BAT AGN Spectroscopic Survey-III. An observed link between AGN Eddington ratio and narrow emission line ratios

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ABSTRACT
We investigate the observed relationship between black hole mass (MBH), bolometric luminosity (LBol), and Eddington ratio (λEdd) with optical emission line ratios ([NII] λ6583/Hα, [SII] λ6716,6731/Hα, [OI] λ6300/Hα, [OIII] λ5007/Hβ, [NeIII] λ3869/Hβ, and HeII λ4686/Hβ) of hard X-ray-selected AGN from the BAT AGN Spectroscopic Survey (BASS). We show that the [NII] λ6583/Hα ratio exhibits a significant correlation with λEdd (RPear = −0.44, p-value=3 × 10−13, σ = 0.28 dex), and the correlation is not solely driven by MBH or LBol. The observed correlation between [NII] λ6583/Hα ratio and MBH is stronger than the correlation with LBol, but both are weaker than the λEdd correlation. This implies that the large-scale narrow lines of AGN host galaxies carry information about the accretion state of the AGN central engine. We propose that the [NII] λ6583/Hα is a useful indicator of Eddington ratio with 0.6 dex of rms scatter, and that it can be used to measure λEdd and thus MBH from the measured LBol, even for high redshift obscured AGN. We briefly discuss possible physical mechanisms behind this correlation, such as the mass-metallicity relation, X-ray heating, and radiatively driven outflows.

Key words: galaxies: active – galaxies: nuclei – quasars: general – black hole physics

1 INTRODUCTION

Nebular emission lines are a powerful tool for diagnosing the physical state of ionized gas and studying central nuclear activity. Optical emission line ratios can be used to discriminate between emission from the star formation in galaxies and harder radiation such as from the central nuclear activity around a supermassive black holes (e.g., Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kewley et al. 2001; Kauffmann et al. 2003). Compared to star forming galaxies, active galactic nuclei (AGN) produce greater numbers of higher energy photons (e.g., UV and X-rays) and, therefore drive higher ratios of the collisionally excited forbidden lines compared to the photoionization-induced Balmer emission lines. Although such line ratios provide useful AGN diagnostics, even for obscured AGN
Reyes et al. 2008; Yuan et al. 2016), they may not be effective in selecting all heavily obscured AGN and/or AGN that lack significant amounts of low density gas (Elvis et al. 1981; Iwasawa et al. 1993; Griffiths et al. 1995; Barger et al. 2001; Comastri et al. 2002; Rigby et al. 2006; Caccianiga et al. 2007).

With the recent advent of hard X-ray (> 10 keV) facilities, such as INTEGRAL (Winkler et al. 2003), Swift (Gehrels et al. 2004) and NuSTAR (Harrison et al. 2013), it is now possible to study samples of AGN that are less biased to obscuration and include even Compton thick sources (N_H > 10^{24} cm^{-2}, Ricci et al. 2015; Koss et al. 2016). In particular, the Burst Alert Telescope (BAT, Barthelmy et al. 2005) on board the Swift satellite has been observing the sky in the 14-195 keV energy band since 2005, reaching sensitivities of 1.3 × 10^{-12} erg cm^{-2} s^{-1} over 90% of the sky. The 70 month Swift-BAT all-sky hard X-ray survey detected 1210 objects, of which 836 are AGN (Baumgartner et al. 2013). While the BAT detection is relatively unabsorbed up to Compton thick levels (e.g., N_H < 10^{24} cm^{-2}, Koss et al. 2016) heavily Compton thick AGN (N_H > 10^{25} cm^{-2}) are missed by X-ray surveys but may sometimes be detected using optical emission line diagnostics and strong [O III] λ5007 emission lines (e.g., Maiolino et al. 1998).

The relationship between Eddington ratio (λ_Εdd ≡ L/L_Εdd, where L_Εdd ≡ 1.3 × 10^{38} M_☉ / (M/Δ) and the position of AGN in emission-line diagrams is an important topic of study because of the difficulty in measuring black hole mass (M_☉) from velocity dispersion in high redshift AGN. Kewley et al. (2006) investigated host properties of nearby emission-line galaxies (0.04 < z < 0.1) from the SDSS. They found that the λ_Εdd (inferred from L_{OIII}/σ^4, where σ is a stellar velocity dispersion) shows an increase with φ, a measure of distance from the LINER regime in the [OIII] λ5007/Hβ vs. [O I] λ6300/Hα diagram. Similarly, an SDSS study of unobscured AGN by Stern & Laor (2013) found a dependence of emission-line diagnostics on the λ_Εdd. However, the estimation of λ_Εdd and the introduced relationship between the angle φ and L_{OIII}/σ^4 were both dependent on the strength of [O I] λ5007. Also, the previous studies did not take into account X-ray selection focusing on the large sample of optically selected AGN. Both high ionized optical emission lines and X-rays are thought to be a measure of the AGN bolometric luminosity. However, hard X-rays are less biased against dust obscuration and the contribution from star-forming activity than optical emission lines.

The BAT AGN Spectroscopic Survey (BASS) Data Release 1 (Koss et al., submitted) compiled 642 optical spectra of nearby AGN (z ~ 0.05) from public surveys (SDSS, 6dF; Abazajian et al. 2009; Jones et al. 2009; Alam et al. 2015) and dedicated follow-up observations (e.g., from telescopes at the Kitt Peak, Gemini, Palomar, and SAAO observatories). The data release provided emission line measurements as well as M_☉ and λ_Εdd estimates for the majority of obscured and un-obscured AGN (74%, 473/642), including 340 AGN with M_☉ measurements reported for the first time.

In this paper, we use the BASS measurements to investigate the observed relationship between black hole mass (M_☉), bolometric luminosity (L_ bol), and Eddington ratio (λ_Εdd) with optical emission line ratios ([N II] λ6583/Hα, [S II] λ6716, 6731/Hα, [O I] λ6300/Hα, [O III] λ5007/Hβ, [Ne II] λ3869/Hβ, and He II λ4686/Hβ) for both obscured and unobscured AGN.

We assume a cosmology with h = 0.70, Ω_M = 0.30, and Ω_Λ = 0.70 throughout this work.

2 SAMPLE SELECTION, DATA, AND MEASUREMENTS

In this section, we briefly summarize the measurement procedures for optical emission lines, M_☉, and λ_Εdd. The BASS DR1 measured nebular emission line strengths by performing a power-law fit with Gaussian components to model the continuum and emission lines. For unobscured AGN, two Gaussian components are allowed in the Hα and Hβ emission line regions to account for both broad (FWHM > 1000 km s^{-1}) and narrow (FWHM < 1000 km s^{-1}) components. When broad Hβ is detected, M_☉ is measured using the single-epoch method following Trakhtenbrot & Netzer (2012). If no broad Hβ is detected, M_☉ is measured based on the line width and luminosity of broad Hα (equation 9 from Greene & Ho 2005). For obscured AGN, the estimation of M_☉ relies on the close correlations between M_☉ and the stellar velocity dispersion (σ, e.g., Kormendy & Ho 2013). Stellar velocity dispersion is derived from the penalized pixel fitting method (pPXF, Cappellari & Emsellem 2004) by implementing a modified version of the masking procedure introduced for the analysis of SDSS DR7 (Abazajian et al. 2009) galaxy spectra (the OSSY catalog2, Sarzi et al. 2006; Oh et al. 2011, 2015).

Since the obscuration mostly affect the estimation of L_ bol for Compton thick AGN (N_H > 10^{24} cm^{-2}), we estimated L_ bol from the intrinsic (i.e., absorption and k corrected) 14-150 keV luminosities reported in Ricci et al. (2015) and Ricci et al. (in prep.), transforming them into 14-195 keV luminosities assuming a power-law continuum with a photon index of Gamma=1.9. After converting the 14-195 keV luminosity to the intrinsic 2-10 keV luminosity the procedure described by following Rigby et al. (2009), we then applied the median bolometric correction introduced by Vanden Berk et al. (2009). It is noteworthy to mention that the estimation of L_ bol comes solely from hard X-ray band (14-195 keV) and its constant conversion factor (k = 8). We briefly discuss the effect of different L_ bol estimation in Section 3. We then combined the measured M_☉ with the L_ bol to calculate λ_Εdd (λ_Εdd ≡ L_ bol/L_ bol) assuming L_ bol ≡ 1.3 × 10^{38} (M_☉ / (M/Δ)). For more details, refer to the first data release (Koss et al., in submitted).

We focus on the sub-sample of the 642 optical spectra from the BASS DR1. We consider only non-beamed AGN, which were selected by cross-matching the BASS sources with the Roma blazar catalog (BZCAT) v5.0 (Massaro et al. 2009). We then restricted our samples to redshifts of 0.01 < z < 0.40 to have coverage of the Hβ and Hα region. Berney et al. (2015) investigated the effect of slit size for the

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1 http://heasarc.gsfc.nasa.gov/docs/swift/results/ls70mon/
2 http://gem.yonsei.ac.kr/ossy/
Figure 1. Emission line diagnostic diagrams for the BASS sources with signal-to-noise (S/N) ratio > 3. Left: The [N\textsc{ii}] $\lambda6583$/H\textalpha
diagnostic diagram. Colour filled circles and triangles indicate type 1 AGNs (including type 1.9) and type 2 AGNs, respectively. The empirical star-formation curve obtained from Kauffmann et al. (2003) (dashed curve) and the theoretical maximum starburst model of Kewley et al. (2001) (solid curve) are used. The solid-straight line is the empirical demarcation of Schawinski et al. (2007) distinguishing the Seyfert AGN from the LINERs. The Eddington ratio of BASS sources is shown with color-filled dots. Middle: The [S\textsc{ii}] $\lambda6716,6731$/H\textalpha
diagnostic diagram. Right: The [O\textsc{iii}] $\lambda5007$/H\textbeta
diagnostic diagram. Demarcation lines from Kewley et al. (2001, 2006) are used. In all panels we also show more than 180,000 SDSS emission-line galaxies with filled contours chosen from the OSSY catalog ($z < 0.2$) with S/N > 3 for [N\textsc{ii}] $\lambda6583$, H\textalpha, [O\textsc{ii}] $\lambda5007$, H\textbeta, [S\textsc{ii}] $\lambda6716$, [S\textsc{n}] $\lambda6731$, and [O\textsc{i}] $\lambda6300$.

Table 1. Bayesian linear regression fit.

| line ratio | N   | $\alpha$ | $\beta$ | RMSD | $R_{\text{Pear},\text{unob}}$ (p-value) | $R_{\text{Pear},\text{obs}}$ (p-value) |
|-----------|-----|----------|---------|------|----------------------------------|----------------------------------|
| [N\textsc{ii}] $\lambda6583$/H\textalpha | 297 | $-0.42 \pm 0.04$ | $-0.19 \pm 0.02$ | 0.28 | $-0.44 (3 \times 10^{-15})$ | $-0.34 (0.00002)$ |
| [S\textsc{ii}] $\lambda6716,6731$/H\textalpha | 288 | $-0.48 \pm 0.03$ | $-0.11 \pm 0.02$ | 0.25 | $-0.29 (9 \times 10^{-7})$ | $-0.26 (0.00080)$ |
| [O\textsc{ii}] $\lambda6300$/H\textalpha | 205 | $-0.30 \pm 0.04$ | $-0.17 \pm 0.03$ | 0.23 | $-0.32 (6 \times 10^{-11})$ | $-0.30 (0.00028)$ |
| [O\textsc{iii}] $\lambda5007$/H\textbeta | 286 | $-0.28 \pm 0.02$ | $-0.18 \pm 0.02$ | 0.25 | $-0.29 (2 \times 10^{-9})$ | $-0.27 (0.00031)$ |
| [Ne\textsc{iii}] $\lambda3869$/H\textbeta | 125 | $-0.35 \pm 0.03$ | $-0.20 \pm 0.02$ | 0.26 | $-0.35 (7 \times 10^{-10})$ | $-0.33 (0.00128)$ |
| He\textsc{n} $\lambda4868$/H\textbeta | 107 | $-0.35 \pm 0.03$ | $-0.20 \pm 0.02$ | 0.26 | $-0.35 (7 \times 10^{-10})$ | $-0.33 (0.00128)$ |

Note. (1) optical emission line ratio; (2) size of sample; (3) intercept; (4) slope; (5) rms deviation; (6) Pearson $R$ coefficient and p-value; (7) Pearson $R$ coefficient and p-value for unobscured AGN; (8) Pearson $R$ coefficient and p-value for obscured AGN.

BASS DR1 sources and showed that the ratio between extinction corrected $L[O\text{iii}]$ and $L_{14.195\text{keV}}$ is constant when excluding the nearest galaxies ($z < 0.01$) while the scatter slightly decreases towards larger slit sizes. We used the same redshift range following this approach. However, it should be noted that aperture effect does not change our results shown in Section 3. We tested whether sources with large physical coverage (> 2 kpc) still found a significant correlation in a smaller sample size suggesting that slit size is not important for this study. We also selected only spectral fits with a good quality as listed in the DR1 tables (Koss et al., in submitted). We note that sources with spectra taken from the 6dF Galaxy Survey (Jones et al. 2009) are only used to derive emission line ratios and to measure stellar velocity dispersions (e.g., Campbell et al. 2014) due to the lack of flux calibration as necessary for broad line black hole mass measurements. Samples sizes for each emission line ratio used in this paper are listed in Table 1.

3 RELATIONS BETWEEN OPTICAL EMISSION LINE RATIOS AND BASIC AGN PROPERTIES

Fig. 1 shows the emission-line diagnostic diagrams for the BASS sources according to $\lambda_{\text{Edd}}$ (colour-coded). The majority of the BASS sources ($> 90\%$) are found in the Seyfert region in each panel.

In order to study the statistical significance of any correlations with $\lambda_{\text{Edd}}$, we show optical emission line ratios as a function of $\lambda_{\text{Edd}}$ in Fig. 2. We performed Bayesian linear regression fit (equation 1) to all points using the method of Kelly (2007) which accounts for measurement errors in both axes. The relation between $\lambda_{\text{Edd}}$ and optical emission line ratio (black solid line in Fig. 2) is determined by taking the median of 10,000 draws from the posterior probability distribution of the converged parameters (intercept and slope). The errors of intercept and slope are reported from
Figure 2. Optical emission line ratio versus Eddington ratio diagram. Black open circles and triangles indicate type 1 AGN (including type 1.9) and type 2 AGN, respectively. Median at each bin is shown with colour-filled symbols. Bin size is determined to have at least 10 sources. Black solid lines indicate the Eddington ratio - optical emission line ratio relations (equation 1). The grey shaded regions account for the errors in the slope and intercept of the relation. The rms deviation is shown with dotted lines. An error bar in the bottom-left corner at each panel indicates typical uncertainties in Eddington ratio and optical emission line ratio. The ionization potential for each emission line is shown in the legends. Also, Pearson correlation coefficients and p-values are shown in the bottom-right corner of each panel. An emission line detection at S/N \(< 3\) (upper- or lower-limit) is shown with grey symbols.

\[
\log \left( \frac{F_{\text{line}}}{F_{\text{Balmer}}} \right) = \alpha + \beta \log \lambda_{\text{Edd}} \tag{1}
\]

The values of \(\alpha\) (intercept), \(\beta\) (slope), Pearson correlation coefficient, rms deviation, and p-value are summarised in Table 1.

We find that the \(\lambda_{\text{Edd}}\) is significantly anti-correlated with optical emission line ratios for both the [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) and [S\textsc{ii}] \(\lambda 6716, 6731/\text{H}\alpha\) ratios but not for the other line ratios. The larger the \(\lambda_{\text{Edd}}\), the smaller the line ratio of [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) and [S\textsc{ii}] \(\lambda 6716, 6731/\text{H}\alpha\). We find that Pearson R coefficient and p-value of the anti-correlation between [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) and \(\lambda_{\text{Edd}}\) are \(-0.44\) and \(3 \times 10^{-13}\), respectively, with 0.28 dex of rms deviation. We also found a significantly anti-correlated relationship for both the [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) and [S\textsc{ii}] \(\lambda 6716, 6731/\text{H}\alpha\) ratios with a more stringent S/N cut of optical emission lines (> 10). AGN variability may induce the scatter shown in the anti-correlation between [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) and \(\lambda_{\text{Edd}}\). Since X-ray emission that we used to derive \(L_{\text{bol}}\) and \(\lambda_{\text{Edd}}\) has different time-scales compared to optical narrow emission lines, a scatter around the anti-correlation can be explained (Mushotzky et al. 1993; Schawinski et al. 2015). Also, differences in metallicities and/or structures of the narrow-line regions may contribute to the scatter shown above. In order to quantitatively investigate if the \(\lambda_{\text{Edd}}\) shows a stronger anti-correlation with [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) or with [S\textsc{ii}] \(\lambda 6716, 6731/\text{H}\alpha\), we run a z-test based on the two Pearson correlation coefficients (Fisher r-to-z transformation). The p-value (0.019) suggests that [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) shows a significantly stronger anti-correlation than [S\textsc{ii}] \(\lambda 6716, 6731/\text{H}\alpha\) with \(\lambda_{\text{Edd}}\).

Moreover, we also find that the observed anti-
correlation between [N\textsc{ii}] $\lambda$6583/H\alpha and $\lambda_{\text{Edd}}$ is valid for obscured AGN (blue filled triangles in Fig. 2) as well as unobscured AGN (red filled circles in Fig. 2). Pearson $R$ coefficient and $p$-value for obscured AGN are $-0.28$ and $0.00128$, respectively. For unobscured AGN, we report $-0.34$ and $0.00002$ as Pearson $R$ coefficient and $p$-value. We report that $\lambda_{\text{Edd}}$ can be estimated from the measured [N\textsc{ii}] $\lambda$6583/H\alpha ratio as follows, with 0.6 dex of rms deviation:

$$\log \lambda_{\text{Edd}} = (-1.52 \pm 0.04) + (-1.00 \pm 0.13) \times \log ([\text{N\textsc{ii}}] \lambda 6583/H\alpha)$$  \hspace{1cm} (2)$$

Another way to study the location on the emission line diagnostic diagram is to measure the shortest distance from the star-forming and LINER lines in [N\textsc{ii}] $\lambda$6583/H\alpha. The $\lambda_{\text{Edd}}$ distribution shown in the [N\textsc{ii}] $\lambda$6583/H\alpha emission line diagnostic diagram (left panel of Fig. 1) enables us to infer that AGN falling in the Seyfert region exhibit different $\lambda_{\text{Edd}}$ according to their location, i.e., combinations of emission line ratios. We define the distance between the location of a given object and the empirical demarcation line of Schawinski et al. (2007) ($d_{\text{LINER}}$) and the theoretical maximum starburst model of Kewley et al. (2001) ($d_{\text{SF}}$). The separation between Seyfert and LINER was obtained by visual determination based on [N\textsc{ii}] $\lambda$6583/H\alpha vs. [O\textsc{iii}] $\lambda$5007/H\beta diagram for nearly 50,000 nearby SDSS galaxies ($0.05 < z < 0.10$, Schawinski et al. 2007). For Seyfert and LINERs classified using the [S\textsc{ii}] $\lambda$6716, 6731/H\alpha and [O\textsc{i}] $\lambda$6300/H\alpha diagrams, the authors determined the demarcation line in the [N\textsc{ii}] $\lambda$6583/H\alpha diagram. In particular, we measured $d_{\text{SF}}$ by moving the demarcation line of Kewley et al. (2001) in parallel with the original one until it matches the location of the given object. The measured distance, $d_{\text{LINER}}$, that originated from optical emission line ratios which depict the physical state of the innermost region of the galaxy is a function of the $\lambda_{\text{Edd}}$ (middle panel in Fig. 3). We report Pearson $R$ coefficient and $p$-value for $d_{\text{LINER}}$ and $\lambda_{\text{Edd}}$ with 0.31 and $5 \times 10^{-7}$ while $d_{\text{SF}}$ shows less significant statistics ($R_{\text{Pear}} = -0.18$, $p$-value=0.00423) suggesting that $\lambda_{\text{Edd}}$ is less likely a function of $d_{\text{SF}}$. We also ran a test to see if sources with extreme $\lambda_{\text{Edd}}$ were driving correlations we found. For this test, we used a limited range of $\lambda_{\text{Edd}}$ ($-2.67 < \log \lambda_{\text{Edd}} < 0.00$) which excludes small number of objects shown at both high- and low-end of $\lambda_{\text{Edd}}$ and we found a significant correlation.

We further study the observed anti-correlation by looking for correlations with $M_{\text{BH}}$ (Fig. 4). We find that the [N\textsc{ii}] $\lambda$6583/H\alpha, [S\textsc{ii}] $\lambda\lambda$6716, 6731/H\alpha, [O\textsc{i}] $\lambda$6300/H\alpha, and [O\textsc{iii}] $\lambda$5007/H\beta show positive correlations with $M_{\text{BH}}$, with $p$-values of $5 \times 10^{-8}$, 0.00218, 0.00009, and 0.00174, respectively. In order to understand whether the anti-correlation of [N\textsc{ii}] $\lambda$6583/H\alpha with $\lambda_{\text{Edd}}$ is stronger than the correlation of [N\textsc{ii}] $\lambda$6583/H\alpha with $M_{\text{BH}}$ we run the $z$-test based on the two Pearson correlation coefficients and find that the $p$-value suggests a stronger anti-correlation for the $\lambda_{\text{Edd}}$ ($p$-value=0.025). We also investigate the observed anti-correlation between optical emission line ratios and $\lambda_{\text{Edd}}$ with fixed $M_{\text{BH}}$ ($7 < \log (M_{\text{BH}}/M_\odot) < 8$, $8 < \log (M_{\text{BH}}/M_\odot) < 9$). We find that [N\textsc{ii}] $\lambda$6583/H\alpha is indeed significantly anti-correlated with $\lambda_{\text{Edd}}$ in each of these mass bins, with $p$-value of 0.00488 ($7 < \log (M_{\text{BH}}/M_\odot) < 8$) and $3 \times 10^{-7}$ ($8 < \log (M_{\text{BH}}/M_\odot) < 9$). On the other hand, the other line ratios do not show correlation with $\lambda_{\text{Edd}}$ at any fixed $M_{\text{BH}}$ except [S\textsc{ii}] $\lambda\lambda$6716, 6731/H\alpha which shows $p$-value of $5 \times 10^{-5}$ in high $M_{\text{BH}}$ bin. We also test how the relationships between emission line ratios and $M_{\text{BH}}$ change at fixed $\lambda_{\text{Edd}}$ ($-2.5 < \log \lambda_{\text{Edd}} < -1.5$, $-1.5 < \log \lambda_{\text{Edd}} < -0.5$). We find that [O\textsc{i}] $\lambda$6300/H\alpha and [O\textsc{iii}] $\lambda$5007/H\beta only show weak correlation at both fixed $\lambda_{\text{Edd}}$ bins with less than 1% level of $p$-value.

Finally, we find a negative correlation with the $L_{\text{bol}}$ (Fig. 5) for [N\textsc{ii}] $\lambda$6583/H\alpha ($p$-value=0.00577) while a positive correlation is found for [O\textsc{iii}] $\lambda$5007/H\beta ($p$-value=2.0 \times 10^{-6}$). Running the $z$-test based on the two Pearson correlation coefficients for [N\textsc{ii}] $\lambda$6583/H\alpha with $\lambda_{\text{Edd}}$ compared to [N\textsc{ii}] $\lambda$6583/H\alpha with $L_{\text{bol}}$ again suggests a statistically stronger correlation ($p$-value=0.0001) in $\lambda_{\text{Edd}}$. While [N\textsc{ii}] $\lambda$6583/H\alpha shows correlations with $M_{\text{BH}}$ and $L_{\text{bol}}$, the correlation with $M_{\text{BH}}$ is more significant at the less than 5% level based on a Fisher $z$ test ($p$-value=0.036).

In order to understand effect of the different bolometric luminosities, we find a slightly stronger correlation with $L_{\text{bol}}$ ($p$-value=0.00577) than with $M_{\text{BH}}$ ($p$-value=0.0001) while the test using $M_{\text{BH}}$ and $L_{\text{bol}}$ shows a weak correlation ($p$-value=0.00577).
metric correction, we estimate $L_{\text{bol}}$ and $\lambda_{Edd}$ following Marconi et al. (2004) who uses bolometric correction that depends on 2-10 keV luminosity (equation 21 in their paper). The mean difference between the newly estimated $L_{\text{bol}}$ and the one derived by our prescription is 0.03 dex with 0.33 dex of scatter, which gives a mean difference in $\lambda_{Edd}$ of 0.03 dex (0.33 dex of scatter). We find that [NII] λ6583/Hα (p-value $= 10^{-12}$) and [SII] $\lambda$λ6716, 6731/Hα (p-value $= 10^{-12}$) show significant anti-correlation with $\lambda_{Edd}$.

If we adopt more steep bolometric correction curve that varies with 2-10 keV luminosity (see Figure 3 in Marconi et al. 2004) covering wide range of bolometric correction, we may get flattened relationship in [NII] $\lambda$λ6583/Hα and $\lambda_{Edd}$ as sources in low $\lambda_{Edd}$ and high $\lambda_{Edd}$ move toward each end. However, we find that the application of such extreme case of bolometric correction does not significantly change the Pearson R coefficient ($-0.43$) and $p$-value ($10^{-12}$) but shows slightly moderate slope ($-0.10 \pm 0.01$).

4 DISCUSSION

We have presented the observed relationship between the $\lambda_{Edd}$ and optical emission line ratios ([NII] $\lambda$λ6583/Hα, [SII] $\lambda$λ6716, 6731/Hα, [O I] $\lambda$$\lambda$6300/Hα, [O III] $\lambda$$\lambda$5007/Hβ, [NeIII] $\lambda$λ3869/Hβ, and He II $\lambda$λ4686/Hβ) using local obscured and unobscured AGN ($z = 0.05, z < 0.40$) from the 70-month Swift-BAT all-sky hard X-ray survey with follow-up optical spectroscopy. We show that there is a significant anti-correlation between [NII] $\lambda$λ6583/Hα emission line ratio and $\lambda_{Edd}$, and this correlation is stronger than trends with $M_{\text{BH}}$ or $L_{\text{bol}}$ or with other line ratios. The observed trend suggests that optical emission line ratios, which are widely used to classify sources as AGN, may also be an indicator of $\lambda_{Edd}$. The use of [NII] $\lambda$λ6583 and Hα emission lines as a $\lambda_{Edd}$ indicator has potential implications for high redshift obscured AGN whose $M_{\text{BH}}$ and $\lambda_{Edd}$ are difficult to estimate. This would require to additionally assume that any relevant physical relations that might affect our $\lambda_{Edd}$ - [NII] $\lambda$λ6583/Hα relation (e.g., the stellar mass-metallicity, AGN outflows), do not evolve significantly with redshift. The relationship shown in this work may serve as a basis for future studies toward measuring $M_{\text{BH}}$ and $\lambda_{Edd}$ of individual AGN.

A number of complications arise when measuring $L_{\text{bol}}$ and $M_{\text{BH}}$ from a large ($N > 100$) sample of galaxies. The majority of the total luminosity is emitted from the accretion disk in the extreme ultraviolet and ultraviolet energy bands (Shields 1978; Malkan & Sargent 1982; Mathews & Ferland 1987). While we used a fixed bolometric correction from the X-ray, this correction has been observed to vary depending on $\lambda_{Edd}$ (Vasudevan et al. 2009) and $L_{\text{bol}}$ (e.g., Just et al. 2007; Green et al. 2009). This issue deserves further study, though we would expect any biases to affect all line ratios whereas we find a much stronger correlation with [NII] $\lambda$λ6583/Hα. Another complication is the use of separate methods of BH mass estimates. We note, however, that these two methods are tied to reproduce similar masses for systems where both are applicable (Graham et al. 2011; Woo et al. 2013), and that we find significant correlations for both type 1 and type 2 AGN, separately (Table 1). We will explore $M_{\text{BH}}$ measurements for both types of AGN via different methods in a future study.

There are several possible physical mechanisms that might lead to the trends found between $\lambda_{Edd}$ and emission line ratios such as [NII] $\lambda$λ6583/Hα. Groves et al. (2006) and Stern & Laor (2013) found a dependence of emission-line diagnostics, particularly of the [NII] $\lambda$λ6583/Hα, with host galaxy stellar mass. They postulated that this was a result of the mass metallicity relationship with more massive galaxies having more metals (Lequeux et al. 1979; Tremonti et al. 2004; Erb et al. 2006; Lee et al. 2006; Ellison et al. 2008; Maiolino et al. 2008; Mannucci et al. 2010; Lara-López et al. 2010). As more massive galaxies have more massive black holes, this follows the correlation found here with [NII] $\lambda$λ6583/Hα being positively correlated with $M_{\text{BH}}$ and negatively correlated with $L_{\text{bol}}$. Stern & Laor (2013) showed that [OIII] $\lambda$$\lambda$5007/Hβ mildly decreases with stellar mass since reduced [OIII] $\lambda$λ5007 emission is expected from higher metallicity and massive systems as [OIII] $\lambda$λ5007 is a main coolant and the temperature will be lower in massive systems. The less significant correlation between [OIII] $\lambda$$\lambda$5007/Hβ and $M_{\text{BH}}$ shown in Fig. 4 as compared to the [NII] $\lambda$λ6583/Hα which scales strongly with metallicity can be explained in this context. Another interesting possibility affecting this correlation could be from higher $\lambda_{Edd}$ AGN have relatively weaker [OIII] $\lambda$λ5007 lines, as found by the “Eigenvector 1” relationships (e.g., Boroson & Green 1992).

A further possibility is that X-ray heating is inducing some of the negative correlation found between $L_{\text{bol}}$ and the [NII] $\lambda$λ6583/Hα ratio. Ionizing ultraviolet photons produce a highly ionized zone on the illuminated face of the gas cloud while deeper in the cloud penetrating X-rays heat the gas and maintain an extended partially ionized region. Higher energy photons such as Lyα are destroyed by multiple scatterings ending in collisional excitation which enhances the Balmer lines (Weisheit et al. 1981; Krolik & Kallman 1983; Maloney et al. 1996). Strong X-rays (i.e., harder SEDs) that heat up hot electrons in partially ionized region also enhance collisional excitation of Oδ, Nδ, and Sδ. As a result, it is expected to see high [NII] $\lambda$λ6583/Hα, [SII] $\lambda$λ6716, 6731/Hα, and [O I] $\lambda$λ6300/Hα.

Alternatively, the observed anti-correlation between emission line ratios ([NII] $\lambda$λ6583/Hα and [SII] $\lambda$λ6716, 6731/Hα) and $\lambda_{Edd}$ may be due to radiatively driven outflows in high $\lambda_{Edd}$ systems. Radiatively accelerated wind is predicted to be proportional to $\lambda_{Edd}$ (Shlosman et al. 1985; Arav et al. 1994; Murray et al. 1995; Hamann 1998; Proga et al. 2000; Chelouche & Netzer 2001). This is consistent with the observed blueshift of broad as well as narrow absorption lines (Mizawa et al. 2007) often seen in quasars. In the context of a prevalent outflow in high $\lambda_{Edd}$ AGN, the optical-UV SED of the accretion disk is expected to be softer when $\lambda_{Edd}$ is $\gtrsim 0.3$ (King & Pounds 2003; Pounds et al. 2003; Reeves et al. 2003; Tombesi et al. 2010, 2011; Stone & Netzer 2012; Veilleux et al. 2016; Woo et al. 2016). As hot accreting gas is removed by ejecting outflows, the formation of collisionally excited emission lines is expected to be suppressed. It is important to note, however, that the anti-correlation between optical emission line ratio and $\lambda_{Edd}$ is only appeared in [NII] $\lambda$λ6583/Hα and [SII] $\lambda$λ6716, 6731/Hα but not in other line ratios.
Figure 4. Optical emission line ratio versus black hole mass. The format is the same as that of Fig. 2.

Figure 5. Optical emission line ratio versus bolometric luminosity. The format is the same as that of Fig. 2.
5 SUMMARY

We present observed correlations between AGN Eddington ratio ($\lambda_{\text{Edd}}$), black hole mass ($M_{\text{BH}}$), and bolometric luminosity ($L_{\text{bol}}$) and narrow emission line ratios ($\lambda$[N\text{II}] 6583/\lambda[O\text{I}] 6300, $\lambda$[O\text{II}] 5007/\lambda[O\text{I}] 6300, and $\lambda$[He\text{I}] 6686/\lambda[O\text{I}]) for hard X-ray selected AGN from the BASS. The results of this study are:

- $\lambda_{\text{Edd}}$ is anti-correlated with both the $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] and $\lambda$[O\text{II}] 6300/\lambda[O\text{I}] ratios, but not with other line ratios.
- $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] exhibits a significantly stronger anti-correlation with $\lambda_{\text{Edd}}$ than $\lambda$[O\text{II}] 6300/\lambda[O\text{I}].
- The correlation shown in $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] with $M_{\text{BH}}$ is more significant than with $L_{\text{bol}}$.
- The correlation appeared in $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] with $M_{\text{BH}}$ might be a result of the mass metallicity relationship.
- The observed relationship between $\lambda_{\text{Edd}}$ and $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] ratio could be explained by considering X-ray heating processes and removal of material due to energetic outflow in the high $\lambda_{\text{Edd}}$ state.
- The $\lambda$[N\text{II}] 6583/\lambda[O\text{I}] ratio could in principle be used to measure accretion efficiencies and black hole masses of high redshift obscured AGN (equation 2).

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