THE LINK BETWEEN THE HIDDEN BROAD LINE REGION AND THE ACCRETION RATE IN SEYFERT 2 GALAXIES

ANDREA MARINUCCI 1,2, STEFANO BIANCHI 1,3,4, FABRIZIO NICASTRO 2,4,5, GIORGIO MATT 1, AND ANDY D. GOULDING 2

1 Dipartimento di Fisica, Università degli Studi Roma Tre, via della Vasca Navale 84, I-00146 Roma, Italy
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138, USA
3 INAF - Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807, Merate, Italy
4 IESL, Foundation for Research and Technology, 711 10, Heraklion, Crete, Greece
5 Osservatorio Astronomico di Roma (INAF), Via Frascati 33, I-00040 Monte Porzio Catone, Italy

Received 2011 August 22; accepted 2012 January 25; published 2012 March 15

ABSTRACT

In the past few years, more and more pieces of evidence have been presented for a revision of the widely accepted unification model of active galactic nuclei. A model based solely on orientation cannot explain all the observed phenomenology. In the following, we will present evidence that accretion rate is also a key parameter for the presence of hidden broad line regions (HBLRs) in Seyfert 2 galaxies. Our sample consists of 21 sources with polarized hidden broad lines and 18 sources without hidden broad lines. We use stellar velocity dispersions from several studies on the Ca II and Mg b triplets in Seyfert 2 galaxies to estimate the mass of the central black hole via the $M_{\text{BH}}-\sigma_*$ relation. The ratio between the bolometric luminosity, derived from the intrinsic (i.e., unabsorbed) X-ray luminosity, and the Eddington luminosity is a measure of the rate at which matter accretes onto the central supermassive black hole. A separation between Compton-thin HBLR and non-HBLR sources is clear, both in accretion rate (log $L_{\text{bol}}/L_{\text{Edd}} = -1.9$) and in luminosity (log $L_{\text{bol}} = 43.90$). When properly luminosity-corrected Compton-thick sources are included, the separation between HBLR and non-HBLR is less sharp but no HBLR source falls below the Eddington ratio threshold. We speculate that non-HBLR Compton-thick sources with accretion rate higher than the threshold do possess a BLR, but something, probably related to their heavy absorption, is preventing us from observing it even in polarized light. Our results for Compton-thin sources support theoretical expectations. In a model presented by Nicastro, the presence of broad emission lines is intrinsically connected with disk instabilities occurring in proximity of a transition radius, which is a function of the accretion rate, becoming smaller than the innermost stable orbit for very low accretion rates and therefore luminosities.

Key words: galaxies: active – galaxies: Seyfert

Online-only material: color figures

1. INTRODUCTION

The widely accepted unification model for active galactic nuclei (AGNs) invokes the same paradigm for Seyfert 2 and Seyfert 1 galaxies (Antonucci 1993). The two different types of galaxies are believed to be intrinsically the same but differ, observationally, due only to orientation: Seyfert 1 galaxies are observed at large accretion disk-line of sight angles (face-on) while Seyfert 2 galaxies are seen edge-on through large column densities of obscuring material in the accretion disk plane, which prevent the direct view of the nuclear regions of these sources. This scenario came into existence after the discovery of polarized broad permitted emission lines in one of the brightest Seyfert 2 galaxies, NGC 1068 (Antonucci & Miller 1985; Miller & Antonucci 1983), suggesting a geometry in which: (1) BLRs are confined in a relatively small region (~light-days) surrounding the central source, (2) their direct view (in Seyfert 2s) is obscured by a flat distribution of distant material coplanar with the disk-plane, and (3) their line emission is Compton-scattered into the line-of-sight direction off a population of hot electrons extending at large radii above and below the accretion disk.

In the past few years, exceptions to orientation-based unification models have been found, suggesting the possibility that not all Seyfert 2 galaxies host a Seyfert 1 nucleus. Indeed, spectropolarimetric surveys find that only about the 50% of the brightest Seyfert 2 galaxies show hidden broad-line regions (HBLRs) in their optical-polarimetric spectra (Tran 2001, 2003). Several authors have suggested that the presence of BLRs in Seyfert 2s can be linked to the luminosity of the active nucleus, and may disappear at low luminosities (Lumsden & Alexander 2001; Tran 2001, 2003; Gu & Huang 2002; Martocchia & Matt 2002; Laor 2003; Elitzur & Ho 2009) or low accretion rates (Nicastro 2000; Nicastro et al. 2003; Czerny et al. 2004). In both cases, the presence of the BLR is not an inescapable feature of all Seyfert galaxies, as postulated by the unification model, but it is tightly linked to a physical parameter of the AGN, either the luminosity or the accretion rate. However, recent works cast doubts on these conclusions (e.g., Bian & Gu 2007). In these works large, but inhomogeneous, samples were used to identify a physical parameter responsible for the existence or absence of HBLR in AGNs, but no clear indication for the existence of such a parameter was found. We think that this is largely due to the use of the [O iii] luminosities as a proxy of the nuclear activity of the AGN, and the difficulty in correcting this for extinction in obscured objects. It has been shown by several authors, by comparing AGN luminosities derived from [O iii] and [O iv] emission line luminosities, that the observed [O iii] luminosities often suffer significant attenuation in typical Seyfert 2 galaxies (e.g., Haas et al. 2005; Meléndez et al. 2008; Diamond-Stanic et al. 2009; Goulding & Alexander 2009; Baum et al. 2010; Kraemer et al. 2011) and that the efforts to use standard extinction correction for [O iii] are not always reliable (e.g., Goulding & Alexander 2009; LaMassa et al. 2010). [O iv] emission line luminosities might therefore be more reliable than [O iii] luminosities, as tracers of the intrinsic nuclear emission. However, they are still an indirect proxy of...
the nuclear continuum emission. In this paper, instead, we use the observed X-ray (2–10 keV) continuum emission as a direct probe of the AGN activity. We selected a sample of type 2 AGNs with good quality spectropolarimetric and X-ray observations, for which we can give a good estimate of the mass of the central supermassive black hole (BH).\(^6\) By doing so, we find evidence suggesting that accretion rate is the main parameter that sets the existence of HBLRs in Seyfert 2 galaxies.

2. THE SAMPLE

Our starting sample is mostly based on the spectropolarimetric surveys performed by Tran (1995, 2001, 2003) on the Seyfert 2 galaxies included in the CfA (Huchra & Burg 1992) and 12 μm (Rush et al. 1993) samples. Additionally, we included objects from other high-quality spectropolarimetric studies (Tran et al. 1992; Young et al. 1996; Moran et al. 2000; Lumsden & Alexander 2001). From this sample, consisting of 90 candidates, we selected only sources with available mass (Section 2.1) and bolometric luminosity (Section 2.2) estimates, and so for which their accretion rate can be evaluated. For each source, we evaluate their accretion rate in units of Eddington, as the ratio \(L_{\text{bol}} / L_{\text{Edd}}\) (hereafter \(\lambda_{\text{Edd}}\)), where

\[
L_{\text{Edd}} = 1.2 \times 10^{38} \left( \frac{M_{\text{BH}}}{M_\odot} \right) \text{ erg s}^{-1}.
\]

\[1\]

2.1. The BH Mass Sub-selection

In this work, BH masses are homogeneously derived for the entire sample by using uniquely the \(M_{\text{BH}} - \sigma_*\) relation (Tremaine et al. 2002):

\[
M_{\text{BH}} = 1.35 \times 10^8 \left( \frac{\sigma_*}{200 \text{ km s}^{-1}} \right)^{4.02} \text{ M}_\odot.
\]

\[2\]

 Stellar velocity dispersions (\(\sigma_*\)) were mainly taken from Nelson & Whittle (1995) and Garcia-Rissmann et al. (2005). These estimates are all based on direct measurements of Ca ii (8498 Å, 8542 Å, and 8662 Å) and Mg ii 3p → 4s (5167 Å, 5172 Å, and 5183 Å, hereafter Mg b) triplet absorption, imprinted by the interstellar medium of Seyfert 2 galaxies. For sources with more than one measurement, we used that with smaller error bars. Uncertainties on the BH mass estimates based on the \(M_{\text{BH}} - \sigma_*\) relation, come from the statistical errors on the \(\sigma_*\) measurements (listed in Table 1) as well as from the spread in the \(M_{\text{BH}} - \sigma_*\) relation itself, estimated to be 0.44 dex (Gültekin et al. 2009). This spread is generally much larger than the statistical error on \(\sigma_*\). We therefore assumed an uncertainty of 0.44 dex for all our BH mass estimates. Stellar velocity dispersions and their associated uncertainties, as well as BH masses, are listed in Table 1 (columns (d) and (e), respectively).

The \(\sigma_*\) selection reduced the original spectropolarimetric sample to 46 sources with direct \(\sigma_*\) measurements.

2.2. The X-Ray Sub-selection and the Final Sample

To estimate the bolometric luminosity of the sources of our sample, we use the 2–10 keV luminosity, which is a direct tracer of the primary emission, and apply a bolometric correction. We searched the XMM-Newton, Chandra, Suzaku (the front-illuminated CCDs have the largest area at high energies), and Swift archives for observations of the sources of our sample of 46 objects with accurate BH-mass estimate. When multiple observations of a single target were available, we selected that with the highest signal-to-noise ratio (S/N) in the 2–10 keV band. For all sources of our final sample, a minimum of 150 counts in the 2–10 keV band was required, to derive reliable estimates of the column density and, therefore, intrinsic X-ray luminosity. These criteria reduced the final sample to a total of 39 sources: 21 with polarized HBLRs and 18 sources without non-HBLRs. These are listed in Table 1, together with the selected X-ray observations.

3. DATA ANALYSIS

3.1. X-Ray Data Reduction and Analysis

Suzaku X-ray Imaging Spectrometer (XIS) data were processed with the latest calibration files available at the time of the analysis (2011 February 10 release) by using FTOOLS 16 and SUZAKU software Version 2.3 and adopting standard filtering procedures. Response matrices and ancillary response files were generated using XISRMFGEN and XISSIMARFGEN. The 0.5–10 keV spectra extracted from the front-illuminated XIS0 and XIS3 have been co-added via the tool ADDASCASPEC.

We used only XMM-Newton observations performed with the EPIC-Pn camera (Strüder et al. 2001) operated in large window and medium filter modes. Source data “cleaning” (exclusion of flaring particle background intervals) and spectra extraction, were performed with SAS 10.0.0 (Gabriel et al. 2004) via an iterative process which leads to a maximization of the S/N, similarly to that described in Piconcelli et al. (2004). For each source, background spectra were extracted from source-free circular regions of the source field.

Finally, Chandra data were reduced with the Chandra Interactive Analysis of Observations (CIAO; Fruscione et al. 2006) 4.3 and the Chandra Calibration Data Base (CALDB) 4.4.1 software, by adopting standard procedures.

All the spectra with a high S/N were binned in order to oversample the instrumental resolution by at least a factor of three and to have no less than 30 counts in each background-subtracted spectral channel. This allows the applicability of the \(\chi^2\) statistics. The adopted cosmological parameters are \(h_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_M = 0.73\), and \(\Omega_{\Lambda} = 0.27\). Errors are quoted at a confidence level of 90% for one interesting parameter (\(\Delta \chi^2 = 2.7\)), if not otherwise stated. The spectral analysis was performed with the package xspec 12.7.0 (Arnaud 1996).

For all sources of our sample, we fit their 2–10 keV spectra with a general baseline model, consisting of a power-law continuum attenuated by the line-of-sight column of Galactic absorption plus intrinsic absorption at the source redshift, plus three additional emission components: (1) a photoionized plasma emitter, to model the soft excess often detected in Seyfert 2s at \(E \lesssim 2\) keV, (2) a cold Compton Reflector, scattering the primary nuclear photons off the inner walls of cold circumnuclear material and along the line of sight, and (3) positive Gaussian profiles, to model fluorescence emission lines of high-Z elements such as Fe at 6.4 keV, as required by the data. The model can be parameterized as

\[
F(E) = e^{-\sigma(E)N_{H}^{\odot}} \left[ P h_c + e^{-\sigma(E)N_{H}^{\odot}} B E^{-\Gamma} + R(\Gamma) + \sum_i G_i(E) \right],
\]

\[3\]
column density (Dickey & Lockman 1990); $\Phi_{HC}$ is the photonized plasma emission (see Bianchi et al. 2010 for details on the adopted CLOUDY model); $N_{\text{HI}}$ is the neutral absorbing column density at the redshift of the source; $B$ is the normalization of the primary power law with slope $\Gamma$; $R(\Gamma)$ is the Compton-reflection component (modeled in XSPEC with PEXRAV; Magdziarz & Zdziarski 1995); and $G_1(E)$ are the required Gaussian profiles.

### Table 1

| Object Name   | ObsID             | C-thin  | $\sigma_v$ (km s$^{-1}$) | $\log (M_{\text{BH}}/M_\odot)$ | $N_{\text{HI}}$ | $\log (L_{\text{2-10 keV}})$ | $\log (L_{\text{Edd}})$ | $\log (L_{\text{Edd}}/L_\text{Edd})$ | $\log (L_{\text{1400}})$ | $\log (L_{\text{100}})$ | References |
|---------------|-------------------|---------|--------------------------|-------------------------------|----------------|-----------------------------|-------------------------|-----------------------------------|------------------------|----------------------|-------------|
| CIRCINUS PN-0111240101 | X | 75 ± 5 | 6.42 | 430$^{+40}_{-30}$ | 42.62 | 43.76 | −0.75 | 40.92 | 40.58 | 1, 13 |           |
| IC 3639 XIS-702011010 | X | 99 ± 5 | 6.90 | >150 | 42.64 | 43.80 | −1.20 | 41.89 | 40.66 | 1.8 |           |
| IC 5063 XIS-704010010 | ✓ | 160 ± 25 | 7.4 | 25$^{+2}_{-1}$ | 42.83 | 44.03 | −1.81 | 41.56 | 41.40 | 2.8 |           |
| IRAS01475-0740 PN-0200431101 | X | 108 ± 17 | 7.05 | >200 | 43.52 | 44.90 | −0.25 | 41.76 | 40.74 | 1.8 |           |
| MCG-2-8-39 PN-0301150201 | ✓ | 126 ± 11 | 7.32 | 44$^{+2}_{-2}$ | 42.57 | 43.70 | −1.72 | 41.16 | 41.07 | 1.8 |           |
| Mk 3 XIS-100004010 | X | 249 ± 4 | 8.51 | 140$^{+8}_{-12}$ | 44.44 | 46.10 | −0.51 | 43.27 | 43.97 | 1.10 | 1, 10 |
| Mk 38 PNGS-0067540201 | ✓ | 117 ± 18 | 7.19 | 15$^{+2}_{-1}$ | 43.41 | 44.77 | −0.52 | 41.96 | 40.95 | 2.8 |           |
| Mk 1200 PNGS-0002940701 | ✓ | 82 ± 16 | 6.57 | 22$^{+6}_{-5}$ | 43.02 | 44.24 | −0.43 | 42.37 | ... | 1.9 |           |
| NGC 513 PN-0301150401 | ✓ | 150 ± 25 | 7.63 | 7$^{+2}_{-2}$ | 42.72 | 43.93 | −1.80 | 41.14 | 40.74 | 2.8 |           |
| NGC 591 PNGS-0200431001 | X | 107 ± 18 | 7.04 | >160 | 43.02 | 44.27 | −0.87 | 41.97 | ... | 2.10 |           |
| NGC 788 XIS-703032010 | ✓ | 140 ± 20 | 7.51 | 85$^{+7}_{-5}$ | 43.15 | 44.43 | −1.18 | 40.73 | 40.97 | 2.10 |           |
| NGC 1608 PN-0111200201 | ✓ | 147 ± 3 | 7.59 | >1000 | 43.02 | 44.27 | −1.42 | 42.38 | 41.81 | 1.8 |           |
| NGC 2273 XIS-702003010 | X | 136 ± 22 | 7.46 | 120$^{+110}_{-46}$ | 42.73 | 43.90 | −1.65 | 41.13 | 40.07 | 2.10 |           |
| NGC 3081 PNGS-0301130101 | ✓ | 113 ± 4 | 7.13 | 89$^{+13}_{-15}$ | 42.50 | 43.61 | −1.62 | 41.43 | 40.19 | 1.10 |           |
| NGC 4388 XIS-7000170101 | ✓ | 119 | 7.22 | 31$^{+2}_{-1}$ | 42.90 | 44.12 | −1.20 | 41.85 | 41.58 | 3.8 |           |
| NGC 4507 PNGS-702048010 | ✓ | 152 ± 4 | 7.65 | 87$^{+7}_{-5}$ | 43.11 | 44.39 | −1.36 | 42.19 | 41.02 | 1.10 |           |
| NGC 5252 PNG-0152940101 | ✓ | 190 ± 27 | 8.04 | 2.2$^{0.1}_{-0.1}$ | 43.04 | 44.30 | −1.84 | 42.05 | ... | 2.11 |           |
| NGC 5506 PNG-0554170101 | ✓ | 180 | 7.95 | 3.0$^{0.1}_{-0.1}$ | 43.05 | 44.30 | −1.75 | 41.45 | 41.28 | 4.8 |           |
| NGC 7212 PNG-0200430201 | X | 140 ± 9 | 7.51 | >150 | 43.77 | 45.22 | −0.38 | 42.73 | ... | 1.13 |           |
| NGC 7674 PNG-0206600101 | ✓ | 144 ± 32 | 7.56 | >100 | 43.96 | 45.47 | −0.18 | 45.27 | 41.97 | 2.8 |           |
| NGC 7682 PN-0301150501 | X | 123 ± 17 | 7.28 | >100 | 43.02 | 44.27 | −1.11 | 41.76 | 41.01 | 2.8 |           |

### Notes
- X-ray and bolometric luminosities are already corrected for a factor 70 for all Compton-thick sources. Columns: (a) name of the object; (b) instrument (AS: Chandra ACIS-S; PN: XMM-Newton EPIC pn; XIS: Suzaku XIS0+3) and obsid; (c) ✓ if Compton-thin, X if Compton-thick; (d) stellar velocity dispersions; (e) mass of the central BH in solar mass units; (f) absorbing column density in $10^{22}$ cm$^{-2}$ units; (g) absorption corrected 2–10 keV luminosity; (h) Bolometric luminosity; (i) accretion rate in Eddington units; (j) extinction-corrected O iii $\lambda 5007$ luminosity; (k) O iv $\lambda 1548$ luminosity; (l) reference for stellar velocity dispersions, HBLR (in this order).

### References
1. Garcia-Rissmann et al. 2005; 2. Nelson & Whittle 1995; 3. Terlevich et al. 1990; 4. Oliva et al. 1999; 5. Barth et al. 2002; 6. Shaw et al. 1993; 7. McElroy 1995; 8. Tran 2003; 9. Tran 1995; 10. Moran et al. 2000; 11. Young et al. 1996; 12. Lumsden & Alexander 2001; 13. Other surveys.
Our adopted models do not aim at obtaining the “best fit” for each source, but only a reliable estimate of the observed 2–10 keV luminosity (Table 1, column (g)). A more detailed description of the results of the fits, in particular for the photoionization CLOUDY component, is deferred to a future work.

3.2. Nuclear 2–10 keV Luminosity for Compton-thick Sources

Compton-thick sources are defined as sources for which the intrinsic column of absorbing gas, N_H, is greater than \( \lesssim 10^{23} \text{ cm}^{-2} \), thus preventing us from directly observing the primary power law below 10 keV. The 2–10 keV spectra of Compton-thick sources are therefore generally adequately modeled by a pure-reflection component (i.e., reflection-dominated Seyfert 2s), which can only provide a measurement of the reflected, and not the nuclear, luminosity.

Several tracers can be used to estimate the bolometric luminosity of Compton-thick objects, e.g., [O iii] (Lamastra et al. 2009) and [O iv] (Rigby et al. 2009). For homogeneity with the Compton-thin sources of our sample, here we use the observed X-ray luminosity by applying the following procedure.

We compare the extinction-corrected [O iii] luminosities of the sources of our sample (Table 1, column (j), taken from Wu 2009) and [O iv] (Rigby et al. 2009). For homogeneity with the Compton-thin sources of our sample, here we use the observed X-ray luminosity by applying the following procedure.

We decided to adopt this correction for all Compton-thin sources of our sample. For each source of our sample, we used their intrinsic Balmer decrement (H\(_\alpha\)/H\(_\beta\))=3 is adopted. The results are shown in Figure 1, top panel. All the Compton-thick sources have an \( L_{\alpha}/L_{[O\,iii]} \) ratio smaller than the best fitting relation found by Lamastra et al. (2009) for a large sample of Compton-thin Seyfert 2s (solid line in Figure 1: compare with the dotted line in the same figure, which best-fits the subsample of Compton-thin sources of our sample). For the Compton-thick sources of our sample, we find a mean value of \( \log (L_{\alpha}/L_{[O\,iii]})=0.76\pm0.09 \). For the Compton-thick sources of their sample, instead, Lamastra et al. (2009) found a mean \( \log (L_{\alpha}/L_{[O\,iii]})=1.09 \). The ratio between these two means can be used as an estimate of the correction factor needed to infer the nuclear 2–10 keV luminosity of Compton-thick sources, from their observed 2–10 keV luminosity: \( 10^{0.09-(0.76)} \approx 70 \). The bottom panel of Figure 1 shows the \( L_{\alpha}-L_{[O\,iii]} \) plane for all the sources of our sample, after applying a correction factor of 70 to the observed 2–10 keV luminosity of all Compton-thick sources. Now all the sources of our sample lie on the Lamastra et al. (2009) relation for Compton-thin sources.

We decided to adopt this correction for all Compton-thin sources, also for those where \( E > 10 \) keV data were available (\textit{Suzaku} PIN) and so a direct estimate of the nuclear continuum above 10 keV could in principle be attempted. This is because Compton scattering at high column densities may significantly suppress the observed intrinsic luminosity even at \( E > 10 \) keV, and the modelization of these effects are highly dependent on the (unknown) geometry of the absorber (e.g., Matt et al. 1999). In the cases where objects presented observations in both Compton-thin and Compton-thick states in the past few years, we chose the former, to infer the unabsorbed luminosity of the source with a higher precision. In one case (IRAS01475-0740), the 2–10 keV source spectrum is ambiguous: following the detailed analysis presented in Brightman & Nandra (2008) we classify this object as Compton-thick.

3.3. Bolometric Luminosities and Eddington Ratios

For each source of our sample, we used their intrinsic 2–10 keV luminosity (observed, for Compton-thin sources, or inferred, for Compton-thick sources, see previous section) to derive their bolometric luminosity, and thus Eddington ratio (Table 1, columns (h) and (i)), by adopting the luminosity-dependent relation presented in Marconi et al. (2004). We tested the importance of this assumption in our calculations by trying different bolometric corrections (e.g., Elvis et al. 1994; Vasudevan & Fabian 2009) and comparing the results. The most significant differences between these methods were found at the extremes of the luminosity (accretion) range spanned by the sources of our sample. Therefore, the exact choice of the bolometric correction does not significantly affect our results.

The major contribution to the bolometric luminosity error determination comes from the uncertainty on the bolometric correction itself, which is generally significantly larger than the uncertainty on the X-ray luminosity. The bolometric correction proposed by Marconi et al. (2004) is based on the correlation between the UV luminosity at 2500 Å and the 2–10 keV X-ray luminosity, whose spread is estimated as 0.37 dex (see Equation (3) of Young et al. 2010). Therefore, we assume this uncertainty on our derived bolometric luminosities.

For the Eddington ratios, we propagated the uncertainties on the BH mass and bolometric luminosity. This leads to an uncertainty of 0.5 dex in the Eddington ratios.

4. RESULTS

We first considered only the Compton-thin sources of our sample. In the top panel of Figure 2, we plot the bolometric luminosity against the Eddington ratio for all the Compton-thin sources of our sample. HBLR and non-HBLR sources are clearly separated both in luminosity and in accretion rate. To address the statistical significance of this separation (both in luminosity and accretion rate), we performed a two-sample Kolmogorov–Smirnov test on our data. These tests give probabilities of 0.5% (luminosity) and 0.1% (Eddington ratio) that the two classes are taken from the same parent population. These correspond to two-sided Gaussian-equivalent significances of 2.8\( \sigma \) and 3.3\( \sigma \), respectively. The threshold Eddington ratio and luminosity that minimize the probability of chance separation are \( \log \lambda_{\text{Edd}} = -1.9 \) and \( \log L_{\text{bol}} = 43.9 \), respectively.

We then repeated our analysis by also including Compton-thick sources (for which the inferred intrinsic 2–10 keV luminosity estimates are uncertain: see Section 2.2). The inclusion of Compton-thick sources makes the HBLR versus non-HBLR separation less sharp (Figure 2, bottom panel), and less significant, with probabilities of chance separation of 1.0% and 1.8%, for the Eddington ratio and bolometric luminosity, respectively (Table 2), corresponding to statistical significances of only 2.4\( \sigma \) and 2.6\( \sigma \). However, we note that no HBLR source falls below the Eddington ratio threshold.

4.1. Comparison with Other Works and Methodologies

Other authors investigated larger (but, in most cases, inhomogeneous) samples to search for physical parameters responsible for the existence or absence of HBLRs in AGNs, and often found no clear indication for the existence of such a parameter.
Figure 1. 2–10 keV luminosities derived from our X-ray analysis are plotted against \([\text{O}\text{ iii}]\) luminosities. A correction factor of 70 is used in the bottom panel.

(A color version of this figure is available in the online journal.)
Figure 2. Bolometric luminosity inferred from the 2–10 keV luminosity against the Eddington ratio for all the Compton-thin sources of our sample is plotted in the top panel while in the bottom plot Compton-thick sources are introduced, using a correction factor of 70. The dotted lines represent the maximal separation values between the cumulative distribution of the two samples with respect to $L_{\text{bol}}$ and $\lambda_{\text{Edd}}$.

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

relation to derive the stellar velocity dispersions. We then compared these estimates with the measurements of $\sigma_*$, Figure 3 shows the result of this comparison: clearly, the two values differ significantly and do not appear to be linearly correlated with one another. We, therefore, use only BH estimates based on direct measures of the $\sigma_*$ in order to avoid further uncertainties due to the indirect derivation of this parameter.

Another important source of potential error is the proxy used to derive the nuclear bolometric luminosity of an obscured AGN. In our work, we use 2–10 keV luminosities, which are a direct probe of the intrinsic nuclear activity. However, such luminosities are available only for a limited number of Seyfert 2s. On the contrary, [O iii] luminosities only echo the intrinsic nuclear activity but are available for a much larger number of obscured AGNs. To check the goodness of the [O iii] luminosity estimator, we compared our results with those obtained, for the sources of our sample, by using the [O iii] luminosities and the bolometric luminosities derived from them, through the
Table 2
Results from the Two-sample K-S Test

| Sample                      | N  | P (Lbol) | P (L2−10 keV) | P (λEdd) | Lmax bol | Lmax 2−10 keV | λmax Edd |
|-----------------------------|----|----------|---------------|----------|----------|---------------|----------|
| (1)                         | (2)| (3)      | (4)           | (5)      | (6)      | (7)           | (8)      |
| Non-HBLR Compton Thin       | 4  | 0.5%     | 4.4%          | 0.1%     | 43.90    | 42.73         | −1.9     |
| HBLR Compton Thin           | 11 |          |               |          |          |               |          |
| Non-HBLR Compton Thick and Thin | 18| 1.8%     | 6.9%          | 1.0%     | 43.90    | 42.56         | −1.8     |
| HBLR Compton Thick and Thin | 21 |          |               |          |          |               |          |
| [Oiii]                      | P (L(Oiii)) | Lmax [Oiii] |          |           |          |               |          |
| Non-HBLR Compton Thin       | 4  | 38.5%    | 38.5%         | 8.7%     | 43.51    | 41.36         | −2.5     |
| HBLR Compton Thin           | 11 |          |               |          |          |               |          |
| Non-HBLR Compton Thick and Thin | 18| 23.2%   | 23.2%         | 25.7%    | 43.54    | 41.39         | −2.1     |
| HBLR Compton Thick and Thin | 21 |          |               |          |          |               |          |
| [Oiv]                       | P (L(Oiv)) | Lmax [Oiv] |           |           |          |               |          |
| Non-HBLR Compton Thin       | 3  |          |               |           |          |               |          |
| HBLR Compton Thin           | 9  |          |               |           |          |               |          |
| Non-HBLR Compton Thick and Thin | 15| 10.4%   | 10.4%        | 1.1%     | 43.82    | 40.57         | −1.4     |
| HBLR Compton Thick and Thin | 17 |          |               |           |          |               |          |

Notes. For Compton-thick sources, a correction factor of 70 is used for the calculation of the 2–10 keV luminosity and hence for the bolometric luminosity. (1) Description of the sample; (2) number of objects in the sample; (3) percentage probability that the two samples derive from the same parent population in Lbol; (4) percentage probability that the two samples derive from the same parent population in L2−10 keV, L[Oiii], or L[Oiv]; (5) percentage probability that the two samples derive from the same parent population in λEdd; (6)–(8) maximal separation value between the cumulative distributions of the two samples.

Figure 3. Stellar velocity dispersions obtained from the Ca ii and Mg b absorption lines against those derived through the FWHM of the [O iii] emission line (on the Y axis). The two estimates are very different and not correlated. Only the BH masses estimated with the first method will be used in this work.

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

The Astrophysical Journal, 748:130 (10pp), 2012 April 1

Marinucci et al.

5. DISCUSSION

Since the seminal results by Miller & Antonucci (1983) on the archetypical Seyfert 2 galaxy, NGC 1068, much effort has been exerted to understand whether the Unification Model is valid for all Seyfert galaxies, or the presence/absence of the BLR may be also linked to intrinsic properties of different classes of sources. Intrinsic differences were strongly advocated by Tran (2001) and Tran (2003), who found that HBLR Seyfert 2s are normally associated with typical obscured Seyfert 1 nuclei, while non-HBLR sources have observed luminosities, confirms (e.g., Lamastra et al. 2009; Trouille & Barger 2010 and references therein) that the [O iii] luminosity is not a direct proxy for the bolometric luminosity of an AGN.

A large number of sources in our sample (32 out of 39) also have [O iv] measurements (Pereira-Santaella et al. 2010; Weaver et al. 2010). For a few sources, we inferred [O iv] luminosities following the method presented in Goulding & Alexander (2009). Using the relation in Goulding et al. (2010), both bolometric luminosities and accretion rates can be inferred from the [O iv] luminosities. The results are shown in the bottom panel of Figure 4 and Table 2. The two classes show a more significant separation in accretion rate than in bolometric luminosity (probability of chance separation of 1.1% and 10.4%, respectively). Both HBLR and non-HBLR Compton-thick sources are included in the sample and the separation between the two different populations in accretion rate resembles the one inferred from our X-ray analysis, suggesting that the efforts to use standard extinction correction for [O iii] are not always reliable (e.g., Goulding & Alexander 2009; LaMassa et al. 2010).

Since the seminal results by Miller & Antonucci (1983) on the archetypical Seyfert 2 galaxy, NGC 1068, much effort has been exerted to understand whether the Unification Model is valid for all Seyfert galaxies, or the presence/absence of the BLR may be also linked to intrinsic properties of different classes of sources. Intrinsic differences were strongly advocated by Tran (2001) and Tran (2003), who found that HBLR Seyfert 2s are normally associated with typical obscured Seyfert 1 nuclei, while non-HBLR sources have observed luminosities...
Figure 4. In the top panel, bolometric luminosities derived from the \([O\text{III}]\) and Eddington ratios for all 39 Compton-thin and Compton-thick sources of our sample are shown. In the bottom panel, bolometric luminosities derived from \([O\text{IV}]\) and Eddington ratios for 32 sources are shown. We used a dispersion value of \(\sigma = 0.3\) dex for uncertainties in the estimates of the \([O\text{III}]\) bolometric luminosities, based on a recent study presented in Risaliti et al. (2011) where the flux of the \([O\text{III}]\) line is used as a reliable indicator of the bolometric emission of quasars. For \([O\text{IV}]\) bolometric luminosities we used a dispersion value of \(\sigma = 0.35\) dex (Goulding et al. 2010). The dotted lines represent the maximal separation values between the cumulative distribution of the two samples with respect to \(L_{\text{bol}}\) and \(\lambda_{\text{Edd}}\). (A color version of this figure is available in the online journal.)

Seyfert 2 galaxies host, on average, significantly weaker nuclei that are, likely incapable of generating classical BLRs.

This evidence supports theoretical models that link the presence or absence of BLRs in Seyferts to intrinsic nuclear properties. In a model proposed by Nicastro (2000), the presence of broad emission lines is intrinsically connected to disk instabilities occurring in the proximity of a transition radius at which the accretion disk changes from gas-pressure dominated to radiation-pressure dominated. The transition radius is a function of the accretion rate, and becomes smaller than the
innermost stable orbit for accretion rates (and therefore luminosities) lower than a threshold that depends weakly on the BH mass. Weak AGN should, therefore, lack the BLR.

In this work, we try to test this model in the least biased observational way, by collecting the “cleanest” possible sample of Seyfert 2 galaxies with the best spectropolarimetric data available at the moment, and robust estimates of their BH masses performed homogeneously on the basis of the observed stellar velocity dispersion. When only Compton-thin sources are considered, the estimate on their accretion rate is done directly on the observed nuclear X-ray emission, and the modest absorption is likely not able to affect severely the detection of the hidden BLR, if present. We find that the separation between HBLR and non-HBLR Compton-thin sources is highly significant both in accretion rate and luminosity. In particular, no HBLR is found below the threshold Eddington rate \( \log \lambda_{\text{Edd}} = -1.9 \), and no non-HBLR above the same limit. Even when Compton-thick sources are included, no HBLR is still found at accretion rates lower than the above threshold. This threshold accretion rate is in good agreement with the value presented in a recent work (Trump et al. 2011).

This result supports the theoretical expectations of the model proposed by Nicastro (2000), albeit with a slightly higher value of the threshold accretion rate (\( \log \lambda_{\text{Edd}} \sim -2.5 \)) in Nicastro (2000). We stress here that the model proposed by Nicastro (2000) applies only to radiatively efficient AGNs, accreting through a Shakura–Sunyaev disk (SS-disk hereinafter, Shakura & Sunyaev 1973). Broad Emission lines are known to exist in some objects (mostly LINERs or transition objects; e.g., Elitzur & Ho 2009) accreting at rates as low as \( \log \lambda_{\text{Edd}} \sim -6 \) (e.g., M81, Ho 2008). These objects are highly radiatively inefficient, and therefore most likely do not host a classic SS-disk.

If BLRs do not exist in weakly accreting AGN, one would expect the absence of unabsorbed, genuine Seyfert 2 galaxies. Such objects do indeed exist, and the best examples (where the lack of optical broad lines and of X-ray obscuration are unambiguously assessed in simultaneous high S/N observations) have Eddington rates lower than the threshold estimated in this paper: NGC 3147 (\( \log \lambda_{\text{Edd}} \sim -4 \); Bianchi et al. 2008), Q2131427 (\( \log \lambda_{\text{Edd}} \sim -2.6 \); Panessa et al. 2009), NGC 3660 (\( \log \lambda_{\text{Edd}} \sim -2 \); S. Bianchi et al. 2012, in preparation; Brightman & Nandra 2008).

It is interesting to note that among all the 156 X-ray unobscured (\( N_H < 2 \times 10^{22} \) cm\(^{-2} \)) AGNs observed with XMM-Newton (CAIXA; Bianchi et al. 2009), only 6 have an Eddington rate lower than the threshold found in this work.\(^8\) Four of these six sources were previously classified as unabsorbed Seyfert 2s (Panessa & Bassani 2002; Panessa et al. 2009; Brightman & Nandra 2008; but see also, e.g., Shi et al. 2010, who recently claimed the presence of very broad and weak broad emission lines in two of these objects, and references therein). The remaining two objects are PG 1011-040 and NGC 7213, and both show the presence of BLR in their optical spectra. Both objects are peculiar. PG 1011-040 is only slightly below the accretion rate threshold of \( \log \lambda_{\text{Edd}} \sim -1.9 \) that we find here and, most importantly, is severely underluminous in X-rays with respect to its multwavemagnitude luminosity, so that the accretion rate derived from its 2–10 keV luminosity by simply applying the Marconi et al. (2004) correction is likely severely underestimated (Gallagher et al. 2001; Vasudevan & Fabian 2007). NGC 7213 is the only bright Seyfert 1 galaxy known to unambiguously lack reproprocessing features from Compton-thick distant material (Bianchi et al. 2003, 2004; Lobban et al. 2010).

The inclusion of Compton-thick sources in our sample makes the HBLR versus non-HBLR separation, in terms of either Eddington ratios or bolometric luminosities, less significant. Several non-HBLR Compton-thick sources now lie in the HBLR \( L_{\text{bol}} \sim 0.5 \lambda_{\text{Edd}} \) plane, i.e., at an accretion rate higher than the threshold we find for Compton-thin sources. This mixing could be, at least partially, due to the difficulties in assessing the intrinsic 2–10 keV luminosity of Compton-thick sources because of the unknown geometry of the absorbers and reflectors.\(^9\)

However, such uncertainties should in principle affect equally over- and underestimates of the luminosities. Instead, while no Compton-thick HBLR is still found below the Eddington rate threshold, a significant fraction (64%) of Compton-thick non-HBLR has accretion rates higher than this limit. Moreover, uncertainties in the exact geometry of absorbers and reflectors, could only be responsible for modest (factor of 2–3) overestimates of the intrinsic bolometric luminosity and so of the Eddington accretion rate. This could perhaps explain the presence of a few non-HBLR with Eddington ratios closely above the Eddington ratio threshold, but can hardly explain order-of-magnitude overestimations of the bolometric luminosity, as inferred from the 2–10 keV spectra.

If the scenario proposed by Nicastro (2000) is correct, non-HBLR Compton-thick sources with Eddington accretion rate estimates much above the threshold are likely to be peculiar objects, where BLR line emission cannot be seen, not even in polarized light. These source should possess a BLR, but something prevents us from observing it. Different, alternative scenarios about the intrinsic lack of a BLR have already been proposed in the past (Lumsden & Alexander 2001; Gu & Huang 2002; Martocchia & Matt 2002; Tran 2003; Moran 2007). This could be either because of the lack of an unobscured population of hot electrons scattering the line emission along our line of sight, or because the orientation of these sources is such that our line of sight intercepts larger portions of absorbing gas, and this covers both the nuclear source and at least part of the line-reprocessing electron region (e.g., Shu et al. 2007; Wu et al. 2011 and references therein).

6. CONCLUSIONS

The main results of this paper can be summarized as follows.

1. We presented evidence suggesting that accretion rate is the main ingredient which drives the presence of HBLRs in Seyfert 2 galaxies. By selecting a sample of 39 type 2 AGNs with good quality spectropolarimetric and X-ray data, and for which we derived homogenous estimates of the mass of the central supermassive BH, we found a clear separation between Compton-thin HBLR and non-HBLR sources, both in luminosity (\( \log L_{\text{bol}} = 43.90 \)) and in accretion rate (\( \log \lambda_{\text{Edd}} = -1.9 \)). A statistically similar separation is seen when bolometric luminosities are derived from infrared [O Iv] emission lines.

Our results agree with the ones discussed in Nicastro et al. (2003) but have higher statistical significance (due to the larger sample we use here, compared to Nicastro et al. 2003), and probably more robust due to the more accurate estimates of the BH masses that we derive here.

---

\(^8\) An updated catalog was used for this search.

\(^9\) The same uncertainties are probably also responsible for the lack of HBLR and non-HBLR separation when indirect estimators of the nuclear bolometric luminosity (e.g., \([\text{O} \text{III}]\)) are used.
2. The inclusion of Compton-thick sources washes out the separation between HBLR and non-HBLR, but still no HBLR source falls below the Eddington ratio threshold. We propose that the presence of a significant fraction (64%) of Compton-thick non-HBLRs at accretion rates higher than the threshold found for Compton-thin sources is not due to the lack of BLRs but to heavy line-of-sight absorption preventing us from observing not only the direct line emission, but also their polarized light scattered off an—at least partly—obscured population of hot electrons.

A.M., S.B., and G.M. acknowledge financial support from ASI under grant I/088/06/0. F.N. acknowledges financial support from ASI grants AAE and ADAE, as well as NASA grant NNG04GD49G. A.M. and F.N. acknowledge support from NASA grant NNX11AD16G. We thank M. Elvis for useful advices and discussions. We thank the anonymous referee for his/her important comments that greatly improved this work.

REFERENCES
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Antonucci, R. 1993, ARA&A, 31, 473
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Barth, A. J., Ho, L. C., & Sargent, W. L. W. 2002, AJ, 124, 2607
Bassani, L., & Dadina, M. 1999, ApJS, 121, 473
Baum, S. A., Gallimore, J. F., & O'Dea, C. P. 2010, ApJ, 710, 289
Diamond-Stanic, A. M., Rieke, G. H., & Rigby, J. R. 2009, ApJ, 700, 1878
Elitzur, J. M., & Ho, L. C. 2009, ApJ, 701, L91
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Elitzur, J. M., & Ho, L. C. 2009, ApJ, 701, L91
Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1
Fruscione, A., McDowell, J. C., Allen, G. E., et al. 2006, Proc. SPIE, 6270, 62701V
Gabriel, C., Denby, M., Fyfe, D. J., et al. 2004, in ASP Conf. Ser. 314, Astronomical Data Analysis Software and Systems (ADASS) XIII, ed. F. Ochsenbein, M. G. Allen, & D. Egret (San Francisco, CA: ASP), 759
Gallagher, S. C., Brandt, W. N., Laor, A., et al. 2001, ApJ, 546, 795
Garcia-Rissmann, A., Vega, L. R., Asari, N. V., et al. 2005, MNRAS, 359, 765
Goulding, A. D., & Alexander, D. M. 2009, MNRAS, 398, 1165
Goulding, A. D., Alexander, D. M., Lehmer, B. D., & Mullaney, J. R. 2010, MNRAS, 406, 597
Greene, J. E., & Ho, L. C. 2005, ApJ, 627, 721
Gu, Q., & Huang, J. 2002, ApJ, 579, 205
Gültekin, K., Richstone, D. O., & Gebhardt, K. 2009, ApJ, 698, 198
Haas, M., Siebenmorgen, R., & Schulz, B. 2005, A&A, 442, L39
Ho, L. C. 2008, ARA&A, 46, 475
Huchra, J., & Burg, R. 1992, ApJ, 393, 90
Kraemer, S. B., Schmitt, H. R., et al., 2011, ApJ, 727, 130
LaMassa, S. M., Heckman, T. M., et al. 2010, ApJ, 720, 786
Lamastra, A., Bianchi, S., Matt, G., et al. 2009, A&A, 504, 73
Laor, A. 2003, ApJ, 590, 86
Lobban, A. P., Reeves, J. N., Porquet, D., et al., 2010, MNRAS, 408, 551
Lumsden, S. L., & Alexander, D. M. 2001, MNRAS, 328, L32
Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 237, 837
Marconi, A., Risaliti, G., Gilli, R., et al., 2004, MNRAS, 351, 169
Martocchia, A., & Matt, G. 2002, in Inflows, Outflows, and Reprocessing around Black Holes, ed. I. Cagnoni, 34
Matt, G., & Pompilio, F. 1999, New Astron., 4, 191
McElroy, D. B. 1995, ApJS, 100, 105
Melendez, M., & Kraemer, S. B. 2008, ApJ, 682, 94
Miller, J. S., & Antonucci, R. R. J. 1983, ApJ, 271, L7
Moran, E. C. 2007, in ASP Conf. Ser. 373, The Central Engine of Active Galactic Nuclei, ed. L. C. Ho & J.-M. Wang (San Francisco, CA: ASP), 425
Moran, E. C., Barth, A. J., Kay, L. E., & Filipenko, A. 2000, ApJ, 540, L73
Nelson, C. H., & Whittle, M. 1995, ApJS, 99, 67
Nicastro, F. 2000, ApJ, 530, L65
Nicastro, F., Martocchia, A., & Matt, G. 2003, ApJ, 589, L13
Oliva, E., Origlia, L., Maiolino, R., & Moorwood, A. F. M. 1999, A&A, 350, 9
Panessa, F., & Bassani, L. 2002, A&A, 394, 435
Panessa, F., Carrera, F. J., Bianchi, S., et al. 2009, MNRAS, 398, 1951
Pereira-Santaella, M., Diamond-Stanic, A. M., Alonso-Herrero, A., & Rieke, G. H. 2010, ApJ, 725, 2270
Piconcelli, E., Jimenez-Bailón, E., Guainazzi, M., et al. 2004, MNRAS, 351, 161
Rigby, J. R., Diamond-Stanic, A. M., & Aniano, G. 2009, ApJ, 700, 1878
Risaliti, G., Salvati, M., & Marconi, A. 2011, MNRAS, 411, 2223
Rush, B., Malkan, M. A., & Spinoglio, L. 1993, ApJS, 89, 1
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shaw, M., Wilkinson, A., & Carter, D. 1993, A&A, 268, 511
Shi, Y., Rieke, G. H., Smith, P., et al. 2010, ApJ, 714, 115
Shu, X. W., Wang, J. X., Fan, L. L., & Wang, T. G. 2007, ApJ, 657, 167
Stephens, M. A. 1970, J. R. Stat. Soc. B, 32, 115
Struder, L., Briul, E., Dennerl, K., et al. 2001, A&A, 365, L18
Terlevich, E., Diaz, A. I., & Terlevich, R. 1990, MNRAS, 242, 271
Tran, H. D. 1995, ApJ, 440, 565
Tran, H. D. 2001, ApJ, 554, L19
Tran, H. D. 2003, ApJ, 583, 632
Tran, H. D., Miller, J. S., & Kay, L. E. 1999, ApJ, 397, 452
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740
Trouille, L., & Barger, A. J. 2010, ApJ, 722, 212
Trump, J. R., Impey, C. D., et al. 2011, ApJ, 733, 60
Vasudevan, R. V., & Fabian, A. C. 2007, MNRAS, 381, 1235
Vasudevan, R. V., & Fabian, A. C. 2009, MNRAS, 392, 1124
Weaver, K. A., Meléndez, M., & Mushotzky, R. F. 2010, ApJ, 716, 1151
Wu, Y., Zhang, E., Liang, Y., Zhang, C., & Zhao, Y. 2011, ApJ, 730, 121
Young, S., Hough, J. H., Efstathiou, A., et al. 1996, MNRAS, 281, 1206

10