A GROWTH-RATE INDICATOR FOR COMPTON-THICK ACTIVE GALACTIC NUCLEI

M. Brightman1, A. Masini2,3, D. R. Ballantyne4, M. Baloković1, W. N. Brandt5, C.-T. Chen6, A. Comastri7, D. Farrah6, P. Gandhi7, F. A. Harrison1, C. Ricci8, D. Stern9, and D. J. Walton1,9
1 Cahill Center for Astrophysics, California Institute of Technology, 1216 East California Boulevard, Pasadena, CA 91125, USA
2 INAF Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
3 Dipartimento di Fisica e Astronomia (DIFA), Università di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy
4 Center for Relativistic Astrophysics, School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
5 Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
6 Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
7 Department of Physics and Astronomy, University of Southampton, Highfield, Southampton S017 1BJ, UK
8 Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
9 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Received 2016 March 31; revised 2016 May 18; accepted 2016 June 11; published 2016 July 25

ABSTRACT

Due to their heavily obscured central engines, the growth rate of Compton-thick (CT) active galactic nuclei (AGNs) is difficult to measure. A statistically significant correlation between the Eddington ratio, ΛEdd, and the X-ray power-law index, Γ, observed in unobscured AGNs offers an estimate of their growth rate from X-ray spectroscopy (albeit with large scatter). However, since X-rays undergo reprocessing by Compton scattering and photoelectric absorption when the line of sight to the central engine is heavily obscured, the X-ray luminosity, Lx, cannot be calculated, and ΛEdd related to the mass accretion rate onto the black hole, ṛBH. This is de

Key words: black hole physics – galaxies: general – galaxies: nuclei – galaxies: Seyfert – masers

1. INTRODUCTION

Determining the growth rates of active galactic nuclei (AGNs) is important for understanding the build up of supermassive black holes. The key parameter to describe black hole growth is the Eddington ratio, ΛEdd. This is defined by the ratio of the bolometric luminosity of the AGN, Lbol, to the Eddington luminosity, LEd (i.e., ΛEdd ≡ Lbol/LEdd). Lbol is related to the mass accretion rate onto the black hole, ṛBH, via the accretion efficiency, η, by Lbol = ṛBH. LEd is the theoretical maximal luminosity (although observed to be exceeded in some sources e.g., Lanzuisi et al. (2016)) achieved via accretion when accounting for radiation, and is dependent on the black hole mass (LEdd = 4πGMBHmpc/σT ≈ 1.26 × 1038(MBH/M⊙) erg s⁻¹).

For unobscured AGNs, ΛEdd is determined from the intrinsic disk emission observed in the optical/UV, from which Lbol can be calculated, and MBH that is estimated from measurements of the broad emission lines which trace the motions of gas close to the black hole (e.g., Shen 2013; Peterson 2014).

In obscured AGNs however, the intrinsic disk emission is completely extinguished by intervening material, and the broad line region is obscured from view, so ΛEdd is difficult to measure in these systems and must be estimated from indirect methods. For example, the observed relationship between the stellar velocity dispersion in the bulge of the galaxy and the black hole mass is often used to estimate MBH. However, this relationship has a large intrinsic scatter in it, especially at low masses (e.g., Greene et al. 2010; Läsker et al. 2016). It is therefore important to have as many indirect methods as possible for estimating ΛEdd for both unobscured and obscured AGNs.

Studies of the X-ray emission of AGNs have found that ΛEdd is strongly correlated with the X-ray spectral index, Γ, in the range 0.01 ≲ ΛEdd ≲ 1 (e.g., Shen et al. 2006, 2008; Risaliti et al. 2009; Jin et al. 2012; Brightman et al. 2013). ΛEdd depends on both the electron temperature and optical depth to Compton scattering in the hot corona (Rybicki & Lightman 1986; Haardt & Maraschi 1993; Fabian et al. 2015) that up-scatters the optical/UV emission from the accretion disk (e.g., Shakura & Sunyaev 1973). This relationship is thought to arise due to higher ΛEdd systems cooling their coronae more effectively than lower ΛEdd through enhanced optical/UV emission.

The observed relationship between Γ and ΛEdd suggests that a measurement of Γ could be used to estimate ΛEdd. This would be particularly useful for heavily obscured AGNs due to the fact that ΛEdd is, as mentioned, difficult to measure for such systems. However, this has its own challenges, since X-rays are also absorbed in these sources and at large column densities (N H ~ 1024 cm⁻²) X-rays undergo Compton-scattering within the obscuring medium, which modifies their trajectory and energy. Nonetheless, up to N H ~ 1025 cm⁻² and at high energy (E > 10 keV) absorption is negligible, and furthermore spectral
models exist that take these effects into account, assuming a torus geometry of the obscuring medium, e.g., mytorus (Murphy & Yaqoob 2009) and torus (Brightman & Nandra 2011). In order to recover the intrinsic $\Gamma$ using these models, broadband X-ray spectral measurements, especially above 10 keV where the scattering dominates, are required. NuSTAR (Harrison et al. 2013), with its sensitivity at these energies, is the ideal instrument with which to uncover the intrinsic X-ray emission from heavily obscured AGNs and since its launch in 2012 has amassed a large archive of data on these sources (e.g., Arévalo et al. 2014; Baloković et al. 2014; Gandhi et al. 2014; Puccetti et al. 2014; Annuar et al. 2015; Bauer et al. 2015; Brightman et al. 2015; Koss et al. 2015; Rivers et al. 2015; Marinucci et al. 2016; Ricci et al. 2016).

In this work our goal is to examine the relationship between $\Gamma$ and $\lambda_{\text{Edd}}$ for heavily obscured AGNs to test if it is consistent with the results from unobscured AGNs. This will reveal how well X-ray spectral modeling with the X-ray torus models recovers the intrinsic AGN parameters, or if orientation effects in the corona are present, related to AGN unification, and show if $\Gamma$ can be used as a $\lambda_{\text{Edd}}$ indicator for these heavily obscured systems.

This requires a sample of heavily obscured AGNs where the black hole mass has been measured reliably and broadband X-ray spectra are available. The most robust black hole mass measurements for obscured AGNs come from disk water megamasers (see Lo 2005, for a review), where the Keplerian motion of the masing material reveals the mass within (e.g., Greenhill et al. 1996). Due to the edge-on geometry of the medium required to produce masing emission, a high fraction of megamasers are heavily obscured AGNs (Zhang et al. 2006; Masini et al. 2016), making megamasers particularly well suited to our study.

Furthermore, megamasers are of interest since they are at the low-mass end of the supermassive black hole mass distribution, having a mass range of $M_{\text{BH}} \approx 10^6$–$10^7 M_\odot$. Previous analyses of the $\Gamma$–$\lambda_{\text{Edd}}$ relationship have concentrated on samples where the black hole mass has been measured from optical broad line fitting (e.g., Brightman et al. 2013) with $M_{\text{BH}} \approx 10^7$–$10^8 M_\odot$. More recently, lower-mass black holes ($M_{\text{BH}} \sim 10^5 M_\odot$) have been investigated (e.g., selected via their rapid X-ray variability, Kamizasa et al. 2012), where it has been found that they are not fully consistent with the results from higher mass (Ai et al. 2011; Ho & Kim 2016). The megamaser AGNs thus give us the opportunity to further assess the validity of the relationship in this low-mass regime with a different sample selection.

We describe our sample and its selection in Section 2, give our results in Section 3 and discuss and conclude in Section 4.

2. MEGAMASER SAMPLE

There are $\sim$20 sources where megamaser emission has been used to measure black hole mass (e.g., Kuo et al. 2011). For our analysis, we require results from sensitive broadband X-ray spectral data, especially above 10 keV where Compton scattering effects dominate. For this reason we compile NuSTAR results on the megamaser AGNs. This was done recently by Masini et al. (2016) who compiled and analyzed X-ray spectral information of megamaser AGNs in order to study the connection between the masing disk and the torus. These AGNs include well-studied sources that have been the subject of detailed spectral analysis of NuSTAR data, such as Circinus (Arévalo et al. 2014), NGC 4945 (Puccetti et al. 2014), NGC 1068 (Bauer et al. 2015; Marinucci et al. 2016), and NGC 3393 (Koss et al. 2015), as well as samples of sources such as IC 2560, NGC 1368, and NGC 3079 (Baloković et al. 2014; Brightman et al. 2015).

In all of these studies, the mytorus and torus models were used to obtain the intrinsic $\Gamma$ and 2–10 keV luminosities, $L_X$, correcting for columns of $10^{23}$–$10^{26}$ cm$^{-2}$. In most studies of the megamaser AGNs listed above, both mytorus and torus models were fitted, with generally good agreement between spectral parameters (for a direct comparison see Brightman et al. 2015). For our study, we take the results on $\Gamma$ and $L_X$ from the model that the original authors found to be the best fitting one.

In order to test the $\Gamma$–$\lambda_{\text{Edd}}$ relationship for the megamaser AGNs, we require good constraints on $\Gamma$, thus we exclude sources where the uncertainty on $\Gamma$ is $>0.25$, which excludes NGC 1386 and NGC 2960 from our sample. Our final sample consists of nine AGNs. For NGC 4945, Puccetti et al. (2014) present a flux resolved analysis of the source, whereby they investigated the variation of $\Gamma$ with the source luminosity (and hence $\lambda_{\text{Edd}}$), which is of particular interest here, so we include those individual results here, giving us 12 separate measurements of $\Gamma$ for the sample. With the exception of NGC 4388 ($N_H = 4 \times 10^{23}$ cm$^{-2}$, Masini et al. 2016), this sample consists wholly of CT ($N_H \geq 1.5 \times 10^{24}$ cm$^{-2}$) AGNs.

With black hole masses from the megamasers and good measurements of $\Gamma$, the final ingredient required for our investigation is $L_{\text{bol}}$, needed to calculate $\lambda_{\text{Edd}}$. Since the X-ray spectral modeling also yields intrinsic 2–10 keV luminosities, $L_X$, for our sample, the simplest approach is to apply a bolometric correction, $\kappa_{\text{bol}}$, to $L_X$. Several works have presented results on $\kappa_{\text{bol}}$, reporting that it is an increasing function of $L_{\text{bol}}$ (e.g., Marconi et al. 2004; Hopkins et al. 2007), or that it is a function of $\lambda_{\text{Edd}}$ (Vasudevan & Fabian 2007). From a large X-ray selected sample in XMM-COSMOS, Lusso et al. (2012) confirm that $\kappa_{\text{bol}}$ is a function of both $L_{\text{bol}}$ and $\lambda_{\text{Edd}}$. Given the relatively low X-ray luminosities of our sample ($L_X \sim 10^{42}$–$10^{43}$ erg s$^{-1}$) which correspond to bolometric luminosities of $\sim 10^{44}$–$10^{45}$ $L_\odot$, the results from Lusso et al. (2012) show that $\kappa_{\text{bol}} = 10$ would be appropriate for these sources. Thus for our initial investigation we calculate $\lambda_{\text{Edd}}$ in this way.

The uncertainty on $\lambda_{\text{Edd}}$ is propagated from the uncertainty in $M_{\text{BH}}$ and in $L_X$ by adding them in quadrature. For $M_{\text{BH}}$ the uncertainty is typically $\sim$5% or higher. For $L_X$ we assume a systematic 25% uncertainty to account for uncertainties in the flux from spectral modeling and any uncertainty in the distance to the source, which for these nearby galaxies can be non-negligible. We explore the effect of calculating $L_{\text{bol}}$ from a bolometric correction on our results later in the paper, as well as the use of $L_{\text{bol}}$ estimated from multiwavelength data. The properties of our sample are summarized in Table 1.

3. ARE THE HEAVILY OBSCURED MEGAMASERS CONSISTENT WITH UNOBSCURED AGNs?

For our comparison of the $\Gamma$–$\lambda_{\text{Edd}}$ relationship for megamaser AGNs with unobscured AGNs, we use the sample of Brightman et al. (2013) (B13), who studied a sample of 69 unobscured AGNs in the Cosmic Evolution Survey (COSMOS, Scoville et al. 2007) and Extended Chandra Deep Field-South (E-CDF-S, Lehmer et al. 2005) survey up to $z \sim 2$ with black
hole masses measured from optical broad line measurements. B13 fit the X-ray spectra of their sources in the 2–10 keV range with a simple power-law model. We plot the $M_{\rm BH}$ and $L_X$ distributions of the megamaser sample in Figure 1 compared to the sample of B13. This shows that the megamaser sample extends the study of the $\Gamma$–$\lambda_{\text{Edd}}$ relationship to lower black hole masses.

We first test for the significance of a correlation between $\Gamma$ and $\lambda_{\text{Edd}}$ in the megamaser AGNs with a Spearman rank correlation test. This yields $r_S = 0.73$ and $p = 0.007$, where $r_S$ is the Spearman rank correlation coefficient and $p$ is the probability of obtaining the absolute value of $r_S$ at least as high as observed, under the assumption of the null hypothesis of zero correlation. The small value of $p$ indicates a significant correlation as observed in samples of unobscured AGNs.

We present a comparison of the distribution of $\Gamma$ and $\lambda_{\text{Edd}}$ for the megamaser AGNs to the unobscured AGNs in Figure 2. This shows that the two AGN samples occupy the same locus, given the measurement uncertainties, suggesting that they are drawn from the same underlying population. We test this quantitatively by fitting a linear regression to the megamaser AGN data, as done for the unobscured AGNs, and compare the results. So that a direct comparison can be made, we use the IDL function LINFIT as done by B13, which fits the paired data ($\lambda_{\text{Edd}}, \Gamma$) to the linear model, $\Gamma = m \log_{10} \lambda_{\text{Edd}} + c$, by minimizing the $\chi^2$ error statistic. The measurement uncertainties on $\Gamma$ are used to compute the $\chi^2$ statistic (the uncertainty on $\lambda_{\text{Edd}}$ is neglected).

The result from the linear fitting yields $\Gamma = (0.31 \pm 0.07) \log_{10} \lambda_{\text{Edd}} + (2.24 \pm 0.06)$, where $\chi^2 = 59.9$ for 10 degrees of freedom (dof). The same fit to the sample of B13 gave $\Gamma = (0.32 \pm 0.05) \log_{10} \lambda_{\text{Edd}} + (2.27 \pm 0.06)$. Both the slopes and offsets of the linear relationships are in very good agreement.

Other results on unobscured AGNs from Shenmer et al. (2008) (S08) and Risaliti et al. (2009) (R09) found similar values for the slope of the relationship, $0.31 \pm 0.01$ and $0.31 \pm 0.06$, respectively; thus, the results from the megamaser

Table 1

| AGN Name | Redshift | $M_{\text{BH}}/10^6 M_\odot$ | $\log_{10}(L_X/\text{erg s}^{-1})$ | $\Gamma$ | $N_H/10^{24} \text{ cm}^{-2}$ | $\lambda_{\text{Edd}}$ | References |
|----------|----------|----------------|------------------|--------|-----------------|--------|-----------|
| NGC 1068 | 0.0038   | 8.0 ± 0.3    | 43.34            | 2.10 ± 0.07 | 5.0 ± 1.2   | 0.210 ± 0.053 | c, l |
| NGC 1194 | 0.0136   | 65.0 ± 3.0   | 42.78            | 1.59 ± 0.15 | 1.4 ± 0.3   | 0.007 ± 0.002 | f, m |
| NGC 2273 | 0.0061   | 7.5 ± 0.4    | 43.11            | 2.10 ± 0.10 | >7.3         | 0.132 ± 0.034 | f, m |
| NGC 3079 | 0.0037   | 7.4 ± 2.4    | 41.53            | 1.86 ± 0.25 | 1.8 ± 0.32  | 0.011 ± 0.009 | a, j |
| NGC 3393 | 0.0125   | 31.0 ± 2.0   | 43.40            | 1.82 ± 0.09 | 2.2 ± 0.4   | 0.062 ± 0.016 | e, k |
| NGC 4388 | 0.0084   | 8.5 ± 0.2    | 42.59            | 1.65 ± 0.08 | 0.44 ± 0.06 | 0.035 ± 0.009 | f, m |
| NGC 4945 (L) | 0.0019 | 1.4 ± 0.7    | 42.09            | 1.77 ± 0.09 | 3.5 ± 0.2   | 0.068 ± 0.038 | a, i |
| NGC 4945 (M) | 0.0012 | 1.8 ± 0.8    | 42.39            | 1.88 ± 0.05 | 3.0 ± 0.1   | 0.135 ± 0.075 | a, j |
| NGC 4945 (H) | 0.0026 | 1.9 ± 0.5    | 42.62            | 1.95 ± 0.04 | 3.6 ± 0.1   | 0.229 ± 0.128 | h, j |
| NGC 4945 (SH) | 0.0027 | 1.9 ± 0.5    | 42.74            | 1.96 ± 0.07 | 3.5 ± 0.1   | 0.302 ± 0.169 | b, h |
| IC 2560   | 0.0098   | 3.5 ± 0.5    | 42.90            | 2.50 ± 0.20 | >13         | 0.175 ± 0.050 | g, j |
| Circinus  | 0.0014   | 1.7 ± 0.3    | 42.50            | 2.27 ± 0.05 | 8.9 ± 1.2   | 0.143 ± 0.044 | b, h |

Note. Column (1) lists the name of the megamaser AGNs, where four different entries for NGC 4945 are given when it was observed at low (L), medium (M), high (H), and super-high (SH) flux levels (see Puccetti et al. 2014). Column (2) gives the redshift of the source, column (3) lists the black hole mass in units of $10^6 M_\odot$, column (4) gives the logarithm of the intrinsic 2–10 keV luminosity of the AGN determined through spectral modeling, column (5) gives $\Gamma$, column (6) gives the $N_H$ in $10^{24} \text{ cm}^{-2}$, and column (7) shows the Eddington ratio, $\lambda_{\text{Edd}}$ given a bolometric correction of 10 to $L_X$. In column (8), we give the reference for the black hole mass—a. Greenhill et al. (1997), b. Greenhill et al. (2003), c. Lodato & Bertin (2003), d. Kordas et al. (2005), e. Kondratko et al. (2008), f. Kuo et al. (2011), g. Yamauchi et al. (2012), and the X-ray spectral information—h. Arévalo et al. (2014), i. Puccetti et al. (2014), j. Brightman et al. (2015), k. Koss et al. (2015), l. Bauer et al. (2015), and m. Masini et al. (2016).
AGNs are also consistent with these results. As for the offsets, S08 measure 2.11 ± 0.01 and R09 measure 1.97 ± 0.02. However, R09 calculate their linear fit with log_{10}\lambda_{Edd} = -1 as their reference point, rather than 0 as we have done here, which corresponds to c = 2.28 with log_{10}\lambda_{Edd} = 0 as the reference point. Thus the offsets are consistent within ~1–2\sigma.

Other authors have, however, found steeper slopes in the relationship. Jin et al. (2012) find a slope of 0.58 from a sample of unobscured nearby type 1 AGNs, while Keek & Ballantyne (2016) find that the slope is 0.54 when fitting for \Gamma versus \lambda_{Edd} in varying states of Mrk 335. These slopes are similar to that found by R09 for black hole masses based on the Hβ line only (0.58). Some of this disagreement appears to be due to the different statistical analyses used. Jin et al. (2012) suggest that \chi^2 minimization may not be appropriate for quantifying this relation because it can be biased by small measurement errors in \Gamma for individual sources. The \chi^2 normalization also does not take into account uncertainties in \lambda_{Edd} or any intrinsic scatter. Indeed the \chi^2/dof of 59.9/10 that we find from this indicates significant scatter is indeed present.

Kelly (2007) presented a Bayesian method to account for measurement errors in linear regression of astronomical data, LINMIX_ERR, which also takes into account uncertainties in the independent variable and allows for intrinsic dispersion in the regression. Applying this code to our data yields \Gamma = (0.41 ± 0.18)log_{10}\lambda_{Edd} + (2.38 ± 0.20) with an intrinsic scatter of 0.19 ± 0.19. While the slope is steeper compared to the \chi^2 minimization result, the uncertainties are larger due to the inclusion of the \lambda_{Edd} uncertainties. The slopes of the \chi^2 minimization and Bayesian methods are within 1\sigma of each other as well as with the slopes from the unobscured AGNs. This is likewise true of the offset, which is slightly higher with respect to the \chi^2 minimization result, but the larger uncertainty makes it consistent within 2\sigma of all the results on the unobscured AGNs.

We plot the data with the result of the linear fit with the Bayesian method along with the upper and lower 1\sigma confidence bounds in Figure 3. The confidence bounds have been determined from a draw from the posterior distribution of the slope and offset parameters.

3.1. How Does the Calculation of L_{Bol} Affect Our Results?

The largest source of systematic uncertainty in these results come from our estimation of L_{Bol} and consequently \lambda_{Edd}, which we calculate given a bolometric correction, \kappa_{Bol} to the intrinsic 2–10 keV luminosity, L_{X}. Our initial choice of \kappa_{Bol} comes from the relatively low L_X of our sample, for which the results from Lusso et al. (2012) show that \kappa_{Bol} ≈ 10. First, Lusso et al. (2012) find that \kappa_{Bol} is in increasing function of L_{Bol}. In the range of L_X we consider here, the function is relatively flat, which justifies our use of a constant value. However, we check our results using the functional form of \kappa_{Bol} against luminosity presented by Lusso et al. (2012) for type 2 AGNs from their combined spectroscopic and photometric redshift sample. We find no change in the resulting slope and offset in the \Gamma–\lambda_{Edd} relationship from this.

In addition to this, the relationship between \kappa_{Bol} and L_{Bol} has a large intrinsic scatter, with \kappa_{Bol} greater than 100 inferred for the most luminous sources. We therefore examine the effect of different choices of \kappa_{Bol} on our results, testing \kappa_{Bol} = 5, 10, 20, 30 and 50. Table 2 presents the results from this analysis, which shows how the the linear fit to the data \Gamma = mlog_{10}\lambda_{Edd} + c with \chi^2 minimization is affected. As expected, the choice of a constant \kappa_{Bol} does not effect the slope of this relationship since increasing \kappa_{Bol} systematically increases \lambda_{Edd}. The effect of increasing \kappa_{Bol} is to decrease the offset of the relationship from 2.33 ± 0.08 for \kappa_{Bol} = 5 to 2.02 ± 0.02 for \kappa_{Bol} = 50.

We also test the case that \kappa_{Bol} is dependent on \lambda_{Edd}. Vasudevan & Fabian (2007) find a transitional region at \lambda_{Edd} ~ 0.1, below which \kappa_{Bol} = 15–25, and above which it is 40–70. To apply this, we apply an initial \kappa_{Bol} of 20 to the sample. For sources where \lambda_{Edd} > 0.1 results from this, we recalculate L_{Bol} using \kappa_{Bol} = 40. The result of this is to flatten out the linear relationship, such that the slope becomes 0.26 ± 0.05 with the offset more consistent with higher \kappa_{Bol} values (2.05 ± 0.03).

| \kappa_{Bol} | \Gamma | \chi^2 | L_{Bol} |
|---------------|-------|-------|---------|
| 5             | 2.33  | 0.08  | 0.08    |
| 10            | 2.24  | 0.06  | 0.06    |
| 20            | 2.15  | 0.04  | 0.04    |
| 30            | 2.09  | 0.03  | 0.03    |
| 50            | 2.02  | 0.02  | 0.02    |
| 100           | 2.47  | 0.01  | 0.01    |

Note: Results of the fit of \Gamma = mlog_{10}\lambda_{Edd} + c given different values of \kappa_{Bol} where column (1) lists the \kappa_{Bol} used, column (2) lists the slope, m, and column (3) lists the offset, c, both with 1\sigma uncertainties. The last three lines give the results from samples of unobscured AGNs for comparison.

R09 calculate their linear fit with log_{10}\lambda_{Edd} = -1 as their reference point, rather than 0 as we have done here, which corresponds to c = 2.28 with log_{10}\lambda_{Edd} = 0 as the reference point.
Table 3

| AGN Name | $I_{\text{bol}}$ (1) | $\kappa_{\text{bol}}$ (2) | Method (3) | Reference (5) |
|----------|----------------------|-------------------------|------------|--------------|
| NGC 1068 | 45.0                 | 44                      | Flux integration | a             |
| NGC 1194 | 44.7                 | 91                      | MIR        | b             |
| NGC 2273 | 44.0                 | 8.7                     | Flux integration | a             |
| NGC 3079 | 43.6                 | 120                     | MIR        | b             |
| NGC 3393 | 44.9                 | 33                      | [Ne V]     | c             |
| NGC 4388 | 43.4                 | 5.9                     | MIR        | d             |
| Circinus | 43.6                 | 13                      | MIR        | e             |

Note. Column (1) lists the AGN name for which a bolometric luminosity could be found in the literature, column (2) lists the logarithm of $L_{\text{bol}}$ in erg s$^{-1}$, column (3) lists the corresponding $\kappa_{\text{bol}}$, column (4) lists the method used for estimating $L_{\text{bol}}$ and column (5) gives the reference, where a—Woo & Urry (2002), b—Gruppioni et al. (2016), c—Koss et al. (2015), d—Ramos Almeida et al. (2011), e—Moorwood et al. (1996).

Finally, we investigate other sources of bolometric luminosity that are independent of the X-ray measurements. These usually come from fitting spectral energy distributions of the AGNs from optical to mid-infrared wavelengths. Table 3 lists these, along with the corresponding $\kappa_{\text{bol}}$ for the given $L_X$ of the AGNs. No independent $L_{\text{bol}}$ measurement could be found for NGC 4945 or IC 2560. First this shows that $\kappa_{\text{bol}}$ for our sample shows a large spread of ~6–120, with a median value of 33, an average of 45 and a standard deviation of 44. Although the sample is small, this appears systematically higher than the results from Lusso et al. (2012). If indeed $\kappa_{\text{bol}}$ is dependent on $\lambda_{\text{edd}}$, a systematically higher $\kappa_{\text{bol}}$ for these CTAGNs may imply a systematically higher $\lambda_{\text{edd}}$ given the same $L_X$ for unobscured AGNs. Alternatively, the mid infrared from which the $L_{\text{bol}}$ values have been estimated may include contributions from star-formation that have not been underestimated in the SED fitting. Indeed, NGC 3079, which stands out in our sample with $\kappa_{\text{bol}} = 120$, has a known nuclear starburst.

When using these values of $L_{\text{bol}}$ instead of $L_{\text{bol}}$ derived from $L_X$ (and retaining the values from $L_X$ for NGC 4945 and IC 2560), we obtain $\Gamma = (0.28 \pm 0.06) \log_{10} \lambda_{\text{edd}} + (2.18 \pm 0.05)$ from $\chi^2$ minimization and $\Gamma = (0.31 \pm 0.20) \log_{10} \lambda_{\text{edd}} + (2.21 \pm 0.19)$ (intrinsic scatter of 0.24 ± 0.24) from the Bayesian method. Despite the large spread in $\kappa_{\text{bol}}$ and it being apparent systematically higher than the value of 10 that we use, the slope of the relationship is within 1σ of the $\kappa_{\text{bol}} = 10$ result, and the results from unobscured AGNs.

3.2. How Does the X-Ray Spectral Modeling Affect Our Results?

Our results on $\Gamma$ and $\lambda_{\text{edd}}$ for the heavily obscured megamasers are also dependent on the X-ray torus model used to model the spectrum. As described above, for our analysis we have compiled results from both mytorus and torus. For most sources, the authors fitted both models and presented the best fitting case. We test to what extent this choice may have affected our results by compiling the results from mytorus only, since this model was more commonly used. When using mytorus, however, two sources produced ambiguous results. For NGC 2273 the model produced two degenerate results, one where $\Gamma > 2.44$ and one where $\Gamma < 1.4$ (A. Masini 2016, private communication). Since there is ambiguity we do not include this source in our analysis with mytorus. For IC 2560, mytorus reaches the upper limit in both $\Gamma$ (2.5) and $N_{\text{H}} (10^{22}$ cm$^{-2}$). Since the torus model indicates that $N_{\text{H}} > 10^{26}$ cm$^{-2}$ in this source, beyond the range of mytorus, the result from mytorus may not be reliable and thus we also do not include this source in our analysis with mytorus. This is in agreement with Baloković et al. (2014) where more detailed spectral modeling of this source is presented. Given then the 11 remaining data points, we carry out the same analysis as above, with $\log_{10} \lambda_{\text{edd}} = 10$ yielding $\Gamma = (0.31 \pm 0.07)$ log$_{10} \lambda_{\text{edd}} + (2.35 \pm 0.06)$ from $\chi^2$ minimization and $\Gamma = (0.36 \pm 0.21) \log_{10} \lambda_{\text{edd}} + (2.31 \pm 0.25)$ (intrinsic scatter of 0.27 ± 0.26) from the Bayesian method. While the slope of this relationship is slightly steeper than for the mixed sample, it is statistically consistent within the uncertainties, as is the offset, indicating the the choice of torus model does not affect our result significantly.

Lastly, we discuss the two sources that we excluded from our analysis, NGC 1386 and NGC 2960. As with NGC 2273, fits with mytorus to NGC 1386 yielded two degenerate solutions, one with a low $\Gamma$ and one with a high $\Gamma$ (Masini et al. 2016). With the torus model, Brightman et al. (2015) found $\Gamma = 2.9 \pm 0.4$, which is very high for any value of $\lambda_{\text{edd}}$. Similarly, the torus model yields $\Gamma = 2.6 \pm 0.4$ for NGC 2960 (Masini et al. 2016) fix $\Gamma$ in their fit with mytorus). It is not clear whether these very high values of $\Gamma$ are related to the low-count nature of their spectra, or if they represent true outliers in the $\Gamma$–$\lambda_{\text{edd}}$ relationship for the megamasers. Only longer exposures with NuSTAR will solve this question. We estimate that around ~2000 counts at minimum in NuSTAR FPMA and FPMB are required for an accurate determination of $\Gamma$ in CTAGNs, where NGC 1386 and NGC 2960 have less than 1000.

4. DISCUSSION AND CONCLUSIONS

From the above analysis, albeit with a small sample, we conclude that the low-mass, heavily obscured megamaser AGNs are statistically consistent with the higher mass, unobscured AGNs through the $\Gamma$–$\lambda_{\text{edd}}$ relationship, where NGC 1386 and IC 2560 have less than 1000. For NGC 1386 or IC 2560. First this shows that $\Gamma$–$\lambda_{\text{edd}}$ reaches the upper limit in both $\Gamma$ (2.5) and $N_{\text{H}} (10^{22}$ cm$^{-2}$). Since the torus model indicates that $N_{\text{H}} > 10^{26}$ cm$^{-2}$ in this source, beyond the range of mytorus, the result from mytorus may not be reliable and thus we also do not include this source in our analysis with mytorus. This is in agreement with Baloković et al. (2014) where more detailed spectral modeling of this source is presented. Given then the 11 remaining data points, we carry out the same analysis as above, with $\log_{10} \lambda_{\text{edd}} = 10$ yielding $\Gamma = (0.31 \pm 0.07)$ log$_{10} \lambda_{\text{edd}} + (2.35 \pm 0.06)$ from $\chi^2$ minimization and $\Gamma = (0.36 \pm 0.21) \log_{10} \lambda_{\text{edd}} + (2.31 \pm 0.25)$ (intrinsic scatter of 0.27 ± 0.26) from the Bayesian method. While the slope of this relationship is slightly steeper than for the mixed sample, it is statistically consistent within the uncertainties, as is the offset, indicating the the choice of torus model does not affect our result significantly.

Lastly, we discuss the two sources that we excluded from our analysis, NGC 1386 and NGC 2960. As with NGC 2273, fits with mytorus to NGC 1386 yielded two degenerate solutio
(Kamizasa et al. 2012; Ho & Kim 2016) do not find a significant correlation between Λ and λ_{Edd}. However these results cover a smaller range in λ_{Edd} (~1 order of magnitude) and with larger uncertainties on their black hole mass estimates, which may be the reason they did not detect the correlation.

Third, since the megamaser AGNs are edge-on systems, our results imply the lack of strong orientation effects when viewing the corona, which is assumed to be viewed more face-on in the unobscured AGNs. This gives broad support to the AGN unification scheme (Antonucci 1993; Urry & Padovani 1995) and theoretical modeling of the AGN disk-corona system that predicts that the spectral shape in the X-ray band is insensitive to the viewing angle.

Furthermore, this research has made use of the NASA NuSTAR National Aeronautics and Space Administration. We thank the NuSTAR mission, a project led by the California Institute of Technology, NNG08FD60C, and made use of data from the NED. A.M. and A.C. acknowledge support from NASA Headquarters under the NASA Earth and Space Science Fellowship Program, grant NNX14AQ07H.

**REFERENCES**

Ai, Y. L., Yuan, W., Zhou, H. Y., Wang, T. G., & Zhang, S. H. 2011, ApJ, 727, 31

Annuar, A., Gandhi, P., Alexander, D. M., et al. 2015, ApJ, 815, 36

Antonucci, R. 1993, ARA&A, 31, 473

Arévalo, P., Bauer, F. E., Puccetti, S., et al. 2014, ApJ, 791, 81

Baloković, M., Comastri, A., Harrison, F. A., et al. 2014, ApJ, 794, 111

Bauer, F. E., Arévalo, P., Walton, D. J., et al. 2015, ApJ, 812, 116

Brightman, M., Baloković, M., Stern, D., et al. 2015, ApJ, 805, 41

Brightman, M. & Nandra, K. 2011, MNRAS, 413, 1526

Brightman, M., Silverman, J. D., Mainieri, V., et al. 2013, MNRAS, 433, 2485

Fabian, A. C., Lohfink, A., Kara, E., et al. 2015, MNRAS, 451, 4375

Furui, S., Fukazawa, Y., Odaka, H., et al. 2016, ApJ, 818, 164

Gandhi, P., Lansbury, G. B., Alexander, D. M., et al. 2014, ApJ, 792, 117

Greene, J. E., Peng, C. Y., Kim, M., et al. 2010, ApJ, 721, 26

Greenhill, L. J., Giovonnii, C. R., Antonucci, R., & Barvains, R. 1996, ApJL, 472, L21

Greenhill, L. J., Konradtko, P. T., Lovell, J. E. J., et al. 2003, ApJL, 582, L11

Greenhill, L. J., Moran, J. M., & Hernstein, J. R. 1997, ApJL, 481, L23

Grupponi, C., Berta, S., Spinoglio, L., et al. 2016, MNRAS, 458, 4297

Haardt, F., & Maraschi, L. 1993, ApJ, 413, 507

Harrison, F., Church, W. C., Christensen, F. E., Hailey, C. I., & Zhang, W. 2013, ApJ, 770, 103

Heil, L. M., Uttley, P., & Klein-Wolt, M. 2015, MNRAS, 448, 3348

Ho, L. C., & Kim, M. 2016, ApJ, 821, 48

Hopkins, P. F., Richards, G. T., & Hernquist, L. 2007, ApJ, 654, 731

Jin, C., Ward, M., & Done, C. 2012, MNRAS, 425, 907

Kamizasa, N., Terashima, M., & Awaki, H. 2012, ApJ, 751, 39

Keek, L., & Ballantyne, D. R. 2016, MNRAS, 456, 2722

Kelly, B. C. 2007, ApJ, 665, 1489

Kondratko, P. T., Greenhill, L. J., & Moran, J. M. 2005, ApJ, 618, 618

Kondratko, P. T., Greenhill, L. J., & Moran, J. M. 2008, ApJ, 678, 87

Koss, M. J., Romero-Calzicules, C., Baronchelli, L., et al. 2015, ApJ, 807, 149

Kuo, C. Y., Braatz, J. A., Condon, J. J., et al. 2011, ApJ, 727, 20

Lanzuisi, G., Perna, M., Comastri, A., et al. 2016, arXiv:1604.02462

Läsker, R., Greene, J. E., Seth, A., et al. 2016, arXiv:1602.06960

Lawrence, A., & Elvis, M. 2010, ApJ, 714, 561

Lehmer, B. D., Brandt, W. N., Alexander, D. M., et al. 2005, ApJS, 161, 21

Luo, Y., & Li, X. 2014, ApJ, 787, 72

Lo, K. Y. 2005, ARA&A, 43, 625

Lodato, G., & Bertini, G. 2003, A&A, 398, 517

Lusso, E., Comastri, A., Simmons, B. D., et al. 2012, MNRAS, 425, 623

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

Marinucci, A., Bianchi, S., Matt, G., et al. 2016, MNRAS, 456, L94

Masini, A., Comastri, A., Baloković, M., et al. 2016, A&A, 589, A59

Merloni, A., Predehl, P., Becker, W., et al. 2012, arXiv:1209.3114

Murowood, A. F. M., Lutz, D., Oliwa, E., et al. 1996, A&A, 315, L109

Murphy, K. D., & Yaqoob, T. 2009, MNRAS, 397, 1549

Nandra, K., Barret, D., Barcons, X., et al. 2013, arXiv:1306.2307

Peterman, B. M. 2014, SSRv, 183, 253

Puccetti, S., Comastri, A., Bauer, F. E., et al. 2016, A&A, 585, A157

Puccetti, S., Comastri, A., Fiore, F., et al. 2014, ApJ, 793, 26

Ramos Almeida, C., Levenson, N. A., Alonso-Herrero, A., et al. 2011, ApJ, 731, 92

Ricci, C., Bauer, F. E., Treister, E., et al. 2016, ApJ, 819, 4

Risaliti, G., Salvati, M., Elvis, M., et al. 2009, MNRAS, 393, L1

Rivers, E., Baloković, M., Arévalo, P., et al. 2015, ApJ, 815, 55

Rybicki, G. B., & Lightman, A. P. 1986, in Radiative Processes in Astronomy, ed. B. R. George & P. L. Alan (New York: Wiley), 400

Scoville, N., Aussel, H., Brusa, M., et al. 2007, ApJS, 172, 1

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shemmer, O., Brandt, W. N., Netzer, H., Maiolino, R., & Kaspi, S. 2006, ApJ, 646, L29

Shemmer, O., Brandt, W. N., Netzer, H., Maiolino, R., & Kaspi, S. 2008, ApJ, 682, 81

Shen, Y. 2013, BASI, 41, 61

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

Vasudevan, R. V., & Fabian, A. C. 2007, MNRAS, 381, 1235

Woo, J.-H., & Urry, C. M. 2002, ApJ, 579, 530

Xu, Y.-D. 2015, MNRAS, 449, 191

Yamauchi, A., Nakai, N., Ishihara, Y., Diamond, P., & Sato, N. 2012, PASJ, 64, 103

Yang, Q.-X., Xie, F.-G., Yuan, F., et al. 2015, MNRAS, 447, 1692

You, B., Cao, X., & Yuan, Y.-F. 2012, ApJ, 761, 109

Zhang, J. S., Henkel, C., Kadler, M., et al. 2006, A&A, 450, 933

**Facility:** NuSTAR.