Black Holes from Stars to Galaxies – Across the Range of Masses
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Radiatively inefficient accretion disks in low-luminosity AGN†

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Abstract. We study a complete and distance-limited sample of 25 LINERs, 21 of which have been imaged with the Hubble Space Telescope to study their physical properties and to compare their radio and optical properties with those of other samples of local AGNs, namely Seyfert galaxies and low-luminosity radio galaxies (LLRG). Our results show that the LINERs population is not homogeneous, as there are two subclasses: i) the first class is similar to LLRG, as it extends the population of radio-loud nuclei to lower luminosities; ii) the second is similar to Seyferts, and extends the properties of radio-quiet nuclei towards the lowest luminosities. The different nature of the various classes of local AGN are best understood when the fraction of the Eddington luminosity they irradiate, L_o/L_{Edd}, is plotted against the nuclear radio-loudness parameter: Seyferts are associated with relatively *high* radiative efficiencies $L_o/L_{\mathrm{Edd}} \gtrsim 10^{-4}$ (and high accretion rates onto *low* mass black holes); LLRG are associated with *low* radiative efficiencies (and low accretion rates onto *high* black hole masses); all LINERs have low radiative efficiency (and accretion rates), and can be radio-loud or radio quiet depending on their black hole mass.

Keywords. galaxies: active — accretion, accretion disks — galaxies: individual (NGC 4565)

1. Introduction

Low luminosity active galactic nuclei (LLAGN) are believed to be powered by accretion of matter onto the central supermassive black hole, similarly to powerful AGN. In a large fraction of LLAGN, the central black hole is as massive as in powerful distant quasars ($M_{\mathrm{BH}} \sim 10^8$–$10^9 M_\odot$), thus their very low nuclear luminosity implies that accretion occurs with very low radiative efficiency (or at very low rates); Ho (2004), Chiaberge *et al.* (2005). If so, the physics of the accretion process may be different from the "standard" optically thick, geometrically thin accretion disks. Because of the very low radiation they emit at all wavelengths, these objects are very difficult to observe. While the AGN nature of optical nuclear components seen in HST images of a sample of LLAGN have been unambiguously established it is still unclear whether the radiation is from a jet or from the accretion flow. LLAGN have also been found to lie on the so-called "fundamental plane of black hole activity" (Merloni *et al.* 2003; Falcke *et al.* 2004), which attempts to unify the emission from all sources around black holes, over a large range of masses and luminosities, from Galactic sources to powerful quasars. But the origin of such a "fundamental plane" and its relationship with the origin of the radiation is still a matter of debate.

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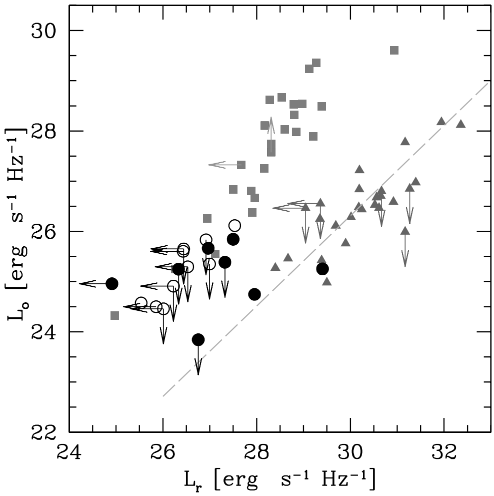

Figure 1. Optical nuclear luminosity vs. radio core luminosity for LINERs (circles), Seyferts (squares) and FR I radio galaxies (triangles). The dashed line is the correlation between the two quantities found for 3CR FR I sample. Open circles are LINERs in late-type hosts, filled circles are LINERs in early-type hosts.

2. LINERs in the framework of the local AGN population

Different accretion disk models are expected to show the largest difference in spectral shape in the IR-to-UV region. RIAFs should lack both the "big blue-bump" and the IR (reprocessed) bump, which instead characterize optically thick, geometrically thin accretion disk emission and the surrounding heated dust. For example, in low luminosity radio galaxies non-thermal emission from the jet dominates the optical nuclear radiation (Chiaberge *et al.* 1999), while the Galactic center is not visible in the optical because it is hidden by a large amount of dust.

We have studied a complete and distance-limited sample of 25 LINERs, 21 of which have been imaged with the Hubble Space Telescope. In nine objects we detect an unresolved nucleus. In order to study their physical properties, we compare the radio and optical properties of the nuclei of LINERs with those of other samples of local AGNs, namely Seyfert galaxies and low-luminosity FR I radio galaxies (LLRG, Fig. 1). The radio-optical correlation found for FR I, which is best explained as the result of a single emission process in the two bands (i.e. non-thermal synchrotron emission from the base of the relativistic jet), provides us with a powerful tool to investigate the origin of the nuclei. We have shown that in the radio-optical plane of the nuclei there is a clear separation between Seyferts and radio galaxies. For similar radio core luminosity, Seyfert 1 are significantly brighter in the optical than FR I. Therefore, although most Seyferts have $R = L_{5\mathrm{GHz}}/L_B > 10$, radio-quiet and radio-loud AGN appear to be still well differentiated. This implies that the nuclear physical properties of the two classes are significantly different. Our results show that the LINERs population is not homogeneous, as there are two subclasses: i) the first class is similar to LLRG, as it extends the population of radio-loud nuclei to lower luminosities; ii) the second is similar to Seyferts, and extends the properties of radio-quiet nuclei towards the lowest luminosities. Furthermore, all radio-loud LINERs have $M_{\mathrm{BH}}/M_\odot \gtrsim 10^8$, while Seyferts and radio-quiet LINERs have $M_{\mathrm{BH}}/M_\odot \lesssim 10^8$.

We have derived the radiative efficiency of the accretion process around the central black holes in our samples of local AGN. All of them emit only a small fraction of the Eddington luminosity. Although the determination of the bolometric luminosity is uncertain because of the lack of detailed spectral information, the accretion process in LINERs appears to take place on a highly sub-Eddington regime ($L_o/L_{\mathrm{Edd}} < 10^{-5}$, and can be as low as $\sim 10^{-8}$). Such low values are clearly not compatible with the expectations

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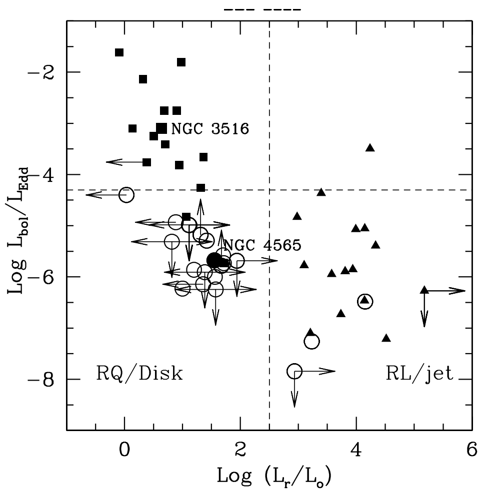

Figure 2. Optical to Eddington luminosity ratio plotted against the radio to optical ratio (the "nuclear radio-loudness") for the sample of nearby LLAGN; cf. Chiaberge *et al.* (2005). Seyfert 1s are plotted as squares, low luminosity radio galaxies are triangles, LINERs are empty circles. NGC 4565 (filled circle) and the Seyfert 1 galaxy NGC 3516 (large square) are also marked in the figure. The dashed lines are only used to guide the eye and divide objects of high and low Eddington ratio (top and bottom of the figure) and radio-quiet (disk-dominated nuclei, left) or radio loud (jet dominated nuclei, right).

from a standard optically thick and geometrically thin (quasar-like) accretion disk. Thus, low accretion rates and/or low efficiency processes appears to be required in all LINERs. Our results are qualitatively in agreement with Ho (2004), who made use of the $H\alpha$ emission line as an indicator of the AGN power for a large sample of Seyferts and LINERs.

The different nature of the various classes of local AGN are best understood when the fraction of the Eddington luminosity they irradiate is plotted against the nuclear radio-loudness (Fig. 2). Our objects populate three different quadrants, according to their physical properties. We identify Seyferts and radio-quiet LINERs as the high and low accretion rate counterparts, respectively. For low accretion regimes, the nuclei appears to be "radio-loud" only when a more massive black hole ($M_{\rm BH} > 10^8 M_\odot$) is present. We speculate that the fourth quadrant, which appears to be "empty" in the local universe, would contain radio-loud nuclei with high $L_o/L_{\rm Edd}$, readily identified with radio loud quasars.

We further tested this picture by studying the nuclear spectral energy distribution of a galaxy, NGC 4565, that seems to be a perfect candidate for hosting a RIAF around the central supermassive black hole. The object is part of the "Palomar sample" of LLAGN (Ho *et al.* 1997a), and it is included in both the Merloni *et al.* (2003) and Falcke *et al.* (2004) samples that were used to define the "fundamental plane of black hole activity". It is worth mentioning that NGC 4565 does not show any significant peculiarity in that plane. NGC 4565 is a nearby (d=9.7 Mpc) LLAGN classified as a Seyfert 1.9 because of the possible presence of a faint, relatively broad (FWHM = 1750 km s^{-1}) Hα line. Although it is a Type 2 Seyfert, this object is only moderately absorbed, and the nuclear radiation is visible in the optical spectral region. NGC 4565 may thus represent the first clear example of low-luminosity accretion onto a supermassive black hole in the optical band.

The SED (Fig. 3) is peculiar, as it is almost flat in a $\log\nu - log(\nu F\nu)$ representation, with no sign of both a UV bump and thermally reprocessed IR emission. The very low luminosity of the source associated with a relatively high central black hole mass imply an extremely small value of the Eddington ratio ($L_o/L_{\rm Edd} \sim 10^{-6}$). This, together with the position occupied by this object on diagnostic planes for low luminosity AGN, represents clear evidence for a low radiative efficiency accretion process at work in its innermost regions.

The fact that the [OIII] emission line flux is substantial in this object implies that an extended narrow line region, similar to other Seyfert galaxies, is still present in NGC 4565.

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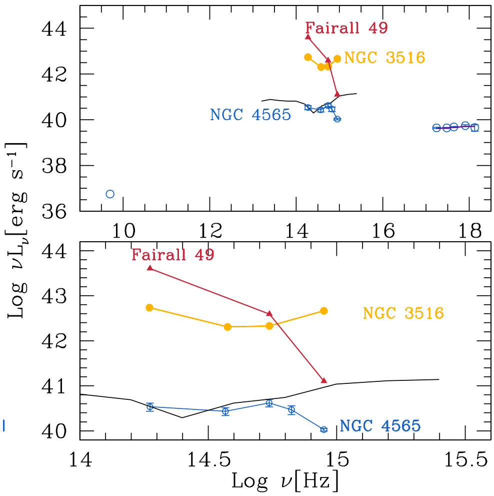

Figure 3. Absorption corrected nuclear spectral energy distribution of NGC 4565 from the radio to the X-ray band. The X-ray spectrum has been significantly re-binned to improve the clarity of the figure. The solid line superimposed to the X-ray data is a spectral model used to fit the data. For comparison, we show the IR-to-UV SED of a Seyfert 1 (NGC 3516) and of a Compton-thin Seyfert 2 (Fairall 49). The solid line is the average SED of radio-quiet QSO from Elvis *et al.* (1994), normalized to the flux of NGC 4565 in the F814W filter. The lower panel is a zoom into the IR-to-UV spectral region.

A possible intriguing scenario is that the active nucleus has recently "turned-off", switching from a high efficiency, standard, accretion disk, to a radiative inefficient accretion process. However, since the EW of the [OIII]5007 emission line is rather small, with the present data we cannot rule out that the amount of ionizing photons from the RIAF is sufficient to produce the observed [OIII] flux.

3. Conclusions

The scenario we propose needs further investigation, since optical detections of the nuclei are available for a minority of the LINER's sample. Thus, deep imaging with high spatial resolution (achievable only with the Hubble Space Telescope) are crucial. In particular, when suitable observations of a large number of LINERs will be available, it will be possible to address whether the dichotomy persists or some of the low black hole mass objects with optical upper limits mix with the population of "radio-loud" LINERs. Clearly this would falsify our scenario for the role of the black hole mass in determining the radio-loudness of the nuclei. Deep imaging of a larger complete sample would also address the issue of whether there is continuous transition between the two classes. This is indeed a subject of great interest in the study of high luminosity quasars and for a more complete understanding of the overall subject should be also extended to lower end of the AGN luminosity function.

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