Measuring the kinetic power of AGN in the radio mode

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ABSTRACT

We have studied the relationship among nuclear radio and X-ray power, Bondi rate and the kinetic luminosity of sub-Eddington active galactic nuclear (AGN) jets, as estimated from the \(\text{pdV}\) work done to inflate the cavities and bubbles observed in the hot X-ray emitting atmospheres of their host galaxies and clusters. Besides the recently discovered correlation between jet kinetic and Bondi power, we show that a clear correlation exists also between Eddington-scaled kinetic power and bolometric luminosity, given by: \(\log(L_{\text{kin}}/L_{\text{Edd}}) = (0.49\pm0.07)\log(L_{\text{bol}}/L_{\text{Edd}}) - (0.78\pm0.36)\). The measured slope suggests that these objects are in a radiatively inefficient accretion mode, and has been used to put stringent constraints on the properties of the accretion flow. Interestingly, we found no statistically significant correlations between Bondi power and bolometric AGN luminosity, apart from that induced by their common dependence on \(L_{\text{kin}}\), thus confirming the idea that most of the accretion power emerges from these systems in kinetic form. We have then analyzed the relation between kinetic power and radio core luminosity. Combining the measures of jet power with estimators of the un-beamed radio flux of the jet cores as, for example, the so-called ‘fundamental plane’ of active black holes, we are able to determine, in a statistical sense, both the probability distribution of the mean jets Lorentz factor, that peaks at \(\Gamma_{\text{m}} \sim 7\), and the intrinsic relationship between kinetic and radio core luminosity (and thus the jet radiative efficiency), that we estimate as: \(\log L_{\text{kin}} = (0.81\pm0.11)\log L_{R} + 11.9^{+4.1}_{-4.4}\), in good agreement with theoretical predictions of synchrotron jet models. With the aid of these findings, quantitative assessments of kinetic feedback from supermassive black holes in the radio mode (i.e. at low dimensionless accretion rates) will be possible based on accurate determinations of the central engine properties alone, such as mass, radio core and/or X-ray luminosity. As an example, we suggest that Sgr A\textsuperscript{*} may follow the same correlations of radio mode AGN, based on its observed radiative output as well as on estimates of the accretion rate both at the Bondi radius and in the inner flow. If this is the case, the supermassive black hole in the Galactic center is the source of \(\sim 5 \times 10^{38}\text{ ergs s}^{-1}\) of mechanical power, equivalent to about 1.5 supernovae every 10\textsuperscript{9} years.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: evolution – quasars: general

1 INTRODUCTION

The growth of supermassive black holes (SMBH) through mass accretion is accompanied by the release of enormous amounts of energy which, if it is not adverted directly into the hole (see e.g. Narayan & Yi 1995), can be either radiated away, as in Quasars and bright Seyferts, or disposed of in kinetic form through powerful, collimated outflows or jets, as observed, for example, in Radio Galaxies. The feedback exerted by such a powerful energy release on the surrounding gas and stars is imprinted into the observed correlations between black hole mass and galaxy properties (Gebhardt et al. 2000, Ferrarese & Merritt 2000; Marconi & Hunt 2003), as well as into the disturbed morphology of the hot, X-ray emitting atmospheres of groups and clusters harboring active SMBH in their centers (Böhringer et al. 1993, Fabian et al. 2000, Churazov et al. 2002, Birzan et al. 2004, Fabian et al. 2006). Radiative and kinetic feedback differ not only on physical grounds, in terms of coupling efficiency with the ambient gas, but also on evolutionary grounds. The luminosity dependent density evolution parameterization of the AGN luminosity functions (Hasinger, Miyaji & Schmidt 2005, Hopkins, Richards & Hernquist 2007) implies a delay between the epoch of Quasar dominance and that of more sedate Radio Galaxies (Merloni 2004, Merloni & Heinz 2006), such that kinetic energy feedback plays an increasingly important role in the epoch of cluster formation and virtualization.

From the theoretical point of view, the idea that AGN were responsible for the additional heating needed to ex-
plain the cooling flow riddle (see e.g. Fabian et al. 2001 and reference therein) in clusters of galaxies has been put forward by many in recent years (Binney & Tabor 1995; Begelman 2001; Charazov et al. 2001; Churazov et al. 2002; Dalla Vecchia et al. 2004; Sijacki & Springel 2006; Cattaneo & Teyssier 2007). However, only very recently was the specific importance of mechanical (as opposed to radiative) feedback for the heating of baryons within the deepest dark matter potential wells fully acknowledged by semi-analytic modelers of cosmological structure formation (Croton et al. 2006; Bower et al. 2006). Within these schemes, because the bright quasar population peaks at too early times, a so-called “radio mode” of SMBH growth is invoked in order to regulate both cooling flows in galaxy clusters and the observed sizes and colors of the most massive galaxies (Springel et al. 2005; Croton et al. 2006).

Such indirect evidence for a radio mode of AGN activity resonates with a recent body of work aimed at understanding the physics of low-luminosity AGN. Detailed multi-wavelength studies of nearby galaxies have revealed a clear tendency for lower luminosity AGN to be more radio loud as the Eddington-scaled accretion rate decreases (see Ho 2002, and references therein; Nagar, Falcke and Wilson 2005). Scaling relations with black hole X-ray binaries (BHXRB) (Merloni, Heinz & Di Matteo 2003; Falcke, Körding & Markoff 2004) have also helped to identify AGN analogues of low/hard state sources, in which the radiative efficiency of the accretion flow is low (Pellegrini 2005a; Chaberge, Capetti & Macchetto 2005; Hardcastle, Evans & Croston 2007) and the radio emitting jet carries a substantial fraction of the overall power in kinetic form (Körding, Fender & Migliari 2006).

Nonetheless, despite such a widespread consensus on the importance of kinetic energy feedback from AGN for galaxy formation, the kinetic luminosity of an AGN remains very difficult to estimate reliably. Recent incarnations of structure formation models (either numerical or semi-analytic) hinge on the unknown efficiency with which growing black holes convert accreted rest mass into jet power. Constraints on this quantity, such as those recently presented in Heinz, Merloni & Schwab (2007) are clearly vital for the robustness of the models.

Observationally, progress has been possible recently, thanks to deep X-ray exposures of nearby elliptical galaxies and clusters which have allowed the first direct estimates of \(L_{\text{kin}}\) by studying the cavities, bubbles and weak shocks generated by the radio emitting jets in the intra-cluster medium (ICM) (Birzan et al. 2004; Allen et al. 2006; Rafferty et al. 2006). Two main results emerged from these studies: first, it appears that AGN are energetically able to balance radiative losses from the ICM in the majority of cases (Rafferty et al. 2006); second, at least in the case of a few nearby elliptical galaxies, there is an almost linear correlation between the jet power and the Bondi accretion rates calculated from the observed gas temperatures and density profiles in the nuclear regions (Allen et al. 2006). The normalization of this relation is such that a significant fraction of the energy associated with matter entering the Bondi radius must be released in the jets.

Here we address a different, complementary issue. By collating all available information on the nuclear (AGN) properties of the sources for which the kinetic luminosity was estimated, we construct a sample of sub-Eddington accreting supermassive black holes with unprecedented level of information on both the inner (black hole mass) and the outer (mass supply through the Bondi radius) boundary condition for the accretion flow, as well as a reliable inventory of the energy output, either in radiative or kinetic form. We demonstrate here that with the aid of this new set of information, strong constraints can be placed on the accretion properties of these objects. In so doing, we derive a new, robust estimator of the kinetic power of a SMBH based on its nuclear properties alone, namely its mass and instantaneous X-ray and radio (core) luminosity.

The structure of the paper is as follows: In section 2 we study the relationships among nuclear radio and X-ray power, Bondi rate and the kinetic luminosity of the AGN in the sample and show that a clear relationship exists between Eddington scaled kinetic power and hard X-ray luminosity. We then analyze the relation between kinetic power and radio core luminosity. In section 4 we discuss our results and present a simple coupled accretion-outflow disc model which is capable to explain the main features of the observed sample. Finally, we summarize our conclusions in 4.5

2 THE RELATIONSHIP BETWEEN KINETIC POWER AND NUCLEAR BOLOMETRIC LUMINOSITY

We have collected from the literature data on the nuclear properties of AGN with published measurements of the jet kinetic power, as estimated from the \(p dV\) work done to inflate the cavities and bubbles observed in the hot X-ray emitting atmospheres of their host galaxies and clusters. We begin by considering the samples of Allen et al. (2006) (9 sources) and Rafferty et al. (2006) (33 sources). By taking into account common objects, there are 38 AGN with kinetic power estimated in such a way. Out of those, we consider only the ones for which black hole mass could be estimated (either through the \(M - \sigma\) relation or via direct dynamical measurements), that amount to 21 objects. Finally, we search in the literature for available measures of the nuclear luminosity in the radio (at 5 GHz) and in the 2-10 keV band. Only 6/21 do not have such information, and we further notice that 4 out of these 6 are at a distance equal to, or larger than, that of the most distant object in our final sample (with the exception of Cygnus A). Therefore, there are only two objects (NGC 708 and ESO 349-010, both from the Rafferty et al. 2006 sample) which have a measure of \(L_{\text{kin}}\), an estimate of the black hole mass and are close enough (\(z < 0.055\)) to qualify as sample members, but which have been dropped due to the lack of X-ray and radio nuclear luminosities. Such a high level of “completeness” of the sample should guarantee us against substantial selection bias due, for example, to beaming effects in the radio band (see section 4 below).

Our selection provided us with a sample of 15 objects, 2 of which have only upper limits to their 2-10 keV nuclear X-ray luminosity. In four cases, estimates of the jet power are also available based on detailed modelling of either radio emission in the jets and lobes (Cyg A, Carilli & Barthel 1996; M87, Bicknell & Begelman 1996; Per A, Fabian et al. 2002), or shock in the IGM induced by the expanding cocoons (NGC 4636, Jones et al. 2002). In another handful of objects (M84, M87, NGC 4696, NGC 6166) both Allen et al. (2006) and Rafferty et al. (2006) report (independent) measures of the jet kinetic power, which, incidentally, differ on average by almost one order of magnitude. In all these cases when more than

\footnote{It is of course important to notice that the overall selection criteria of the sample discussed here are indeed heterogeneous. In particular, the role played by the requirement of having a bright, hot X-ray emitting atmosphere against which detect bubbles and cavities is very hard to assess, as surface brightness effects and different exposure times of the original observations should all contribute to the measurability of kinetic power.}
one measurement of the kinetic power was found, we have used their logarithmic average for our study, and increased the uncertainty accordingly. These are reported in Table 2 where a summary of the sample adopted is presented. For all these objects we define the Bondi power as

\[ P_{\text{Bondi}} = 0.1 \dot{M}_{\text{Bondi}} c^2, \]

where the Bondi accretion rate is calculated from measures of gas temperature and density under the assumption of spherical symmetry and negligible angular momentum (see Allen et al. 2006, and references therein). For the nine AGN studied in Allen et al. (2006) the Bondi rate is calculated extrapolating the observed inner density profile of the X-ray emitting gas down to the Bondi radius. For the others, more luminous (and more distant) objects from the Rafferty et al. (2006) sample, the Chandra resolution corresponds to a size several orders of magnitude larger than the true Bondi radius. For these objects, the Bondi power is estimated by assuming a \( r^{-1} \) inner density profile. This inevitably implies very large uncertainties on \( P_{\text{Bondi}} \) that we have taken into account by increasing the nominal error bars associated with the measurements found in the literature.

As mentioned in the introduction, our sample provides us with information on both the inner and the outer boundary condition for the accretion flow, as well as a reliable inventory of the energy output, both in radiative and kinetic form. In principle, if all these objects were to be described by the same physical model for the accretion flow (coupled to the jet/outflow), one should expect simple scaling relationships between the mass supply at the outer boundary (Bondi power), and the energy emitted in kinetic or radiative form from the accretion flow \( (L_{\text{kin}} \text{ and } L_X) \) respectively.

We first perform a partial correlation analysis in order to test whether any correlation between these quantities is statistically significant in our sample. We choose the partial Kendall's \( \tau \) correlation test for censored data sets (Akritas & Siebert 1996). The results of the correlation analysis are shown in Table 2. The correlations between the kinetic power and both Bondi power and X-ray luminosities are significant at more than 3-sigma level. Interestingly, the correlation between \( L_X \) and \( P_{\text{Bondi}} \) does not appear to be statistically significant once the common dependence of these two quantities on \( L_{\text{kin}} \) is accounted for. This is consistent with previous studies (Pellegrini 2005a; Soria et al. 2006) which failed to detect any clear correlation between \( L_X \) and \( P_{\text{Bondi}} \), and might indicate that the X-ray luminosity, and thus the accretion power released radiatively, is not sensitive to the outer boundary condition, while it depends more strongly on the mechanical output of the flow. This is indeed expected, for example in adiabatic inflow-outflow (ADIOS) models (Blandford & Begelman 1999) or Blandford & Begelman 2004, but is also true for more general disk-wind models provided that a negligible fraction of the binding energy of the accreting gas is converted directly into radiation (Merloni & Fabian 2002; Kuncic & Bicknell 2004), as we will show in more detail in section 4.

On physical grounds, one might expect that both the black hole mass and the accretion rate should determine the power channeled through the jet, thus enforcing the need to perform multivariate statistical analysis on any multi-wavelength database of AGN, a point already discussed in MHD03. However, we notice here that the sample in question spans only a very limited range...
of black hole masses\(^2\). Attempts to quantitatively account for the mass dependence of the kinetic luminosity based on such a sample were made, and yielded negative results. Therefore in what follows we limit ourselves to a simple bivariate correlation analysis between Eddington-scaled quantities. Future, more detailed, studies of the physical connection between jet kinetic power and black hole accretion processes will greatly benefit from samples with much wider distributions of black hole masses.

Figure 1 shows the relationship between Bondi power and kinetic luminosity, both in units of the Eddington luminosity, \(L_{\text{Edd}} = 4\pi M_{\text{BH}} m_p c / \sigma_T\), where \(m_p\) is the mass of a proton and \(\sigma_T\) is the Thomson cross-section. The best fit linear regression slope, estimated via a symmetric algorithm that takes into account errors on both variables (see MHD03) gives:

\[
\log(L_{\text{kin}} / L_{\text{Edd}}) = (1.6^{+0.4}_{-0.3}) \log(P_{\text{Bondi}} / L_{\text{Edd}}) + (1.2^{+1.0}_{-0.8}) \tag{2}
\]

consistent, within the 1-\(\sigma\) uncertainty, with the best fit slope found by Allen et al. (2006) (1.3\(^+0.2\)\(^-0.2\)).

We have then studied the relationship between kinetic power and bolometric (radiated) luminosity. The bolometric correction for objects of such a low power is not well known. In general terms, it has been argued that low luminosity AGN in nearby galaxies display a spectral energy distribution markedly different from classical quasars, lacking clear signs of thermal UV emission usually associated to standard, optically thick accretion discs (see e.g. Ho 2005, and references therein; for a contrasting view, Maoz 2007).

The bolometric correction is probably dominated by the hard X-ray emission, but quantitative assessments of the bolometric corrections for low luminosity AGN based on well defined samples are still missing. Here, for the sake of simplicity, we adopt a common 2-10 keV bolometric correction factor of 5 for all objects in our sample, and define \(\lambda_X = 5 L_X / L_{\text{Edd}}\).

The best fit linear regression slope, estimated via a symmetric algorithm that takes into account errors on both variables\(^3\) gives the following result:

\[
\log(L_{\text{kin}} / L_{\text{Edd}}) = (0.49 \pm 0.07) \log \lambda_X - (0.78 \pm 0.36) \tag{3}
\]

with an intrinsic scatter of about 0.39 dex.

\(2\) This is likely the result of a specific selection bias, as the method used to estimate the average jet kinetic power can only be used effectively for radio galaxies at the center of bright X-ray emitting atmospheres, as those of clusters of galaxies (X-ray surface brightness selection). This in turn tend to select the more massive elliptical galaxies, with large central black holes.

\(3\) We assume here that the errors on \(\lambda_X\) are dominated by the statistical uncertainties on the black hole mass determinations, which we estimate to be of the order of \(\sim 0.2\) dex from the intrinsic scatter in the M-\(\sigma\) relation, see Tremaine et al. (2002).

Table 2. Results of partial correlation analysis

| Variables | Correlation |
|-----------|-------------|
|            | X (1) | Y (2) | Z (3) | \(\tau\) (4) | \(\sigma_K\) (5) | \(P_{\text{null}}\) (6) |
| \(\log L_X\) | \(\log L_{\text{kin}}\) | \(\log P_{\text{Bondi}}\) | 0.49 | 0.1818 | 7.0 \times 10^{-3} |
| \(\log P_{\text{Bondi}}\) | \(\log L_{\text{kin}}\) | \(\log L_X\) | 0.5872 | 0.2815 | 3.7 \times 10^{-2} |
| \(\log L_X\) | \(\log P_{\text{Bondi}}\) | \(\log L_{\text{kin}}\) | 0.1289 | 0.1422 | 0.3647 |

NOTE: Col. (1): Variable X. Col. (2): Variable Y. Col (3): Variable Z. Correlation between variables X and Y is studied, taking into account the mutual correlation of X and Y with Z. Col. (4)-(6): Results of partial correlation analysis, giving the partial Kendall’s \(\tau\) correlation coefficient, the square root of the calculated variance \(\sigma_K\), and the associated probability \(P_{\text{null}}\) for accepting the null hypothesis that there is no correlation between X and Y.
Figure 2. Eddington-scaled kinetic power vs. bolometric nuclear luminosity for the AGN in the sample (black solid circles) and for the BHXRB Cyg X-1 (empty red star). The solid line shows the best fit linear regression, while the dashed line is the $L_{\text{kin}} = 5 L_X$ relation shown as a term of comparison.

2006), supporting the notion that AGN are indeed scaled-up galactic black holes. However, physical models for the disc-jet coupling in BHXRB based on the observed correlations between radio and X-ray luminosity (Fender, Gallo & Jonker 2003; Körding, Fender & Migliari 2006) all face a large uncertainty due to the lack of reliable measurements of the jet kinetic power. In this context, it is interesting to include in Figure 2 the only GBH for which a measurement of the kinetic output has been made, Cyg X-1 (Gallo et al. 2005), which turns out to be consistent with the relationship derived from the AGN sample. Clearly, systematic efforts to estimate kinetic power of BHXRB in the low/hard state are needed in order to assess their similarity with radio mode AGN.

3 THE RELATIONSHIP BETWEEN KINETIC POWER AND RADIO CORE LUMINOSITY

If the above correlation directly reveals fundamental physical properties of jet-producing AGN of low power, it still shows a non-negligible intrinsic scatter. On the other hand, one should expect a more direct relationship between the nuclear radio core emission and the larger scale kinetic power, as both originate from the jet. All theoretical models for AGN flat-spectrum compact jet cores (Blandford & Königl 1979; Falcke & Biermann 1996; Heinz & Sunyaev 2003) predict a dependence of the radio luminosity on the jet power in the form $L_R \propto L_{\text{kin}}^{17/12}$. The current sample provides by far the best opportunity to test these predictions.

A Kendall’s tau correlation test reveals that the kinetic power is correlated with the observed radio core luminosity $L_{R,\text{obs}}$, with $P_{\text{null}} = 9.2 \times 10^{-5}$ (see the empty circles in Figure 3). We have fitted the data with a linear relationship: $\log L_{\text{kin}} = A_{\text{obs}} + B_{\text{obs}} \log L_{R,\text{obs}}$, once again making use of a symmetric regression algorithm that takes into account errors on both variables. We obtain $A_{\text{obs}} = (22.1 \pm 3.5), B_{\text{obs}} = (0.54 \pm 0.09)$, with a large intrinsic scatter of $\sigma = 0.47$.

Such a correlation, however, must be at some level biased by relativistic Doppler boosting of the radio emission in the relativistic jets. An alternative way to proceed would be to use indirect estimators of the nuclear radio core luminosity which are less affected by relativistic beaming (Heinz & Grimm 2005), as, for example, the multivariate relation between BH mass, radio core and hard X-ray luminosity, the so-called ‘fundamental plane’ (FP) of active black holes (MHD03). Recent analysis of this correlation (Heinz & Merloni 2004; Körding, Falcke & Corbel 2006 [KFC06]; Merloni et al. 2006) have shown that both Doppler boosting and sample selection play a crucial role in the exact determination of the intrinsic correlation coefficients of the FP, which also need to be accounted for. In the Appendix, we discuss in detail a possible way to overcome such a bias with the aid of a Monte Carlo simulation of the samples used to derive the FP relation. That study allows us to estimate statistically the intrinsic (un-boosted) radio core luminosity of the AGN jets as a function of their (mean) Lorentz factor, $\Gamma_m$ in a way that can be approximated by the following expression:

$$\log L_{R,\text{FP}} = (1 - 0.14 \log \Gamma_m) [\xi_{RX} \log L_X + \xi_{RM} \log M_{BH}] + cR(\Gamma_m),$$

where $L_{R,\text{FP}}$ is the intrinsic (un-boosted) radio core luminosity of the jet at 5 GHz, $L_X$ the nuclear 2-10 keV intrinsic (un-absorbed) luminosity and $\Gamma_m$ the mean Lorentz factor of the jets.

In what follows, we will adopt the specific version of the FP relation derived from a sample of low luminosity AGN only, i.e. free from the bias introduced by the inclusion of bright, radiatively efficient AGN or QSOs (see discussion in KFC06). For that, the correlation coefficients are $\xi_{RX} = 0.71$, $\xi_{RM} = 0.62$, slightly different (but only at the 1-σ level) from those found in MHD03.

Given Eq. (3), assuming a distribution of Lorentz factors for the AGN jets (or its mean, provided that the distribution is not too broad), we determine the “true” relationship between the Kinetic luminosity and radio core luminosity by fitting the 15 data points in our sample with the linear relationship

$$\log L_{\text{kin}} = A_{\text{int}}(\Gamma_m) + B_{\text{int}}(\Gamma_m) \log L_{R,\text{FP}}.$$

The fitted values for the intrinsic slope, $B_{\text{int}}$, as a function of $\Gamma_m$, are shown as a dot-dashed line in the bottom panel of Figure 3. From this we can see that the higher the mean Lorentz factor of the jets, the steeper must the intrinsic correlation between kinetic power and jet core luminosity be, and the larger the discrepancy with the measured slope, $B_{\text{obs}} = 0.54 \pm 0.09$ (solid lines in Figure 3), obtained using simply the observed radio core luminosity, without any attempt to correct for relativistic beaming. In fact, such a discrepancy between the intrinsic and the observed slopes of the $L_R - L_{\text{kin}}$ relation is indeed expected if the 15 sources of our sample harbor relativistic jet randomly oriented with respect to the line of sight.

In order to show this quantitatively, we have simulated (10^4 times) the observed sample, assuming an underlying relationship between intrinsic radio core luminosity and kinetic luminosity given by Eq. (5). In order to do that we have assumed distribution distances, black hole masses radio and X-ray core flux limits that closely resemble the observed ones. We then Doppler-boost

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4 It is worth noting here that the sample has no a priori selection against beamed objects (indeed, 3C 84, the radio source at the core of NGC 1275, is most likely beamed, Kirchbaum et al. 1992).
the intrinsic radio core luminosity picking $\Gamma$ from a normal distribution with mean $\Gamma_m$ and variance $\sigma_{\Gamma} = 0.1\Gamma_m$. Fits of the $L_{\text{kin}}$-$L_{R,\text{obs}}$ correlation for the $10^4$ simulated samples result in a distribution of slopes $B_{\text{obs}}$ as a function of $\Gamma_m$ (shaded areas in the lower panels figure 3). We can now assess the probability of observing $B_{\text{obs}} = (0.54 \pm 0.09)$ for any value of $\Gamma_m$, by simply integrating these (properly normalized) distributions in the range $0.54 \pm 0.09$. The result of such an integration is shown in the upper panel of Figure 3.

The distribution of the simulated sources in the $L_{R,\text{obs}}/L_R$ vs. $L_{\text{kin}}$ plane shows tantalizing evidence of a discrepancy with the observed sample, with a slight deficit of luminous, de-boosted (i.e. seen at large angles with respect to the line of sight) objects. Statistically, we found that this discrepancy mainly effects the normalization of the intrinsic $L_{\text{kin}}$-$L_R$ relation, rather than its slope. The reason for such a discrepancy is not clear at this point, but we believe it may signal a problem in the modellization of the selection criteria of the sample, rather than a problem with the FP scaling. This is by no means surprising, in particular given the lack of any realistic constraint on the distribution and selection functions of the kinetic power measurements.

From this Monte Carlo test, we can reach the following conclusions:

(i) For any given $\Gamma_m$, the beaming-corrected FP relation can be used to derive the intrinsic radio core luminosity of the jets, $L_{R,\text{FP}}$:

(ii) The correlation between $L_{\text{kin}}$ and $L_{R,\text{FP}}$ in our sample has a slope $B_{\text{int}}(\Gamma_m)$, that is an increasing function of the mean jet Lorentz factor;

(iii) The relation between $L_{\text{kin}}$ and observed radio core luminosity is flattened with respect to the intrinsic one (i.e. $B_{\text{obs}} < B_{\text{int}}$) because of the unaccounted-for Doppler boosting in the small sample at hand. We have corrected for such an effect statistically: Figure 3 shows that a fully consistent interpretation of the data can be given for a broad range of mean Lorentz factors, with a broad probability distribution that peaks at $\Gamma_m \approx 7$, corresponding to the following intrinsic correlation:

$$\log L_{\text{kin}} = (0.81 \pm 0.11) \log L_R + 11.9^{+4.4}_{-3.3}$$ (6)

Reassuringly, the probability distribution of mean Lorentz factors, although broad, clearly excludes low values of $\Gamma_m$. More detailed studies of the relativistic speeds of Blazars emitting regions give similar results (see e.g. Cohen et al. 2007).

Interestingly, the relationship between kinetic power and radio luminosity gets tighter if one uses the FP relation as an estimator of the un-boosted radio flux, as shown in Figure 4 the intrinsic scatter is reduced from 0.47 dex to 0.37 dex. This is expected if this steeper correlation reflects more directly the intrinsic relation between jet kinetic and radiative power, and lends support to our statistical method to correct for the bias induced by relativistic beaming.

Finally, we note that the slope of the correlation between $L_{R,\text{FP}}$ and $L_{\text{kin}}$ is consistent with the predictions of synchrotron models for the flat spectrum jet cores according to which (Heinz & Sunyaev 2003) $L_R \propto L_{\text{kin}}^{17+8\alpha_V}/12 M^{-\alpha_V}$, where $\alpha_V$ is the radio spectral index. For flat spectrum cores, like the ones we are considering here, $\alpha_V \sim 0$ and the logarithmic slope of the $L_{\text{kin}} - L_R$ correlation is expected to be $\sim 12/17 = 0.71$, within 1-$\sigma$ from our estimate.
The intrinsic relation between radio and kinetic luminosity of the jets can also be used to determine the total radiative efficiency of the jet cores, \( \eta_{\text{jet}} \), the ratio of radiated to kinetic luminosity. This will of course depend on the maximal frequency, \( \nu_{\text{max}} \), up to which the flat radio core spectrum extends. Assuming a constant spectral index (i.e. neglecting spectral steepening at \( \nu < \nu_{\text{max}} \)) we have:

\[
\log \eta_{\text{jet}} = (\alpha + 1) \log(\nu_{\text{max}}/5\text{GHz}) + 0.19 \log L_B - 11.9 \quad (7)
\]

Many nearby low-luminosity radio galaxies observed with the HST show unresolved optical nuclei the flux of which clearly correlates with the radio one (Chiaberge, Capetti & Celotti 1999), suggesting that in those objects the jet emission extends up to the optical band, and the corresponding radiative efficiency can be as high as 10-20%. This result is not substantially modified if we allow at least a non negligible fraction of the X-ray core luminosity to originate in the jet, as recently argued on the basis of either X-ray spectroscopy alone (Evans et al. 2006) or on model fitting of multiband spectral energy distribution (SED) (Wu, Yuan & Cao 2007). This is because the available constraints on broad band SED of low-luminosity radio AGN (mostly FR I) based on radio-to-optical-to-X-ray indexes (see e.g. Hardcastle & Worrall 2000; Heinz 2004; Balmaverde, Capetti & Grandi 2006) show that the spectra must be concave everywhere between the radio and X-ray bands, and this alone ensures that the radiative output of the jet cores is dominated by the emission at the peak frequency, \( \nu_{\text{max}} \), thus justifying the use of the above equation.

4 DISCUSSION

4.1 Testing accretion flow models

In section 2 we have shown that there is a significant correlation between kinetic power and Bondi power, as well as between X-ray (bolometric) luminosity and kinetic power, while the Bondi power and the X-ray luminosity are not correlated. Here we try to interpret this fact, as well as the observed slopes of the statistically significant correlations within simple models for sub-Eddington accretion flows.

The idea that low-luminosity AGN accrete in radiatively inefficient fashion was first put forward by Rees et al. (1982) and Fabian & Rees (1995), while efforts were made at the same time to accommodate advection dominated accretion flows (ADAF; Narayan & Yi 1995) within the general framework of accretion theory. Very early on it was also recognized that such kind of adiabatic (i.e. non radiative) accretion flows are prone to the production of strong outflows, so that in fact only a tiny fraction of the gas entering the black hole sphere of influence finally makes its way onto the black hole (Blandford & Begelman 1999, Blandford & Begelman 2004). While the observational evidence for low radiative efficiency in many nearby galactic nuclei has grown significantly in recent years (see e.g. Ho 2002; MHD03; Pellegrini 2005; Chiaberge et al. 2005) there remains substantial uncertainty on the true dynamical state of such flows.

Here we want to exploit the unique possibility offered by this sample with its comprehensive information on both inner and outer boundary conditions for the accretion flow, as well as its reliable inventory of the energy output. We start from a very general accretion disc model coupled to a disk wind such as those studied in detail in Kuncic & Bicknell (2004). There the interested reader will find an analytic description of the most general MHD disk accretion, specifically addressing the relationship between radial and vertical mean field transport of mass, momentum and energy.

In what follows, we will use as a starting point Eq. (84) of Kuncic & Bicknell (2004) for the rate of energy released by the viscous torques within the disc as:

\[
Q^+ = \frac{3GM_{BH}M_{\text{out}}}{8\pi r^3} \zeta_K(r) - \frac{3\zeta_K}{8\pi r^2} \int_{r_{\text{in}}}^{r_{\text{out}}} \frac{M_{\text{out}}(r')v_K(r')}{2} \, dr' \quad (8)
\]

where \( M_{\text{out}} \) is the accretion rate at the outer boundary, \( \zeta_K = 1 - (\nu_{\text{in}}/r)^{1/2} \), \( \Omega_K \) is the Keplerian angular velocity \( \Omega_K = v_K/r = \sqrt{GM/r^3} \), \( M_w(r) \) is the mass loss rate in the outflow, and we have neglected any additional torque at the disc inner boundary, as well as all additional terms due to vertical Poynting flux and irradiation of the disc from outside, for the sake of simplicity.

The first term on the right hand side of Eq. (8) represents the binding energy flux associated with the net mass flux, and is familiar from standard accretion disc theory (Shakura & Sunyaev 1973), while the second term is related to the flux of kinetic and gravitational energy in the outflow.

We adopt here the simplest phenomenological model for the accretion rate through the disc:

\[
\dot{M}_a(r) = \begin{cases} 
M_{\text{out}}, & r \geq r_{\text{out}} \\
\frac{M_{\text{out}}}{r_{\text{out}}^{p-1}}, & r < r_{\text{out}} 
\end{cases} \quad (9)
\]

with \( 0 \leq p < 1 \) (Blandford & Begelman 1999), where \( r_{\text{out}} \) represents a critical radius beyond which mass outflow is negligible. Correspondingly, mass conservation implies that the mass outflow as a function of radius can be expressed as \( \dot{M}_w = \dot{M}_{\text{out}} - \dot{M}_a = \dot{M}_{\text{out}}[1 - (r/r_{\text{out}})^{p-1}] \). With such a simple ansatz, the kinetic energy properties of the outflow closely resemble those of the adiabatic ADIOS solutions.

By integrating Eq. (8) from the inner radius, \( r_{\text{in}} \) to \( r_{\text{out}} \), we obtain for the power dissipated within the disc:

\[
P_d = \int_{r_{\text{in}}}^{r_{\text{out}}} 4\pi r Q^+ \, dr = P_B - L_{\text{mech}}
\]

\[
= \frac{GM_{\text{M}_{\text{out}}}}{2r_{\text{in}}} \left[ \frac{\xi^p}{(1-p)^{3/2}} - \frac{3}{2p+1} \frac{1}{(1-p)} \xi \right] + \frac{2}{2p+1} \xi^{p+3/2} \quad (10)
\]

where we have introduced the parameter \( \xi = \frac{r_{\text{in}}}{r_{\text{out}}} \). In the above expression, \( P_B \) represents the total power released by the accretion process, while \( L_{\text{mech}} \) is the mechanical energy carried by the outflow. The latter is given by:

\[
L_{\text{mech}} = v_{\text{in}}^2 \int_{r_{\text{in}}}^{r_{\text{out}}} \frac{3\Omega_K}{2r} \int_{r_{\text{in}}}^{r} v_K(r') r' \frac{d\dot{M}_a}{dr'} \, dr' = \frac{GM_{\text{M}_{\text{out}}}}{2r_{\text{in}}} \left[ \frac{2p}{(1-p)^{3/2}} \right] \xi^p - \frac{3}{2p+1} \xi \right] \]

\[
+ \frac{2p}{2p+1} \xi^{p+3/2} \quad (11)
\]

where \( v_{\text{in}} \) is the ratio of the terminal wind speed to the Keplerian velocity, here assumed to be independent of \( r \).

The radiative power depends on micro-physical properties of the disc (capability of heating electrons as opposed ions), on its vertical structure and on the radiative processes involved. Radiatively efficient disc, as those discussed in Kuncic & Bicknell (2004), would obviously have \( L_{\text{bol}} = P_B \), and we can already guess that this option is not allowed by the observed correlations. Indeed, in the limit of very large \( r_{\text{out}} \), \( \xi \ll 1 \), we have that both the mechanical luminosity of the disc, \( L_{\text{mech}} \) and \( P_B \) scale as the accre-
tion rate through the disc in its inner part $\dot{M}_\text{a} \sim \dot{M}_\text{out} \xi^p$, so that $L_{\text{mech}} \propto L_{\text{bol}}$, rather than the observed $L_{\text{mech}} \propto L_{\text{bol}}^{\frac{3}{2}}$ (see section 2). The only way in which this can be altered is by considering the effect of magnetic fields in the accretion flow. As it was proposed by Merloni & Fabian (2002) and discussed also in Kuncic & Bicknell (2007), strong magnetic field threading a thin disc may remove energy and angular momentum (and very little mass) without radiating efficiently, and in so doing generating powerful, Poynting dominated outflows. However, the specific scaling between kinetic and radiative power in this case depends in a complicated way on the dynamo properties of the disc, and is not yet as fully understood as the adiabatic (ADIOS) solutions we discuss here.

This suggests a simple phenomenological scaling for the radiative output of mass-losing low luminosity discs, that can be written as $\log(L_{\text{bol}}/L_{\text{edd}}) = C + \gamma \log(P_0/L_{\text{edd}})$. The normalization $C$ is related to the value of the dimensionless accretion rate above which radiatively inefficient accretion ceases to be a viable solution due to the increase of disc density and cooling rate. The value of the parameter $\gamma$, instead, depends on the radiative cooling properties of the accreting gas, and within our approach has to be fixed by comparison with observations.

To fully characterize the model, and make it suitable to be tested against the available data, one still needs to specify the relationship between $r_\text{out}$ and $\dot{M}_\text{out} = \dot{M}_\text{Bondi}$. In adiabatic solutions with outflows, the radius beyond which radiative losses are significant and the adiabatic self-similar solution breaks down will depend on the outer supply of mass and angular momentum and on the cooling properties of the outer disc (Blandford & Begelman 2004). In our case, we simply assume:

$$\log(\xi) = A + B \log(\dot{M}_\text{out}/\dot{M}_\text{Bondi})$$

(12)

and use the data to put limits on $A$ and $B$.

Our accretion/outflow model has the desired properties of simplicity and generality, which make it suitable to be tested against the dataset at hand. Indeed, variations of the indexes $p$ and $\gamma$ allow us to span the full range of dynamical accretion models from pure ADAF ($p = 0$ and $\gamma \simeq 2$) to ADIOS ($1 > p > 0$ and $\gamma \simeq 2$) to radiatively efficient, wind dominated discs ($1 > p > 0$ and $\gamma \simeq 1$) down to standard, radiatively efficient, conservative thin discs ($p = 0$ and $\gamma = 1$). The parameters $A$ and $B$, in turn, give us an handle on the large-scale geometrical properties of the flows, with $C$ representing an overall normalization of the radiative efficiency of the system. The sixth and final parameter of the model, $v_\infty$, turns out to be strongly degenerate with the normalization parameters $A$ and $C$. Given the amount of information in the data, we have chosen to keep its value fixed, either to a value of 1 (terminal velocity equal to the local Keplerian speed) or 2 (terminal velocity twice the local Keplerian speed), and perform two separate fits. Detailed dynamical modelling of the jets and outflows at different luminosities and black hole masses will be needed in order to constrain its value reliably.

In summary, our model has just five free parameters: $p$, $\gamma$, $C$, $A$ and $B$. We have fitted this model to the observed relationships between kinetic power and Bondi power, and between kinetic power and bolometric luminosity. In Figure 5 we show the best fit to the data for the two independent correlations with the model described above (in the case $v_\infty = 2$, blue solid line and $v_\infty = 1$, green solid line). Our simple illustrative model provides an excellent description of the data both in the case of $v_\infty = 2$ and $v_\infty = 1$. The best-fit values for the model parameters (with their 90% confidence errors, calculated by letting each single parameter vary while fixing all others to their best fit value) are given by: $p = 0.85^{+0.11}_{-0.16}$, $A = 0.13 \pm 0.30$, $B = 0.63 \pm 0.10$ and $\gamma = 1.98 \pm 0.06$ and $C = 2.27 \pm 0.24$ in the case $v_\infty = 2$, and $p = 0.92^{+0.11}_{-0.16}$, $A = 0.1 \pm 0.19$, $B = 0.45 \pm 0.10$ and $\gamma = 2.04 \pm 0.06$ and $C = 2.00 \pm 0.22$ in the case $v_\infty = 1$.

A crucial prediction of the model is the dependency of $r_\text{out}$ on the outer accretion rate. According to our fit, we have, in units of the Schwarzschild radius $r_S = 2GM/c^2$,

$$\frac{r_\text{out}}{r_S} \approx 6 \times 10^2 \left( \frac{\dot{m}_\text{out}}{10^{-4}} \right)^{-0.63}$$

(13)

where $\dot{m}_\text{out} = \dot{M}_\text{out}/\dot{M}_\text{Bondi}$. For the objects in our sample, this is reassuringly smaller than either the inferred Bondi radius and the radius beyond which radiative losses are significant and adiabatic self-similar outflow dominated solutions are not viable. In the sample under study, the two brightest objects (Cyg A and Hydra A) have $\dot{m}_\text{out} \approx 10^{-2.5}$ and therefore outer outflow radii of just a few tens of Schwarzschild radii. They may therefore qualify as “intermediate” objects in a transition between radiatively efficient (hidden QSO-like) and inefficient AGN. In this case, the self-similar assumption becomes poorer, and clear signs of the presence of an outer standard disc may be expected (Ogle et al. 1997, Sambruna et al. 2000).

As we have discussed above, a clear distinction exists between those parameters that describe the nature of the outer boundary conditions of the flow and solely determine slope and normalization of the $L_{\text{Kin}} - P_{\text{Bondi}}$ relation ($A$, $B$ and $p$) and those that instead describe the nature and radiative properties of the inner accretion flow and determine the slope of the $L_X - L_{\text{Kin}}$ relation ($\gamma$ and $p$). This might explain why we found no statistically significant correlation between radiative output and Bondi power.

It is worth stressing here that the above model represents a very schematic description of the physical properties of a low-luminosity accretion flow and the accompanying powerful outflow.
As mentioned above, a full exploration of all possible theoretical alternatives for such flows should also take into account dynamically important magnetic fields and their role in the jet production mechanisms. The reason we have chosen not to do so here is merely the quality of the data available, which would not have allowed to put meaningful constraints on the parameters of such complicated MHD disc-outflow solutions. What we have instead shown is that future, better samples like that assembled here promise to be extremely useful for constraining the complex physical properties of accretion at the lowest rates.

4.2 The kinetic power output of Sgr A*

The quiescent radio and X-ray luminosities of the ~ 4 × 10^6 M☉ nuclear black hole at the center of the Milky Way, Sgr A* (log L_R ≈ 32.5 and log L_X ≈ 33.3) would be both consistent with a Bondi accretion rate of about 10^-6 M☉/yr, in line with the Chandra measurements of the inner hot gas properties of the galactic center [Baganoff et al. 2001; Baganoff et al. 2003]. If the same model outlined in section 4.1 applied to Sgr A*, it would predict an outer radius of the outflow of about r_out ~ 2.5 × 10^17 Schwarzschild radii (~ 0.025 pc at the distance of the galactic center) and an inner accretion rate M_in(r_in) = M_out (approx. 4 × 10^-9 M☉/yr), also consistent with the gas density in the inner accretion flow implied by linear polarization measurements [Aitken et al. 2000; Bower et al. 2003; Bower et al. 2005]. Altogether, this would indicate that the SMBH at the galactic center is the source of about 10^7 years. Such a mechanical power input into the galactic center could play a significant role in the production of the TeV γ-rays recently observed by the HESS (High Energy Stereoscopic System) collaboration [Aharonian et al. 2004; Atoyan & Dermer 2004], as well as in the heating of the hot (> 8 keV) diffused plasma detected by Chandra [Muno et al. 2004].

4.3 The effect of variability on the observed correlations

In section 3 we have concentrated our attention on the assessment of the effects of relativistic beaming on the measured slope of the L_kin-L_R correlation. However, one should expect a second source of scatter in any correlation between kinetic power and nuclear luminosity (in any waveband). The large scale power is an average over the typical age of the cavities and bubbles observed in the X-ray atmosphere of the galaxies in our sample. Such an age may be assumed to be of the order of either the buoyant rise time, or the sound crossing time, or the refill time of the radio lobes [Birzan et al. 2004]. These estimates typically differ by about a factor of 2, and, for the sample in question, lie in the range t_age ~ 10^7 – 10^8 years. On the other hand, the core power is variable on time scale much shorter than that. The bias introduced by this fact can be quantified as follows.

First of all, we notice that AGN X-ray lightcurves, where most of the accretion power emerges, show a characteristic rms-flux relation which implies they have a formally non-linear, exponential form [Uttley, McHardy & Vaughan 2005], and the luminosity follows a log-normal distribution [Nipoti & Binney 2005]. Let us, for the sake of simplicity, define as \( L(t) \) the instantaneous luminosity of the AGN, be it bolometric, kinetic or radio, under the implicit assumption that very close to the central engine jet and accretion are strongly coupled, so that all of them follow a log-normal distribution. Thus, log \( L \) is normally distributed with mean \( \mu_t \) and variance \( \sigma_t^2 \). The measured kinetic power \( L_{\text{kin}} \) discussed in this work being a long-term time average, it should be determined by the mean of the log-normally distributed \( L, i.e. \langle L \rangle = \exp(\mu_t + \sigma_t^2/2) \). Because the log-normal distribution is positively skewed, the mode \( m \) of the distribution of \( L, i.e. \) the most likely value of a measurement of \( L_{\text{obs}} \), is smaller than the mean: \( L_{\text{obs}} = m = \exp(\mu_t - \sigma_t^2) \). Therefore the most likely value of the ratio of the mean to the observed luminosity is given by [Nipoti & Binney 2005; Uttley et al. 2005]:

\[
\frac{\langle L \rangle}{L_{\text{obs}}} = e^{\frac{3}{2}\sigma_t^2} = \left(\sigma_{\text{rms}}^2 + 1\right)^{3/2},
\]

where we have introduced the rms (fractional) variability of the observed lightcurve \( \sigma_{\text{rms}}^2 = \exp(\sigma_t^2) - 1 \), an easily measurable quantity. The higher the rms variability of a lightcurve, the higher is the probability that an instantaneous measurement of the luminosity yields a value smaller than \( \langle L \rangle \) [Nipoti & Binney 2005], and also the higher the most likely ratio between the two values.

Before discussing what are the appropriate values of \( \sigma_{\text{rms}}^2 \) to be used in Eq. (14), we also note that the observed slope of the \( \langle L \rangle-L_{\text{obs}} \) correlation may deviate from unity for a log-normal distribution, thus skewing any observed correlation between mean and instantaneous power, like those we have discussed so far. It is easy to show that from Eq. (14) we obtain:

\[
\frac{\partial \log \langle L \rangle}{\partial \log L_{\text{obs}}} = 1 + \frac{3}{2} \frac{\sigma_{\text{rms}}^2}{1 + \sigma_{\text{rms}}^2} \frac{\partial \log \sigma_{\text{rms}}^2}{\partial \log L_{\text{obs}}},
\]

Log-normal AGN variability may thus skew the observed relation between jet average kinetic power and instantaneous core luminosity much in the same way relativistic beaming does. Inspection of Eqs. (14) and (15) suggests that the measured slopes of any correlation of the (average) kinetic vs, core power will be substantially affected by variability if, and only if, both \( \sigma_{\text{rms}}^2 \) and \( \partial \log \sigma_{\text{rms}}^2/\partial \log L_{\text{obs}} \) are at least of the order of unity.

Unfortunately, very little is known observationally about the variability amplitude of AGN on very long timescales, especially for AGN of low luminosity as those considered here. Brighter AGN (Seyferts), on shorter timescales (1-10 years), have indeed rms variability amplitudes that rise steeply with decreasing luminosity, from about \( \sigma_{\text{rms}}^2 \approx 10^{-2} \) for \( L_X \approx 10^{14} \) up to \( \sigma_{\text{rms}}^2 \approx 10^{-1} \) for \( L_X \approx 10^{12} \) [Nandra et al. 1997; Markowitz & Edelson 2001]. However, no evidence is yet found of such a trend continuing down to lower luminosities. On the contrary, suggestions have been made that \( \sigma_{\text{rms}}^2 \) may flattens out at lower \( L_X \) [Papadakis 2004; Paolillo et al. 2004] at values of a few times \( 10^{-1} \) for the typical X-ray luminosity of the objects in our sample. This would imply that the observed correlations between large scale and core powers are not skewed by variability bias.

However, we should also consider the possibility that, if measured on the \( t_{\text{age}} \) timescale, rather than on years or decades, AGN variability amplitude can be much higher, perhaps exceeding unity [Nipoti & Binney 2005]. Specifically for the case of radio galaxies, various indirect pieces of evidence of intermittency have been presented, such as the ripples and shock waves detected in the X-ray emitting atmosphere of M87 [Forman et al. 2005], or the number vs. size counts of small radio galaxies [Reynolds & Begelman 1997], both obviously relevant for our current discussion.

All AGN Power Spectral Densities (PSD): the variability power \( P(\nu) \) at frequency \( \nu \), or timescale \( 1/\nu \) are best fitted by
a power-law of index $-1$ ($P(\nu) \propto \nu^{-1}$) on long timescales, which breaks to a steeper slope on timescales shorter than a break timescale, which itself appear to be correlated with the central black hole mass and accretion rate ($t_{\text{break}} \propto M_{\text{BH}}^2/L_{\text{bol}}$, McHardy et al. 2006). Indeed, if the PSD of AGN at very low frequencies, $\nu \sim 1/t_{\text{age}}$, are a seamless extension of the flicker noise observed on days-years timescales, then their rms variability amplitude could be very large: $\sigma_{\text{rms}} \simeq 1 - 10$.

If we define the duty cycle of $L(t)$ as $\delta \equiv \langle L^2 \rangle / \langle L \rangle^2 = (1 + \sigma_{\text{rms}}^2)^{-1}$ (Ciotti & Ostriker 2001), then large rms amplitudes would imply very bursty lightcurves, with very short duty cycles $\delta \sim 10^{-1} - 10^{-2}$. Within this picture, the measured $L_{\text{kin}}$ would be dominated by very short, “quasar-like phases”, rather than by quasi-continuous radio mode AGN activity.

Although this possibility cannot be easily ruled out, we feel it is currently disfavored for two main reasons: first of all, it would imply a typical QSO lifetime for these objects of $t_{\text{QSO}} \lesssim 10^5$ yrs, much less than current estimates (Martini 2004); secondly, if the variability properties of low luminosity AGN are scaled up versions of those of low/hard state GBH, as it is the case for bright objects (McHardy et al. 2006), then we should expect a second, lower frequency break to white noise slope ($P(\nu) = \text{const.}$) in the PSD (Uttley, McHardy & Vaughan 2005). Such a break should be present at timescales $t_{\text{flat}}$ between 10-100 times longer than $t_{\text{break}}$, but still much smaller than $t_{\text{age}}$. In this case, $\sigma_{\text{rms}}^2 \sim N[2 + \ln(t_{\text{flat}}/t_{\text{break}})] \simeq 6N$, where $N$ is the frequency independent amplitude of $\nu \times P(\nu)$ in the flicker noise part of the PSD, which has been measured for many AGN and GBH to be of the order of a few times $10^{-2}$ (Papadakis 2004, Done & Gierlinski 2005). Thus, at most, we should expect $\sigma_{\text{rms}} \sim$ a few times $10^{-1}$ also for low luminosity AGN on very long timescales, implying a much higher duty cycle (not much smaller than unity).

To summarize, the effects of the AGN intermittency on the observed relations between time-averaged kinetic power and instantaneous core luminosities will be comparable to that of beaming if AGN have very bursty lightcurves (duty cycles less than 10%). However, available estimates of rms variability as a function of luminosity on shorter timescales, scaling relations with galactic black holes as well as nuclear luminosity of the jets. Interestingly, there is no statistically significant correlation between Bondi power and bolometric luminosity apart from that induced by their common dependence on $L_{\text{kin}}$.

- The observed correlations are in very good agreement with theoretical predictions of adiabatic accretion models with strong outflows. We have also shown that meaningful constraints on some specific physical properties of such models can be placed by fitting the observed data set.
- The available measures of the average jet power provide a very useful tool to assess, in a statistical sense, both the jet radiative efficiency and the effects of relativistic beaming on the observed AGN jet population. Combining information on the kinetic jet power with estimators of the un-beamed radio flux of a jet core (as, for example, the so-called fundamental plane of active black holes, MHD03), we are able to determine both the probability distribution of the mean jets Lorentz factor, that peaks at $\Gamma \sim 7$, and the intrinsic relationship between kinetic and radio core luminosity, log $L_{\text{kin}} = (0.81 \pm 0.11) \log L_R + 11.9^{+4.1}_{-4.4}$ which is in good agreement with theoretical predictions of synchrotron jet models: $L_{\text{kin}} \propto L_R^{12/7(1+8\alpha_{\nu})}$, where $\alpha_{\nu}$ is the radio spectral index of the jet core.
- The total radiative efficiency of the jet can be expressed as a function of the observed 5 GHz luminosity ($L_R$) and spectral index, $\epsilon_{\text{jet}} = 3.2 \times 10^{-5} (L_R/10^{39} \text{erg/s})^{0.19} (\nu_{\text{max}}/5\text{GHz})^{4+4.4}$, where $\nu_{\text{max}}$ is the high turnover frequency of the synchrotron emission.
- The relation between $L_{\text{kin}}$ and observed radio core luminosity is flattened with respect to the intrinsic one because of the unaccounted-for Doppler boosting in the small sample at hand. Results of previous works that have studied the relationship between total extended radio power and kinetic power (Birzan et al. 2004, Birzan et al. 2006), found both flat slopes and very large intrinsic scatter (much larger than what we found here). As Birzan et al. (2006) noticed, such a scatter is "intrinsic to the radio data, for reasons that include radio aging and adiabatic expansion." This might be considered as a further argument in support of our approach of using core radio luminosities, instead, as estimator of the AGN kinetic power.
- The intrinsic variability of the AGN could affect our results due to the fact that the measured kinetic power is a long-term average of the instantaneous power, and that the luminosity of accreting black holes are log-normally distributed, and therefore positively skewed. Very little is known about the long-term ($10^{-3}-10^3$ years) variability properties of low luminosity AGN. However, available estimates of rms variability as a function of luminosity on shorter timescales, scaling relations with galactic black holes as well as current estimates of quasar lifetimes all seem to suggest that the variability cannot be so extreme to affect the results of a correlation analysis more dramatically than relativistic beaming does.

With the aid of these findings, quantitative assessments of kinetic feedback from supermassive black holes in the radio mode (i.e. at low dimensionless accretion rates) will be possible based on accurate determinations of the central engine properties alone, such as mass, radio core and/or X-ray luminosity. This will provide useful

5 CONCLUSIONS

We have presented a statistical analysis of a sample of 15 nearby AGN for which the average kinetic power has been estimated from the study of the cavities and bubbles produced by the jets in the IGM. In particular, rather than focusing on the relationship between the kinetic power and the IGM physical state, as was done before, we have tried to derive the relationship between jet kinetic power and nuclear properties of the AGN, specifically in terms of their black hole masses, 2-10 keV and 5 GHz radio core luminosities.

Following our analysis, we reach the following conclusions:
- A clear relationship exists between Eddington-scaled kinetic power and bolometric luminosity, given by: $\log(L_{\text{kin}}/L_{\text{Edd}}) = (0.49 \pm 0.07) \log(L_{\text{tot}}/L_{\text{Edd}}) - (0.78 \pm 0.36)$. The measured slope suggests that these objects are in a radiatively inefficient accretion mode.
- We confirm previous claims of a correlation between Bondi power (i.e. accretion rate at the Bondi radius) and Kinetic luminosity of the jets. Interestingly, there is no statistically significant correlation between Bondi power and bolometric luminosity apart from that induced by their common dependence on $L_{\text{kin}}$.
- The observed correlations are in very good agreement with theoretical predictions of adiabatic accretion models with strong outflows. We have also shown that meaningful constraints on some specific physical properties of such models can be placed by fitting the observed data set.
- The available measures of the average jet power provide a very useful tool to assess, in a statistical sense, both the jet radiative efficiency and the effects of relativistic beaming on the observed AGN jet population. Combining information on the kinetic jet power with estimators of the un-beamed radio flux of a jet core (as, for example, the so-called fundamental plane of active black holes, MHD03), we are able to determine both the probability distribution of the mean jets Lorentz factor, that peaks at $\Gamma \sim 7$, and the intrinsic relationship between kinetic and radio core luminosity, log $L_{\text{kin}} = (0.81 \pm 0.11) \log L_R + 11.9^{+4.1}_{-4.4}$ which is in good agreement with theoretical predictions of synchrotron jet models: $L_{\text{kin}} \propto L_R^{12/7(1+8\alpha_{\nu})}$, where $\alpha_{\nu}$ is the radio spectral index of the jet core.
- The total radiative efficiency of the jet can be expressed as a function of the observed 5 GHz luminosity ($L_R$) and spectral index, $\epsilon_{\text{jet}} = 3.2 \times 10^{-5} (L_R/10^{39} \text{erg/s})^{0.19} (\nu_{\text{max}}/5\text{GHz})^{4+4.4}$, where $\nu_{\text{max}}$ is the high turnover frequency of the synchrotron emission.
- The relation between $L_{\text{kin}}$ and observed radio core luminosity is flattened with respect to the intrinsic one because of the unaccounted-for Doppler boosting in the small sample at hand. Results of previous works that have studied the relationship between total extended radio power and kinetic power (Birzan et al. 2004, Birzan et al. 2006), found both flat slopes and very large intrinsic scatter (much larger than what we found here). As Birzan et al. (2006) noticed, such a scatter is "intrinsic to the radio data, for reasons that include radio aging and adiabatic expansion." This might be considered as a further argument in support of our approach of using core radio luminosities, instead, as estimator of the AGN kinetic power.
- The intrinsic variability of the AGN could affect our results due to the fact that the measured kinetic power is a long-term average of the instantaneous power, and that the luminosity of accreting black holes are log-normally distributed, and therefore positively skewed. Very little is known about the long-term ($10^{-3}-10^3$ years) variability properties of low luminosity AGN. However, available estimates of rms variability as a function of luminosity on shorter timescales, scaling relations with galactic black holes as well as current estimates of quasar lifetimes all seem to suggest that the variability cannot be so extreme to affect the results of a correlation analysis more dramatically than relativistic beaming does.
APPENDIX A: THE EFFECT OF RELATIVISTIC BEAMING ON THE FUNDAMENTAL PLANE RELATION FOR ACTIVE BLACK HOLES

We are concerned here with the following question: What is the effect of relativistic beaming on the determination of the slope of the fundamental plane (FP, MHD03) relation? Or, put it in another way, can we safely assume that the FP relation (in any of its incarnations) is free from biases due to relativistic beaming, and thus suitable to use as a calibrator to estimate the intrinsic radio core luminosity?

As originally discussed in MHD03, we introduce the “observed” FP relation as

$$\log L_{R,\text{obs}} = \xi_{RR} \log L_X + \xi_{RM} \log M_{\text{BH}} + b_R,$$  \hspace{1cm} (A1)

where the observed correlation coefficients depend, at the 1-sigma level, on the specific choice of sample, as discussed in KFC06.

The strongest effect on the slope of any intrinsic correlation (i.e., any correlation between the intrinsic, un-boosted luminosities of jetted sources) comes from the inclusion/exclusion of object with jet axis close to our line of sight (see e.g. Heinz and Merloni 2004). If we define a “cut-off” angle, $\theta_c$, such that all object with inclination $\theta < \theta_c$ are excluded from a sample, then the slope of the observed correlation deviates from the intrinsic one as a strong function of $\theta_c$, once the Lorentz factor $\Gamma > 1/\theta_c$.

In order to assess this effect, we have simulated a sample of nearby SMBH according to the selection criteria of MHD03 and K"ording, Falcke and Corbel (2006) [KFC06], with a simple Monte Carlo routine. In our fiducial calculation, an effective cut-off angle of $\theta_c = 15^\circ$ is assumed, as these samples have been “cleaned” of relativistically boosted radio cores by excluding (or correcting for) all known BL Lac objects. The radio fluxes are drawn from the observed local ($z=0$) flat spectrum radio luminosity function (Dunlop & Peacock 1990). Distances are drawn from a distribution that closely resembles that of the sources in our sample (see Table 2), and objects with a flux smaller than $0.1$ mJy at 5 GHz and $10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ in the 2-10 keV band are excluded. The radio luminosity is then un-boosted assuming random orientation of the jet between $\theta_c$ and $90^\circ$. The jet Lorentz factor is assumed to be normally distributed around $\Gamma_c = 0.11 \Gamma_{\text{in}}$, and we studied the effects of varying $\Gamma_{\text{in}}$ between 1.5 and 50. We fitted the simulated data with the (symmetric) OLS Bisector regression algorithm (Isobe et al. 1990) in order to determine the relationship between the intrinsic radio luminosity $L_R$ and the observed one: $\log L_R = \xi_{RR} (\Gamma_{\text{in}}) \log L_{R,\text{obs}} + b_R$. As expected, we found that the larger the mean Lorentz factor of the objects, the more the observed correlations are skewed away from the $\xi_{RR} = 1$ intrinsic slope. In particular, the best fit slopes can be approximated by the following log-linear relation:

$$\xi_{RR} \approx 1 - 0.14 \log \Gamma_{\text{in}},$$  \hspace{1cm} (A2)

can be regarded as a “calibrator” of the fundamental plane relationship.

The above relation (A2) is plotted in both upper and lower panels of Fig. A1 as a solid line, while the dark red shaded areas represent the 1-sigma contours. Figure A1 also illustrates the effects of slightly varying our fiducial assumptions on the distribution of the Lorentz factors and on the cut-off angle. In particular, the upper panel shows the results of increasing the width of the Lorentz factor distribution by a factor of 3 (from $0.1 \Gamma_{\text{in}}$ to $0.3 \Gamma_{\text{in}}$, dot-dashed lines). In this case the best fit slope is approximated by another log-linear with slope $-0.16$ (thick dot-dashed line). This translates into a difference in the FP slope from our fiducial case around $\Gamma_{\text{in}} \approx 7$ of just about 3%, much less than the statistical uncertainties. Similar is the case when different cut-off angles are considered. In the lower panel of Fig. A1 we show how the observed correlations are skewed due to relativistic beaming when $\theta_c = 10^\circ$ (dot-dashed contours and thick dot-dashed line) or $\theta_c = 20^\circ$ (dashed contours and thick dashed line). In these cases the difference with respect to our fiducial case corresponds to
Figure A1. The effects of relativistic beaming on the observed radio luminosities in simulated samples resembling those used to derive the “fundamental plane” relation. In the upper panel we show, as a function of the mean jet Lorentz factor, the best-fit slope $\xi_{\text{RR}}$ of the relation between intrinsic and observed radio core luminosity for two values of the width of the $\Gamma$ distribution: $\sigma_\Gamma/\Gamma = 0.1$ (solid contours and thick solid line) and $\sigma_\Gamma/\Gamma = 0.3$ (dot-dashed contours and thick dot-dashed line). In the lower panel we show $\xi_{\text{RR}}$ vs. $\Gamma_m$ for three values of the cut-off angle: $\theta_c = 10^\circ$ (dot-dashed contours and thick dot-dashed line), $\theta_c = 15^\circ$ (solid contours and thick solid line) and $\theta_c = 20^\circ$ (dashed contours and thick dashed line).

A difference in the “corrected” FP coefficients of less than $\sim 3\%$ at $\Gamma_m \simeq 7$.

In summary, for any value of mean jet Lorentz factor of the sampled AGN, $\Gamma_m$, we have shown that it is possible to derive statistically an intrinsic (un-boosted) radio core luminosity based on the observed hard X-ray one, $L_X$ and on the black hole mass, $M_{\text{BH}}$ according to:

$$\log L_{R,\text{FP}} = (1 - 0.14 \log \Gamma_m)[\xi_{\text{RX}} \log L_X + \xi_{\text{RM}} \log M_{\text{BH}}] + c_R(\Gamma_m),$$

where we have defined the new constant $c_R = \xi_{\text{RR}} b_R + b_{\text{RR}}$. The term in the first parenthesis in the right hand side thus represents our simple way to estimate the relativistic beaming bias introduced in the samples used originally to define the FP relation. Its numerical value do indeed depends on the assumptions of our fiducial Monte Carlo model, but to an extent that is negligible when compared to the statistical uncertainties on the FP parameters themselves. This above relation, then allows a meaningful statistical test of the intrinsic correlation between radio core luminosity and kinetic power of AGN jets, as we show in section 3.