Jets and accretion processes in Active Galactic Nuclei: further clues

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\textbf{ABSTRACT}

We present evidence in favour of a link between the luminosity radiatively dissipated in the central engine of radio–loud Active Galactic Nuclei and the kinetic power in their jets. This piece of evidence is based on the relation we find between the luminosity in broad emission lines and the kinetic power in pc-scale radio jets, for a sample of radio–loud quasars for which suitable data are available in the literature. We find that the ionizing luminosity and the kinetic one are of the same order of magnitude, suggesting that the processes responsible for them are somehow related. A strong magnetic field in equipartition with the radiation field could be responsible for regulating both processes. BL Lac objects seem to follow a similar behaviour, but with comparatively fainter broad line emission.

\textbf{Key words:} galaxies: active - galaxies : jets - quasars: emission lines

\section{INTRODUCTION}

A key ingredient in our understanding of the physics and energetics of Active Galactic Nuclei (AGN), is the relation between the spectacular phenomenon of jets and the accretion process and/or the power supply in the central ‘engine’. The supposed presence of material in the form of an accretion disc in the sources associated with jets, in forming stars, galactic X-ray binaries and in powerful AGN, strongly suggests a fundamental link between these two phenomena (e.g. Pringle 1993, Lynden–Bell 1996 and references therein). Direct observational evidence for this connection has been revealed by the recent HST images of the jet and disc of M87 (Ford et al. 1994).

A possible approach to get insight into this link is to establish correlations and dependences among observable/measurable quantities which are likely to be connected to the accretion and jet processes. This approach has been adopted by several authors, who have discussed the relationship between luminosity in line emission, on different scales, and radio and/or kinetic luminosity on large (kpc-Mpc) (e.g. Stockton & MacKenty 1987; Baum & Heckman 1989a,b; Rawlings & Saunders 1991 [RS91]; Miller, Rawlings & Saunders 1993) and small (radio core) scales (Falcke, Malkan & Biermann 1995). Recently, using radio data on VLBI (∼parsec) scales and the standard synchrotron self–Compton theory, Celotti & Fabian (1993) [CF93] estimated the jet kinetic power to put constraints on the matter content of jets. Despite the fact that this method does not directly face the fundamental questions of the mechanism(s) responsible for the collimation and acceleration of jets, it still offers quantitative constraints and reveals important clues.

In the light of the above results, here we focus on the luminosity in broad emission lines, and explore its relation with the kinetic one for a sample of radio–loud objects for which the pc-scale kinetic power can be estimated from VLBI data. The advantage of considering the luminosity in broad lines, instead of narrow ones, as a (possibly isotropic) indicator of the accretion power is threefold. Firstly, there are indications that the narrow line emission could be partly caused by photoionization induced by shocks associated with jets or high velocity gas and therefore not necessarily from the putative accreting material (e.g. Sutherland, Bicknell & Dopita 1993; Capetti et al. 1996). Secondly, by looking for information on broad line emission we are able to find more data compared to the narrow line luminosities, and therefore increase the size of the sample for which we can estimate the line luminosity. Finally, the expected typical size of the broad line region is in fact roughly comparable with the parsec scale. This implies that we are more likely to look at phenomena over the same temporal scale in the active life of the nucleus. We stress that the ‘isotropy’ of broad line emission we refer to is relative to objects which, according to the current unification schemes, are observed within the opening angle of the putative obscuring torus (see e.g. Urry & Padovani 1995 for a recent review).
The outline of the paper is as follows. In Section 2, we describe the sample of sources, while in Sections 3 and 4 the methods applied to estimate the luminosity in broad lines and the jet kinetic power are outlined. In Section 5 we examine the case for considering also BL Lacs objects in our study. The results are presented in Section 6 and discussed in Section 7. Section 8 summarizes our conclusions.

Cosmological parameters $H_0=50\ \text{km/s/Mpc}$ and $q_0=0$ have been adopted throughout the paper.

2 THE SAMPLE

We consider the sample of radio–loud AGN assembled by Ghisellini et al. (1993) [G93], which includes 105 sources with VLBI angular diameter data available in the literature, and for which it is therefore possible to apply the synchrotron self-Compton (SSC) model and estimate the kinetic luminosity in the mas (milliarcsec) scale jet. This is the only criterion applied to select the sources, and therefore the sample is not, in any sense, complete. As already mentioned, we exclude from it radio galaxies, which we expect to be observed at large angles with respect to the jet axis and whose broad line emission is therefore likely hidden by obscuring material.

Among these radio–loud sources, we then consider the three subsamples of broad line objects, namely core dominated High and Low Polarization Quasars (HPQ and LPQ respectively) and lobe dominated quasars (LDQ), obtaining a sample of 64 sources. For a more detailed discussion about their classification as well as further data and references we refer to G93. Fluxes at 1 keV for four sources without X-ray data in G93 are derived from the ROSAT WGA catalogue (White, Giommi & Angelini 1994) as described in Padovani, Giommi & Fiore (1996). This translates into a better determination of the Doppler factor (see below), which is otherwise based, for sources without X-ray data, on the optical flux.

3 BROAD LINE LUMINOSITY

We then have to estimate the total luminosity emitted in broad lines, $L_{\text{BLR}}$. There is not any solidly established procedure to derive $L_{\text{BLR}}$ and (unlike for example Falcke et al. 1995) we adopt the following method, which involves three steps: i) define a set of lines which dominates the total broad line emission; ii) establish their relative flux ratios; iii) extrapolate, using these ratios, from the luminosity in lines with measured flux to the luminosity in all lines.

i) Clearly, the more measured line fluxes are available, the more the estimate is correct. Furthermore, the use of fluxes from several lines increases the statistics in term of number of sources in the sample and allows a better coverage in redshift. We consider fluxes for the following lines: Ly$\alpha$, C IV, Mg II, H$\gamma$, H$\beta$, and H$\alpha$, which are amongst the major contributors to the total $L_{\text{BLR}}$ (making up in fact about 60 per cent of it) and are well identified in quasar spectra. We then collect from the literature data on the broad line fluxes. In order to obtain data as homogeneous as possible, and minimize the uncertainties, we only consider values of line fluxes (or luminosities) either when directly given or when the equivalent width and continuum flux at the corresponding line frequency are reported by the same authors (for small differences between the line and continuum frequencies, we extrapolate the continuum, adopting a slope $\alpha_{\text{UV}}=0.5$ between 2200 Å and 2800 Å, $F(\nu)\propto \nu^{-\alpha}$).

We find line fluxes for a subsample of 43 of the 64 objects, with an average of about two lines per source. When more than one value of the same line flux was found in the literature we either considered the most recent reference, which was likely to report values measured with more accurate techniques, or estimate the arithmetic average of the flux (in almost all the cases the difference was minimal). We have not applied a reddening correction to the line fluxes, because the average data are not corrected.

ii) We use the line ratios reported by Francis et al. (1991) (see their Table 1 for a complete list), mainly because of the large statistic and the range of lines included. They refer to an optical sample, mostly consisting of radio quiet sources, but no major differences in the broad line fluxes between radio quiet and radio loud objects has been clearly determined (e.g. Corbin 1992, see also Steidel & Sargent 1991, Boroson & Green 1992, Wills et al. 1993; Zheng et al. 1996).

iii) We then consider the sum of the line luminosities of all the lines reported by Francis et al. (1991) with respect to the Ly$\alpha$, to which we assign a reference value of 100 (hereafter the asterisk refers to luminosities in the same units). To this, we also add the contribution from $L_{\text{H}\alpha}$ (which is not included in the list of Francis et al.), with a value of 77 (from Gaskell et al. 1981). This gives a total ($L_{\text{BLR}}^* = 555.77 \sim 5.6 \times L_{\text{Ly}\alpha}$). Therefore, given the sum of the observed luminosities in a certain number of broad lines $\sum_i L_{i,\text{obs}}$, the total $L_{\text{BLR}}$ can be calculated as

$$L_{\text{BLR}} = \sum_i L_{i,\text{obs}} \times \frac{L_{i,\text{est}}^*}{\sum_i L_{i,\text{est}}^*} \quad (1)$$

where $\sum_i L_{i,\text{est}}^*$ is the sum of the luminosities from the same lines, estimated through the adopted line ratios. That is, the sum of the luminosities of the lines for which we have data is scaled by the ratio of the total ($L_{\text{BLR}}^*$) divided by the sum of the luminosities of the same lines in the composite spectrum of Francis et al. (1991).

By using eq. (1), we then derive $L_{\text{BLR}}$. Information on the lines used, relative references and values of $L_{\text{BLR}}$ for each of the 43 objects are reported in Tables 1a,b,c for the different classes of quasars.

* The lack of complete information on the line spectra at all redshifts as well as some intrinsic scatter lead to significant differences in the line ratios reported by different authors. The ratios given (e.g. Boyle 1990, Netzer 1990, see also Baldwin et al. 1995 and references therein) differ both for the number of lines reported and for individual flux ratios. In this sense, the adopted procedure necessarily introduces an unavoidable dispersion. For example, the line ratios recently reported by Zheng et al. (1996) from HST data, lead to a difference of about 25 per cent in the total luminosity with respect to Francis et al. (when the lines in common to the two works are considered).
4 KINETIC LUMINOSITY

The estimate of the kinetic luminosity is based on the adoption of the SSC model, applied to the radio (VLBI) data and X-ray (or optical) fluxes. The standard SSC theory allows one to derive limits on the comoving number density of the emitting particles, $n$, the magnetic field intensity and the relativistic Doppler factor, $\delta = \Gamma^{-1}(1 - \beta \cos \theta)^{-1}$. Here $\Gamma$ is the Lorentz factor relative to the bulk motion with velocity $\beta c$ of the emitting plasma, and $\theta$ is the angle between the direction of motion and the line of sight. We refer to CF93 and references therein for a complete description of the (standard) method applied.

Given $n$, $\delta$ and the VLBI angular size, the kinetic luminosity is then derived as

$$L_{\text{kin}} \simeq \pi r_{\text{VLBI}}^2 n m_e c^2 \Gamma^2 \beta c \quad \text{erg s}^{-1}$$

(2)

for $\Gamma \gg 1$, where $r_{\text{VLBI}} = \theta d_L/(1 + z)$ is an estimate of the jet cross section from the measured VLBI angular diameter $\theta d$ and the luminosity distance $d_L$. $m_e$ is the electron rest mass. The adopted spectral index of the nonthermal (synchrotron) radiation is $\alpha = 0.75$. The $\Gamma^2$ term in eq. (2) accounts for the particle energy flux ($\propto \Gamma \beta$) and the transformation of the density ($n$ is the comoving number density).

In the following, we present the main assumptions adopted in the estimate of $L_{\text{kin}}$ through eq. (2).

As extensively discussed in CF93, the major uncertainties are: a) the matter content of jets, i.e. whether it is made of an electron–proton and/or an electron–positron pair plasma; b) the extension of the (differential) energy distribution of the emitting particles, $N(\gamma) \simeq 2 \alpha \gamma^{-1} n(\gamma/\gamma_{\text{min}})^{-(2\alpha + 1)}$, where $\gamma$ is the electron Lorentz factor, and $\gamma_{\text{min}}$ therefore determines the total particle number density. Eq. (2) apparently neglects both a contribution from heavy particles (i.e. protons) and any possible advection term from either components. However, following the findings and discussion of CF93, the kinetic power seems to be correctly estimated by that expression (see CF93 for further details). Considering, for simplicity, only plasmas dominated either by an electron–positron or electron–proton component, eq. (2) corresponds to the assumption of an electron–proton plasma with a low energy cutoff in the (electron) distribution at around $\gamma_{\text{min}} \sim 100$, or a pair plasma in which the particles cool down to $\gamma_{\text{min}} \sim 1$. We do not include the possibility of a two-fluid jet (see e.g. Henri & Pelletier 1991).

Another relevant point is the assumption about the derivation of the Lorentz factor $\Gamma$ from the Doppler factor. As in CF93, we use the minimum $\Gamma$ for any given $\delta$ [i.e. $\Gamma = 0.5(\delta + 1/\delta)$]. Lacking more accurate information,

† We note that the estimate of the jet cross section could take into account both a projection factor and the jet opening angle (e.g. estimated from the relativistic Mach number). However, given the uncertainties on the direction of the line of sight with respect to the jet axis for the different classes of objects, and the fact that the observed components do not show an elongated structure along the jet axis, we assume that we are measuring the dimension of a quasi–spherical component. Therefore we choose not to include these corrections (whose product in any case results to be of the order of one)

this seems to be the wisest choice. In fact, the other observational parameter, which enters in the estimate of $L_{\text{kin}}$, is the X-ray (or optical) flux, which we assume is all due to the SSC process. An overestimate of this flux, $F_x$, would lead to an overestimate of the kinetic luminosity. In fact the estimate of the particle density $n \propto F_x$ while the estimate of the Doppler factor $\delta \propto 1/F_x^{1/(2+2\alpha)}$, yielding $L_{\text{kin}} \propto F_x^{(1+\alpha)/(2+\alpha)}$. Therefore the choice of a minimum $\Gamma$ would tend to reduce the total uncertainty in the estimate of $L_{\text{kin}}$. It is worth noticing that the X-ray flux can be particularly overestimated for sources where clearly the synchrotron component still dominates at X-ray energies (fluxes used here are estimated at 1 keV).

The only difference in the computation of $L_{\text{kin}}$ with respect to CF93 is the treatment of sources with estimated $\delta < 1$. In fact, because here we are interested in an average value of $L_{\text{kin}}$, rather than upper limits on it, for sources with $\delta < 1$ we derive $\Gamma$ from an average $\delta$ (while CF93 assumed $\Gamma^2 \beta = 1$). In agreement with current unification schemes (e.g. Urry & Padovani 1995), we consider the average $\delta$ of the core dominated quasars (or BL Lacs), as derived by G93 ($\langle \delta \rangle \simeq 6$ and 3, respectively), which should better correspond to the intrinsic Lorentz factor. As shown in Table 1, the 13 sources with $\delta < 1$ are mainly LDQ, and make up about 24 per cent of the sample. In any case, these objects are considered separately in our analysis.

5 THE CASE OF BL LAC OBJECTS

In order to further explore the connection between $L_{\text{kin}}$ and $L_{\text{BLR}}$, and in view of the recent findings of (weak) broad emission lines in BL Lac objects (Stickel, Fried & Kühr 1993b; Vermeulen et al. 1995), we also estimated the above quantities for 12 BL Lacs belonging to the G93 sample. However these sources have been treated somehow separately in all the analysis. In fact, in agreement with current unification schemes, while the three classes of quasars should be intrinsically identical, BL Lacs are likely to represent a separate class.

The list of BL Lac objects as well as the estimated luminosities are reported in Table 1d. As discussed below, an important point to be stressed is that for this class of sources the estimated $L_{\text{BLR}}$ is an upper limit.

6 RESULTS

6.1 Luminosity correlations

Fig. 1 shows $L_{\text{kin}}$ vs. $L_{\text{BLR}}$ for the different classes. As one can see from the spread in the data, when all sources of the current sample are considered, there is only a weak statistical indication of a linear correlation between the two luminosities, at a significance level of 95.8 per cent. An even weaker hint of correlation is present when individual classes

† Note that to estimate the BLR flux of BL Lac itself we have not used the recent observations of strong, broad Balmer lines of Vermeulen et al. (1995), as most likely they represent an atypical state of the object (see discussion in Vermeulen et al. 1995).
of sources or only sources with $\delta > 1$ are considered. An exception is constituted by the class of BL Lacs (with $\delta > 1$), whose kinetic and BLR luminosities appear to be correlated at the 98.4 per cent level.

An interesting point is that the luminosities show the same general trend of the distribution reported by CF93 for the Narrow Line emission. However a direct comparison of these two sets of data is rather difficult because it would require the inclusion of different covering factors in order to “rescale” the line luminosities.

As can be seen in Fig. 1, the spread in the correlation is quite large, plausibly due to intrinsic dispersion, but also to the significant uncertainties of our assumptions. In order to ascertain the likely causes of this spread we have first looked for a possible relation between the core radio luminosity ($L_{\text{core}}$) and $L_{\text{BLR}}$ and indeed found that the two quantities appear to be highly correlated at the > 99.9 per cent level (note however that part of this strong correlation is due to the common redshift dependence). As shown in Fig. 2, the two luminosities appear to be of the same order of magnitude, with the expected tendency for the LDQ to have relatively lower core radio power.

We therefore examined the possible spread introduced by the other quantities on which the estimate of $L_{\text{kin}}$ is based, namely $\delta$ and $F_{\text{r}}$. In order to do this, we assumed that in turn these two quantities have no intrinsic spread: we found that, while the assumption of a constant $\delta$ does not lead to a better correlation, the tentative hypothesis of an intrinsic relation of $F_{\text{r}}$ with the core radio flux $F_{\text{r,core}}$, $F_{\text{r}} \propto F_{\text{r,core}}$, gives values of $L_{\text{kin}}$ highly correlated with $L_{\text{BLR}}$ at the 99.9 per cent level. This supports the view that the large scatter plausibly reflects a scatter in the observed $F_{\text{r}}$. Indeed, we expect that the observed strong variability in the X–ray band, as well as the possible contribution of emission not due to SSC (see e.g. Sikora et al. 1994), would introduce large uncertainties. §

Because of the large scatter found and the corresponding weak correlation, we instead consider the ratio between the kinetic and broad line luminosities to determine if this shows any interesting average property. In Fig. 3, the distribution of this ratio is shown for the different types of objects. Shaded areas refer to sources with an estimated $\delta < 1$. As already discussed, the distributions are quite broad, but the average (and median) of this ratio for quasars is $\approx 10$. The distributions for HPQ, LPQ, and LDQ are consistently similar according to a Kolmogorov–Smirnov (KS) test. Adopting a typical BLR covering factor of $\approx 0.1$ (e.g. Netzer 1990), this implies that $L_{\text{kin}} \approx L_{\text{ion}}$, the ionizing radiation.

This result is certainly intriguing, given: a) the uncertainties in the estimates of $L_{\text{BLR}}$ and especially $L_{\text{kin}}$; b) the fact that they are based on completely independent calculations (where the only parameter in common is the red shift); c) the sample used, which does not have any characteristic of completeness or clear selection criteria.

In Table 2, we report the results on the average values (and medians) of $\log(L_{\text{kin}}/L_{\text{BLR}})$ with their dispersions, for the different types of sources. It can be seen that the same result on the ratio $L_{\text{kin}}/L_{\text{ion}}$ roughly holds separately for the three classes of quasars (the ratio is slightly higher for LDQ when all sources are considered but goes down considerably for the objects with $\delta > 1$).

It is worth noticing that the choice of estimating $L_{\text{BLR}}$ instead of trying to directly measure $L_{\text{ion}}$ from the optical/UV/X–ray fluxes, is mainly due to the difficulty in disentangling the non–thermal anisotropic radiation from the more isotropic one (the ‘blue bump’) in the observed flux (as well as to the paucity of IUE data for these sources). We would in fact expect the ratio of these two components to be strongly dependent on the observation angle, as discussed below (see also Browne & Murphy 1987; Wills et al. 1993).

6.2 BL Lac objects versus quasars

Figures 1 and 3 and Table 2 show that $L_{\text{kin}}/L_{\text{BLR}}$ for BL Lacs is much larger than for quasars. Moreover, a KS test shows that the $L_{\text{kin}}/L_{\text{BLR}}$ distribution for BL Lacs is different from that of quasars at the 99.1 per cent level, independently of the exclusion of sources with $\delta < 1$ (but is consistent with that of LDQ only, which however include only very few objects, especially if $\delta > 1$ is required). This difference is reinforced by the fact that for BL Lacs this ratio should be considered as a lower limit. In fact, due to the lack of better information, $L_{\text{BLR}}$ has been derived using the same line ratios adopted for quasars, as if all those lines were also present (but very broad) in the spectrum of BL Lacs. Moreover, in many sources absolutely no emission line is detected: inclusion of these objects would have increased further the mean ratio $L_{\text{kin}}/L_{\text{BLR}}$.

7 DISCUSSION

The main finding of this work is the approximate ‘equivalence’ between $L_{\text{kin}}$ and $L_{\text{ion}}$.

Intriguingly, a comparison of our results with those found in previous works (e.g. RS91) about the correlation between the Narrow Line luminosity and the power required to feed the extended lobes, shows that the same behaviour seems to hold in an analogous way (when a different covering factor is assumed) for the luminosity both in broad and in narrow lines. Also in the latter case, in fact, one obtains an approximate equivalence between the ionizing radiation and the kinetic power supplied to the lobes or to the extended radio structures.

The first implication of these findings is to reinforce and stress the fact that the channeling of material into jets is indeed a powerful process in term of the total energy budget of radio–loud AGN, and more precisely this is comparable with the amount of the radiative power emitted isotropically. In this sense, it is relevant to point out that, in the most accepted scenario on the physical processes operating in the central regions of AGN, $L_{\text{BLR}}$ is related to a (semi)isotropic and unbeamed radiation. Both luminosities would be therefore unaffected by beaming and represent ‘intrinsic’ powers. As shown in Fig. 1, the energy output can reach up to $10^{48}$ erg s$^{-1}$.

Furthermore, if $L_{\text{ion}}$ is indeed related to the power dissipated during the accretion phase, this finding would suggest

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that there is a close link between the accretion process and the phenomenon of jets, or, alternatively, that a common 'element' regulates the amount of luminosity radiatively dissipated during the accretion process and the power channeled into the jet in kinetic form. This 'element' should be indeed tightly linked to the above quantities if it can produce a significant correlation between the observed variables.

This deep link has also been suggested by Saunders (1991) on the basis of the observational similarity found between the luminosity in narrow line and the kinetic power, estimated on the large radio scales (RS91; see also Falcke et al. 1995, Wills & Brotherton 1995). An interesting possibility is that the key role is played by magnetic fields.

7.1 The possible role of magnetic fields

On one side, recent theories of disc accretion and observations at high energies favor the idea that most of the accreted power is dissipated in a corona above the disc, due e.g. to magnetic reconnection. On the other hand, the most accredited possibility for the collimation and acceleration of jets involves the presence of magnetic fields. In fact this hypothesis accounts for different aspects of the physics of jets, as well as different environments for their formation. The power would be 'extracted' from the rotational/gravitational energy of an accretion disc or the black hole itself, and then channeled as kinetic power and/or Poynting flux (see e.g. the reviews by Blandford 1993, Spruit 1996 and references therein).

If the magnetic field indeed plays an important part in both processes, then one could expect some sort of correlation between the energy dissipated and the kinetic power. In other words, the correlation found here could be the signature of the equivalence of the power generated through accretion and the one extracted from the disc/black hole rotational energy and converted into kinetic form. The direct comparison of the predictions of this models with observational data is still quite limited, and substantially concerns jets associated with star-size objects. In the case of AGN, we can only perform a rough estimate, assuming that the magnetic field is in equipartition with the radiation field, which plausibly dominates the pressure in the inner region of an accretion disk, and that a similar efficiency regulates the conversion of the produced energy into radiation and bulk energy. This estimate is consistent with obtaining similar values for the kinetic and ionizing power. For example, for an isolated Kerr black hole, the spin energy which can be extracted in electromagnetic form is approximately given by (e.g. Blandford 1990)

$$L_{\text{rot}} \cong 10^{45} \left( \frac{a}{m} \right)^2 B^2 \alpha^4 M_{\odot}^2 \text{erg s}^{-1}$$

where ac is the specific angular momentum and $m = GM/c^2$ the gravitational radius (a < m). Then for a rapidly rotating black hole

$$L_{\text{rot}} \sim 8\pi \times 10^{37} U_B M_{\odot}^2 \sim 2 \times 10^{37} \left( \frac{L_{\text{acc}}}{cR_\odot^2} \right) M_{\odot}^2 \sim 0.8L_{\text{acc}}$$

In this estimate equipartition between the magnetic ($U_B$) and the radiation energy density ($U_{\text{rad}} \simeq L_{\text{acc}}/4\pi cR_\odot^2$) has been assumed, with a typical size for the region of the order of a Schwarzschild radius, $R_\odot$. If these luminosities are converted with similar efficiency into kinetic and ionizing luminosities, respectively, then $L_{\text{kin}} \sim L$ ion. Clearly, the above evaluation is based on gross approximations and physical hypothesis, which currently are still at the level of speculation (e.g. Spruit 1996 and references therein).

It is worth noticing that if energy is extracted from a spinning objects, it can propagate in electromagnetic and/or kinetic form. Here we are indeed assuming that this power ultimately, and on scales smaller than a parsec, is largely converted into kinetic power (from a theoretical point of view, this balance depends on the boundary conditions of the hydromagnetic problem, see e.g. Begelman 1994 and references therein). It is then conserved as such up to much larger scales, as shown by the comparison with the results of RS91 and the fact that radiative dissipation within the jet itself (unbeamed radiation) is a negligible fraction of the estimated $L_{\text{kin}}$ (CF93). Further support to this possibility comes from the recent results by Bowman, Leahy & Komissarov (1996), who show that even dissipation caused by entrainment of material in the jet and the consequent deceleration, cause only a relatively small loss in kinetic power.

Alternatively, one could argue that the found similarity between $L_{\text{kin}}$ and $L$ ion supports the hypothesis that the acceleration of the jet is indeed caused by the radiation field generated in the disc. Our main objection to this point is the inefficiency of radiative acceleration to produce highly relativistic flows, even in the most favourable situation where the momentum is transferred through synchrotron absorption (G93). Our findings would indeed require a very high, close to $\sim 100$ per cent, efficiency in the conversion of radiative to kinetic luminosity.

7.2 Anisotropic ionizing continuum?

In what discussed it has been assumed that the radiation ionizing the broad line emitting gas is generated (semi-)isotropically by the plasma accreting onto the central object. In fact, a further possible interpretation of the results is that another anisotropic ionizing source, namely the beamed radiation from the jet itself, could be responsible for ionizing a significant fraction of the BLR emitting material (see e.g. Wilson 1993 on photoionization of the narrow line emitting gas). While this has been suggested as a possible explanation of the relatively rapid line variability observed in some radio–loud objects (e.g. Pérez, Penston & Moles 1989; see also Ghisellini & Madau 1996), it would raise the problem of understanding the similarity of the broad line component in radio–quiet and radio–loud sources, the former ones lacking evidence of a powerful (and beamed) jet. Furthermore, if the beamed continuum dominates the ionizing flux, then misaligned objects should systematically have broad lines of much larger equivalent widths than observed.

In this respect, it is also interesting to note that, while the luminosity itself depends on the class of sources considered (namely HPQ, LPQ and LDQ), in agreement with the most popular unification models, still the typical ratios between kinetic and broad–line luminosities appear to be independent of the type of object. This does indeed support the fact that $L_{\text{BLR}}$ is most likely to be an orientation independent parameter (for sources viewed down the "obscuring torus"). One could even think of determining, by measuring $L$ ion directly through optical/UV/X–ray data, how the
ratio of isotropic (as derived from $L_{\text{BLR}}$) versus anisotropic radiation varies with different objects, as a further orientation parameter. As an example, an estimate of this kind for $L_{\text{ion}}/L_{\text{BLR}}$ (by using the values of $L_{\text{ion}}$ derived by Padovani & Rafanelli 1988 and Padovani 1989) gives a ratio of about 10 for 3C 120, 3C 273, 3C 390.3, and PKS 1510−089 but about 100 for a highly beamed source like 3C 279. Finally, this ratio could be also expected to have some correlation with the degree of linear polarization (e.g. Wills 1991).

7.3 BL Lac objects

One could interpret the results for the class of BL Lac objects as due to a paucity of $L_{\text{BLR}}$, compared to quasars. This can derive from inefficient dissipation during accretion and/or a smaller accretion rate, and therefore a lower $L_{\text{ion}}$. This possibility is also reinforced by the fact that our estimate of the broad line emission in BL Lacs, as previously discussed, tends to overestimate $L_{\text{ion}}$. If Fanaroff-Riley type I radio galaxies (FR I: Fanaroff & Riley 1974) are the parent population of BL Lacs, as currently believed (e.g. Urry & Padovani 1995), this would also be an independent piece of evidence in agreement with the findings of Baum, Zirbel & O’Dea (1995). These authors, by studying the optical and radio properties of FR I and FR II radio galaxies (the latter thought to be the parent population of radio quasars), have in fact shown that, at the same host galaxy magnitude or radio luminosity, FR Is have an order of magnitude weaker line emission than FR IIs. However, it is also possible that the lower $L_{\text{BLR}}$ is caused by a lack of reprocessing broad line material.

Alternatively, one could argue that the $L_{\text{kin}}/L_{\text{ion}}$ ratio is similar for BL Lacs and quasars, but that eq. (2) overestimates $L_{\text{kin}}$ in the former objects. In particular, an intriguing possibility is that jets in BL Lacs and their ‘parent population’ (namely FR I radio galaxies) are mainly composed of an electron–positron plasma, while jets in quasars have a dominant electron–proton component, even if the number density of emitting particles is the same in the two classes of objects. This would reduce $L_{\text{kin}}$ in BL Lacs with respect to quasars, and may indeed be responsible for the different kinetic power and possibly the different morphology of FR I radio galaxies compared to their powerful counterparts. Such a hypothesis has been indeed formulated very recently by Reynolds et al. (1996), on the basis of a detailed study of the dynamics and radiative properties of the jet in M87, and will be further investigated elsewhere (Bodo et al., in preparation).

8 CONCLUSIONS

We have estimated the kinetic luminosity in the pc–scale radio jets of a sample of radio–loud AGN, by applying the standard SSC theory and compared it to the luminosity observed in broad lines. This has shown a quantitative similarity in quasars between these two forms of power, which could be translated into the equivalence between the ionizing luminosity, which is most likely the luminosity radiatively dissipated during the accretion process, and the luminosity channeled into jets in kinetic form. BL Lacs, however, show a deficit of $L_{\text{BLR}}$ or, alternatively, an excess of $L_{\text{kin}}$.

We find only a weak hint of correlation between $L_{\text{kin}}$ and $L_{\text{BLR}}$ which would extend over ~ 5 orders of magnitude and, when a different covering factor is taken into account, confirms the analogous behaviour of the Narrow Line luminosity with the power needed to feed the extended radio lobes (e.g. RS91), and the kinetic jet power (CF93). This is likely to be of the same nature of similar correlations between the radio luminosity and the emission of narrow lines on extended scales (e.g. Baum & Heckman 1989a,b). The large scatter we find in the correlation is probably due to the non–simultaneous radio and X–ray data which enter in our calculation, as $L_{\text{kin}}$ depends rather strongly on $F_X$.

In any case, the similarity of $L_{\text{kin}}$ and $L_{\text{ion}}$ seems to indicate that a common factor regulates both the luminosity dissipated during the accretion phase and the kinetic power of the jet. This clearly does not univocally define the factor responsible, however we suggest that this can be a piece of evidence in favour of the key role of magnetic fields.

It is also interesting to point out that the estimate of the broad line luminosity can have important predictive power on the models for the generation of the X– and especially $\gamma$–ray radiation in different classes of blazars (see e.g. the review by Sikora 1994) which stress the importance of Comptonization of the diffuse radiation field through which the jet propagates. It should be however noticed that here the estimates of the jet Doppler factor implicitly assume that the X–ray emission is mostly produced by the SSC mechanism. Polarization information in the X–ray band (e.g. Celotti & Matt 1994) will be therefore extremely important to constrain the emission models.

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FIGURE CAPTIONS

**Fig. 1** The kinetic luminosity of pc-scale jets, as estimated from the SSC theory, is plotted against the estimated luminosity in broad lines, for different classes of radio-loud sources, namely Core Dominated High Polarization Quasars (*full circles*), Core Dominated Low Polarization Quasars (*open circles*), Lobe Dominated Quasars (*open squares*), and BL Lac objects (*crosses*). The underlined symbols refer to sources for which the derived Doppler factor is less than one (see text). The dashed line corresponds to $L_{\text{kin}} = L_{\text{BLR}}$.

**Fig. 2** The core radio luminosity, $\nu L_c,\text{core}$ vs the luminosity in broad lines, for the same objects of Fig. 1. The dashed line corresponds to $\nu L_c,\text{core} = L_{\text{BLR}}$. While the correlation between the two luminosities is largely due to the common redshift dependence, it still suggests that the large spread in the correlation $L_{\text{kin}}$ vs $L_{\text{BLR}}$ is due to uncertainties in the estimate of $L_{\text{kin}}$.

**Fig. 3** The distribution of $\log(L_{\text{kin}}/L_{\text{BLR}})$ for the various classes of sources, that is (from top to bottom): Core Dominated High Polarization Quasars, Core Dominated Low Polarization Quasars, Lobe Dominated Quasars, all Quasars, and BL Lac objects. Dashed areas indicate objects with an estimated $\delta < 1$ (see text).
## Table 1a: Core-dominated HPQ

| Source      | Name | $z$ | log L<sub>BLR</sub> | Lines          | Refs.  | log L<sub>KIN</sub> |
|-------------|------|-----|----------------------|----------------|--------|----------------------|
| 0106+013    | 4C 01.02 | 2.107 | 46.98              | Lyα,Crv        | B89  | 46.92                |
| 0234+285    | CTD 20 | 1.213 | 45.90              | Crv            | B89  | 45.66                |
| 0336–019    | CTA 26 | 0.852 | 45.23              | Hβ,Hγ          | J91  | 46.53                |
| 0420–014    | PKS   | 0.915 | 45.59              | MgII           | B89,SS91 | 47.39          |
| 0521–365    | PKS   | 0.055 | 43.38<sup>a</sup> | Lyα,Hα,Hβ      | SC95 | 46.52*               |
| 1034–293    | OL-259 | 0.312 | 43.50              | Hβ,Hα          | S89  | 46.12                |
| 1156+295    | 4C 29.45 | 0.729 | 45.16<sup>a</sup> | MgII           | W83  | 44.98                |
| 1253–055    | 3C 279 | 0.538 | 44.78              | Lyα,Crv,MgII,Hβ,Hα | N94,N79 | 46.41          |
| 1335–127    | PKS   | 0.541 | 44.43              | MgII           | S93a | 46.80                |
| 1510–089    | PKS   | 0.361 | 44.87              | Lyα,MgII,Hα,Hβ,Hγ | O94,N79,SM87,Y80,BK84 | 45.79 |
| 1641+399    | 3C 345 | 0.595 | 45.57              | Lyα,Crv,MgII,Hβ,Hγ | O94,O84,N79,J91 | 45.10 |
| 1741–038    | OT-68 | 1.054 | 44.77              | MgII           | S89  | 47.12                |
| 1921–293    | OV 236 | 0.352 | 43.92              | Hα,Hβ          | J91  | 47.17                |
| 1958–179    | PKS   | 0.65  | 44.42              | MgII           | O94  | 46.88                |
| 2223–052    | 3C 446 | 1.404 | 45.93              | Lyα,Crv,MgII   | W95,P89 | 46.83          |
| 2230+114    | CTA 102 | 1.037 | 46.16              | Lyα,Crv        | W95  | 45.71                |
| 2234+282    | B2    | 0.795 | 44.78              | MgII,Hβ,Hγ     | RS80,J91 | 45.42          |
| 2251+158    | 3C 454.4 | 0.859 | 45.94              | Lyα,Crv,MgII,Hβ,Hγ | W95,N79,J91 | 46.51 |
| 2345–167    | PKS   | 0.576 | 44.62              | Hβ,Hγ          | J91  | 46.14                |

## Table 1b: Core-dominated LPQ

| Source      | Name | $z$ | log L<sub>BLR</sub> | Lines          | Refs.  | log L<sub>KIN</sub> |
|-------------|------|-----|----------------------|----------------|--------|----------------------|
| 0229+131    | 4C 13.14 | 2.065 | 46.61              | Lyα,Crv        | W93  | 45.27                |
| 0333+321    | NRAO 140 | 1.258 | 46.65              | MgII           | SS91 | 47.82                |
| 0430+052    | 3C 120 | 0.033 | 43.62              | Hα,Hβ,Hγ       | S81  | 46.09                |
| 0836+710    | 4C 71.07 | 2.170 | 45.91              | Crv            | SK93a | 47.37                |
| 0923+392    | 4C 39.25 | 0.699 | 46.06              | Lyα,Crv,MgII,Hβ | W95,OS84 | 46.34 |
| 1226+023    | 3C 273 | 0.158 | 45.82              | Lyα,Hβ,Hγ,Crv,MgII | C92,SM87 | 46.41 |
| 1404+286    | MKN 668 | 0.077 | 43.91              | Hα,Hβ,Hγ       | M93  | 44.25*               |
| 1548+114    | 4C 11.50 | 0.436 | 44.74              | Hβ,Hγ          | BK84 | 45.48                |
| 1730–130    | NRAO 530 | 0.902 | 44.92              | MgII,Hβ,Hγ     | BM87,J84 | 45.67 |
| 1928+738    | 4C 73.18 | 0.302 | 45.43              | Crv,Hβ,Hγ      | M96,S93a | 45.84 |
| 1954+513    | OV 591 | 1.220 | 45.21              | MgII           | B81  | 47.59*               |
| 2134+004    | PHIL 61 | 1.936 | 47.07              | Lyα,Crv,MgII   | B89,C92 | 46.43          |
| 2145+067    | 4C 06.69 | 0.990 | 46.24              | Lyα,Crv,MgII   | G90,N79 | 46.28          |
| 2216–083    | 4C 03.79 | 0.901 | 46.07              | Lyα,Crv,MgII   | W95,J91 | 46.94          |
| 2351+456    | 4C 45.51 | 2.000 | 45.11              | Crv,MgII       | SK93b | 47.16*               |
### Table 1c: Lobe dominated quasars

| Source | Name  | z    | \( \log L_{BLR} \) | Lines          | Refs.  | \( \log L_{KIN} \) |
|--------|-------|------|---------------------|----------------|--------|-------------------|
| (1)    | (2)   | (3)  | (4)                | (5)            | (6)    | (7)               |
| 0906+430 | 3C 216 | 0.670 | 44.98              | Mg\( \text{II} \) | SS80   | 46.97             |
| 1040+123 | 3C 245 | 1.029 | 45.38              | Mg\( \text{II} \) | N79    | 44.76             |
| 1222+216 | 4C 21.35 | 0.435 | 44.98              | H\( \beta \)    | SM87   | 45.97             |
| 1317+520 | 4C 52.27 | 1.060 | 46.34              | Mg\( \text{II} \) | SS91   | 48.95*            |
| 1618+177 | 3C 334 | 0.555 | 45.79              | L\( \text{Ly} \alpha \),C\( \text{IV} \),Mg\( \text{II} \),H\( \alpha \),H\( \beta \),H\( \gamma \) | W95, O84, N79, S81 | 46.79* |
| 1721+343 | 4C 34.47 | 0.206 | 45.38              | L\( \text{Ly} \alpha \),C\( \text{IV} \),H\( \alpha \),H\( \beta \),H\( \gamma \) | O94, R84, S81 | 47.29* |
| 1830+285 | 4C 28.45 | 0.594 | 45.56              | Mg\( \text{II} \) | RS80   | 48.13*            |
| 1845+797 | 3C 390.3 | 0.057 | 44.02*             | L\( \text{Ly} \alpha \),C\( \text{IV} \),H\( \alpha \),H\( \beta \),H\( \gamma \) | CW87, R84, S81 | 46.65* |
| 2209+080 | 4C 08.64 | 0.484 | 44.67              | Mg\( \text{II} \),H\( \beta \) | RS80   | 48.34*            |

### Table 1d: BL Lac

| Source | Name  | z    | \( \log L_{BLR} \) | Lines          | Refs.  | \( \log L_{KIN} \) |
|--------|-------|------|---------------------|----------------|--------|-------------------|
| (1)    | (2)   | (3)  | (4)                | (5)            | (6)    | (7)               |
| 0235+164 | AO    | 0.940 | 44.13              | Mg\( \text{II} \) | S93b   | 46.01             |
| 0537-441 | PKS   | 0.896 | 45.31              | Mg\( \text{II} \) | S93b   | 46.76             |
| 0823+033 | OJ 038 | 0.506 | 43.64              | Mg\( \text{II} \) | S93b   | 45.44             |
| 1101+384 | MKN 421 | 0.031 | 41.69              | H\( \alpha \)    | M92    | 46.80*            |
| 1308+326 | B2    | 0.996 | 44.96              | Mg\( \text{II} \) | S93b   | 46.26             |
| 1400+162 | 4C 16.39 | 0.244 | 42.27              | H\( \beta \)    | SJ85   | 46.57*            |
| 1538+149 | 4C 14.60 | 0.605 | 43.36              | Mg\( \text{II} \) | S93b   | 44.88             |
| 1652+398 | MKN 501 | 0.034 | 41.62              | H\( \alpha \)    | S93b   | 45.70             |
| 1803+784 | S5    | 0.684 | 44.59              | Mg\( \text{II} \) | S93b   | 46.05             |
| 1807+698 | 3C 371 | 0.051 | 41.68              | H\( \beta \)    | SJ85   | 45.45*            |
| 2200+420 | BL Lac | 0.069 | 41.28              | H\( \alpha \)    | SJ85   | 45.47             |

**Notes for Table 1**

Col. (1), Source designation. Col. (2), Source name. Col. (3), Redshift. Col. (4), Estimated \( L_{BLR} \) (erg/s).  
Col. (5), Lines from which the total \( L_{BLR} \) has been estimated. Col. (6), References for the line fluxes. Col. (7), Estimated \( L_{KIN} \) (erg/s). The * indicates those objects with an estimated \( \delta < 1 \) (see text for details).
References for Table 1

B81: Baldwin et al. (1981)
B89: Baldwin et al. (1989)
BK84: Bergeron & Kunth (1984)
BM87: Browne & Murphy (1987)
CW87: Clavel & Wamsteker (1987)
C92: Corbin (1992)
G90: Gondhalekar (1990)
J84: Junkkarinen (1984)
J91: Jackson & Browne (1991)
M92: Morganti et al. (1992)
M93: Marziani et al. (1993)
M96: Marziani et al. (1996)
N79: Neugebauer et al. (1979)
N94: Netzer et al. (1994)
O84: Oke et al. (1984)
O94: Osmer et al. (1994)
P89: Pérez et al. (1989)
R84: Rudy (1984)
RS80: Richstone & Schmidt (1980)
S81: Steiner (1981)
S89: Stickel et al. (1989)
S93a: Stickel et al. (1993a)
S93b: Stickel et al. (1993b)
SJ85: Sitko & Junkkarinen (1985)
SK93a: Stickel & Kühr (1993a)
SK93b: Stickel & Kühr (1993b)
SC95: Scarpa et al. (1995)
SM87: Stockton & MacKenty (1987)
SS80: Smith & Spinrad (1980)
SS91: Steidel & Sargent (1991)
V95: Vermeulen et al. (1995)
W83: Wills et al. (1983)
W93: Wills et al. (1993)
W95: Wills et al. (1995)
Y80: Yee (1980)
Table 2: $\log \frac{L_{\text{KIN}}}{L_{\text{BLR}}}$

| Sample       | Mean ±$\sigma_M$ | Median | N  | Mean ±$\sigma_M$ | Median | N  |
|--------------|------------------|--------|----|------------------|--------|----|
| All          | 1.56±0.19        | 1.46   | 55 | 1.20±0.19        | 1.23   | 42 |
| All_no BLLacs | 1.22±0.18        | 1.00   | 43 | 0.91±0.19        | 0.87   | 33 |
| CDQ          | 1.05±0.20        | 0.89   | 34 | 0.92±0.20        | 0.81   | 30 |
| HPQ          | 1.27±0.28        | 1.30   | 19 | 1.16±0.27        | 1.11   | 18 |
| LPQ          | 0.77±0.27        | 0.74   | 15 | 0.57±0.28        | 0.67   | 12 |
| LDQ          | 1.86±0.42        | 1.99   | 9  | 0.79±0.76        | 0.99   | 3  |
| BL Lacs      | 2.81±0.40        | 2.36   | 12 | 2.28±0.38        | 1.80   | 9  |
