OPTICAL–RADIO MAPPING: THE KINETIC EFFICIENCY OF RADIO-LOUD AGNs

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ABSTRACT

We constrain the mean kinetic efficiency of radio-loud active galactic nuclei by using an optically selected sample for which both the optical and the radio luminosity functions (LFs) have been determined; the former traces the bolometric luminosity $L$, while the latter traces the kinetic power $L_k$, empirically correlated to the radio emission. Thus in terms of the ratio $g_k = L_k/L$, we can convert the optical LF of the sample into a radio one. This computed LF is shown to match the directly observed LF for the same sample if $g_k = 0.10^{\pm0.05}_{-0.01}$ holds, with a scatter $\sigma = 0.38^{\pm0.04}_{-0.09}$ dex; with these values we also match a number of independent correlations between $L_k$, $L$ and radio emission, that we derive through Monte Carlo simulations. We proceed to translate the value of $g_k$ into a constraint on the kinetic efficiency for the production of radio jets or winds, namely, $\epsilon_k = L_k/M_a c^2 \sim 0.01$ in terms of the rate $M_a$ of mass accretion onto the central black hole. Then, on assuming that on average the radio sources share the same kinetic efficiency, we compute a solid lower limit of about 25% on the contribution of radio sources to the local black hole mass density.

Subject headings: galaxies: active — galaxies: jets — quasars: general

1. INTRODUCTION

The origin of the radio-loudness of active galactic nuclei (AGNs) still constitutes an open issue. There is evidence suggesting that the formation of a relativistic jet or a fast wind (e.g., Blundell & Kuncic 2007) sustaining the radio emission is tightly related to the mass of the central black hole (BH; e.g., Laor 2000). On the other hand, the wide scatter observed between radio and optical luminosities (e.g., Cirasuolo et al. 2003) suggests that other parameters such as the mass accretion rate onto the BH and possibly its spin could play a significant role in determining when a galaxy becomes radio-loud (e.g., Blandford 2000; Ho 2002; Best et al. 2005, Sikora et al. 2007 and references therein).

At one enticing extreme, Blandford & Zhurkov (1977) proposed the jets to be powered by the extraction of energy already accumulated in a rotating BH. On the other hand, the spin, however important to set the jet direction, may not provide the necessary power for energizing the very luminous sources such as some steep-spectrum radio sources (SSRs) and many flat-spectrum quasars (FSQs).

Alternative models (e.g., Livio et al. 1999) have proposed the dominant fraction of the jet or wind kinetic power to be directly linked to the rest-mass energy of the currently accreting matter, as is the case for the radiative power. In any event, the kinetic power must originate at some time from the accretion energy; thus a constraint on the link between these two quantities is of key importance to probe the still unsettled issues of the jet’s composition and production mechanisms (e.g., Celotti 2004).

In this work we propose a simple but efficient and statistically significant way to constrain the fraction of kinetic to accretion power. In the case of the radiative bolometric luminosity $L$, the emitted power is written as $L = \epsilon M_a c^2$, where $M_a$ is the current accretion rate of matter onto the central massive BH and $\epsilon$ is the efficiency to extract $L$ from $M_a$. In an analogous way we can set the kinetic output as $L_k = \epsilon_k M_a c^2 = (\epsilon_k/\epsilon) L$. We assume that the AGN kinetic output represents a fraction $g_k$ of the bolometric luminosity, i.e.,

$$L_k = g_k L;$$

this implies that $g_k = \epsilon_k/\epsilon$ if the two outputs draw from the same accretion flow. Thus one could constrain $g_k$ and in turn $\epsilon_k$ by selecting a statistically significant sample of radio-loud AGNs for which both the radio and optical luminosities are known. The latter is in fact a good tracer of the bolometric emission, given that AGN spectral studies have provided over the years a reliable average bolometric correction $C_B = L/L_{BR} \approx 10$, where the $B$-band luminosity $L_B$ is in units of ergs s$^{-1}$ Hz$^{-1}$ and $\nu_B = 6.8 \times 10^{14}$ Hz (Elvis et al. 1994). In turn, significant radio emission is always associated with kinetic power, and several papers (referred to in § 2) provide and discuss empirical correlations between $L_k$ and the radio luminosity $L_R$.

Our aim is to statistically derive the fraction of the accreting rest mass energy that powers the jets or winds by computing the average ratio $g_k$, and then derive a lower limit to the predicted local BH mass density associated with radio-loud AGNs. In § 2 we present our method, the results of which are given in § 3. In § 4 we describe in detail how to compute the corresponding contribution to the BH mass density using the value of $\epsilon_k$. In § 5 we discuss our results and give our conclusions.

In the following we adopt the “concordance cosmology” (see Spergel et al. 2007) with round parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. THE METHOD

In this section we describe how we statistically constrain the ratio between kinetic and bolometric luminosities $g_k$. Our database is constituted by the optical and the radio luminosity functions (LFS) derived by Cirasuolo et al. (2005; henceforth CMC05) for the same sample of optically selected radio-loud AGNs; this is collected by cross-correlating the Two Degree Field Quasar Redshift survey (2dF) with the Faint Images Radio Sky at Twenty cm (FIRST). The sample spans a considerable range in magnitude $-24 \leq M_B \leq -28$ and redshift $0.8 \leq z \leq 2.2$. In the following
we will start from their optical LF\(^5\) with parameters adjusted to our cosmology.

We then convert the adopted optical LF to a bolometric one by using the average value \(C_B = 10.4\) with a lognormal scatter of 0.1 dex around the mean. We have checked that our results are not sensitive to the precise value of \(C_B\), as very similar conclusions are found also on using \(C_B \approx 8\) (e.g., Marconi et al. 2004, Richards et al. 2006). The direct link between optical and radio luminosities has been already extensively studied by CMC05 (and references therein), who find that a correlation between these two quantities exists, although with a wide scatter.

In this work we are mainly focused on constraining the average kinetic output of radio-loud AGNs. Several studies have been able to empirically define the relation between radio emissions and kinetic outputs, showing that on average the former are associated to high levels of the latter (e.g., Rawling & Saunders 1991). After expressing the bolometric LF in terms of kinetic luminosities via equation (1), we convert to radio powers on the relation of Willott et al. (1999),

\[
L_k = 3 \times 10^{45} f^{3/2} L_{151}^{6/7} \text{ergs s}^{-1} ,
\]

where \(L_{151}\) is the observed radio luminosity in units of \(10^{28} \text{W Hz}^{-1} \text{sr}^{-1}\) at 151 MHz.

In equation (2) \(L_k\) was empirically measured on tracing the integrated \(p dV\) work done by radio AGNs in excavating the cavities observed in the hot gaseous medium around them. The relation calibrated by Willott et al. (1999) relies therefore on specific assumptions on how to link the age of the source to its kinetic power. Following Hardcastle et al. (2007), the factor \(f\) is introduced in equation (2) to account for systematic underestimates of the true jet power that this technique may induce; for example, the quantity \(f\) also includes the coupling efficiency between the AGN kinetic output and the surrounding medium. In the following we use (and discuss in § 5) the average value \(f = 15\), as measured for a sample of Faranoff-Rayleigh I and II radio galaxies (Hardcastle et al. 2007 and references therein).

Note that both \(L_k\) and \(L_{151}\) in equation (2) are calibrated on samples mainly composed of radio galaxies; however, if the unification model is to hold on average for all radio sources (see Urry & Padovani 1995), AGNs and radio galaxies are similar physical systems only observed at different angles; so we will take equation (2) to hold also for our sample of radio-loud AGNs. Throughout we adopt an average AGN radio spectral slope \(\alpha_R = 0.7\), typical of the bright steep-spectrum radio sources sampled by CMC05 (see also references therein). A Gaussian scatter with variance \(\sigma\) is adopted around the mean of both equations (1) and (2).

Thus we obtain a radio LF which depends on only two free parameters, \(g_k\) and \(\sigma\), once \(f\) is fixed. The values of \(g_k\) and \(\sigma\) are then constrained through a \(\chi^2\) analysis by matching our result to the radio LF independently measured by CMC05.

3. RESULTS OF OPTICAL-RADIO MAPPING

Our computed radio LF, shown as a solid line in Figure 1, fits the CMC05 data on the empirical radio LF (filled circles) when

\[
\begin{align*}
    g_k &= 0.10^{+0.05}_{-0.01}, \\
    \sigma &= 0.38^{+0.04}_{-0.09}.
\end{align*}
\]

The gray area in Figure 1 shows the propagated 1 \(\sigma\) uncertainty from the optical LF. The match is good at all luminosities and redshifts in the sample using the same value for \(g_k\) (shown are the results for \(z = 1.3\) and \(z = 2\)).

We note that on adopting a Gaussian scatter we are able to reproduce the mean and extent of the observed scatter around it, within a given bin of optical luminosity. Figure 2 shows our results (solid lines) for \(-24 \leq M_B \leq -25\) and \(-25 \leq M_B \leq -26\) compared to the data collected by CMC05 (dashed lines). Neglecting scatter in the relations (dotted lines) would instead lead to a severe underestimate of the significant spread observed in the data.

We have also performed other checks and tests on our results. To look for possible biases in the optical selection of radio sources, we have compared our determination of the optical LF with the recent results by Jiang et al. (2007). These authors have cross-correlated a large sample of optically selected quasars from SDSS with FIRST, determining the radio-loud fraction of quasars as a function of redshift and luminosity. By multiplying the LF by Richards et al. (2005), representative of the whole population of optical AGNs, by the Jiang et al. (2007) fraction of radio sources as a function of optical luminosity, we can evaluate the radio-optical LF expected from the SDSS data; in Figure 3 we show this with a dashed line in two reference redshift bins at \(z = 1.3\) and \(z = 2\). Also shown with a striped area is the 1 \(\sigma\) uncertainty region derived from the uncertainty in the Jiang et al. (2007) radio-loud fraction. On the same plots we compare the completeness-corrected evaluations by CMC05 for their radio-optical sample; we show their data points as solid filled circles with error bars, together...
with their best-fit estimate represented with a solid line. The
good match between the two evaluations supports the absence of
any specific bias in our adopted LFs, at least for
MB/P\textsuperscript{24} = 5,
where most of the sample sources reside (see Fig. 2).

Through Monte Carlo sampling we then extract a sample of
sources from the optical LF with a given LB,\textsuperscript{6} from which we
compute L, Lk, and LR by using equations (1) and (2) with their
scatters having fixed gk to the value given in equation (3). In this
way we build simulated distributions and correlations among these
observables, which we compare with a number of different data
sets.

Figure 4 (left panel) shows our simulated LR-Lk correlation,
which is equivalent in slope, and slightly lower in normalization
but still compatible, relative to the one derived by Heinz et al.
(2007), and shown by the long-dashed line with 1\sigma
uncertainties shown as dotted lines. Note that their relation is calibrated on a
sample of FSQs, which could be more beamed and/or energetic
than our SSR dominated sample (see also \textsuperscript{x57}). Also shown with
solid points and error bars are the sets of data by Birzan et al.
(2004) and Allen et al. (2006).

As equation (2) might appear to be model-dependent, in the
right panel of Figure 4 we also show how our results on Lk relate
to the narrow emission lines luminosities LNLR,\textsuperscript{7} and compare
with the data points collected by Rawlings & Saunders (1991).
The good agreement between our results and theirs, which were
derived under different assumptions from Willott et al. (1999),
is encouraging.

4. THE KINETIC CONTRIBUTION
TO THE BH MASS FUNCTION

Constraining the total kinetic power from massive BHs is of key
importance for several models of galaxy evolution (e.g., Croton
et al. 2006, Cavaliere & Lapi 2008) which require a significant
amount of kinetic feedback from the massive BHs to prevent ca-
tastrophic cooling in the cores of groups and clusters of galaxies and
limit the formation of too massive galaxies in the local universe.

Thus in this section we use our above results to evaluate
the total kinetic energy associated to SSRs. As discussed later in
\S 5, we shall not include additional contributions to the kinetic
integrated AGN emission from other kinds of AGNs, such as
FSQs or radiatively inefficient sources, whose modeling is uncer-
tain. Rather, our aim is to provide a firm lower limit to the actual
contribution of radio-kinetic AGNs to the local mass density in
black holes.

\textsuperscript{6} All simulation results presented in the following are provided by averages
over 1000 realizations, each one with 10,000 points.

\textsuperscript{7} We use the conversions
LNLR = 3(3L\textsubscript{O\textsubscript{II}} + 1.5L\textsubscript{O\textsubscript{III}}), L\textsubscript{O\textsubscript{II}} = L\textsubscript{O\textsubscript{III}} and L\textsubscript{O\textsubscript{II}} =
L/5 \times 10^3 with scatter equal to \sigma (e.g. Willott et al. 1999).
To compute this, we reverse the classic Sołtan (1982) approach, which consists of estimating the average radiative efficiency \( \epsilon \) by dividing the integrated energy density observed from AGNs by the local mass density in relic BHs. After computing the integrated kinetic energy from SSRs, we divide it by our best-fit value for the kinetic efficiency \( \epsilon_k \), and time-integrate to derive the local BH mass function expected from kinetically active SSRs. By comparing the latter with the local mass function of the whole BH population, we derive a lower limit to the fraction of the relic BHs which have been kinetically active in their past.

We start from considering that during an accretion episode onto the central BH a fraction of the accreting mass energy is released as radiative and/or kinetic power. In \( \S \ 3 \) we evaluated the ratio \( g_k \) to be of order \( 10^{-1} \), which in turn implies a kinetic efficiency of \( \epsilon_k \sim 10^{-2} \), if the sources in the CMC05 sample possess on average the same radiative efficiency \( \epsilon \sim 0.1 \) typical of AGNs (e.g., Sołtan 1982). Here we make the specific assumption that this value of \( \epsilon_k \) is common to all steep-spectrum radio-loud AGNs, irrespective of their radiative emission. The total energy extracted reads

\[
L_{\text{tot}} = L + L_k = (\epsilon + \epsilon_k)M_\odot c^2. \tag{4}
\]

Therefore the total mass accreted onto the central BH is

\[
M_{\text{BH}} = (1 - \epsilon - \epsilon_k)M_\odot, \tag{5}
\]

which converts to

\[
\dot{M}_{\text{BH}} = \frac{(1 - \epsilon - \epsilon_k)L_k}{\epsilon_k c^2} \tag{6}
\]

on using equation (4).

By integrating the last equation over time and luminosity, and equating it to the local mass density \( \rho_{\text{BH}} \) in relic BHs, we obtain the kinetic “Sołtan-type” argument

\[
\rho_{\text{BH}} = \int \frac{dt}{dz} \int d\log L_k \Phi(L_k, z) \frac{(1 - \epsilon - \epsilon_k)L_k}{\epsilon_k c^2}, \tag{7}
\]

where \( \Phi(L_k, z) \) is the kinetic luminosity function of AGNs in units of Mpc\(^{-3}\) dex\(^{-1}\) defined below.

The value of \( g_k \) derived in \( \S \ 3 \) was calibrated on the CMC05 sample, which is representative of radio-loud and optically bright AGNs, mostly composed of SSRs. Neglecting to lowest order \( \epsilon \) and \( \epsilon_k \) in the numerator of equation (7) does not alter our conclusions. We now use as our wider database the 5 GHz radio LF by De Zotti et al. (2005) specific for SSRs. The steep-spectrum kinetic luminosity function \( \Phi(L_k, z) \) is then derived by convolving this luminosity function with a Gaussian with mean given by equation (1), where \( g_k \) and the dispersion \( \sigma \) are given in equation (3).

Our result is shown by the solid line in Figure 5. It is seen that at \( z \approx 0 \) the BH mass density we evaluate to be associated to the steep-spectrum radio-loud population is about 25% of the BH mass density found in local galaxies (light gray area).

This amount is not far from the cumulative mass density obtained from the optical LF by Richards et al. (2005), representative of the whole population of optical AGNs at \( z \lesssim 3 \), which is shown with a long-dashed line in Figure 5. The latter mass density is obtained via the standard radiative Sołtan argument which is formally equivalent to equation (7) with \( \epsilon_k \) in the denominator replaced by \( \epsilon \) and \( L_k \) by \( L \). Also shown with a dotted line in Figure 5 is the BH mass density obtained by integrating the SSR LF by Dunlop & Peacock (1990); a slightly higher value would be obtained by integrating the SSR LF by Willott et al. (2001).

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**Fig. 4.** Comparison between simulations and data. **Left panel:** The results from our best-fit model are compared with the set of data (filled circles) presented in Heinz et al. (2007) and with their model (long-dashed and dotted lines). **Right panel:** Our simulated best-fit relation (solid line, with dispersion shown by the gray area) is compared with data derived by Rawling & Saunders (1991). All data have been converted to our adopted cosmology.

**Fig. 5.** Cumulative black hole mass densities computed as a function of redshift. The long-dashed line represents the mass density associated with optical AGNs, obtained by integrating the Richards et al. (2005)’s LF above \( M_B = -21 \) [i.e., \( \log P_{1.4\text{GHz}}/(\text{WHz sr}^{-1}) \sim 23.1 \) and \( \log L_4/(\text{ergs s}^{-1}) \sim 43.9 \), on using eq. (3)]. The solid and dotted lines are the results of integrating above the same luminosity threshold the LFs by De Zotti et al. (2005) and Dunlop & Peacock (1990), respectively. The value of \( \epsilon = 0.1 \) and our best-fit value \( g_k = 0.10 \) have been used for all curves. The boxes show the local black hole mass density \( \rho_{\text{BH}} \) in massive spheroids (dark gray area) and 30% of this value (light gray area).
These differences in BH mass densities simply reflect differences in the SSR LF adopted at given kinetic efficiency.

In any event, our computations converge to show that the accreted mass density associated with steep-spectrum radio-loud kinetic AGNs alone is comparable to the total BH mass density accreted by optical AGNs. Note that the optical luminosity function has been extended down to $M_B \sim -21$, which is the minimum luminosity probed by Richards et al. (2005). On the other hand, our mass density evaluations derived from the SSR LF's have been computed by extending the computations to the corresponding limiting luminosity, i.e., $\log L_k/(\text{ergs s}^{-1}) \sim 43.9$ and $\log P/(\text{W Hz}^{-1} \text{ sr}^{-1}) \sim 23.1$, on the basis of equations (2) and (3).

In the left panel of Figure 6 we show the differential mass density as a function of $z$ for radio-loud and optical AGNs. It can be seen that the approximate match between the mass density accreted by kinetic and optical AGNs holds at each redshift, supporting a scenario in which the optical and kinetic outputs are produced by similar accretion events at each time.

The match also holds in the final cumulative BH mass functions, as shown in the right panel of Figure 6. The gray area in the figure represents the local BH mass function with its systematic uncertainties. Keeping in mind that below a BH mass $M_\bullet \sim 10^8 M_\odot$ our results are actually extrapolated, it can be seen that the fraction of the local BH population which has been kinetically active as steep-spectrum sources in its past grows with $M_\bullet$ from about 25% to reach near totality for masses $\geq 10^{9.5} M_\odot$. This was computed on adopting an average Eddington ratio of $\dot{m} = L/L_{\text{Edd}} = 0.5$, where $L_{\text{Edd}} = 1.3 \times 10^{38} M_\bullet/M_\odot$ ergs s$^{-1}$. This ratio is found to provide a good match between the local and accreted mass functions for the overall AGN population by, e.g., Marconi et al. (2004) and Shankar et al. (2004, 2007); our results however do not significantly depend on the precise choice for the adopted Eddington ratio, within the range of several tenths.

The results presented in this section indicate a considerable contribution to the local mass density from radio-kinetically active SSRs, in fact comparable to the one from optical/X-ray sources (e.g., Shankar et al. 2004). The latter ones, not explicitly accounted for here, are able to explain the mass around $M_\bullet \sim 10^8 M_\odot$ needed to attain full match with the local mass function (see Fig. 6, right panel). In other words, a considerable fraction of relic black holes have possibly undergone a kinetically loud phase in their past.

5. DISCUSSION AND CONCLUSIONS

We have proposed a powerful method for estimating the average efficiency of the kinetic power production process, derived essentially from observational constraints, i.e., from intercalibrating the radio and the optical LFs. Our result therefore is independent of specific assumptions on the jet or wind dynamics and composition; it can be actually used to constrain theoretical models of jets. The value for the constant $f \simeq 15$ discussed by Hardcastle et al. (2007) and inserted in equation (2), supports the picture of “heavy” jets with a dominant protonic component; this enhances the kinetic output associated with even modest radio luminosities. We have adopted equation (2) for all radio-loud sources, irrespective of their redshift and/or environment.

So far we did not consider effects of beaming in the steep-spectrum radio LF. We expect the degree of beaming in these sources to be small on average. In fact, we have checked that on correcting the observed luminosities in the CMC05 radio LF with the beaming parameters appropriate for SSRs as done in the unification models of Urry & Padovani (1991, 1995), the resulting intrinsic LF is very similar to the one observed by CMC05, only $\approx 0.06$ dex fainter on average. This in turn implies values about 10% smaller for the $g_k$ best value, still within our 1σ uncertainties.

Our statistical results on the average kinetic efficiency of SSRs do not exclude that FSQs could have a higher kinetic efficiency, or that there could be sources with exceptionally high kinetic outputs. For example, on discussing individual powerful blazars Maraschi & Tavecchio (2003) find higher values for the kinetic efficiency than derived here. This is partly due to their selection of the brightest jets for which the SEDs can be determined up to γ-ray range. In addition, the high energy emissions probe the jet closer to the nucleus; conceivably the jet decelerates before reaching the radio hot spots and lobes, so that part of its kinetic energy is lost on the way. Thus the extended radio emissions on which equation (2) has been calibrated could only set a lower limit to the full kinetic energy imparted to the jet at its origin. Heinz et al. (2007) have recently estimated the cumulative FSQ kinetic energy, finding average kinetic efficiencies a factor of a few higher than our best-fit value, but still on the order of a few percent of accreted rest-mass energy.

To make contact with these independent studies, we have redone our calculation on adopting for the correction factor $f$ a higher value than the already significant one used here; for example, setting $f = 45$ in equation (2), we get a relation very similar to that derived by Heinz et al. (2007). Our $\chi^2$ fitting yields in this case $g_k = 0.53 \pm 0.20$ and $\sigma = 0.307 \pm 0.003$, which implies kinetic efficiencies a factor of 5 higher than derived in § 3. While more stringent calibrations on relations such as that in equation (2) are essential to pin down the average value of $g_k$, all methods support kinetic efficiencies of order a few percent. Consider that having increased $f$ and $g_k$ will proportionally increase the kinetic efficiency.
and mean kinetic luminosity, although leaving the BH mass density $\rho BH \propto L_k/\epsilon_k$ unaltered.

Finally, we note that the levels of kinetic efficiency derived in this work agree with the amount of energy kinetic feedback required in theoretical studies of massive galaxies (e.g., Granato et al. 2004, Cavaliere & Lapi 2006, Shankar et al. 2006).

Summarizing, we have used an optically selected sample of radio loud AGNs dominated by SSRs to convert the optical LF to a radio one. We have found that the kinetic output in jets or winds must amount to a fraction $g_k \sim 10^{-1}$ of the bolometric luminosity to match the empirical radio LF for the same sample; with this value we have been able to reproduce also a number of empirical correlations relating $L_R$, $L_k$, and $L_R$. From typical values for the AGN radiative efficiency $\epsilon \sim 10^{-1}$, we have derived an average kinetic efficiency $\epsilon_k \sim 10^{-2}$ which we have assumed to be common to all SSRs. By using equation (7), we have then constrained the contribution of kinetically loud SSRs to the local BH mass density to be $\geq 25\%$, comparable to what is found from optical/X-ray selected AGNs. We consider the latter estimate to provide a firm lower limit; additional contributions to the kinetic integrated AGN emission could come from the more numerous and less luminous AGNs (e.g., Heinz et al. 2007), from AGNs in radiatively inefficient but kinetically efficient accretion states (e.g., Churazov et al. 2005), and/or from FSQs with intrinsically higher kinetic power than here considered (see Maraschi & Tavecchio 2003). An additional contribution arises from radio galaxies which should have comparable kinetic outputs according to unification models; in agreement with our findings in fact, Koerding et al. (2008) find $g_k \approx 0.2$ for a significant sample of FR I and FR II radio galaxies.

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