The Astrophysical Journal, 600:L31–L34, 2004 January 1

MULTIWAVELENGTH SCALING RELATIONS FOR NUCLEI OF SEYFERT GALAXIES[1]

M. Salvato[2] and J. Greiner[2]
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
and
B. Kuhlbrodt
Hamburg Observatory, Gojenbergsweg 112, D-21029 Hamburg, Germany
Received 2003 September 25; accepted 2003 November 25; published 2003 December 16

ABSTRACT

We analyze an X-ray flux-limited, complete sample of 93 active galactic nuclei (AGNs) at $z < 0.1$, selected from the *ROSAT* Bright Survey. Two-thirds of the sample are Seyfert 1 galaxies, and one-third are narrow-line Seyfert 1 galaxies. We have obtained optical images of all objects. By modeling the host galaxy and the AGN central component, we decompose the optical emission into nuclear bulge and disk components, respectively. We find that the nuclear optical luminosity, thought to be associated with the accretion disk surrounding the active black hole, correlates with the X-ray luminosity, the radio luminosity, and the black hole mass.

Subject headings: galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

On-line material: color figures

1. INTRODUCTION

The last few years have brought fundamental progress in our understanding of the suspected connection between active galactic nuclei (AGNs), which are characterized by nonthermal emission from massive (10^6–10^9 $M_\odot$) black holes (BHs), and normal galaxies, whose extended emission is thermal. In particular, now (1) there is robust evidence that quasars reside in galaxies (Bahcall et al. 1997); (2) it is established that massive "quiescent" BHs are also present in the central regions of normal galaxies (Magorrian et al. 1998); (3) a statistical correlation between BH mass and the mass or velocity dispersion of the host galaxy's bulge exists (Gebhardt et al. 2000; Ferrarese & Merritt 2000), which suggests a common evolution for galaxies and their central, massive BHs; and (4) the previous correlations hold for normal as well as AGN-host galaxies (McLure & Dunlop 2002).

For AGNs with typical masses of 10^6–10^9 $M_\odot$, the bulk of the accretion radiation is emitted in the soft X-ray and EUV/UV range. A fraction of this optically thick radiation is Compton-upscattered by a corona of electrons surrounding the BH. This process is thought to produce the typical power-law X-ray spectra observed in all AGNs. The primary soft X-ray/EUV radiation of the accretion disk also ionizes the surrounding gas, producing the well-known AGN emission lines. At radio frequencies, the core luminosity of the AGN is due to synchrotron emission by relativistic electrons immersed in a seemingly global magnetic field. It is conceivable that these electrons are the same that Compton-upscatter the disk photons. It is therefore interesting to ask whether there is a direct correlation between radio, optical, and X-ray emission in the central part of the AGN where the accretion disk is located.

While information on the radio and X-ray bands is already available from all-sky surveys like the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), FIRST (Faint Images of the Radio Sky at Twenty centimeters; Becker, White, & Helfand 1995), and the *ROSAT* Bright Survey (RBS; Schwope et al. 2000), optical data for the central kiloparsec of AGNs are more difficult to obtain. Indeed, in modeling AGNs and their host galaxies, the information contained in the central pixels has been usually rejected (see, e.g., Virani, De Robertis, & VanDalfsen 2000). With a new well-tested, well-performing, and robust-fitting algorithm (Kuhlbrodt et al. 2001), it has recently been possible to model both the host galaxy *and* the nucleus from optical images.

Here we apply this decomposition algorithm to a new sample of objects and use the results of the decomposition to study the relations between the properties of the central point source, in particular, the X-ray (0.5–2.0 keV), optical (*R* band), and radio (1.49 GHz) emission. After presenting the sample selection in § 1 and the catalog data in § 2, the relations between the different parameters are described in § 3 and discussed in § 4. Unless specified differently, a value of $H_0 = 50$ km Mpc^{-1} s^{-1} has been used throughout this Letter.

2. CONSTRUCTION OF THE SAMPLE

We used the RBS (Schwope et al. 2000), consisting of the ~2000 brightest, optically identified sources detected during the *ROSAT* All-Sky Survey (Voges et al. 1999). Selecting from X-rays has the advantage that the contribution of the emission from the host galaxy is small with respect to the AGN. We selected the strongest (ROSAT PSPC count rate above 0.3 counts s^{-1} in the 0.5–2.0 keV range), local ($0.009 < z < 0.1$) AGN in order to achieve reasonable spatial resolution with ground-based optical observations. The sample consists of 93 AGNs (the black crosses in Fig. 1). At the time the work started, all of them were classified in the NASA/IPAC Extragalactic Database as Seyfert 1 (Sy1) galaxies, but in the meantime about 30% of them have been found to be narrow-line Seyfert 1 (NLSy1) galaxies (Véron-Cetty, Véron, & Gonçalves 2001). The size of the sample thus allows us to work with two independent, complete samples, Sy1 (64) and NLSy1 (29) galaxies, with comparable X-ray luminosity. In both cases, the observer has a direct view of the AGNs, i.e., unobstructed by the torus.

[1] Partly based on observations collected at the European Southern Observatory, La Silla, Chile, and at Calar Alto, Spain.

[2] Formerly at Astrophysikalisches Institut Postdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany.

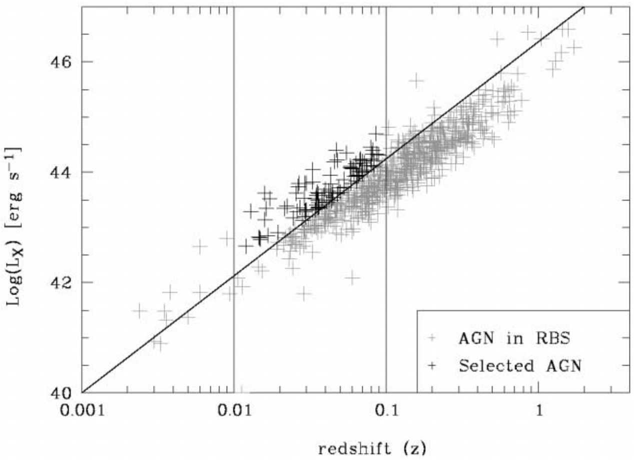

FIG. 1.—AGNs in the RBS catalog. The solid lines define the selection criteria in redshift ($0.009 < z < 0.1$; *vertical lines*) and in flux (count rate above 0.3 counts s^{-1}; *diagonal line*). The black crosses form the sample used in this work. [*See the electronic edition of the Journal for a color version of this figure.*]

3. DATA COLLECTION

All optical data were acquired in dedicated observing runs, described in detail elsewhere (Salvato 2002; M. Salvato 2003, in preparation). Here we give only some brief characteristics. In order to explore the relationship of nuclear luminosities in various wavelengths, we collected data from public catalogs for the X-ray and radio wavelengths.

Optical data.—The entire sample has been observed in the *R* band with a typical exposure time of 10 minutes at the 1.5 m Danish telescope (Bessel *R* filter) at La Silla and of 20 minutes at the 1.2 m telescope (Johnson *R* filter) at Calar Alto. We have applied the two-dimensional decomposition algorithm (Kuhlbrodt et al. 2001) to all images, which takes into account the point-spread function of the corresponding image. A three-component model has been applied that involves a pointlike nuclear component, a bulge component with an $R^{1/4}$ radial dependence, and an exponential disk component. Besides the spatial parameters, we therefore obtain magnitudes of these three components. These derived magnitudes have been corrected for Galactic absorption using the maps of Dickey & Lockman (1990) and converted to the visual extinction as derived by Predehl & Schmitt (1995). A comparison of our fit parameters (colors, disk and bulge parameters, etc.) with a subsample of galaxies already studied earlier (e.g., McLure & Dunlop 2001) reveals perfect agreement (see details in Salvato 2002) and thus provides us with some confidence that the nuclear light component is also fitted correctly. *In* § 4, *this optical nuclear luminosity is supposed to represent the accretion disk surrounding the BH.*

Black hole masses.—BH masses are computed from the derived bulge luminosity using a unique equation for Sy1 and NLSy1 galaxies found in McLure & Dunlop (2002): $\log(M_{BH}/M_{\odot}) = -0.50(\pm0.02)M_R - 2.96(\pm0.48)$, which is valid under the assumption that differences between Sy1 and NLSy1 galaxies are due to geometrical rather than physical effects. Our masses (Table 1), after correcting for the different cosmology, agree well with those derived by reverberation mapping (Kaspi et al. 2000) for the common sources.

X-ray luminosity.—Typically, nonactive galaxies have very low X-ray luminosities; thus, the X-ray emission at a *ROSAT* PSPC count rate above 0.3 counts s^{-1} is likely produced only in the nuclei of AGNs. However, the X-ray emission is not directly related to the accretion disk because of the canonical temperatures of the disk emission peaks in the UV. The X-ray luminosity has been computed using the X-ray flux in the 0.5–2.0 keV range (see Table 2 in Schwope et al. 2000), by assuming a power-law spectrum with a photon index of −2 and applying the corresponding Galactic absorption and *k*-correction. We caution that this approach yields unreliable and inconsistent results for few NLSy1 galaxies in our sample, having very steep, soft X-ray spectra.

TABLE 1
COMPARISON OF BH MASSES OBTAINED FOLLOWING MCLURE & DUNLOP (2002) AND VIA REVERBERATION MAPPING (KASPI ET AL. 2000)

	$\log(M_{BH}/M_{\odot})$	
SOURCE NAME	Kaspi et al.	This Work
n011 (Fairall 9)	7.59–8.01	7.89–8.83
n054 (PG 1211+14)	7.45–7.7	8.44–9.34
n065 (IC 4329A)	<7.25	6.76–7.78
n069 (NGC 5548)	8.02–8.16	7.14–8.12

NOTE.—All values are computed using $H_0 = 75$ km Mpc^{-1} s^{-1}.

Radio data.—We cross-correlated our sample with the NVSS and FIRST radio catalogs, and, owing to their limited sky coverage, 53 matches were found. Both surveys are centered at 1.49 GHz ($\lambda = 20$ cm), where the synchrotron emission of our targets may not only be associated with the nuclear activity but also with the spatially extended star formation activity, if any. NVSS and FIRST map the sky at different spatial resolutions (45″ and 5″, respectively) and thus allow us to disentangle the two potential contributions. In fact, if the unresolved AGN produces all the radio emission, the fluxes listed in the two catalogs must be consistent, otherwise the NVSS flux must be larger. A flux-flux plot shows that galaxies with and without the extra contribution to the radio emission from star formation activity can be separated by a line of the equation $\log L_{1.49\,GHz}(\mathrm{NVSS}) = \log L_{1.49\,GHz}(\mathrm{FIRST}) + 0.3$. This selection criterion is robust against a maximal 20% variability of the AGN radio flux (Falcke et al. 2001). Thus, the radio luminosities of 21 out of 53 galaxies are attributed only to their nuclear activity.

4. CORRELATION ANALYSIS

Optical versus X-ray emission.—A strong linear relation is found between the optical accretion disk and the X-ray luminosity (Fig. 2), of the form

$$\log L_X = a \log L_R(\mathrm{Nuc}) + b, \quad (1)$$

where the coefficients "*a*" and "*b*" have been determined separately for the whole sample ("All") and for the Sy1 and NLSy1 galaxies alone, respectively (Table 2). The consistency of the relations is confirmed by the Spearman rank correlation coefficient ρ, which is higher than 0.7. From the plot and the table, it is obvious that Sy1 and NLSy1 galaxies behave in the same way. The scatter is about ±0.5 dex. There are (at least) two obvious reasons for this scatter: First, optical and X-ray fluxes have not been measured simultaneously, and due to the known variability of Seyfert galaxies, a factor of a few can easily be accounted for. Second, the X-ray fluxes have been computed on the basis of the total measured counts and an *assumed* power-law slope. It would have been more correct (although not possible in most cases because of photon statistics) to fit the power-law slope also and thus obtain a more

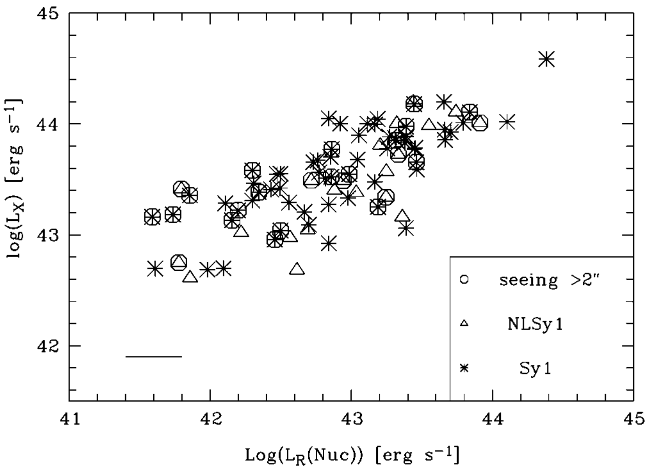

FIG. 2.—X-ray vs. optical (*R* band) luminosity for the sample. Asterisks (open triangles) represent Sy1 (NLSy1) galaxies. For 30 out of the 93 objects, imaging was obtained under bad seeing conditions (>2″). These are marked by open circles around their respective symbols and were ignored for determining the linear correlation between the X-ray and optical luminosities. Larger seeing implies more flux in the nuclear component relative to the bulge component, and therefore those encircled data points have to be treated as upper limits on the nuclear optical emission. At bottom left, the expected error for the nuclear, optical luminosity is given. Sy1 and NLSy1 galaxies behave in the same way.

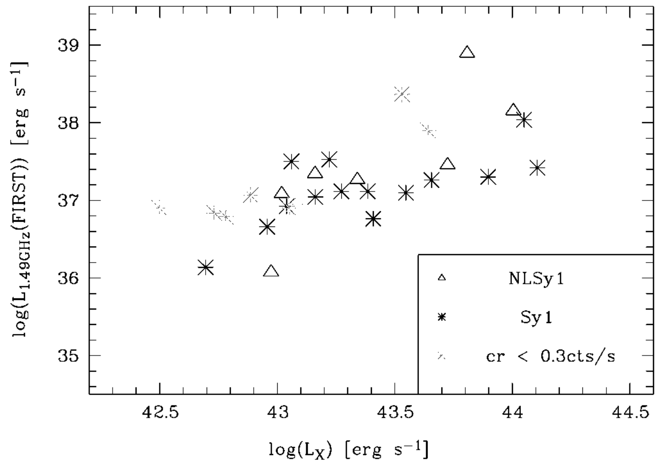

FIG. 3.—Radio vs. X-ray luminosity for the sample. Symbols are the same as in Fig. 2. AGNs with lower count rates than those we considered (*gray asterisks*) are also plotted, with the intention of showing that our relation is not driven by the Malmquist bias. [*See the electronic edition of the Journal for a color version of this figure.*]

accurate X-ray flux. One may think that the Hα line may produce a nonnegligible contribution to the continuum emission in the *R* band. For testing this hypothesis, the template spectrum of a Sy1 galaxy has been convolved with the transmission curve of the *R*-band filter. We computed the dilution factor from Hα, for different [N II]/Hα ratios and for different EW(Hα), also taking into account that Hα may be enhanced by galaxy interaction. The dilution factor is not more than 1% and thus is negligible.

Radio versus X-ray emission.—We also find that the X-ray emission correlates well with the radio continuum emission (Fig. 3). As in the previous case, the relation is linear and has been fitted in the form

$$\log L_{\rm FIRST}({\rm Nuc}) = c \log L_{\rm X} + d. \qquad (2)$$

The coefficients "*c*" and "*d*" are listed in Table 2. Here we used only those 21 galaxies for which we have information about nuclear radio emission. As previously, the linear regression has been computed for all objects, and for the Sy1 (14) and NLSy1 (7) galaxies independently. Due to the small size of the two subsamples, the errors are quite high, and the Spearman rank correlation coefficient is not really reliable. Nevertheless, it appears that the NLSy1 galaxies may have a steeper slope than the Sy1 galaxies.

Optical versus BH masses.—The optical luminosity of the accretion disk is also correlating with the BH mass computed according to § 3 (Fig. 4). The solid line indicates the predicted relationship for an optically thick accretion disk around a nonrotating BH (Shakura & Sunyaev 1973), where, for a given BH mass, the *R*-band flux depends on the temperature (and thus on the accretion rate $\dot{M}$) of the object ($\dot{M} = 0.1\dot{M}_{\rm Edd}$ chosen here). The curvature of this line is basically a measure of the differing bolometric correction for the varying BH mass (and thus temperature).

5. CONCLUSIONS

We find that the optical luminosity of the nuclei of Seyfert galaxies correlates with the power-law X-ray emission, the radio emission from the core, and the BH mass. These relations are not driven by the Malmquist bias, which is introduced whenever a sample is selected via a flux limit. In fact, the additional nine Sy1 galaxies with count rates less than 0.3 counts s^{-1} and their NVSS/FIRST counterpart confirm the general trend (see Fig. 3, *gray asterisks*).

The correlation of the optical nuclear luminosity with the X-ray luminosity could potentially be understood if the canonical blackbody-like continuum emission from the accretion disk is enhanced because of irradiation by soft X-rays so that an increase in the X-ray flux would create a larger optical flux. This is a well-known effect in X-ray binaries, although it has not been possible so far to quantify this relation since it depends on too many parameters (e.g., the X-ray spectrum of the irradiating source, the temperature and ionization state of the disk, and the geometry of the disk).

Kriss, Canizares, & Ricker (1980) and Koratkar et al. (1995) found a strong correlation between the soft X-ray luminosity and the broad Hβ and Hα line luminosity, respectively, in quasars and Sy1 galaxies. It has been argued that an increased accretion disk flux would not only cause a larger photoioni-

TABLE 2
COEFFICIENTS FOR EQUATIONS (1) AND (2)

Galaxies	Equation (1)			Equation (2)		
	a	*b*	ρ	*c*	*d*	ρ
All	0.58 ± 0.06	18.44 ± 2.6	0.74	0.96 ± 0.24	−4.18 ± 10.7	0.68
Sy1	0.56 ± 0.07	19.48 ± 3.0	0.72	0.74 ± 0.22	4.80 ± 9.6	0.60
NLSy1	0.61 ± 0.11	17.09 ± 4.9	0.82	1.18 ± 0.52	−13.95 ± 22.9	0.92

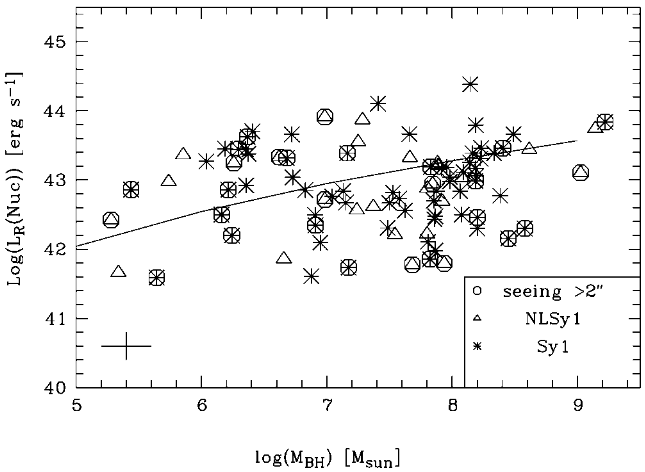

FIG. 4.—*R*-band luminosity vs. BH mass for the sample. Symbols are the same as in Fig. 2. At bottom left, typical errors are shown. The plotted line is not a fit but is the predicted relationship for an optically thick accretion disk with $\dot{M} = 0.1\dot{M}_{\rm Edd}$.

zation (and thus Hα flux) but would also provide more seed photons that would be upscattered to produce the power-law X-ray spectrum and thus the X-ray flux. This effect is unlikely to explain our correlation since simulations show that the contribution of the Hα emission line to the *R*-band flux is less than 1%.

Including the correlation with the radio luminosity leads to the consideration of a less direct, yet at least as plausible, coupling between the luminosities in the different wavelengths, namely, via the electron corona that is supposed to surround the accretion disk. The electron temperature distribution is expected to depend on the accretion disk properties, primarily the accretion rate and disk temperature. On the other hand, the temperature and density of the corona determine the efficiency of the Compton scattering and thus directly determine the slope and power of the X-ray spectrum. Thus, a change in the accretion rate, for example, would not only lead to a varying optical emission but, via the corona, would also lead to a varying X-ray and radio emission. The physical relation between the processes that produce the emission in the X-ray and radio remains at the level of speculation. In microquasars, the stellar-binary analogs of jet-emitting objects in our Galaxy, Rau & Greiner (2003) have recently found a similar correlation between the strength of the radio emission and the X-ray power-law slope. Owing to the smaller timescales involved in microquasars (due to their smaller BH mass), a whole continuum of jet strengths has been observed from bright, spatially resolved ejections over "baby jets" down to quasi-steady radio (synchrotron) emission. Adopting this similarity, one could argue that the core radio emission in Seyfert galaxies is associated with matter outflow from the central BH. Objects with higher activity at X-ray wavelengths, i.e., a higher accretion rate, may thus also show higher mass outflows from their central engine, thus implying a larger radio flux. Indeed, this is what has been found when comparing the X-ray and radio fluxes of galactic BH binaries in the low/hard state (Gallo, Fender, & Pooley 2003) and also of a sample of supermassive BHs of different classes (Merloni, Heinz, & Di Matteo 2003): the radio flux scales as X-ray flux to the power of 0.6–0.7. Surprisingly, this is (within the errors) the same correlation as we find (coefficient *c* in Table 2). Certainly, further investigations are necessary to understand the processes involved and their interrelation, but it is encouraging that seemingly the same processes are at work in AGNs and galactic BH binaries.

M. S. is grateful to Günther Hasinger and the AIP for their scientific and human support while M. S. was working on her Ph.D. M. S. also thanks A. Merloni, D. Pierini, and M. Radovich for their help and discussions. The authors thank the anonymous referee for his/her useful comments that improved the final version of this Letter. We made use of the publicly available NVSS and FIRST radio catalogs.

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