On the origin of radio-loudness in AGNs and its relationship with the properties of the central supermassive black hole

Marco Chiaberge\textsuperscript{1,2} and Alessandro Marconi\textsuperscript{3}

\textsuperscript{1}Space Telescope Science Institute, Baltimore, MD 21218
\textsuperscript{2}INAF - IRA, Via P. Gobetti 101, Bologna, I-40129
\textsuperscript{3}Dipartimento di Fisica e Astronomia, Università di Firenze, L.go E. Fermi 2, Firenze I-50125

ABSTRACT
We investigate the relationship between the mass of central supermassive black holes (SMBH) and the radio loudness of active galactic nuclei. We use the most recent calibrations to derive “virial” black hole masses for samples of radio loud QSOs for which relatively small masses ($M_{BH} < 10^8 M_\odot$) have been estimated in the literature. We take into account the effect of radiation pressure on the BLR which reduces the “effective” gravitational potential experienced by the broad-line clouds and affects the mass estimates of bright quasars. We show that in well defined samples of nearby low luminosity AGNs (LLAGN), QSOs and AGNs from the SDSS, radio-loud AGN invariably host SMBHs exceeding $\sim 10^8 M_\odot$. On the other hand, radio–quiet AGNs are associated with a much larger range of black hole masses. The overall result still holds even without correcting the BH mass estimates for the effects of radiation pressure. We present a conjecture based on these results, which aims at explaining the origin of radio-loudness in terms of two fundamental parameters: the spin of the black hole and the black hole mass. We speculate that in order to produce a radio-loud AGN both of the following requirements must be satisfied: 1) the black hole mass $M_{BH}$ has to be larger than $\sim 10^8 M_\odot$; 2) the spin of the BH must be significant, in order to satisfy theoretical requirements. Taking into account the most recent observations, we envisage a scenario in which the merger history of the host galaxy plays a fundamental role in accounting for both the properties of the AGN and the galaxy morphology, which in our picture are strictly linked. On the one hand, radio loud sources might be obtained only through major “dry”mergers involving BH of large mass, which would give rise to both the “core” morphology and the significant black hole spin needed. On the other hand, radio quiet AGNs might reside in galaxies that underwent different evolutionary paths, depending on their black hole mass.

Key words: galaxies: active – galaxies: evolution – galaxies: nuclei – galaxies: fundamental parameters.

1 INTRODUCTION
Radio-loud (RL) and radio quiet (RQ) AGNs exist at all luminosities. The distinction between the two classes is usually made by using the so-called radio loudness parameter $R$, i.e. the ratio between the radio flux at 5GHz and the optical flux in the B band. While powerful RL and RQ quasars quasars typically separate at values of $R \sim 10$, at the lowest luminosities, the transition occurs at a much higher value (e.g. Xu, Livio, & Baum 1999; Terashima & Wilson 2003; Chiaberge et al. 2005; Sikora et al. 2007). The general interpretation is that the output of radio-loud nuclei is energetically dominated by the jet, while that of radio-quiet AGNs is mostly dominated by the accretion disc. However, the physical reasons for the origin of the observed differences still remain unknown. How can an AGN develop a radio jet on either large scales (hundreds of kpc or even larger) or small (pc or sub-pc) scales? Why some AGN posses such energetically dominant jets and others do not? How are the mass and the spin of the central SMBH related to the radio-loudness? These questions are central not only for a complete understanding of the AGN phenomenon but also to assess the role of the central supermassive black hole in the evolution of the galaxy, the rise of a “radio phase” and its impact on the
evolution of the galaxy itself and on the environment (e.g. Best et al. 2005; Bower et al. 2006; Croton et al. 2006).

Jets are most likely formed by extracting rotational energy from the black hole and the accretion disc through magnetic forces (Blandford & Znajek 1977; Blandford & Payne 1982). Jet production may also help to remove angular momentum and drag material towards the black hole. Understanding under which physical conditions accreting black holes are capable of producing some sort of collimated outflow is not the only critical point. It is more crucial to understand which mechanism may be able to produce a (relativistic) jet whose radiative output is a significant fraction of the accretion luminosity, and which may even become the dominant source of radiation (e.g. Allen et al. 2006; Celotti & Ghisellini 2008). The jet power is somehow related to the spin of the black hole, as the B-Z mechanism clearly establishes (Blandford & Znajek 1977). However, other parameters such as the magnetic field and, possibly, the mass of the black hole, may also come into play. Significant effort has been devoted to investigate such an issue, but no general consensus has yet been reached. Franceschini, Vercellone, & Fabiani (1999) found a tight correlation of the black hole mass with radio power in a sample of local AGNs. Lao (2000) studied a sample of PG QSOs, and set a limit for radio loud objects at M ∼ 10^8 M⊙, a similar result being found by Dunlop et al. (2003) and Best et al. (2003). Xu, Livio, & Baum (1999) pointed out that the distribution of L_{Q(II)} for radio loud AGN extends to higher luminosities than that of radio quiet sources, and noted that such a result is consistent with a higher “maximum” black hole mass in radio loud AGNs. However, other authors have found evidence for the opposite, i.e. there is a significant fraction of radio-loud AGNs associated with black holes of relatively small mass (e.g. Ho 2002; Woo & Urry 2002; Rafter et al. 2009).

Clearly, our understanding of the link between the radio-loudness and the BH mass critically depends on the accuracy of the BH mass estimate. Direct BH mass estimates based on spatially resolved stellar and gas kinematics are possible only in the local universe (D < ∼ 200 Mpc), and their complexity does not allow their application to large samples (e.g. Ferrarese & Ford 2005). Estimates of BH masses in large samples of objects at all redshifts are only possible in AGNs with broad emission lines: BH masses are estimated by applying the virial theorem M_BH = fAV^2R_{BLR}/G (see e.g. Peterson 2004; Vestergaard 2011; for recent reviews on the subject) where f is a calibration factor, AV is the broad line width and R_{BLR} is the average BLR size, usually estimated from the AGN continuum luminosity following the R_{BLR} - L relation by Kaspi et al. (2004, see also Bentz et al. 2009). It is currently believed that the accuracy of these estimates is of the order of 0.3-0.5 dex r.m.s. (Peterson 2014). Recently, Marconi et al. (2008, 2009) pointed out that BLR clouds are subjected to radiation pressure from the absorption of ionizing photons and provided a simple additive correction to the above virial relation, which is proportional to the continuum luminosity. Such correction increases BH mass estimates in AGN with significant luminosities compared to their BH mass.

In this paper, we build on the results shown in Chiaberge et al. (2005) and we further investigate the relationship between the mass of the central supermassive black hole (SMBH) and the radio loudness of the active nucleus using samples of AGNs at all luminosities, and BH mass estimates obtained with different methods. In Sect. 2, we briefly describe the samples of AGN we consider; in Sect. 3, we describe the methods we use to estimate the mass of the central black hole; in Sect. 4, we describe the results and in Sect. 5, we discuss our findings, we propose a possible scenario to interpret the results of this work, and we draw conclusions.

2 THE SAMPLES

It is very important to investigate whether the mass of the central BH plays a role in determining the radio-loudness of the associated AGN in objects of all luminosities, from nearby nuclei with faint activity to the most powerful quasars. However, it is also extremely important to discuss objects of different AGN powers separately, in order to avoid misinterpreting the results. In the following sections we briefly describe the AGN samples used in this paper.

2.1 Low luminosity AGNs

We consider the following samples of nearby low luminosity AGN:

1) The complete sample of FR I Radio Galaxies at redshift z < 0.1 (i.e. low luminosity radio galaxies) from the 3CR catalog (Spinrad et al. 1983; Chiaberge et al. 1999). The 3C sample is selected in the radio band at a low frequency (178MHz), therefore it is free from any orientation biases.

2) Seyfert 1 galaxies from the optically selected Palomar Survey of nearby galaxies and from the CfA sample (Ho & Peng 2001). We include only the Type 1 objects, since the line-of-sight to the nuclei is thought to be obstructed by dust in those belonging to the Type 2 class.

3) A complete, distance limited (d < 19 Mpc) sample of LINERs taken from the Palomar Survey of nearby galaxies (Ho et al. 1997).

4) 51 nearby early-type galaxies (E+S0) with radio emission > 1 mJy at 5 GHz (optical + radio selection) (Capetti & Balmaverde 2003, and references therein). The large majority of the galaxies in the sample are spectroscopically classified as either LINER or Seyfert. A detailed description of this sample is given in Capetti & Balmaverde (2003).

5) The 12 broad-line radio galaxies with z < 0.3 included in the 3CR catalog (Chiaberge et al. 2005, and references therein).

Samples 1, 2 and 3 have been studied in detail in Chiaberge et al. (2005) and more details about those samples can be found in that paper. The sample of nearby ellipticals (4) partially overlaps with samples 1, 2, and 3. However, there are only 10 objects in common, so the total number of objects considered here is 142. Note that being selected according to different criteria, these objects do not constitute a complete sample. However, they well represent the overall properties of all kinds of low power active nuclei in the local universe.

We do not discuss in detail the sample of Hα (2002), which also claimed to find radio-loud AGNs associated with low mass black holes, for two reasons. Firstly, the sample
on the origin of radio-loudness in AGNs

2.2 QSO samples

We focus on samples of radio selected radio-loud QSOs taken from Oshlack, Webster, & Whiting (2002) and Gu, Cao, & Jiang (2001, and references therein), which were found to include a significant number of SMBH with estimated mass lower than $\sim 10^8 M_\odot$. The sample of Oshlack, Webster, & Whiting (2002) comprises flat-spectrum radio loud quasars. These objects might be significantly affected by relativistic beaming, which enhances the radiation both in the radio and in the optical. The redshifts of all QSOs in the above samples are in the range 0 $< z < 1$.

We also consider the sample of high-z (2.0 $< z < 2.5$) QSOs of McIntosh et al. (1999), which includes very luminous ($L \sim 10^{49} - 10^{50} \, \text{erg s}^{-1}$) quasars of both radio-loud and radio-quiet class.

Note that all of the above samples of quasars were included in the study of SMBH masses in AGN made by Woo & Urry (2002a) and Woo & Urry (2002b).

2.3 SDSS AGNs

We also include in our analysis the sample of “broad lined” AGNs from Rafter et al. (2009) and references therein, which consists of objects selected from the Sloan Digital Sky survey (DR5, Schneider et al. 2007) with $z < 0.35$, for which radio counterparts have been found in the VLA FIRST survey (Becker, White, & Helfand 1995). The sample includes a significant number of low luminosity AGNs ($L_{\text{H}\alpha} < 10^{42} \, \text{erg s}^{-1}$) and is extracted from the list originally selected by Greene & Ho (2007). However, higher luminosity objects ($L_{\text{H}\alpha} \sim 10^{43-44} \, \text{erg s}^{-1}$) are also represented in the sample.

3 METHODS FOR BLACK HOLE MASS ESTIMATES

The SMBH masses for the objects belonging to the samples considered here are estimated using different methods, from gas kinematics to single epoch estimates based on scaling relations (see e.g. Vestergaard 2009).

The BH masses of LLAGNs taken from Chiaberge et al. (2003) are derived using either the relation with the stellar velocity dispersion (Tremaine et al. 2002) or more direct measurements from e.g., gas kinematics taken from the literature. For a fraction of the Seyfert 1 galaxies (the brightest objects belonging to that sample), the estimates were made using reverberation mapping. More details for the samples of FRs, Seyferts and LINERs can be found in Chiaberge et al. (2003, and references therein). For the samples of early-type galaxies of Capetti & Balmaverde (2003), the BH mass estimates are made using the relation of Tremaine et al. (2002). Black hole masses for 3CR BLRG are also derived using the same method, with the only exception of 3C290.3 for which we used data from reverberation mapping (Kaspi et al. 2000). For these LLAGN samples we use the SMBH masses from the literature since the updated scaling relations do not provide significantly different values for those objects.

Furthermore, we note that the updated relation between the BH mass and the central velocity dispersion provided by G"ultekin et al. (2009) does not return values significantly different from those obtained with the $\text{[Tremaine et al. (2002)]}$ formula, for the purpose of this work.

In the following we will also make use of the relation between BH mass and near-IR host spheroid luminosity (Marconi & Hunt 2003). Such relation has a scatter similar to the relation with the stellar velocity dispersion, and has therefore a similar accuracy (e.g., Marconi & Hunt 2003; Graham 2007; Hui 2004).

The BH virial masses for all of the above QSO samples published in the literature were derived using single epoch estimates based on scaling relations. The formulae typically use the FWHM of a broad emission line (usually H$\alpha$ or H$\beta$, and more rarely CIV) and the luminosity of the adjacent continuum as crucial parameters. Those relations are calibrated using calibrated low-z Type 1 AGNs of a broad range of luminosities for which the BH masses are known from reverberation mapping techniques (see Vestergaard 2009 for a review).

Here we first estimate the BH masses for all QSOs using the most updated formulae (Vestergaard & Peterson 2006), calibrated to up-to-date reverberation mapping masses. Furthermore, as noted by Marconi et al. (2008), the radiation from the accretion disc exerts pressure on the broad line clouds which opposes the gravitational attraction of the black hole. Therefore, in particular for the more luminous quasars, the BLR may actually experience a smaller “effective” gravitational field. Thus the mass of the BH might be underestimated when using single epoch estimates and the FWHM of broad emission lines such as H$\alpha$ and H$\beta$ as crucial parameters. Marconi et al. (2008, 2009) calibrated the effects of radiation pressure on the BLR. In this paper we use the most up-to-date version of the radiation pressure-corrected virial relation to estimate BH masses (Marconi et al. 2011, in preparation). The formula we use is the following:

\[
\frac{M_{\text{BH}}}{M_\odot} = 10^{6.6} \left( \frac{\text{FWHM}(\text{H}\beta)}{1000 \, \text{km s}^{-1}} \right)^2 \left( \frac{L_{\lambda}(5100 \AA)}{10^{44} \, \text{erg s}^{-1}} \right)^{0.5} + 10^{7.5} \times \left( \frac{L_{\lambda}(5100 \AA)}{10^{44} \, \text{erg s}^{-1}} \right) \]

(1)

where we use H$\alpha$ when measurements of H$\beta$ are not available. The coefficients $10^{6.6}$ and $10^{7.5}$ correspond to the $f$ and $g$ coefficients in Marconi et al. (2008), respectively. The values used in this work have been improved based on new data, but they do not significantly differ from the original values.

The presence of outward radiation forces on BLR clouds is an unavoidable physical effect due to the injection of momentum from the absorption of ionizing photons; its effect on virial mass estimates is negligible only if one makes the (unlikely) assumption that all BLR clouds have
very large column densities $N_H > 10^{24} \text{cm}^{-2}$ (Netzer 2009, Marconi et al. 2009). Recently, Netzer & Marziani (2011) studied the motions of BLR clouds under the combined effects of gravity and radiation pressure. They concluded that, even if radiation pressure is important, BH masses derived from the simple virial product are not significantly underestimated. However, that conclusion strongly depends on the assumption that BLR clouds are moving in pressure equilibrium within a confining medium, whose assumed pressure gradient tunes cloud column densities during their orbits. All clouds must survive several dynamical timescales (i.e. must complete several orbits) so that on average the virial product will not be affected by radiation pressure. Some kind of magnetic confinement is invoked for the clouds (e.g. Ferland & Rees 1988), but overall it is not clear from this model how can the clouds avoid Rayleigh-Taylor and Kelvin-Helmholtz instabilities (e.g. Mathews & Ferland 1982). Moreover the only direct observations of the structure of BLR clouds based on eclipsing of the X-ray AGN source suggest a cometary-like structure, as expected from supersonic motions of dense clouds in a less dense medium, and indicate a short lifetimes of BLR clouds, less than the orbital time scale (Maiolino et al. 2010). A detailed discussion of these issues will be subject of a forthcoming paper (Marconi et al. 2011, in preparation). See also Sect. 4.3 for a short discussion about the impact of such a correction on our results.

4 RESULTS

4.1 Low luminosity AGNs

In Fig. 1 we plot the estimated BH mass vs. the radio loudness parameter $R$ for the samples of nearby LLAGN. The properties of the objects belonging to that sample are well defined, thus allowing us to derive robust results. Most importantly, their nuclear emission can be resolved by using the VLA and HST for the radio and the optical bands, respectively. This allows us a direct comparison between their faint nuclei and the nuclei of powerful quasars, minimizing the contributions of the host galaxy stellar emission (see Chiaberge et al. 2005). Seyferts are plotted as triangles, power-law galaxies as stars, LINERs as squares, FR Is as filled circles, core-galaxies as empty circles, and BLRGs as pentagons.

The first piece of information that is important to bear in mind is that at low AGN powers, the “separation” between RQ and RL nuclei occurs at a much higher value of the radio loudness parameter (Chiaberge et al. 2005, Sikora et al. 2007) than for powerful QSOs. The reason for such a behavior is still unclear. Sikora et al. (2007) showed that such a separation is a function of the Eddington ratio $L_o/L_{Edd}$. Therefore, it is possible that a change in the nuclear SED, corresponding to, e.g., a change in some of the physical properties of the accretion disc, might result in a different value of $R$ for the transition between a jet-dominated and a disk-dominated AGN. However, a detailed analysis of this subject is beyond the subject of this paper.

The dashed line at $R = 2$ in Fig. 1 is drawn with the purpose of visually separating objects for which the optical emission is disc-dominated (radio-quiet, left-hand side of the plot) from objects that are jet-dominated (radio-loud, right-hand side). Note that BLRG (blue pentagons) are present in both sides of the plane. This is due to the fact that BLRG are objects seen at intermediate viewing angles with respect to the jet direction (see e.g. Barthel 1989, Grandi & Palumbo 2000). Therefore, most likely because of relativistic beaming effects, in some of those objects the jet dominates the optical emission, while in others the jet radiation is “de-beamed” and the disc is bright enough to overshadow the jet. Their location may also be affected by variability. However, independently of their location, it is clear that those are “intrinsically” radio-loud objects, i.e. they do produce powerful relativistic jets, irrespective of the observed dominant radiation source.

As already noted by Chiaberge et al. (2005), all RL LLAGN are associated with BH masses $> 10^8 \text{M}_\odot$, while most of the RQ population has lower BH masses. A similar result has been recently found by Baldi & Capetti (2010). There seems to be a “region of avoidance”, in the bottom-right part of the plot, as radio-loud LLAGN with small black hole mass are absent. While it is clear that radio quiet AGN

\[ \text{Netzer} \]
exist at all BH masses, the question is whether radio loud AGN associated with small BH masses exist at all. Note the location of the Seyfert galaxy MCG–6–30–15 on the left hand side of the plane, at a BH mass of $\sim 6 \times 10^6 \, M_\odot$ (McHardy et al. 2007). This is an extremely important object, since it is probably the most compelling example of maximally spinning SMBH in AGN (e.g. Iwasawa et al. 1994; Miniutti et al. 2007). A high BH spin has been often claimed to be the origin of radio-loudness (Blandford 1990), but MCG–6–30–15 is radio quiet. However, the BH mass is at least 1 dex smaller than any RL AGN in these samples. This points to the idea that the spin alone cannot give rise to radio loudness and is consistent with the suggestion presented in this paper (see Sect. 5).

### 4.2 QSOs

While it is clear that the above results hold for the selected (although well defined) sample of objects, the question is whether it can be extended to larger samples of objects and for AGNs of higher luminosity. In order to do so, in Fig. 2 we plot the samples of QSOs described in Sec. 2.2. These are particularly important samples, since relatively small black hole virial masses ($< 10^8 \, M_\odot$) have been estimated in the literature for a significant fraction of objects.

Firstly, we re-calculated the BH masses for all QSOs in those samples using the most updated formulae for virial mass estimates derived by Vestergaard & Peterson (2006), and adopting the WMAP cosmology (Hinshaw et al. 2009) $H_0 = 71 \, \text{Km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$. The results are shown as open symbols in Fig. 2 (triangles, pentagons and squares represent the Gu et al., Oshlack et al. and McIntosh et al. samples, respectively). Note that although the high-z sample of McIntosh et al. (1999) is clearly biased against low BH masses, it is useful to have it included in our analysis in order to show that RQ QSOs are associated with both high and low BH masses and no physical correlation between radio-loudness and BH mass exists, as already pointed out by various authors (Woo & Urry 2002). Although the number of objects with $M_{BH} < 10^8 \, M_\odot$ is significantly smaller than found in the above cited papers as a result of the updated formulae we used in this paper, a few objects are still present in the radio loud and small BH mass region of the plane (see Fig. 2). Marconi et al. (2009) and Marconi et al. (2008) have recently pointed out that for high luminosity QSOs, the effects of radiation pressure on the broad line clouds (in particular for the Hydrogen lines) should be included in the BH mass estimate. We applied the most updated corrections (Marconi et al. 2011, in preparation) and we calculated the BH mass for all objects. The results are plotted as filled symbols in Fig. 2. It is now clear that all QSOs in these samples, both RQ and RL, have BH masses above a certain threshold, somewhere close to $10^8 \, M_\odot$.

### 4.3 SDSS AGNs

We also want to check that larger samples of AGNs selected with respect to their optical spectroscopic properties behave as the samples of AGNs discussed above. In order to do so, we consider the sample from the SDSS published in Rafter et al. (2009). A number of “radio-loud” AGNs associated with small BH masses have been found in that sample. The BH masses were estimated using the Hα FWHM, under the assumption that the optical continuum flux at 5100Å is indicative of the AGN luminosity. Note that this assumption may not be true for the lowest luminosity objects, in which the stellar emission from the host galaxy may dominate the optical flux at that wavelength.

As already pointed out above, at low luminosities and for low values of the Eddington ratio, the RQ/RL division occurs at or above $\log R \sim 2$ (Chiaberge et al. 2001; Sikora et al. 2004), therefore the number of bona fide “radio loud” AGN in the Rafter et al. sample should be reconsidered taking into account the luminosity class of the objects. In Fig. 3 we plot the BH mass versus radio loudness for the sub-sample of AGN detected in the radio band from Rafter et al. (2009). We use a color coding for different luminosity classes, and we adopt the luminosity of the broad component of the Hα emission line as a (rough) indicator of the AGN power. First of all, we note that the most
luminous AGNs (L_{H α} \gg 3 \times 10^{41} \text{ erg s}^{-1}) are all associated with large BH masses M_{BH} \gg 10^8 M_\odot. The objects appear to be clustered in the RQ region (left hand side) and the peak of the AGN radio-loudness distribution appears to shift from log R \sim 2 for AGNs of very low Hα luminosities, to log R \sim 1 at the highest luminosities. Assuming log R = 1 as the RQ/RL threshold, the percentage of RL objects increases from \sim 20% for objects with L_{H α} > 10^{41} \text{ erg s}^{-1} to 65% in the luminosity bin between L_{H α} = 10^{41} \text{ erg s}^{-1} and L_{H α} = 10^{42} \text{ erg s}^{-1}. Even if we cannot infer the actual fraction of radio-loud AGNs from that sample, it is unlikely that the apparent lack of high luminosity radio loud AGNs (M_{BH} > 8, R > 1, L_{H α} > 10^{42} \text{ erg s}^{-1}) with respect to lower luminosity objects is due to a selection effect. In fact, the sample could in principle be biased against distant radio quiet objects, but the radio loud ones are certainly not affected. Therefore, that just confirms that the RQ/RL dividing line shifts towards higher values of R for objects of decreasing luminosity. In fact, if we assume log R = 2 for the RQ/RL division in the lowest luminosity bin, the percentage of RL objects returns to a more reasonable value of \sim 10%. The diagonal dot-dashed line in Fig. 3 is only used for the purpose of guiding the eye and follow the change in RQ/RL division with AGN luminosity.

Firstly, we search the recent literature for black hole mass estimates based on different indicators. We find five objects in common with the sample analyzed by Shen et al. (2010), which perform careful line width measurement after continuum subtraction. We use the FWHM of the Hβ emission line and the continuum luminosity L_{2500} from that work, and we estimate the BH mass using the updated Marconi et al. (2008) formula, which includes the effect of radiation pressure on the BLR. The BH mass estimates obtained with this method (see Table I) are significantly larger than those estimated by Rafter et al. (2009). The use of Hβ instead of Hα also ensures higher accuracy, since the Hβ line is relatively isolated, and its relation with the BH mass is better calibrated. That is especially true for AGNs of relatively low luminosity, where we do not anticipate a strong contribution from the FeII lines in the Hβ spectral region.

We could not find other BH mass estimates in the literature for the remaining 31 objects. However, the large majority of these AGNs are associated with low redshift bright early-type galaxies. For early-type galaxies, which typically show red colors (u-r > 2.22 [Strateva et al. 2001]) compatible with an old stellar population, we can estimate the mass of the black hole using the correlation with the K-band near IR luminosity (Marconi & Hunt 2003), as obtained from the 2MASS catalog (NED). We can apply such a method to eighteen objects in the sample. For two out of these eighteen objects the K-band magnitude from the 2MASS is not available from NED, therefore we download the fits images and we measure the magnitude from the images. The BH masses we derive using the correlation with the IR magnitude are all larger than 10^8 M_\odot (see Table I). One further object with u-r = 2.22 (namely SDSS J090307.84+021152.2) is a Type 2 QSO/ULIRG, therefore its K-band flux might be contaminated by emission related to the hot dust surrounding the AGN. We checked the HST/WFPC2 image of that object and at 8100 \AA the galaxy morphology appears irregular, with possible presence of dust and star forming clumps. If the 2MASS flux is used, its estimated BH mass is 2 \times 10^9 M_\odot, but we believe that such a value is most likely unreliable.

We still have to check the 12 objects for which the BH mass cannot be reliably estimated using the K-band magnitude because of their blue colors, and for which no other BH mass estimates are found in the literature.

For J142237.91+044848.5 and J163323.58+471858.9 the FWHM of the Hα line is smaller than 1000 km s^{-1}, which is often used as the threshold values between Type 1 and Type 2 AGN (see e.g. Antonucci 1993). In those objects, the mass of the BH cannot be reliably estimated from those measurements, unless the width of the forbidden lines is significantly smaller than that of the permitted lines. From visual inspection of the SDSS spectra (and “quick and dirty” line fitting) that does not appear to be the case. The detected emission lines are most likely produced in large scale regions not under the direct influence of the black hole gravitational field.

J075444.08+354712.8 and J115409.27+023815.0 are “bona fide” Type 1 AGNs (i.e. the measured FWHM of Hα
On the origin of radio-loudness in AGNs

Table 1. Data for AGNs with R > 2 and log $M_{BH} < 7.5$ in the SDSS sample of Rafter et al. (2009).

| SDSS Name | z    | R    | log $M_{BH}$ | u-r  | log $M_{BH}$ | Notes                |
|-----------|------|------|--------------|------|--------------|----------------------|
| J003443.51-000226.6 | 0.042 | 2.44 | 6.1          | 2.31 | 8.3          | –                    |
| J075244.19+455657.3 | 0.0517 | 2.07 | 6.9          | 2.73 | 8.8          | –                    |
| J075444.08+354712.8 | 0.257 | 2.55 | 7.4          | 1.09 | 7.8          | –                    |
| J083045.21+370946.7 | 0.155 | 2.15 | 7.1          | 2.3  | 8.9          | –                    |
| J085010.42+074758.5 | 0.18  | 3.55 | 7.3          | 2.43 | 8.9          | –                    |
| J090307.84+021152.2 | 0.329 | 2.14 | 7.4          | 2.44 | 8.8          | –                    |
| J090615.53+463619.0 | 0.0847 | 3.16 | 6.7          | 2.87 | 8.8          | –                    |
| J092936.73+571149.8 | 0.262 | 2.04 | 6.6          | 1.74 | –            | Type 2               |
| J093712.33+500852.2 | 0.276 | 3.29 | 7.3          | 1.23 | 8.9          | –                    |
| J094003.77+510421.8 | 0.203 | 2.56 | 6.9          | 2.9  | 9.0          | –                    |
| J094525.90+352103.6 | 0.086 | 3.18 | 7.3          | 1.41 | –            | –                    |
| J100410.85+523025.1 | 0.299 | 2.06 | 7.1          | 1.4  | 8.7          | –                    |
| J103143.51+522535.1 | 0.167 | 2.69 | 7.2          | 2.56 | 8.8          | –                    |
| J103305.65+070407.3 | 0.141 | 2.6  | 6.7          | 2.25 | 8.2          | –                    |
| J103915.69-003916.9 | 0.077 | 2.18 | 6.7          | 2.14 | –            | –                    |
| J110845.48+020240.8 | 0.158 | 2.71 | 7.1          | 2.3  | 8.9          | –                    |
| J111807.47+002734.9 | 0.169 | 2.08 | 6.7          | 2.87 | 8.8          | –                    |
| J115409.27+023815.0 | 0.121 | 2.58 | 7.4          | 2.48 | 7.8          | –                    |
| J115437.43+114858.9 | 0.328 | 3.03 | 6.8          | 3.22 | 8.9          | –                    |
| J124651.26+150914.3 | 0.207 | 4.47 | 7.1          | 2.51 | 9.1          | –                    |
| J130633.04+002248.4 | 0.148 | 2.07 | 6.9          | 2.43 | 8.8          | –                    |
| J135646.10+102609.0 | 0.123 | 2.22 | 6.6          | 1.71 | –            | –                    |
| J140638.22+010254.6 | 0.236 | 2.17 | 7.1          | 1.32 | –            | Outflow              |
| J142237.91+044848.5 | 0.087 | 3.75 | 3.9          | 2.07 | –            | –                    |
| J144341.53+383521.8 | 0.162 | 2.29 | 6.2          | 1.94 | –            | –                    |
| J151513.58+525004.2 | 0.288 | 2.5  | 6.7          | 3    | 8.8          | –                    |
| J151640.22+001501.8 | 0.0526 | 3.42 | 6.7          | 2.33 | 8.8          | –                    |
| J155522.04+281323.1 | 0.149 | 2.06 | 6.9          | 2.43 | 8.8          | –                    |
| J164442.53+261913.2 | 0.144 | 2.5  | 6.6          | 0.62 | 7.6          | –                    |
| J211852.96-073227.5 | 0.26  | 2.58 | 7.1          | 1.48 | 7.6          | –                    |
| J21526.03-081024.9  | 0.0347 | 2.18 | 6.5          | 2.37 | 8.5          | –                    |

a Using Hβ from Shen et al. (2010) and applying the correction for radiation pressure.
b BH mass estimated using the K-band magnitude measured from 2MASS images (this work) and the Marconi & Hunt (2003) formula.
c BH mass estimated using the K-band magnitude from 2MASS catalog (as taken from NED) and the Marconi & Hunt (2003) formula.
d Radiation pressure corrected, using FWHM of Hα from Rafter et al. (2009).

is $> 2000\text{km s}^{-1}$). The former is a bright quasar and the latter is either classified as a Sy 1, or as an FSRQ. The BH masses can be estimated using the Marconi et al. relation. Assuming FWHM(Hα) = FWHM(Hβ), we derive are $\sim 6 \times 10^7 M_\odot$ and $\sim 5 \times 10^7 M_\odot$ for the two objects, respectively.

Careful inspection of the SDSS spectra of the other three objects with quoted FWHM(Hα) > 2000 km s$^{-1}$ reveals that J140638.22+010254.6 has both permitted and forbidden emission lines with prominent blue wings, possibly indicative of an outflow which is most likely not produced within the BLR. For J094525.90+352103.6 and J103915.69-003916.9 the classification as broad line objects is extremely uncertain, and they are in fact both classified as “galaxy” in the SDSS.

The remaining five galaxies have FWHM(Hα) between 1000 and 2000 km s$^{-1}$. For J164442.53+261913.2, after taking into account of the effects of radiation pressure, the estimated BH mass is $10^{7.6} M_\odot$. J092936.73+571149.8, J135646.10+102609.0, J144341.53+383521.8, and J164126.91+432121.6 are Type 2 objects. In fact, the SDSS spectra show that the [OIII]5007 line is the same as (or even slightly broader than) the permitted lines. This most likely implies that the line emission region lies outside the BLR, and thus out of the sphere of influence of the black hole.

Summarizing, a careful inspection of the large sample of low-z AGNs from the SDSS shows that there is no clear evidence for bona fide radio loud objects associated with black hole masses significantly smaller than $\sim 10^8 M_\odot$. The smallest BH associated with a radio-loud object we find is SDSS J115409.27+023815.0, for which the estimated BH mass is $\sim 5 \times 10^7 M_\odot$. In other words, even the lowest BH mass we
estimate is still compatible with $10^8 \, M_\odot$, within the typical error.

### 4.4 On the impact of the radiation pressure correction

In the previous paragraphs we have described the methods we use to estimate the BH masses for various objects in the different samples. In doing so, we used the most updated formulae and the [Marconi et al. (2008)] correction to take into account the effects of radiation pressure onto the BLR. Although we strongly believe that that is the correct approach, we must point out that the overall results of this paper are unaltered if we neglect radiation pressure effects.

In fact, using the [Vestergaard & Peterson (2006)] for the SDSS objects for which we used the [Marconi et al. (2008)] formula (the ones marked with "a" and "d" in Table 1), we still obtain that the lowest BH mass is $10^7 \, M_\odot$ (for J115409.27+023815.0). This is because those sources are all low luminosity AGNs, therefore the effects of radiation pressure are small. To be precise, the Marconi formula, in that case, returns an even smaller value of the BH mass than the one obtained with the Vestergaard formula, which neglects radiation pressure effects at all luminosities.

Among the samples of AGN considered in this paper, the only objects that would be inconsistent (assuming a factor of $\sim 3$ error on the BH mass estimate) with the "limit" at $10^8$ solar masses are four QSOs in the [Gu, Cao, & Jiang (2001)] sample. However, for those four objects, the classification as Type 1 AGNs is extremely uncertain. Three out of those four are in fact classified as Type 2 (NED) and one (1045-188) is an FSRQ. Going back to the original paper that reports the spectrum of that object [Stickle, Kuehr, & Fried (1993)] and the values used for deriving its BH mass, we see that the FWHM of Hβ is quoted to be smaller than that of the [OIII]5007 line. Furthermore, a note states that the Hβ line is blended with some atmospheric absorption features. We conclude that even without using the [Marconi et al. (2008)] correction, there is no clear evidence for radio loud AGNs associated with masses smaller than $\sim 10^8 \, M_\odot$.

### 5 DISCUSSION AND CONCLUSIONS

Using the most updated black hole mass estimators, we have shown that there is no evidence for a population of radio-loud AGN associated with supermassive black holes of $M \ll 10^8 \, M_\odot$, in agreement with previous work performed on different samples (e.g. [Laor 2000; Dunlop et al. 2003; Chiaberge et al. 2005; Best et al. 2005; Baldi & Capetti 2014]). Building on this finding, we propose that the RQ/RL dichotomy can be explained by a modification of the spin paradigm in which the radio loudness of an AGN is determined not only by the spin, but also by the mass of the SMBH. RL AGN are only those with BH masses larger than $\sim 10^8 \, M_\odot$. Clearly, it is still possible that the value of $10^8 \, M_\odot$ does not correspond to any specific threshold, and it could just represent a typical value below which the probability of having a radio loud source becomes increasingly small.

While a discussion on the physics of the jet production is beyond the scope of this paper, in the following we will present evidences in support of our conjecture, and we will discuss the consequences for the relations between BHs and their host galaxies.

First of all, it is clear that the mass of the black hole must play a role, at all AGN luminosities, because the lack of radio loud AGN with small BH masses is apparent and it is not due to any trivial selection bias. Second of all, it is important to note that for high BH masses both RL and RQ AGNs exist. Thus, not surprisingly, the BH mass is clearly not the only physical parameter involved in determining the level of radio loudness of each object. The so-called “spin paradigm” [Blandford 1990; Wilson & Colbert 1992] has often been used to explain the RQ/RL dichotomy. In brief, assuming that the jet power is related to the BH spin ($J \sim (a/M_BH)^\beta$), Blandford & Znajek [1977; Tchekhovskoy, Narayan, & McKinney 2010], RL AGNs are explained as objects powered by rapidly spinning black holes. [Sikora et al. (2007)] have recently proposed a modified version of the spin paradigm, which includes two additional elements: i) the spin of the BH in elliptical galaxies can reach higher values with respect to that of spirals, because of their different merger history; ii) only at high accretion rates, intermittency of jets collimation causes an AGN to switch between radio-loud and radio-quiet states. According to the scenario proposed by those authors, powerful RQ QSOs hosted by ellipticals possess rapidly spinning black holes as the RL QSOs, but they are in a state in which the jet is not collimated. In that case, the host galaxies of RL and RQ QSO should be indistinguishable, as well as their large-scale environment. However, there is mounting evidence that the RL QSOs live in significantly richer environments than RQ QSOs (e.g. [Shen et al. 2002; Donoso et al. 2009]).

Here we propose that the RQ/RL dichotomy can be explained by a further modification of the spin paradigm, based on our finding that the mass of the black hole plays a role. Investigating the physical reasons for that is beyond the aim of this paper. However, we note that the BH mass is in fact intimately related to the accretion and ejection region around the BH itself, as it sets both the radius of the innermost stable orbit and the critical Eddington luminosity, as originally pointed out by [Blandford 1990].

In our conjecture, the spin of the black hole plays a role in determining the radio loudness only if the mass of the BH is $\sim 10^8 \, M_\odot$ or higher. For a smaller BH mass, the spin of the BH is irrelevant, as the Seyfert 1 galaxy MCG–6–30–15 and objects similar to that appear to show. MCG–6–30–15 is radio-quiet ultimately resides in the fact that its BH is maximally rotating. The same argument can be applied to other Seyferts with similar properties, e.g. 1H 0707–495 [Fabian et al. 2009], which is also associated with a BH mass of order $10^8 \, M_\odot$. In other words, the objects that are often used as “exceptions” to the spin-paradigm, are simply indicating that for an AGN to be radio loud, not only
the BH has to be spinning, but also its mass must be close to or above \(10^8 \, M_\odot\). Therefore, our conjecture accounts for the fact that radio quiet AGNs can host black holes of all masses, while RL AGNs cannot.

At high BH masses (above \( \sim 10^8 \, M_\odot \)) the spin regulates the radio loudness, as in the original version of the spin paradigm, with the RQ QSO having slowly rotating (or non rotating) black holes, and the RL QSOs having rapidly rotating black holes. Whether the transition occurs “sharply” at some particular value of the BH mass or it is instead a rather smooth transition is not clear from the data. But the lack of RL AGN below \( \sim 10^8 \, M_\odot \) seems to indicate that the existence of a sharp “threshold” value for the BH mass cannot be ruled out.

Another interesting aspect is to explore the connection between the radio loudness of the active nucleus and the structure, origin and evolution of the host galaxy. In low redshift AGNs there is a well established dichotomy in the properties of the radial brightness profiles or AGN hosts: RL nuclei are invariably associated with “core” galaxies, while RQ nuclei reside in “power-law” or spiral galaxies, which in turn have a power-law bulge (Capetti & Balmaverde 2004, 2007). de Ruiter et al. (2005) have also pointed out that radio galaxies are invariably associated with core galaxies. This is indicative of a profound link between the RQ/RL dichotomy and the history of the host galaxy, as originally noted by Capetti & Balmaverde (2006). It has been argued (e.g. Faber et al. 1997; Merritt 2006; Kormendy et al. 2003, and ref. therein) that core galaxies most likely originate in major dry mergers. The binary black hole formed during the merger ejects stars away from the central regions, thus producing gas to fuel a central starburst, which in turn produces a rapidly spinning black hole. Another possible mechanism to “spin-up” a SMBH is through accretion of matter onto the BH (Volonteri, Sikora, & Lasota 2007), although that probably only leads to moderate spin values (King, Pringle, & Hofmann 2008). Therefore, major dry mergers seem to perfectly fit the requirements both to “spin-up” the black hole, and to originate “core” galaxies.

On the other hand, a gas-rich (wet) merger may provide gas to fuel a central starburst, which in turn produces the extra-light observed in power-law galaxies (e.g. Kormendy et al. 2009). Major wet mergers are more likely to involve galaxies with relatively small bulge mass, and thus hosting small mass black holes. Therefore, even if the resulting spin of the black hole may be significant (because of either gas accretion or merger of two BHs of similar mass), the total BH mass is still not sufficient to power a radio-loud AGN. That might be the case for S0 galaxies such as MCG–6–30–15.

Recently, Dotti et al. (2010) have proposed a similar scenario. One major difference resides in the fact that these authors associate radio-loudness with counter-rotating accretion on rapidly spinning black holes resulting from major dry mergers. Counter rotation is necessary to increase the efficiency of jet production. However, one possible complication is that the existence of a significant number of radio-quiet AGN associated with core galaxies is expected in such a scenario (those with co-rotating accretion). Instead, the observations show that, at least at low redshifts, those objects are missing.

Summarizing, our conjecture implies that the RQ/RL dichotomy is strictly linked to the history of the host galaxy, independently of the accretion rate. In order to produce a radio-loud AGN, two conditions have to be satisfied: 1) \( M_{BH} > \sim 10^8 \, M_\odot \); 2) the spin of the BH must be significant. Major dry mergers of two galaxies, whose black holes have masses close to or above \(10^8 \, M_\odot\), lead to radio-loud AGNs. Smaller mass BHs cannot produce a powerful jet, therefore the actual BH spin is unimportant (or less important) in those objects, as far as the radio loudness is concerned.

An obvious criticism is that some stellar mass black holes are capable of producing rather powerful radio jets. Although these objects can be bright in the radio, it is important to estimate their actual radio-loudness. The problem in this case is that their optical emission is generally not observed, for various reasons. However, we can estimate the radio loudness using the radio-to-X-ray luminosity ratio, as proposed by Terashima & Wilson (2003). For example, in the case of GRS1915+105, \( \log R_x = \log(\nu L_{\nu}/L_X) = -6.6 \), while the typical value for radio loud AGNs is \( R_x \sim -1 \), and even the radio quiet AGNs have \( R_x \sim -3 \) (see the compilation of data in e.g. Merloni, Heinz, & di Matteo 2003). These objects are not “radio-loud”, even if they produce a rather bright radio jet. Therefore, besides all of the differences that might exist between the properties of the environment in the vicinity of supermassive black holes and that of stellar mass black holes, which might as well play a role in the physical properties of the outflows, the stellar mass black holes are significantly less radio loud than all AGNs. This confirms our findings, i.e. small mass BH are not capable of producing true radio loud objects.

Differently from Sikora et al. (2007), and building on the results of Capetti & Balmaverde (2006), in our proposed scenario the properties of the host galaxy are strictly connected to the radio loudness of the nuclei, via their formation and evolution, independently of the current accretion rate level. In this way, no “intermittency” and switching between RQ and RL “states” for high accretion rate AGNs is needed, as it seem to contradict the result that RQ and RL QSOs inhabit different environments, as discussed above. Therefore, in our picture, there is no difference between low and high accretion rate AGNs.

4 In most cases, the optical emission of these galactic binaries is difficult to study and may be produced by different competing mechanisms, most importantly by the companion star. In addition to that, in the case of the Galactic superluminal GRS1915+105, heavy absorption (\( A_V \sim 44 \, \text{mag} \)) completely hides the optical source.
high luminosity AGNs, and low and high accretion rate (or Eddington ratio).

Such a scenario implies a straightforward prediction: differently from [Sikora et al. (2002)], we expect powerful radio-quiet QSOs to reside in power-law galaxies, while their RL counterparts would be associated to core galaxies, exactly as observed at low redshifts. Clearly, confirming such a prediction is no easy task, due to the high angular resolution needed to resolve cores in distant galaxies, especially in presence of a bright quasar nucleus. Obscured QSOs might be a better choice for that, under the assumptions that type 1 and type 2 AGNs belong to the same “parent” population (Antonucci 1993; Urry & Padovani 1995). However, even in that case, the core radius in a z=0.5 object would be only ~10 mas. Therefore, other structural parameters of the host galaxy that are found to correlate with the properties or the innermost structure are more likely to be observed with current instruments and in the near future (e.g. the Sersic index, Kormendy et al. 2009).

Another implication of our proposed scenario is that broad iron lines bearing the signature of the Kerr metric (as seen in MCG–6–30–15) should be present in the X-rays in radio loud (lobe-dominated) QSOs and in broad line radio galaxies. These are objects that are thought to be seen at the right orientation to allow direct view of the accretion disc, while the relativistically beamed jet emission should be observed at an angle that is large enough for that not to dominate the overall emission. Therefore, the inner regions of the accretion disc should be visible, unless that region of the accretion disc is “emptied” because of the presence of significant outflows, or if it is in an ADAF state (see e.g. Yuan 2005; Tchekhovskoy, Narayan, & McKinney 2011). Until now, no Fe lines of that kind have been detected in radio-loud objects, to the best of our knowledge. But that might just be explained by the low sensitivity of current instrumentation, which does not allow a clear detection of those features in distant objects.

An obvious way of falsifying our conjecture is the observation of such relativistically broadened Fe lines in the X-ray spectrum of radio-quiet QSOs associated with a large black hole mass. Such a result would disproof the hypothesis that a rapidly spinning black hole with a mass larger than 10^8 M⊙ is sufficient to produce a radio loud AGN.

ACKNOWLEDGMENTS

We are grateful to Mario Livio, Marta Volonteri, Alessandro Capetti, Colin Norman and Gabriele Ghisellini for insightful discussions. We also thank the referee for her/his valuable comments that helped to improve the paper. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Akujor C. E., Jackson N., 1992, AJ, 104, 546
Allen S. W., Dunn R. J. H., Fabian A. C., Taylor G. B., Reynolds C. S., 2006, MNRAS, 372, 21
Antonucci R., 1993, ARA&A, 31, 473
Baldi R. D., Capetti A., 2010, A&A, 519, A48
Barthel P. D., 1989, ApJ, 336, 606
Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Bentz M. C., Peterson B. M., Netzer H., Pogge R. W., Vestergaard M., 2009, ApJ, 697, 160
Berti E., Volonteri M., 2008, ApJ, 684, 822
Best P. N., Kauflmann G., Heckman T. M., Brinchmann J., Charlot S., Ivezić Z., White S. D. M., 2005, MNRAS, 362, 25
Blandford R. D., Netzer H., Woltjer L., Courvoisier T. J.-L., Mayor M., 1990, Active Galactic Nuclei. Saas-Fee Advanced Course 20. Lecture Notes 1990. Swiss Society for Astrophysics and Astronomy, XII, 280 pp. 97 figs.. Springer-Verlag Berlin Heidelberg New York
Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433
Bower R. G., Benson A. J., Malbon R., Helly J. C., Frenk C. S., Baugh C. M., Cole S., Lacey C. G., 2006, MNRAS, 370, 645
Capetti A., Balmaverde B., 2007, A&A, 469, 75
Capetti A., Balmaverde B., 2006, A&A, 453, 27
Capetti A., Balmaverde B., 2005, A&A, 440, 73
Capetti A., Celotti A., Chiaberge M., de Ruiter H. R., Fanti R., Morganti R., Parma P., 2002, A&A, 383, 104
Celotti A., Ghisellini G., 2008, MNRAS, 385, 283
Chiaberge M., Capetti A., Celotti A., 1999, A&A, 349, 77
Chiaberge M., Capetti A., Celotti A., 2002, A&A, 394, 791
Chiaberge M., Capetti A., Macchetto F. D., 2005, ApJ, 625, 716
Croton D. J., et al., 2006, MNRAS, 365, 11
de Ruiter H. R., Parma P., Capetti A., Fanti R., Morganti R., Santantonio L., 2005, A&A, 439, 487
Donoso E., Li C., Kaufmann G., Best P. N., Heckman T. M., 2009, arXiv, [arXiv:0910.3667]
Dotti M., Colpi M., Maraschi L., Perego A., Volonteri M., 2010, arXiv, [arXiv:1004.2849]
Dunlop J. S., McLure R. J., Kukula M. J., Baum S. A., O’Dea C. P., Hughes D. H., 2003, MNRAS, 340, 1095
Faber S. M., et al., 1997, AJ, 114, 1771
Fabian A. C., et al., 2009, Natur, 459, 540
Ferland G. J., & Rees M. J., 1988, ApJ, 332, 141
Ferrarese L., Ford H., 2005, SSRv, 116, 523
Franceschini A., Vercellone S., Fabian A. C., 1998, MNRAS, 297, 817
Graham A. W., 2007, MNRAS, 379, 711
Grandi P., Palumbo G. G. C., 2007, ApJ, 659, 235
Greene J. E., Ho L. C., 2007, ApJ, 667, 131
Gu M., Cao X., Jiang D. R., 2001, MNRAS, 327, 1111
Gültekin K., et al., 2009, ApJ, 698, 198
Hinshaw G., Weiland L. J., Hill R. S., Odegard N., Larson D., Bennett C. L., Dunkley J., Gold B., Greason M. R., Jarosik N., Komatsu E., Nolta M. R., Page L., Spergel D. N., Wollack E., Halpern M., Kogut A., Limon M., Meyer S. S., Tucker G. S., Wright E. L., 2009, ApJS, 180, 225
Ho L. C., 2002, ApJ, 564, 120
Ho L. C., Filippenko A. V., Sargent W. L. W., 1997, ApJS, 112, 315
Ho L. C., Peng C. Y., 2001, ApJ, 555, 650
Hu J., 2009, MNRAS submitted (arXiv:0908.2028)
On the origin of radio-loudness in AGNs

Hughes S. A., Blandford R. D., 2003, ApJ, 585, L101

Iwasawa K., Fabian A. C., Reynolds C. S., Nandra K., Otani C., Inoue H., Hayashida K., Brandt W. N., Dotani T., Kunieda H., Matsuoka M., Tanaka Y., 1996, MNARS, 282, 1038

Kaspi S., Smith P. S., Netzer H., Maoz D., Jannuzi B. T., Giveon U., 2000, ApJ, 533, 631

Kellermann K. I., Sramek R., Schmidt M., Shaffer D. B., Green R., 1989, AJ, 98, 1195

King A. R., Pringle J. E., Hofmann J. A., 2008, MNARS, 385, 1621

Kormendy J., Fisher D. B., Cornell M. E., Bender R., 2009, ApJS, 182, 216

Laor A., 2000, ApJ, 543, L111

Lauer T. R., et al., 1995, AJ, 110, 2622

Maiolino R., et al., 2010, A&A, 517, A47

Marconi A., Axon D. J., Maiolino R., Nagao T., Pastorini G., Pietrini P., Robinson A., Torricelli G., 2008, ApJ, 678, 693

Marconi A., Axon D. J., Maiolino R., Nagao T., Pietrini P., Risaliti G., Robinson A., Torricelli G., 2009, ApJL, 698, L103

Marconi A., Hunt L. K., 2003, ApJL, 589, L21

Mathews W. G., Ferland G. J., 1987, ApJ, 323, 456

McHardy I. M., Gunn K. F., Uttley P., Goad M. R., 2005, MNARS, 359, 1469

McIntosh D. H., Rieke M. J., Rix H.-W., Foltz C. B., Weymann R. J., 1999, ApJ, 514, 40

Merloni A., Heinz S., di Matteo T., 2003, MNARS, 345, 1057

Merritt D., 2006, ApJ, 648, 976

Minuti G., Fabian A. C., Anabuki N., Crummy J., Fukazawa Y., Gallo L., Haba Y., Hayashida K., Holt S., Kunieda H., Larsson J., Markowitz A., Matsumoto C., Ohno M., Reeves J. N., Takahashi T., Tanaka Y., Terashima Y., Torii K., Ueda Y., Ushio M., Watanabe S., Yamauchi M., 2007, PASJ, 59, 315

Netzer H., 2009, ApJ, 695, L793

Netzer H., & Marziani P. 2010, ApJ, 724, 318

Oshlack A. Y. K. N., Webster R. L., Whiting M. T., 2002, ApJ, 576, 81

Peterson B. M., 2010, IAUS, 267, 151

Rafter S. E., Crenshaw D. M., Wiita P. J., 2009, AJ, 137, 42

Schneider D. P., et al., 2007, AJ, 134, 102

Shen Y., et al., 2009, ApJ, 697, 1656

Shen, Y., et al. 2010, arXiv:1006.5178

Sikora M., Starzaw C., Lasota J.-P., 2007, ApJ, 658, 815

Spinrad H., Marr J., Aguilar L., Djorgovski S., 1985, PASP, 97, 932

Stickel M., Kuehr H., Fried J. W., 1993, A&AS, 97, 483

Strateva I., Ivezić Ž., Knapp G. R., Narayanan V. K., Strauss M. A., Gunn J. E., Lupton R. H., Schlegel D., Bahcall N. A., Brinkmann J., Brunner R. J., Budavári T., Csabai I., Castander F. J., Doi M., Fukugita M., Györy Z., Hamabe M., Hennessy G., Ichikawa T., Kunst P. Z., Lamb D. Q., McKay T. A., Okamura S., Racusin J., Sekiguchi M., Schneider D. P., Shimasaku K., York D., 2001, AJ, 122, 1861

Tchekhovskoy A., Narayan R., McKinney J. C., 2010, ApJ, 711, 50

Terashima Y., Wilson A. S., 2003, ApJ, 583, 145

Tremaine S., Gebhardt K., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Green R., Grillmair C., Ho L. C., Kormendy J., Lauer T. R., Magorrian J., Pimney J., Richstone D., 2002, ApJ, 574, 740

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

Vestergaard M., 2009, arXiv:0904.2615

Vestergaard M., 2010, IAUS, 267, 239

Vestergaard M., Peterson B. M., 2006, ApJ, 641, 689

Volonteri M., Sikora M., Lasota J.-P., 2007, ApJ, 667, 704

Xu C., Livio M., Baum S., 1999, AJ, 118, 1169

Wilson A. S., Colbert E. J. M., 1995, ApJ, 438, 62

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

Woo J.-H., Urry C. M., 2002, ApJ, 581, L5

Yuan F., 2007, ASPC, 373, 95

This paper has been typeset from a TeX/LaTeX file prepared by the author.