Multi-wavelength and black hole mass properties of Low Luminosity Active Nuclei

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Abstract.
We investigate the relation between the X-ray nuclear emission, optical emission line, radio luminosity and black hole mass for a sample of nearby Seyfert galaxies. Strong linear correlations between the 2-10 keV and [OIII], radio luminosities have been found, showing the same slopes found in quasars and luminous Seyfert galaxies, thus implying independence from the level of nuclear activity displayed by the sources. Moreover, despite the wide range of Eddington ratios (L/L_{Edd}) tested here (six orders of magnitude, from 0.1 down to 10^{-7}), no correlation is found between the X-ray, optical emission lines, radio luminosities and the black hole mass. These results suggest that low luminosity Seyfert galaxies are a scaled down version of luminous AGN and probably are powered by the same physical processes.

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INTRODUCTION

One of the distinctive characteristic of nearby nuclei is their intrinsic faintness, i.e. L_{Bol} < 10^{44} erg/s, as well as their low level of activity; in terms of Eddington luminosity most of them have L/L_{Edd} < 10^{-2} compared to L/L_{Edd} ∼ 1 of luminous AGN. Whether low luminosity AGN (LLAGN) are a scaled-down luminosity version of classical AGN or objects powered by different physical mechanism is a debated issue. It is not clear in fact, whether LLAGN are powered by radiatively inefficient accretion flows, such as Advection Dominated Accretion Flows (ADAF) and their variants (Narayan & Yi 1994) instead of the standard geometrically thin optically thick accretion disk typically proposed as the accretion mechanism acting in the central regions of luminous AGN (Shakura & Sunyaev 1973). LLAGN could also represent scaled up versions of black hole binaries in the steady-jet, hard X-ray state, as pointed out by the scaling relations reported in Falcke et al. (2004) and references therein. On one hand, ADAF models are able to predict some of the spectral properties observed in many LLAGN, such as the lack of the 'big blue bump' (Ho 1999). On the other hand, some LLAGN show properties which are common to luminous AGN, such as the observed correlations between optical emission lines and ionizing continuum (Ho & Peng 2001) or X-ray emission (Terashima
et al. 2000, Ho et al. 2001).

X-rays and radio emission are among the most direct evidences of nuclear activity and are, therefore, fundamental to study the accretion processes. It is particularly important to have a good characterization of the spectra and determine their nuclear luminosities.

Closely related to the theoretical and observational issues in LLAGN is the determination of the black holes masses. The observed radiative output (e.g., X-ray luminosities) combined with $M_{BH}$ estimates, allows us to measure the Eddington ratios and, therefore investigate the fundamental scaling of black hole properties with $M_{BH}$ and accretion rate, $\dot{m}$.

We have chosen to investigate LLAGN and their relation with luminous AGN by studying the properties of a well defined sample of nearby Seyfert galaxies In this work, we focus on the X-ray, radio and [OIII] emission line properties. The estimates of the central BH masses are then used to test the activity levels of the sources. The strength of our approach resides in the capability to correlate very accurate nuclear multi frequency luminosities for a homogeneous sample of nearby Seyfert galaxies and test them against their nuclear activity.

**THE SAMPLE AND THE DATA**

The Seyfert sample here presented comprises 47 out of 60 Seyfert galaxies from the Palomar optical spectroscopic survey of nearby galaxies (Ho, Filippenko, & Sargent 1995) for which X-ray data are available. The sources are classified as type 2 (34 out of 60), type 1 (13 out of 60), and "mixed" Seyfert galaxies (8), according to their position in the optical emission line diagnostic diagrams (Osterbrock 1981). The "mixed" Seyferts are placed near the boundary between Seyfert and LINER, HII or transition classification, resulting in a double classification (e.g., S2/T2, L2/S2, H/S2, etc.). See Panessa et al. (2006) for a more detailed description of the sample. For the purpose of our study this is one of the best samples available up to now. In fact, it offers an accurate optical classification and the opportunity of detecting weak nuclei. Finally, the sample covers a large range of AGN luminosities ($L_{2−10keV} \sim 10^{37−43}$ erg s$^{-1}$) making it ideal for exploring possible trends with AGN power.

An homogeneous and standard X-ray data analysis has been carried out on our selected Seyfert sample using *Chandra* and *XMM-Newton* observations. *Chandra* and *XMM-Newton* observations are available for 39 objects of the sample with 22 objects having observations with both observatories. The distributions of spectral parameters, in particular for type 1 objects, are found to be within the range of values observed in luminous AGN. The X-ray luminosities have been obtained in a homogeneous way and diffuse emission and/or off-nuclear sources have been excluded in order to get uncontaminated nuclear luminosities. A detailed description of the data analysis is reported in Cappi et al. (2006) and Panessa et al. (2006).
FIGURE 1. Log of 2-10 keV luminosity versus log of [OIII]λ5007 luminosity corrected for the Galactic and NLR extinction. The solid line shows the best fit linear regression line obtained by fitting the total sample of Seyfert galaxies, the PG quasars and bright type 1 Seyfert. Type 1 objects are plotted as filled polygons, type 2 as empty polygons, 'mixed Seyfert' objects as crosses and Compton thick candidates as stars.

LUMINOSITY-LUMINOSITY CORRELATIONS

The detection of an X-ray nucleus in almost all our sources is a strong evidence in favour of the presence of an AGN even at very low luminosities. The activity of the central source can also be investigated through the observed correlations between X-ray and optical emission line luminosities. In luminous sources strong correlations between Hα, Hβ, [OIII]λ5007 luminosities and X-ray luminosities have been found (Mulchaey et al. 1994 and references therein).

In Fig. 1 we show the 2-10 keV luminosity (corrected taking into account the presence of 'Compton thick' sources, Panessa et al. 2006) versus the [OIII]λ5007 luminosity (corrected for the Galactic and NLR extinction, Ho, Filippenko & Sargent 1997). Two comparison samples of bright AGN have been included in the analysis chosen for having both X-rays and [OIII]λ5007 fluxes available: 1) a sample of luminous type 1 Seyfert galaxies (hereafter QSO) from Mulchaey et al. (1994); 2) a sample of PG quasars (hereafter PG) from Alonso-Herrero et al. (1997). Luminosities have been adjusted to $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. The two chosen samples of luminous AGN are not meant to be complete and biases against low luminosity objects are probably introduced. However the low luminosity ranges are covered by our sample and they are just taken as representatives of the class of luminous sources.

The solid line in Fig. 1 is the best fit linear regression line obtained by fitting the Seyfert sample, the QSO and PG samples (Log $L_X = (1.22 \pm 0.06) \log L_{[OIII]} + (-7.34 \pm 2.53)$). The X-ray versus [OIII] correlation still holds in the flux-flux plot (rho=0.78, Prob < 0.001). The [OIII]λ5007 flux appears to be an absorption independent quantity, a good tracer of the AGN power and, therefore, useful to estimate the expected X-ray luminosity. Low Luminosity Seyfert galaxies behave like QSO and PG quasars.
suggesting a common physical nature for low and high luminosity AGN.

We further explore the relationship between the X-ray and radio luminosities, combining for the first time nuclear X-ray and core radio data obtained in recent surveys. Ho & Ulvestad (2001) have undertaken a new radio continuum survey of 52 Palomar Seyfert galaxies using the Very Large Array (VLA). The observations were made at 6 cm and at 20 cm with an angular resolutions of $\sim 1$ arcsec. The intrinsic 2-10 keV luminosity versus the core radio luminosity at 6 cm is plotted in Fig. 2. The X-ray versus radio luminosity correlations are highly significant (with a probability greater than 99.9%, using a partial Kendall $\tau$ correlation test). The best fit linear regression line is overplotted in Fig. 2: $(\log L_X = (0.97 \pm 0.01) \log L_{5\text{GHz}} + (5.23 \pm 0.28))$. The X-ray versus radio luminosity correlation in Fig. 2 shows a group of outliers, i.e. sources that show an excess in the radio emission with respect to the average X-ray/radio ratio shown by the sample. Interestingly, these sources have been classified in previous works as radio-loud objects.

The observed correlation suggests that the physics of the X-ray source is strongly related to the jet, where the radio emission is thought to arise. On one hand, there is a generally accepted physical model which predicts the X-ray emission properties in Seyfert galaxies, i.e. in a disk-corona system the UV-soft X-ray photons from the disk are comptonized and up-scattered into the hard X-ray band from the hot-corona placed above the accretion disk (Haardt & Maraschi 1991). On the other hand, the physics of jets in radio-quiet AGN is still unknown. It is not clear whether the jet is characterized by relativistic or sub-relativistic speed material (Bicknell 2004), or whether it is an aborted jet at the base of the corona (Ghisellini et al. 2004). The fact that the observed correlation is valid over $\sim 8$ orders of magnitude points to a coupling of the two components down to low luminosities.
FIGURE 3. Distribution of the log of $L_{\text{Bol}}/L_{\text{Edd}}$ ratio, assuming that $L_{\text{Bol}}/L_X \sim 30$. In both panels the shaded areas represent the distribution of type 1 Seyferts only.

BLACK HOLE MASS AND ACCRETION RATES

Black hole mass estimates are available for 44 out of 47 objects in our sample. The $M_{BH}$ from the literature, have been estimated in different ways from gas, stellar and maser kinematics to reverberation mapping or inferred from the mass-velocity dispersion correlations (Ferrarese 2002).

Black hole masses are fairly sampled from $\sim 10^5$ to $10^8 \, M_\odot$ with a peak at $10^{7-8} \, M_\odot$. No correlation is found between the X-ray, [OIII], radio luminosity and the black hole mass. Some previous studies found a correlation between the AGN luminosity and $M_{BH}$ (Kaspi et al. 2000 and references therein), however our result is in agreement with the lack of correlation found by Pellegrini (2005), Ho (2002) and Woo & Urry (2002).

The $L_{\text{Bol}}/L_{\text{Edd}}$ ratio distribution is plotted in Fig. 3 and it has been calculated assuming $L_{\text{Bol}}/L_{2-10\text{keV}} \sim 30$. This value is typical of luminous AGN, however it could depend on the shape of the spectral energy distribution. The $L_{\text{Bol}}/L_{\text{Edd}}$ ratio distribution for the total Seyfert sample covers a wide range of Eddington ratios going down to $10^{-7}$. Woo & Urry (2002) have shown that bright local AGN normally show Eddington ratios which span three orders of magnitude down to $L_{\text{Bol}}/L_{\text{Edd}} \sim 10^{-3}$. Indeed, most of our sources are radiating at very low Eddington ratios if compared with luminous AGN. The low Eddington ratios observed in our sample are even lower if the bolometric correction considered is that of LLAGN. At such low Eddington ratios, radiatively inefficient accretion is normally invoked as the putative mechanism for the production of the observed emission. As a matter of fact, ADAF models work in a radiatively inefficient regime at sub-Eddington ratios ($L < 0.01 L_{\text{Edd}}$) and can reproduce the lack of UV excess observed in the SED of LLAGN. However, also radiatively efficient standard accretion disks are stable at low Eddington ratios down to $L \sim 10^{-6} L_{\text{Edd}}$ (Park & Ostriker 2001) and probably could reproduce the shape of the LLAGN SED since the temperatures of a multi-colour disk scale with $m^{1/4}$ (Ptak et al. 2004). Actually, the X-ray versus op-
tical emission line and radio luminosity correlations scale with luminosity, so that low luminosity Seyfert galaxies appear to be a scaled-down version of classical AGN.

CONCLUSIONS

In the effort of further verifying the physical continuity between our sample of Seyfert galaxies and bright AGN, the X-ray luminosities have been correlated with the [OIII] and radio luminosities both suspected to be good tracers of the nuclear emission. These luminosities have also been correlated with $M_{BH}$. Both $L_X$ vs. $L_{[OIII]}$ and $L_X$ vs. $L_{5GHz}$ correlations are highly significant in our sample, indicating that the X-ray emission and the UV ionizing radiation are linked as well as the source of the radio emission, possibly a jet. Moreover, both correlations scale with luminosity over 8 orders of magnitude, suggesting that low luminosity Seyfert galaxies are powered by the same physical processes which operate in brighter AGN such as QSOs. No correlation is found between nuclear multi-band luminosities and $M_{BH}$ in agreement with some previous studies (Woo & Urry 2002, Pellegrini et al. 2005, Ho 2002). Finally, $L/L_{Edd}$ ratios span three orders of magnitude down to $L_{Bol}/L_{Edd} \sim 10^{-7}$, indicating that most of our sources are accreting at very low Eddington ratios. Overall our results suggest that Seyfert nuclei are consistent with being a scaled-down version of luminous AGN.

REFERENCES

1. Alonso-Herrero, A., Ward, M. J., & Kotilainen, J. K. 1997, MNRAS, 288, 977
2. Cappi, M. et al. 2006, A&A, 446, 459
3. Falcke, H., Körding, E., & Markoff, S. 2004, A&A, 414, 895
4. Ferrarese, L. 2002, ApJ, 578, 90
5. Ghisellini, G., Haardt, F., & Matt, G. 2004, A&A, 413, 535
6. Haardt, F., & Maraschi, L. 1991, ApJl, 380, L51
7. Ho, L. C. 2002, ApJ, 564, 120
8. Ho, L. C. & Peng, C. Y. 2001, ApJ, 555, 650
9. Ho, L. C. & Ulvestad, J. S. 2001, ApJs, 133, 77
10. Ho, L. C. et al. 2001, ApJl, 549, L51
11. Ho, L. C. 1999, ApJ, 516, 672
12. Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJ, 487, 568
13. Ho, L. C., Filippenko, A. V., & Sargent, W. L. 1995, ApJs, 98, 477
14. Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631
15. Mulchaey, J. S., Koratkar, A., Ward, M. J., Wilson, A. S., Whittle, M., Antonucci, R. R. J., Kinney, A. L., & Hurt, T. 1994, ApJ, 436, 586
16. Narayan, R., & Yi, I. 1994, ApJl, 428, L13
17. Pellegrini, S. 2005, ApJ, 624, 155
18. Panessa, F. et al. 2006, A&A, 455, 173
19. Park, M.-G., & Ostriker, J. P. 2001, ApJ, 549, 100
20. Ptak, A., Terashima, Y., Ho, L. C., & Quataert, E. 2004, ApJ, 606, 173
21. Shakura, N. I. & Sunyaev, R. A. 1973, A&A, 24, 337
22. Terashima Y., Ho L. C., Ptak A. F. 2000, ApJ, 533, 729
23. Woo, J.-H., & Urry, C. M. 2002, ApJ, 579, 530