 keV) and bolometric/line luminosity is well identified in our sample. Also identified is a strong inverse Baldwin relationship of the Hβ emission line. In addition, all of these hard X-ray AGNs are biased toward luminous objects with a high Eddington ratio (mostly between 0.01 and 0.1) and a low column density (≤10^{22} cm^{-2}), which is most likely due to the selection effect of the surveys. The hard X-ray luminosity is consequently found to be strongly correlated with the black hole mass. We believe the sample completeness will be improved in the next few years by the ongoing Swift and the International Gamma-Ray Astrophysics Laboratory missions, and by the next advanced missions, such as NuSTAR, Simbol-X, and NeXT. Finally, the correlation between the Fe line (=$\text{optical Fe}/H\beta$) and disk temperature as assessed by $T \propto (L/L_{Edd})M_{BH}$ leads us to suggest that the strength of the Fe emission is mainly determined by the shape of the ionizing spectrum.

Key words: galaxies: Seyfert – quasars: emission lines – X-rays: galaxies

Online-only material: color figure

1. INTRODUCTION

It is now generally believed that the power of active galactic nuclei (AGNs) is extracted through the accretion of gas onto a central supermassive black hole (SMBH). Such an energy mechanism means that AGNs are characterized by their strong hard X-ray emission ($h\nu > 2$ keV), which is widely used as direct evidence suggesting the existence of a nuclear accretion activity ($L_{\text{2–8 keV}} > 10^{42}$ erg s^{-1}, e.g., Silverman et al. 2005; Brusa et al. 2007; Hasinger et al. 2005). The commonly accepted model is that the hard X-ray emission from AGNs is primarily produced by the inverse Compton scattering of the UV/soft X-ray photons emitted from the accretion disk (e.g., Zdziarski et al. 1995, 2000; Haardt & Maraschi 1991; Kawaguchi et al. 2001). The absorption-corrected X-ray photon spectra within the energy band 2–10 keV could be best described as a cutoff power law with index Γ ≳ 1.9 (e.g., Zdziarski et al. 1995; Reeves & Turner 2000; Piccioni et al. 2005; Dadina 2008; Panessa et al. 2008). The synthesis spectra become flat beyond 10 keV because of the Compton reflection caused by the ionized surface of the accretion disk (e.g., George & Fabian 1991).

Because the hard X-ray emission from central engine can penetrate the obscuration material much more easily than lower energy emission, it possesses particular importance in testing the traditional unified model (Antonucci 1993) in Seyfert 2 galaxies (e.g., Moran et al. 2002; Cardamone et al. 2007). Studies of the Chandra and XMM-Newton observatories showed that the cosmic X-ray background (CXB) at 2–30 keV might be contributed by many unknown obscured AGNs which are predicted by the CXRB models (e.g., Comastri et al. 1995; De Luca & Molendi 2004; Worsley et al. 2005; Gilli et al. 2007; Severgnini et al. 2003; Levenson et al. 2006). Taking into account the issue of co-evolution of the AGN and bulge of its host galaxy (e.g., Heckman et al. 2004; Kauffmann et al. 2003; Wang et al. 2006; Wang & Wei 2008 and references therein), the hard X-ray emission from AGNs is also an important tool in detecting and separating an AGN’s contribution from the circumnuclear star formation activity. The X-ray luminosities of most known X-ray luminous star-forming and elliptical galaxies are not higher than $L_X = 10^{42}$ erg s^{-1} (Zezas et al. 2003; Lara et al. 2002a, 2002b; O’Sullivan et al. 2001).

Heckman et al. (2005) identified a very tight correlation between the hard X-ray (3–20 keV) and [O iii] luminosities in a sample of hard X-ray selected AGNs when they performed a comparison between the hard X-ray selected and [O iii] emission-line selected AGNs. In 2–10 keV bandpass, similar correlations were identified in the Palomar optimally selected AGNs by Panessa et al. (2006). On the contrary, a very weak $L_{\text{[O iii]/L_X}}$ correlation was identified in the AGNs selected by their bright [O iii] emission lines (Heckman et al. 2005). The result suggests that many AGNs might be missed in the hard X-ray survey. Moreover, Netzer et al. (2006) claimed that the $L_{\text{[O iii]/L_X}}$ ratio depends on the X-ray luminosity.

The questions are therefore naturally raised: Why is the $L_{\text{[O iii]/L_X}}$ correlation broken in some kind of AGNs? Which parameters (or what are the physical reasons that) determine the correlation? Are the hard X-ray selected AGNs particular in some parameters? Both black hole mass ($M_{BH}$) and Eddington ratio ($L/L_{Edd}$) are two key parameters determining the observed properties of AGNs. In addition, with the development of the technology in hard X-ray detection, a major advance in studying AGN hard X-ray emission will be achieved in the next few years due to the launch of new missions with enhanced hard X-ray capability (in sensitivity and imaging), such as NuSTAR, Simbol-X, and NeXT (e.g., Takahashi et al. 2008; Ferrando et al. 2003). The study on the existent surveys certainly prepares the ground for future surveys.

In this paper, we examine the optical spectral properties of a sample of 42 hard X-ray selected broad-line AGNs,
2. THE SAMPLE

Our sample is mainly compiled from the XSS (Revnivtsev et al. 2004). SR04 identified 95 nearby AGNs with \( z_{\text{median}} \approx 0.035 \) detected in XSS. The survey covers about 90% of the sky at \( |b| > 10^\circ \). The sensitivity of the survey in the energy band 3–20 keV is better than \( 2.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \). SR04, therefore, provide a nearly complete sample for bright hard X-ray selected AGNs, although the sample is still biased against sources with absorption column \( N_H \). The IBIS telescope (Ubertini et al. 2003) onboard the INTEGRAL Observatory (Winkler et al. 2003) provides a better capability for heavily obscured objects because of its good sensitivity beyond 20 keV. After about three years of INTEGRAL observation, their all-sky survey project allows Bassani et al. (2006a) to identify 62 AGNs in the energy bandpass 20–100 keV above a flux of \( 1.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \) by analyzing 11,300 INTEGRAL points (see also in Bassani et al. 2006b; Bird et al. 2006; Beckmann et al. 2006).

Both catalogs are then combined to enlarge our sample content, and to attempt to alleviate the bias against the obscuration. We further limit the objects to the broad-line AGNs according to the identification provided by previous optical spectroscopy. The Burst Alert Telescope (BAT) instrument (Barthelmy et al. 2005) onboard the Swift satellite (Gehrels et al. 2004) provides an all-sky hard X-ray survey with a sensitivity down to a few \( 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) in higher energy band 14–195 keV. Markwardt et al. (2005) identified 44 previously known AGNs in the Swift survey. However, considering the spectroscopic observation condition (see below), only three objects are not listed in our sample. It is worth noting that the ongoing Swift/BAT and INTEGRAL survey could provide a larger sample of \( \sim 100 \) hard X-ray selected AGNs at the end of our program (i.e., Krivonos et al. 2007; Sazonov et al. 2007; Tueller et al. 2008). We will perform a subsequent spectroscopic study on these AGNs in the following work.

Figure 1 shows the column density (\( N_H \)) distribution for our sample. \( N_H \) is compiled from SR04, and from Sazonov et al. (2007) for the objects detected by INTEGRAL only. Briefly, these authors determined \( N_H \) by fitting the available spectra from different X-ray instruments by an absorbed power law. Values of \( N_H \) less than \( 10^{22} \text{ cm}^{-2} \) were ignored in the fitting of SR04 and Sazonov et al. (2007). As shown in the figure, the current sample is still strongly biased against AGNs with a large column density.

3. SPECTROSCOPIC OBSERVATIONS

Because of the constraint of the observatory site and the instrumental capability, the spectroscopic observations are only carried out for the bright (\( m_v < 16.5 \text{ mag} \)) objects located in the northern sky with declination \( \delta > -20^\circ \). In total, there are 53 objects fulfilling the selection criterion. Six of these objects are not observed because of the poor weather conditions. Among the remaining objects, five objects (i.e., XSS J02151-0033, XSS J11570+5514, XSS J22363-1230, NGC 788, IGR J21247+5058) are excluded in subsequent spectral modeling because of the weakness or absence of broad H\( \alpha \) and/or H\( \beta \) emission lines.\(^1\)

A total of 42 high (or intermediate high) quality optical spectra were obtained by using the National Astronomical Observatories, Chinese Academy of Science (NAOC) 2.16 m telescope in Xinglong Observatory during several observing runs carried out from 2005 November to 2008 March. The spectra were taken by the OMR spectrograph equipped with a back-illuminated SPEC10 1340 × 400 CCD as detector. A grating of 300 g mm\(^{-1}\) and a slit of 2′ oriented in the south–north direction were used in our observations. This setup results in a final spectral resolution of \( \sim 9 \text{ Å} \) as measured from both comparison spectra and night sky emission lines. The blazed wavelength was fixed to be 6000 Å, which provides a wavelength coverage of 3800–8300 Å in observer frame. This attempt covers both H\( \alpha \) and H\( \beta \) regions in most spectra because of their small redshifts. Each object was observed successively twice. The two exposures were combined prior to extraction to enhance the signal-to-noise ratio (S/N) and eliminate the contamination of cosmic rays easily. The exposure time for each frame is generally between 900 and 3600 s depending on the brightness of the object. The wavelength calibration associated with each

\(^1\)Our spectroscopic observations show that three objects, i.e., XSS J02151-0033, XSS J11570+5514, and XSS J22363-1230, could be further classified as Seyfert 1.9-like galaxies without broad components of Balmer emission lines except a broad H\( \alpha \) emission. In addition, the continuum is dominated by the contribution from starlight of host galaxy rather than AGN in XSS J02151-0033 and XSS J11570+5514, which precludes the measurements of the Fe\( ii \) complex. We include NGC 788 in our observation program because multiclassification is shown in the NED (see also in Beckmann et al. 2006). Our spectrum indicates a Seyfert 2 nucleus in the object. In fact, the object is classified as a Seyfert 2 galaxy with polarized broad emission lines in the catalog of quasars and active nuclei (Veron-Cetty & Veron 2006). Our spectrum taken on 2006 December 20 shows that the spectrum of IGR J21247+5058 is dominated by a typical late-type star, which is consistent with Masetti et al. (2004). By identifying the broad emission bump around 6700 Å as H\( \alpha \), these authors argued that the background AGN is aligned with a F- or early G-type star by chance.
object was carried out by the helium–neon–argon comparison arcs taken between the two successive frames. The arcs were obtained at the position being nearly identical to that of the specified object. Two or three Kitt Peak National Observatory (KPNO) standard stars (Massey et al. 1988) were observed per night for both flux calibration and removal of the atmospheric absorption features. All the objects were observed as close to meridian as possible. Table 1 shows the log of observations of the 42 objects listed in our sample.

4. DATA REDUCTION AND EMISSION LINE MEASUREMENTS

The standard procedures using the IRAF package\(^2\) are adopted by us to reduce the unprocessed frames. The CCD reductions include bias subtraction, flat-field correction, and cosmic rays removal before the extraction of the signal. One-dimensional sky-subtracted spectra are then wavelength and flux calibrated. The uncertainties of the wavelength and flux calibrations are no more than 1 Å and 20%, respectively. The Galactic extinctions are corrected by the color excess, the parameter \(E(B - V)\) taken from the NASA/IPAC Extragalactic Database (NED), assuming an \(R_V = 3.1\) extinction law of milky way (Cardelli et al. 1989). The spectra are then transformed to the rest frame, along with a \(k\)-correction, according to the narrow peak of Hβ.

4.1. Fe II Subtractions

In order to determine the strength of the optical Fe II complex and to reliably profile the emission lines in \(H\beta\) region, at first the Fe II complex should be modeled and then removed from each spectrum. We simply adopt the empirical template of the Fe II complex introduced in Boroson & Green (1992, hereafter BG92). For each object, the template is first

\(^2\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
broadened to the FWHM of the Hβ broad component by convolving with a Gaussian profile (BG92). The broadened template and a broken power law are combined to model the continuum by a $\chi^2$ minimization for an individual object. The minimization is performed over the rest frame wavelength range from 4300 Å to 7000 Å, except for the regions around the strong emission lines (i.e., Hα+[N II], [S II], Hβ, Hγ, [O III], He II). The fittings are illustrated in the left column of Figure 2 for three typical cases. The flux of the Fe II complex is integrated between the rest wavelengths 4434 Å and 4686 Å. The Fe II complex is not measured in XSS J11067+7234 because its continuum is dominated by the starlight from the host galaxy.

4.2. Emission Lines Measurements

After removing the Fe II blends and continuum, the isolated AGN emission lines at Hβ region are modeled by the SPECFIT task (Kriss 1994) in the IRAF package. In each object, each of the [O III]λλ4959,5007 doublet is modeled by a single Gaussian component. The flux ratio of the doublet is fixed to be 3 (e.g., Dimitrijevic et al. 2007). In principle, each Hβ profile is modeled by a set of two Gaussian components: a narrow and a broad Gaussian component (denoted as Hβn and Hβb, respectively). The profile modelings are illustrated for the three cases in the right column in Figure 2. The deblending of the Hβ emission line are, however, difficult in 15 objects because no obvious transition between the narrow and broad components is observed. In these 15 cases, the reported Hβb measurements include both components, and the contribution of Hβn is usually expected to be less than 3% for typical broad-line AGNs as suggested by BG92.

The described modeling works very well in most objects, with the exception of three. In XSS J22539-1735, a very broad Hβ component (FWHM $\sim 10,000$ km s$^{-1}$) is required to properly reproduce the observed profile. Such component has been reported in Hβ and highly ionized emission lines in previous studies (e.g., Sulentic et al. 2000b; Wang et al. 2005; Veron-Cetty et al. 2007; Marziani et al. 2003; Mullaney & Ward 2008; Hu et al. 2008). A double peaked and a boxy Hβ profile is observed in XSS J18408+7947 and XSS J23073+0447, respectively. In all three cases, each Hβ line is modeled by three Gaussian components, i.e., a narrow and two broad components. The modeled narrow component is then subtracted from the observed spectrum to derive a residual profile which is then used to measure FWHM and integrated flux.

5. RESULTS AND DISCUSSION

Table 2 lists the following items measured from the spectra. Columns (2) and (3) list the equivalent widths (EWs) of Hβn and Hβb, respectively. All the EWs refer to the continuum level determined from the continuum fitting at the position of wavelength $\lambda$4861. The line ratio RFe ($=$Fe II/Hβb) is shown in column (4). Column (5) lists the luminosity of the Hβ broad...
Because the objects listed in our sample are generally very nearby, the resolution. Column (7) shows the luminosity of the [O\textsc{iii}] and Hβ, [O\textsc{iii}] emission line. Both [O\textsc{iii}] and Hβ\textsubscript{b} luminosities are calculated from the cosmology-corrected luminosity distance\textsuperscript{3} given by NED. The next two columns show the absorption-corrected hard X-ray luminosities in the bandpass 3–20 keV (XSS) and in 17–60 keV (INTEGRAL).

Six out of the 42 AGNs are detected by INTEGRAL only. In order to estimate their X-ray luminosities in the bandpass 3–20 keV from the luminosities in 17–60 keV, a transformation is derived in terms of the 18 objects detected by both surveys. The left panel of Figure 3 shows the relationship between the two sets of luminosity. An unweighted fitting yields a relationship $\log L_{17–60 \text{keV}} = 1.03 \log L_{3–20 \text{keV}} - 1.39$ with a standard deviation of 0.25. After transforming the luminosities in the bandpass 17–60 keV to 3–20 keV for the six objects, the strong correlation between the [O\textsc{iii}] and 3–20 keV luminosity is shown in the right panel of Figure 3 for a total of 42 objects. The correlation is highly consistent with that derived in Heckman et al. (2005), which firmly demonstrates the accuracy of our observations and calibrations.

5.1. Hard X-ray Versus Bolometric Luminosity

The detection of hard X-ray emission from a nucleus is regarded as strong evidence of accretion activity occurring around the central SMBH. The correlations between X-ray luminosity and luminosities of optical emission lines (e.g., Hα, Hβ, [O\textsc{iii}]) have been extensively established in the previous studies (e.g., Elvis et al. 1984; Ward et al. 1988; Mulchaey et al. 1993a).

\textsuperscript{3} Because the objects listed in our sample are generally very nearby, the radial velocity is corrected by a redshift of 0.017877 to the reference frame defined by the 3K Microwave Background Radiation.
Figure 3. Left panel: the luminosity in the energy bandpass 3–20 keV plotted against the luminosity in 17–60 keV for the 18 objects detected by both XSS and INTEGRAL. The solid line shows the best fit to the data without taking into account of the errors. The 1σ dispersion is marked by the two dashed lines. Right panel: the tight correlation between the [O\textsc{iii}] emission line and 3–20 keV luminosity.

Figure 4. Left panel: \( L_{3-20\text{ keV}} \) plotted against the bolometric luminosity estimated from the H\textbeta\ component. The solid line shows the best fit to the data: \( \log L_X = (0.91 \pm 0.06) \log L_{\text{bol}} + (3.04 \pm 2.78) \). Right panel: distribution on the plot of \( L_X \) vs. black hole mass. The three dashed lines show the \( L_X \) as a function of the black hole mass for different \( L/L_{\text{Edd}} = 0.01, 0.1, \) and 1.

The bolometric luminosity is then derived by adopting the usually used bolometric correction \( L_{\text{bol}} \approx 9\lambda L_\lambda(5100) \) Å (e.g., Kaspi et al. 2000). The significant correlation between \( L_{\text{bol}} \) and \( L_{3-20\text{ keV}} \) is shown in the left panel of Figure 4. An unweighted least-square fitting gives a relationship:

\[
\log L_X = (0.91 \pm 0.06) \log L_{\text{bol}} + (3.04 \pm 2.78) \quad (2)
\]

or \( L_{\text{bol}}/L_X \sim 10 \) for simplification. The correlation strongly indicates a close link between the hard X-ray emission and ionizing radiation emitted from the accretion disk. Note that the bolometric luminosity spans 4 orders of magnitude, down to \( L_{\text{bol}} \sim 10^{43} \text{ erg s}^{-1} \), which is close to the formal definition of low luminous AGNs (i.e., \( L_{\text{bol}} < 10^{43} \text{ erg s}^{-1} \), Ho 2008). These faint galaxies generally radiate at a low state with Eddington ratio marginally exceeding 0.01.

5.2. Black Hole Mass and Eddington Ratio

It is now generally believed that the black hole mass (\( M_{\text{BH}} \)) and the specific accretion rate (\( L/L_{\text{Edd}} \)) are two basic parameters determining the properties of AGNs. The role of \( L/L_{\text{Edd}} \) in driving the Eigenvector I (EI) space\(^4\) has been extensively investigated in numerous previous studies (e.g., Borseon 2002; Sulentic et al. 2006; Xu et al. 2003; Grupe 2004; Sulentic et al. 2007; see Sulentic et al. 2000a for a review).

\(^4\) The EI space is one of the key properties of AGN phenomena. It was first established by BG92 who analyzed the optical spectra of 87 bright PG quasars. In addition to the anti-correlation between the intensity of Fe\textit{ii} and [O \textsc{iii}], the EI space has been subsequently extended to UV and soft X-ray bands (i.e., FWHM(C\textsc{iv}) and \( \Gamma_r \), e.g., Wang et al. 1996; Xu et al. 2003; Grupe 2004; Sulentic et al. 2007; see Sulentic et al. 2000a for a review).
Zamanov & Marziani 2002; Marziani et al. 2001), because of the great progress in the calibration of the $R_{	ext{BLR}}-L$ relationship (e.g., Kaspi et al. 2000, 2005, 2007; McLure & Jarvis 2004; Vestergaard & Peterson 2006; Peterson et al. 2004; Bentz et al. 2006) due to the recent great advance in the reverberation mapping (e.g., Kaspi et al. 2000; Peterson & Bentz 2006). We refer the reader to McGill et al. (2008, and references therein) for a summary of the existing formula used to calculate $M_{\text{BH}}$ basing upon “single-epoch” observation. In this work, the black hole mass is estimated by the width and luminosity of H$\beta$ in an individual object, according to the scaling law obtained by Greene & Ho (2005):

$$M_{\text{BH}} = 3.6 \times 10^6 \left( \frac{L_{\text{H}\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.56} \left( \frac{\text{FWHM}_{\text{H}\beta}}{1000 \text{ km s}^{-1}} \right)^2 M_\odot. \quad (3)$$

For each object, the estimated $M_{\text{BH}}$ and $L/L_{\text{Edd}}$ are listed in columns (10) and (11) in Table 2, respectively. The bolometric luminosity, $L_{\text{bol}}$, is estimated from the H$\beta$ component as described above.

The calculations of both $L_{\text{bol}}$ and $L/L_{\text{Edd}}$ allow us to find that the current sample is strongly biased against subluminous AGNs usually with low $L/L_{\text{Edd}}$. In fact, the left panel of Figure 4 shows the lack of AGNs with $L_{\text{bol}} < 10^{41} \text{ erg s}^{-1}$. Figure 5 displays the distributions of the $L/L_{\text{Edd}}$ (left panel) and $M_{\text{BH}}$ (middle panel) for a total of 42 AGNs. As shown in the middle panel, $M_{\text{BH}}$ is sampled within a wide range ($\sim 3$ dex) from $10^6 M_\odot$ to $10^9 M_\odot$ with a peak at $10^8 M_\odot$. In contrast, the left panel shows that $L/L_{\text{Edd}}$ distributes in a relatively narrow range as compared with the previous studies. The total range of our $L/L_{\text{Edd}}$ spans from 0.01 to 1. In particular, about $\sim 60\%$ objects listed in the sample have $L/L_{\text{Edd}}$ between 0.01 and 0.1. However, the $L/L_{\text{Edd}}$ of bright local AGNs usually spans at least 3 orders of magnitude from 1 to 0.001 (e.g., Woo & Urry 2002; Boroson 2002). Based upon the $2-10$ keV X-ray luminosity, Panessa et al. (2006) indicated that the $L/L_{\text{Edd}}$ of the Palomar optically selected AGNs ranges from $10^{-5}$ to 0.1. As an additional test, the right panel of Figure 4 shows the $M_{\text{BH}}$ versus $L_{3-20}$ keV plot. $L_{3-20}$ keV as a function of $M_{\text{BH}}$ is over-plotted as dashed lines for three different $L/L_{\text{Edd}}$ (i.e., 1, 0.1, and 0.01). As shown in the plot, the majority of our objects are located below the line with $L/L_{\text{Edd}} = 0.1$ and above the line with $L/L_{\text{Edd}} = 0.01$.

In summary, the hard X-ray selected AGNs listed in our sample are luminous AGNs with a wide range of $M_{\text{BH}}$ but a nearly constant accretion activity (i.e., $L/L_{\text{Edd}}$), which is likely due to the selection effect of the survey that is biased toward X-ray luminous objects. In active (or luminous) AGN, the optical/UV ionizing radiation is believed to be emitted from a standard geometric thin disk (e.g., Shakura & Sunyaev 1973). The low-energy photon is comptonized by a hot corona to produce the hard X-ray emission below 10 keV (Haardt & Maraschi 1991). A Compton recoil of the soft photon is required to occur on the ionized surface of the accretion disk to produce the emission spectrum beyond 10 keV. The main observation feature of the reflection is a bump peaked at about 30 keV (e.g., George & Fabian 1991; Zycki et al. 1994; Ross & Fabian 2002, 2005).

The bias toward active AGNs could possibly be caused by the fact that either intensive Compton reflection takes place only in AGNs at high state with large $L/L_{\text{Edd}}$ or the surveys are biased against the Compton-thick objects. In the first case, the theory of the Compton reflection predicts that the X-ray emission contributed by the reflection depends primarily on the X-ray ionizing parameter, and secondarily on the UV radiation produced by the dissipation inside the accretion disk. In the second case, our analysis implies a possible connection between the less X-ray absorption and high $L/L_{\text{Edd}}$ in broad-line AGNs. In fact, we selected the objects regardless of their X-ray spectral properties. Figure 1 shows the lack of objects with large column density in the sample. We believe that the sample completeness would be improved by including the ongoing Swift/BAT survey with large effective collecting area and harder energy bandpass (14–195 keV) in future studies.

Figure 4 shows that the hard X-ray luminosity is strongly correlated with $M_{\text{BH}}$ in our sample. In fact, the correlation is naturally expected given the tight $L_{3-20}$ keV versus $L_{\text{bol}}$ correlation and nearly constant $L/L_{\text{Edd}}$. The $L_X$ versus $M_{\text{BH}}$ correlation provides us a potential estimate of black hole mass for luminous AGNs within 0.01 and $L/L_{\text{Edd}} \leq 0.1$. The following relationship is obtained by us through a least-square fitting: $\log(M_{\text{BH}}/M_\odot) = (0.82 \pm 0.09) \log L_{3-20}$ keV $- (28.23 \pm 3.78)$. Our results conflict with Panessa et al. (2006) and Pellegrini (2005) who did not find the correlation, but is in agreement with Kiuchi et al. (2006). Panessa et al. (2006) investigated a sample of 47 nearby Seyfert galaxies selected from the Palomar spectroscopy (Ho et al. 1997). The luminosity obtained by different X-ray instruments is down to $L_{2-10}$ keV $\sim 10^{38}$ erg s$^{-1}$. The studies in Pellegrini (2005) are based on the Chandra observations down to a luminosity $L_{2-10}$ keV $\sim 10^{38}$ erg s$^{-1}$. Kiuchi et al. (2006) used the broad-line AGN sample detected by the ASCA Large Sky Survey (ALSS)
and ASCA Medium Sensitivity Survey in the northern sky (AMSSn) with a detection limit of a few $10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in 2–10 keV bandpass. As discussed above, it is worth noting that the correlation most likely does not reflect the physics, but a selection effect of the surveys.

5.3. Fe$^{+}$ Ratio Versus Disk Temperature Relation

As a key parameter in the EI space, the Fe$^{+}$ ratio (RFe) is defined as the ratio of the optical Fe$^{+}$ complex to H$\beta$. Although the total Fe$^{+}$ emission increases by fourfold with a reasonable ionization parameter in AGN (Korista et al. 1997), traditional photoionization models cannot explain the strong Fe$^{+}$ emission in optical and UV bands (e.g., Netzer & Wills 1983; Joly 1987; Collin-Souffrin et al. 1988). At present, the problem is only slightly alleviated by the major improvements in the atomic data and by the improved treatment of the line excitation process (Sigut & Pradhan 2003; Baldwin et al. 2004). We refer the reader to Collin & Joly (2000) for a summary of the mechanisms that can enhance the Fe$^{+}$ emission. BG92 put forward a picture in which the RFe is determined by the vertical structure of the accretion disk. The vertical structure is governed by $L/L_{\text{Edd}}$. A large $L/L_{\text{Edd}}$ leads to a large X-ray heated volume that could generate large Fe$^{+}$ emission. Sulentic et al. (2000b) developed a semi-analysis model in which the RFe depends on $L/L_{\text{Edd}}$ as RFe $\propto 0.55 \log(L/L_{\text{Edd}})$. Although the RFe is found to generally increase with $L/L_{\text{Edd}}$ in optical bright quasars, Netzer et al. (2004) found that a number of high-$z$ quasars deviate the trend, i.e., with very small RFe but large $L/L_{\text{Edd}}$ (see also in Netzer & Trakhtenbrot 2007). Using the large database provided by the Sloan Digital Sky Survey (SDSS), Netzer & Trakhtenbrot (2007) recently suggested that the enhanced RFe is mainly caused by an increased metal abundance.

In the current sample, the distribution of RFe is shown in the right panel of Figure 5. RFe uniformly ranges from $10^{-3}$ to 1. On the contrary, $L/L_{\text{Edd}}$ distributes in a quite narrow range as described above. In fact, no correlation between RFe and $L/L_{\text{Edd}}$ is found in our sample (see the upper panel in Figure 6), which motivates us to suspect that RFe does not depend on $L/L_{\text{Edd}}$ only. RFe is plotted against the characteristic disk temperature $T_{\text{max}}$ in the bottom panel of Figure 6. The temperature scales with $L/L_{\text{Edd}}$ and $M_{\text{BH}}$ as predicted by the standard geometric thin disk model (e.g., Shakura & Sunyaev 1973). The exact formula of disk temperature depends on various accretion disk models. For a rapidly rotating Kerr hole, with a spin parameter $a_{*} = 0.998$ and efficiency of 0.31, we have $T_{\text{max}} = 10^{0.56(L/L_{\text{Edd}})} M_{\text{BH}}^{-1/4} \text{K}$. The diagram indicates an obvious correlation between the two parameters. A Spearman rank-order test calculated by survival analysis yields a formal correlation coefficient $r_{s} = 0.414$ ($P = 0.0088$, where $P$ is the probability of null correlation). The correlation is not highly significant probably because of the small sample size. The estimated temperature spans about 1 order of magnitude ($\Delta \log T_{\text{max}} \approx 1.25$), corresponding to a factor of $\sim 18$. The correlation then suggests a trend of more intensive Fe$^{+}$ emission for higher disk temperature. A marginal dependence of the continuum shape of QSOs on $T_{\text{max}}$ was recently identified by Bonning et al. (2007) who compared the observations of SDSS with the NLTE models of accretion disk. The current result means that the strength of the Fe$^{+}$ emission is likely controlled by the spectral shape of the ionizing continuum.

5.4. EW of H$\beta$ Versus $L_{X}$

The physical reason of the absence of the Baldwin relationship (Baldwin 1977) for low ionization emission lines is still an open question. In fact, a weak inverse Baldwin relationship for H$\beta$ has been demonstrated by recent studies basing upon large AGN samples (e.g., Croom et al. 2002; Greene & Ho 2005). We identify a tight, positive correlation between $L_{X}$ and EW(H$\beta$) in our hard X-ray selected AGNs (i.e., an inverse Baldwin relationship). Figure 7 presents the correlation with correlation coefficient $r = 0.611$ ($P = 10^{-4}$) estimated by the Spearman rank-order analysis. EW(H$\beta$) roughly scales with hard X-ray luminosity as EW(H$\beta$) $\propto L_{X}^{0.39}$. Wilkes et al. (1999) identified a marginal Baldwin effect in H$\beta$ line. Noted that they examined only the luminous local quasars with $L_{1-10 \text{ keV}} > 10^{44}$ erg s$^{-1}$.

Although many models are developed to explain the Baldwin effect for high ionization emission lines (e.g., CIV, Wandell 1999; Korista et al. 1998; Shields et al. 1995; Wills et al. 1993; Baskin & Loar 2004; Bachev et al. 2004), these models cannot explain the difference between CIV and H$\beta$. Croom et al. (2001) suggested that the inverse Baldwin relationship could be explained if the longer wavelength continuum contains emission from other components (e.g., thermal dust emission, nonthermal radio emission, starlight). We estimate the possible contribution of the unknown sources as follows. We start from the relationship $\log L_{X} = 39.08 + 2.56 \log \text{EW}(\text{H}\beta)$, and rewrite $\text{EW}(\text{H}\beta) = L(\text{H}\beta)/(L' + L_{c})$, where $L_{c}$ and $L'$ is the
AGN luminosity and luminosity of other unknown sources at the Hβ wavelength, respectively. The X-ray luminosity could be replaced by \(L_c\) given Equation (2) and the bolometric correction factor of 9. Replacing \(L(\text{H} \beta)\) as \(L_c\) given Equation (1) finally yields a relationship
\[
\log(1 + L/\langle L_c \rangle) = 9.48 - 0.21 \log L_c.
\]
Considering the typical case with \(L_c \sim 10^{44} \text{ erg s}^{-1}\), about 40% of the observed continuum at Hβ wavelength is estimated to be contributed by the unknown sources.

6. CONCLUSION

The properties (\(L/L_{\text{Edd}}\) and \(M_{\text{BH}}\)) of accretion onto SMBH are examined in a sample of 42 hard X-ray selected (3–60 keV) broad-line AGNs in terms of their optical spectra taken by us. The energy range is harder than that usually used in similar previous studies. These AGNs are mainly compiled from the XSS (SR04), and are complemented by the released INTEGRAL AGN sample (Bassani et al. 2006a). The statistical analysis allows us to draw the following conclusions:

1. We confirm the tight correlation between the hard X-ray and optical emission line luminosities (and bolometric luminosity) in our sample, which suggests a close link between the hard X-ray emission reflected by the ionized surface of the accretion disk and UV/optical radiation. Using the hard X-ray luminosity, a strong inverse Baldwin relationship of the Hβ emission line is identified in the sample.

2. The hard X-ray selected broad-line AGNs listed in the sample are found to be strongly biased toward luminous AGNs with high \(L/L_{\text{Edd}}\) and low column density. Since \(L/L_{\text{Edd}}\) is constant (mostly between 0.01 and 0.1) in a first-order approximation, the hard X-ray luminosity is strongly correlated with the black hole mass in our sample, which is most likely due to the selection effect of the surveys.

3. Although the RFe parameter is independent of \(L/L_{\text{Edd}}\) in our sample, it is found to be correlated with the accretion disk temperature as assessed by \(T \propto (L/L_{\text{Edd}})M_{\text{BH}}^{-1}\). This result implies that the strength of the Fe ii emission is determined by the shape of the ionizing spectrum.

Finally, it should be mentioned that a new era in AGN hard X-ray study will be opened in the next few years due to the launch of new missions with enhanced hard X-ray detection capability in not only sensitivity, but also imaging, such as Simbol-X, NeXT, and NuSTAR. These missions will provide larger and more complete samples to study the present open issues.

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Figure 7. Hard X-ray luminosity is plotted as a function of EW of the Hβ broad component. A Spearman rank-order test yields a correlation coefficient \(r = 0.611 (P = 10^{-4})\).
