Mon. Not. R. Astron. Soc. **395,** 518–523 (2009) doi:10.1111/j.1365-2966.2009.14557.x

On the jet contribution to the active galactic nuclei cosmic energy budget

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Accepted 2009 January 25. Received 2009 January 20; in original form 2008 December 8

ABSTRACT

Black holes release energy via the production of photons in their accretion discs but also via the acceleration of jets. We investigate the relative importance of these two paths over cosmic time by determining the mechanical luminosity function (LF) of radio sources and by comparing it to a previous determination of the bolometric LF of active galactic nuclei (AGN) from X-ray, optical and infrared observations. The mechanical LF of radio sources is computed in two steps: the determination of the mechanical luminosity as a function of the radio luminosity and its convolution with the radio LF of radio sources. Even with the large uncertainty deriving from the former, we can conclude that the contribution of jets is unlikely to be much larger than ∼10 per cent of the AGN energy budget at any cosmic epoch.

Key words: black hole physics – galaxies: active – galaxies: jets.

1 INTRODUCTION

Matter can accrete on to a black hole (BH) only if it releases a fraction $\epsilon \sim 0.06$–0.4 of its rest-mass energy, where ϵ depends on the BH spin (Bardeen 1970). In the standard Shakura & Syunyaev (1973) model, the energy is dissipated by viscous torques in the accretion disc and radiated. Accretion from a luminous disc provides a physical model to explain the luminosity of quasars (Lynden-Bell 1969).

Several authors have computed the total energy radiated by BHs over cosmic time and have compared it to the local BH mass density (Soltan 1982; Chokshi & Turner 1992; Yu & Tremaine 2002; Barger et al. 2005; Hopkins, Richards & Hernquist 2007). The two are in good agreement if matter is turned into light with a canonical efficiency of $\epsilon \sim 0.1$. This has been used as an argument to infer that most of the BH mass in the Universe was accreted luminously, but it only proves that >25 per cent of the BH mass in the Universe was accreted luminously, since ϵ could be as large as $\epsilon \sim 0.4$ if most BHs were maximally rotating.

In fact, accreting BHs [active galactic nuclei (AGN)] produce not only light but also jets of matter, which are radio luminous because of the synchrotron radiation from ultrarelativistic electrons accelerated in shocks. Excluding objects beamed towards the line of sight, only a small fraction of the luminosity that is radiated by an AGN comes from synchrotron radiation. However, the synchrotron power represents only a small fraction of the jet mechanical luminosity, most of which may be used to do work on the surrounding gas.

Moreover, at low accretion rates ($\dot{M}_\bullet \lesssim 0.01\dot{M}_{\rm Edd}$, where $L_{\rm Edd} = \epsilon\dot{M}_{\rm Edd}c^2$ is the Eddington luminosity), the accretion disc is not dense enough to radiate efficiently; the disc puffs up, and the energy that needs to be removed to allow the accretion may be carried out more easily by jets. Although the physics of this picture are still speculative, AGN that channel a large fraction of the accretion power into jets while showing little emission from an accretion disc are observed (e.g. Di Matteo et al. 2003; Allen et al. 2006). These radio sources are less powerful than quasars but more common due to their longer duty cycle. For example, around two-third of brightest cluster galaxies are radio galaxies (Burns 1990; Best et al. 2007). In contrast, only one galaxy in 10^4 contains a quasar ($M_B < -23$) at $z \sim 0$ (Wisotzki, Kuhlbrodt & Jahnke 2001). Finally, mechanical energy is thermalized in the intracluster medium more efficiently than luminous energy is. The observational evidence that the mechanical heating by AGN is important to solve the cooling-flow problem in galaxy groups and clusters is getting strong (Best et al. 2005a; Dunn & Fabian 2006; Rafferty et al. 2006; Magliocchetti & Brüggen 2007; see also Cattaneo et al. 2009 and references therein).

For these reasons, it is important to compare the mechanical and radiative output of AGN. This is the goal of this paper. This issue has also recently been addressed by Heinz, Merloni & Schwab (2007), Shankar et al. (2008), Körding, Jester & Fender (2008) and Merloni & Heinz (2008). We adopt a different approach to these authors and produce results that are qualitatively similar. The layout of our paper is as follows. In Section 2, we analyse how we can use radio data to infer the jet mechanical power. We shall see that two different approaches give different $P_{\rm jet}(L_{\rm radio})$ relations. We consider both and use the difference between the results obtained from the two relations to provide an estimate of the uncertainty. We convolve these relations with the radio luminosity function (LF) of radio sources, $\phi(L_{\rm radio})$, to estimate the mechanical LF, $\phi[L_{\rm radio}(P_{\rm jet})]$, first in the local Universe (Section 3), then at different redshifts (Section 4). In both cases, we integrate over luminosity to determine the mechanical power per unit volume, which we compare with the radiative power per unit volume from luminous AGN. In Section 5,

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we summarize the results of comparing the mechanical LF of AGN to the bolometric (LF) of AGN determined by Hopkins et al. (2007) and discuss the implications of our results.

2 THE MECHANICAL LUMINOSITY OF A RADIO SOURCE

Obtaining an estimate of the mechanical power of a radio source is an inherently difficult problem. The observed monochromatic radio luminosity measures only the fraction of the jet power that is currently being converted into radiation. That fraction is small (typically between 0.1 and 1 per cent; cf. Bicknell 1995) and changes during the lifetime of the radio source, since the radio luminosity of a growing radio source first increases and then drops as the source expands into a progressively lower density environment (e.g. Kaiser, Dennett-Thorpe & Alexander 1997). Nevertheless, it is reasonable to expect that radio and mechanical luminosities should show at least a broad degree of correlation on a population basis.

Estimates of the mechanical power of radio sources have followed two approaches. The first (Willott et al. 1999) uses the minimum energy density $u_{\rm min}$ that the plasma in the radio lobes must have in order to emit the observed synchrotron radiation (e.g. Miley 1980). With this approach, the jet mechanical power is $L_{\rm mech} \gtrsim u_{\rm min}\, V/t$, where V is the volume filled by the radio lobes and the radio-source lifetime t is given by the ratio between the jets' length and the hotspots' advancement speed. The largest sources of uncertainties are (i) the nature of the jet plasma (electron–positron or electron–proton?): the value of $u_{\rm min}$ is larger if the lobes contain a hadronic component in addition to the synchrotron radiating particles (relativistic electrons and/or positrons), and (ii) the lack of observational constraints on the low-frequency cut-off of the electron energy distribution: for a synchrotron spectrum $\propto \nu^{\alpha_{\rm s}}$ with radio spectral index $\alpha_{\rm s} < -0.5$, $u_{\rm min}$ is larger when the lower cut-off frequency takes a lower value and thus there is more energy in the synchrotron spectrum. Willott et al. (1999) derive the relation

$$L_{\rm mech} = 3 \times 10^{38} f_{\rm W}^{3/2} \left(\frac{L_{151\,\rm MHz}}{10^{28}\ {\rm W\,Hz^{-1}\ sr^{-1}}} \right)^{6/7} {\rm W}, \quad (1)$$

where $f_{\rm W} \sim 1$–20 incorporates all the unknown factors. Blundell & Rawlings (2000) argue for $f_{\rm W} \simeq 10$ for Fanaroff & Riley (1974) class II sources (FR II), while Hardcastle et al. (2007) suggest $f_{\rm W} = 10$–20 for FR I. We convert the luminosity at 151 MHz, $L_{151\,\rm MHz}$, into a luminosity at 1.4 GHz, $L_{1.4\,\rm GHz}$, where the local radio LF is best determined. This will also allow us later to compare equation (1) with another determination of $L_{\rm mech}$ by Best et al. (2006, 2007). For the conversion, we assume a spectral index $\alpha_{\rm s} = -0.8$ even though measured values of $\alpha_{\rm s}$ show considerable scatter. Using $f_{\rm W} = 10$, equation (1) gives

$$L_{\rm mech} = 1.4 \times 10^{37} \left(\frac{L_{1.4\,\rm GHz}}{10^{25}\ {\rm W\,Hz^{-1}}} \right)^{0.85} {\rm W}. \quad (2)$$

Note that $L_{151\,\rm MHz}$ is given in W Hz^{-1} sr^{-1} while $L_{1.4\,\rm GHz}$ is given in W Hz^{-1} to respect the different conventions used by Willott et al. (1999) and Best et al. (2006), so there is a factor of 4π entering the conversion.

A second approach is to infer $L_{\rm mech}$ from the mechanical work that the lobes do on the surrounding hot gas. The expanding lobes of relativistic synchrotron-emitting plasma open cavities in the ambient thermal X-ray emitting plasma, which advances in X-ray imaging capabilities now allow to be imaged in detail. The minimum work in inflating these cavities is done for reversible (quasi-static) inflation and equals pV, where p is the pressure of the ambient gas. Best et al. (2006) derived a relation between radio and mechanical luminosity based upon this estimate for the energy associated with these cavities, combined with an estimate of the cavity ages from the buoyancy time-scale (from Bîrzan et al. 2004). Comparing the mechanical luminosities of 19 nearby radio sources that have associated X-ray cavities with their 1.4 GHz monochromatic radio luminosities leads to a relation

$$L_{\rm mech} = (3.0 \pm 0.2) \times 10^{36} f \left(\frac{L_{1.4\,\rm GHz}}{10^{25}\ {\rm W\,Hz^{-1}}} \right)^{0.40\pm0.13} {\rm W}, \quad (3)$$

broadly in agreement with that derived by Bîrzan et al. (2004), even though the scatter is almost an order of magnitude in both cases (0.85 dex according to Bîrzan et al. 2008). In equation (3), the factor f, incorporated by Best et al. (2007), accounts for any systematic error in estimating the mechanical luminosities of the cavities. In particular, pV is likely to be an underestimate of the energy needed to inflate a cavity: the enthalpy of the cavity is $\frac{\gamma}{\gamma-1} pV = 4pV$ for the relativistic plasma in the radio lobes, suggesting that $f \sim 4$ may be appropriate. Some authors have even argued for mechanical energies in excess of $10pV$ (Nusser, Silk & Babul 2006; Binney, Bibi & Omma 2007) due to additional heating directly from the jets. For $f = 4$, equation (3) gives

$$L_{\rm mech} = 1.2 \times 10^{37} \left(\frac{L_{1.4\,\rm GHz}}{10^{25}\ {\rm W\,Hz^{-1}}} \right)^{0.40} {\rm W}. \quad (4)$$

Equations (2) and (4) are in excellent agreement at $L_{1.4\,\rm GHz} \sim 10^{25}$ W Hz^{-1}, but the relation derived from the minimum-energy argument has a steeper radio luminosity dependence than the relation derived from the X-ray cavities. Nevertheless, given the totally independent approaches used to derive equations (2) and (4), and the uncertainty factors in both equations, the degree of consistency is encouraging. Indeed, the discrepancy between the two relations may simply reflect the fact that equation (2) is determined from powerful, radiatively efficient radio sources (mostly $L_{1.4\,\rm GHz} \gtrsim 10^{25}$ W Hz^{-1}) while equation (4) is derived predominantly from lower luminosity, radiatively inefficient sources. The mean relation between $L_{\rm mech}$ and $L_{\rm rad}$ may well be different in these two different regimes, in which case a combination of equation (2) at high luminosities and equation (4) at low luminosities would be most appropriate.

In a recent article, Bîrzan et al. (2008) have shown that the correlation of the mechanical power estimated from observations of X-ray cavities with the monochromatic radio luminosity at 327 MHz,

$$L_{\rm mech} = 10^{36.11} \left(\frac{L_{327\,\rm MHz}}{10^{24}\ {\rm W\,Hz^{-1}}} \right)^{0.62} {\rm W}, \quad (5)$$

is a little tighter than the correlation with the monochromatic luminosity at 1.4 GHz because the former is a more accurate tracer of the bolometric radio luminosity (the scatter is 0.65 dex in the relation at 327 MHz). Therefore, equation (5) offers a more accurate estimate of $L_{\rm mech}$ than equation (4) does, even though the method that was used to derive them is the same. However, equation (5) is not necessarily better than equation (4) for the purpose of studying the statistics of $L_{\rm mech}$ in the local Universe because the local radio LF is determined much more accurately at 1.4 GHz than it is at lower frequencies. If one chose to use equation (5) instead of equation (4), then one would need either to convolve equation (5) with a radio LF that is less accurate or to convert $L_{327\,\rm MHz}$ into a luminosity at 1.4 GHz. For $\alpha_{\rm s} = -0.8$, this gives

$$L_{\rm mech} = 1.1 \times 10^{37} \left(\frac{L_{1.4\,\rm GHz}}{10^{25}\ {\rm W\,Hz^{-1}}} \right)^{0.62} {\rm W}. \quad (6)$$

However, this would not improve the accuracy of the calculation because the spectral index used to make the conversion contains considerable scatter. Therefore, we do not consider equation (5) when deriving the local mechanical LF, but we do use it for studies at higher redshift (Section 4) where the LF at low radio frequencies is reasonably well determined.

A third approach towards estimating mechanical luminosities of radio sources has been developed by Heinz et al. (2007) and Merloni & Heinz (2008). These authors used the debeamed radio core emission as a measure of the jet kinetic luminosity, based upon the analogy with X-ray binary sources and the so-called Fundamental Plane relation for BHs (Merloni, Heinz & di Matteo 2003). This approach uses the radio LF of flat-spectrum (i.e. core-dominated) radio sources as a measure of the LF of radio cores. It then requires assumptions about the statistical debeaming of radio sources (i.e. the distribution of Lorentz factors of jets) and about how to correct for the radio cores that are missed from the flat-spectrum radio LF because their radio sources are dominated by extended steep-spectrum emission. These factors can be reasonably estimated for moderate to high-radio-luminosity sources in the local Universe, but they are not so well constrained at low radio luminosities, where the bulk of the jet mechanical power is produced, or at higher redshifts. We therefore do not consider this approach here, but we do compare our results with the results obtained by Merloni & Heinz (2008) in Section 5.

3 THE LOCAL MECHANICAL LF

In order to derive a mechanical LF for radio sources in the nearby Universe, we must convolve equations (2) and (4) with the local radio LF. Here, we adopt the local 1.4 GHz radio LF of Best et al. (2005b), which is derived from the Sloan Digital Sky Survey spectroscopic sample and is fully consistent with other recent determinations of the local radio LF (e.g. Machalski & Godlowski 2000; Sadler et al. 2002). Throughout this paper, we follow the convention of defining the LF $\phi(L)$ as the number of objects per unit volume and logarithmic luminosity interval (e.g. Hopkins et al. 2007), so the number of sources with luminosity between L and $L + \mathrm{d}L$ is $(\phi/\ln 10)\,\mathrm{d}L/L$. With this definition, the Best et al. (2005b) LF can be parametrized using the double power-law model

$$\phi(L) = \phi_* \left[\left(\frac{L}{L_*}\right)^{\alpha} + \left(\frac{L}{L_*}\right)^{\beta}\right]^{-1}, \qquad (7)$$

where $L = L_{1.4\,\mathrm{GHz}}$ (we wrote L without any subscripts because we shall use equation 7 to model other LFs). The best-fitting parameters are $\phi_* = 10^{-5.7}\,\mathrm{Mpc^{-3}}$, $L_* = 10^{25.16}\,\mathrm{W\,Hz^{-1}}$, $\alpha = 0.57$ and $\beta = 2.31$. Combining equation (7) with equations (2) and (4) gives the blue and the red dotted curves in the $z = 0.1$ diagram of Fig. 1, respectively.

The mechanical power that is released per unit volume is

$$\rho_{\mathrm{mech}} = \int_0^{\infty} L_{\mathrm{mech}}(L)\frac{\phi(L)}{\ln 10}\frac{\mathrm{d}L}{L}$$
$$= A\left(\frac{L}{10^{25}\,\mathrm{W\,Hz^{-1}}}\right)^{\eta}\frac{\phi_*}{\ln 10}\int_0^{\infty}\frac{\mathrm{d}x}{x^{\alpha+1-\eta} + x^{\beta+1-\eta}}, \qquad (8)$$

where $A = 3.6 \times 10^{10}\,\mathrm{L_\odot}$ and $\eta = 0.85$ for equation (2) and $A = 3.1 \times 10^{10}\,\mathrm{L_\odot}$ and $\eta = 0.4$ for equation (4). If L_{mech} is computed with equation (2), then $\rho_{\mathrm{mech}}^{\mathrm{synchro}} = 1.6 \times 10^5\,\mathrm{L_\odot\,Mpc^{-3}}$ ($1\,\mathrm{L_\odot} = 3.9 \times 10^{26}$ W). If L_{mech} is computed with equation (4), the problem is more complicated because in that case the integral in equation (8) diverges at $x = 0$. This is because the double power-law model

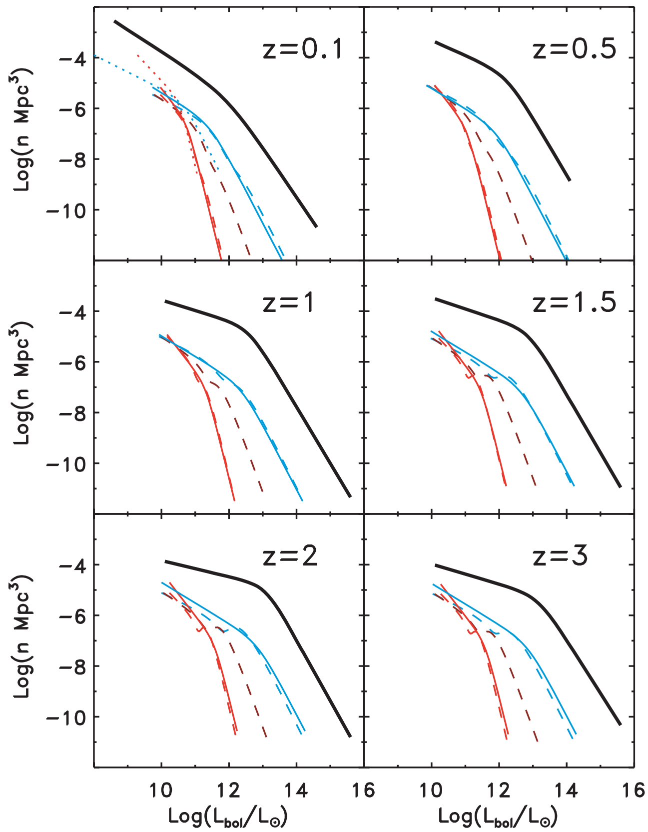

Figure 1. The thick solid lines show the bolometric LF of AGN inferred by Hopkins et al. (2007) from X-ray, optical and infrared data. The thin solid and dashed lines show the mechanical LFs inferred from the radio LFs of Dunlop & Peacock (1990) and Willott et al. (2001), respectively. At $z \simeq 0$, we have also shown the mechanical LFs inferred from Best et al. (2005b)'s local radio LF (dotted lines). For each radio LF, we have determined two mechanical LFs, according to the two different $P_{\mathrm{jet}}(L_{\mathrm{radio}})$ conversions derived in Section 2: the red lines are for $P_{\mathrm{jet}} \propto L_{\mathrm{radio}}^{0.4}$ (equation 4) and the blue lines are for $P_{\mathrm{jet}} \propto L_{\mathrm{radio}}^{0.85}$ (equation 2). For the Willott et al. (2001) radio LF, we have also computed a third mechanical LF, which corresponds to $P_{\mathrm{jet}} \propto L_{\mathrm{radio}}^{0.65}$ (equation 5; dark purple dashes).

in equation (7) cannot be extrapolated down to $L \to 0$, as can be easily seen: the faint-end slope of the local radio LF is steeper than that of both the low-luminosity end of the local galaxy optical LF (e.g. Norberg et al. 2002) and the low-mass end of the local mass function of supermassive BHs (e.g. Shankar et al. 2009). Therefore, if the radio LF extrapolated too far, then the calculated space density of radio-loud AGN would exceed that of galaxies (or supermassive BHs) capable of hosting them. For example, if the slope of the radio LF were to remain unaltered down to $L_{1.4\,\mathrm{GHz}} = 10^{17}\,\mathrm{W\,Hz^{-1}}$, then the local space density of radio galaxies would exceed that of galaxies integrated down to $M_B \sim -15$.

Considering that only massive galaxies with massive BHs have a significant probability of harbouring a radio source powered by an AGN, the local space density of radio sources matches that of supermassive BHs with $M_\bullet \gtrsim 10^6\,\mathrm{M_\odot}$ (i.e. $\sim 5 \times 10^{-3}\,\mathrm{Mpc^{-3}}$ according to Shankar et al. 2009) if the radio LF is extrapolated down to $L_{1.4\,\mathrm{GHz}} \sim 10^{19.2}\,\mathrm{W\,Hz^{-1}}$. This sets a strong lower limit on the luminosity to which the radio LF can be extrapolated, and so for a conservative calculation we evaluate the integral in equation (8) by adopting $10^{19.2}\,\mathrm{W\,Hz^{-1}}/L_* \simeq 10^{-6}$ as the lower extreme of the integration interval. With this choice, the mechanical power per unit volume

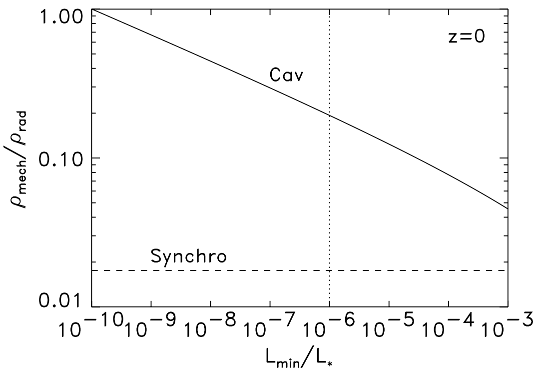

Figure 2. The ratio between the mechanical power of radio sources (equation 8) and the radiative power of luminous AGN (equation 9) in a representative volume of the local Universe. The solid line is computed using the mechanical power estimated from the size of the X-ray cavities (equation 4), in which case $\rho_{\rm mech}$ depends on the minimum luminosity $L_{\rm min}$ at which one can extrapolate the LF in equation (7). The dashed line is computed using the mechanical power estimated from the minimum energy that is needed to explain the observed synchrotron emission (equation 2), in which case $\rho_{\rm mech}$ does not depend on this uncertainty. Both lines are computed using the local LF of Best et al. (2005b). The vertical dotted line is a conservative lower limit for $L_{\rm min}$.

from equation (4), $\rho^{\rm cav}_{\rm mech}$, is about 10 times larger than the mechanical power per unit volume from equation (2), $\rho^{\rm synchro}_{\rm mech}$. Interestingly, recent studies of very weak radio sources in the local Universe have found hints that the radio LF flattens below $L_{15\,\rm GHz} \sim 10^{20}\,\rm W\,Hz^{-1}$ (Nagar, Falcke & Wilson 2005) and $L_{5\,\rm GHz} \sim 10^{21}\,\rm W\,Hz^{-1}$ (Filho, Barthel & Ho 2006). For a spectral index of $\alpha_{\rm s} = -0.8$, these luminosities correspond to $L_{1.4\,\rm GHz} \sim 10^{20.8}$ and $10^{21.4}\,\rm W\,Hz^{-1}$, respectively. If the integral in equation (8) were evaluated adopting the lower limit $L_{1.4\,\rm GHz} \sim 10^{21}\,\rm W\,Hz^{-1}$ suggested by these results, then the discrepancy between $\rho^{\rm cav}_{\rm mech}$ and $\rho^{\rm synchro}_{\rm mech}$ would reduce to a factor of ∼4–5.

We want to compare these values to the radiative power per unit volume from luminous AGN. Hopkins et al. (2007) made the first attempt at determining the bolometric LF of AGN by combining hard X-ray, soft X-ray, optical and infrared data. They found that the double power-law model in equation (7) fits their results with ϕ_*, L_*, α and β dependent on redshift (here, L is the bolometric luminosity, $L_{\rm bol}$, not the radio luminosity). The thick solid lines in Fig. 1 show their best fit at different z. We use their best fit to the bolometric LF at $z = 0.1$ to estimate the power per unit volume radiated by AGN in the local Universe:

$$\rho_{\rm rad} = \int_0^\infty L_{\rm bol} \frac{\phi(L_{\rm bol})}{\ln 10} \frac{{\rm d}L_{\rm bol}}{L_{\rm bol}}. \qquad (9)$$

We find that $\rho^{\rm synchro}_{\rm mech}/\rho_{\rm rad} \simeq 0.018$ (the level of the dashed line in Fig. 2). The value of $\rho^{\rm cav}_{\rm mech}/\rho_{\rm rad}$ depends on the radio luminosity $L_{\rm min}$ that is taken for the lower bound of the integration interval in equation (8) (solid line in Fig. 2). For $L_{\rm min}/L_* \simeq 10^{-6}$, $\rho^{\rm cav}_{\rm mech}/\rho_{\rm rad} \simeq 0.2$. For $\rho^{\rm cav}_{\rm mech}$ to be comparable to $\rho_{\rm rad}$, the power law of the radio LF would have to extrapolate down to $L_{1.4\,\rm GHz} = 10^{15}\,\rm W\,Hz^{-1}$ (Fig. 2), which is well below the allowed limits.

4 THE EVOLUTION OF THE MECHANICAL LF

To go beyond the local Universe, we need to know the evolution of the radio LF with redshift (assuming that there is no redshift dependence in equations 2 and 4). We use the radio LFs determined by Dunlop & Peacock (1990) and Willott et al. (2001). These LFs are constructed using samples that extend to high z, although the very low numbers of low-z sources in these samples means that their local LFs are much more poorly determined than the recent 1.4 GHz local radio LFs of Best et al. (2005b) and other authors.

Dunlop & Peacock (1990) modelled the 2.7 GHz LF with the sum of three contributions: steep-spectrum radio sources in early-type galaxies, flat-spectrum radio sources in early-type galaxies and radio sources in late-type galaxies. The latter are mainly powered by star formation and are thus irrelevant for our analysis. Flat-spectrum radio sources are beamed (the jets are aligned with the line of sight); therefore, the equations in Section 2 overestimate their mechanical luminosity. The addition of the LF of flat-spectrum radio sources to that of steep-spectrum radio sources makes little difference to the latter, and so it is safe to deal with this complication by considering only steep-spectrum radio sources. The 2.7 GHz LF of steep-spectrum radio sources in early-type galaxies computed by Dunlop & Peacock (1990) is a double power-law function of the form of equation (7). In their pure luminosity evolution model (their other models give similar LFs out to $z \sim 2$), $\alpha = 0.69$, $\beta = 2.17$, and the dependence of redshift is entirely contained in $L_* = 10^{24.89+1.26z-0.26z^2}\,\rm W\,Hz^{-1}\,sr^{-1}$. We take this LF, convert it into a 1.4 GHz LF by assuming an $\alpha_{\rm s} = -0.8$ spectral index, and correct for a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$ so that we can compare our results with the bolometric LF determined by Hopkins et al. (2007), since Dunlop & Peacock (1990) had assumed $\Omega_M = 1$, $\Omega_\Lambda = 0$ and $h = 0.5$. The blue and red solid lines in Fig. 1 are obtained by convolving the 1.4 GHz LF determined in this manner with equations (2) and (4), respectively. Both the blue and the red curves are significantly below the bolometric LF estimated by Hopkins et al. (2007; thick solid lines) at all redshifts.

To check this result with an independent determination of the radio LF, we consider Willott et al. (2001)'s best fit to the 151 MHz LF (their model C). We transform it into a 1.4 GHz LF by assuming $\alpha_{\rm s} = -0.8$ and correct for the cosmology (Willott et al. 2001 had assumed the same cosmology as Dunlop & Peacock 1990). The blue and the red dashed lines in Fig. 1 are obtained by convolving the 1.4 GHz LF determined in this manner with equations (2) and (4), respectively. The dashed lines and the thin solid lines of the same colour run very close to each other. This shows that the 2.7 GHz LF determined by Dunlop & Peacock (1990) and the 151 MHz LF determined by Willott et al. (2001) are broadly consistent at all z for a spectral index of $\alpha_{\rm s} = -0.8$. A comparison with the local 1.4 GHz LF determined by Best et al. (2005b) shows that both Dunlop & Peacock (1990) and Willott et al. (2001) are likely to overestimate the number of bright radio sources at low z, where they have few objects in their sample, but overall Fig. 1 demonstrates that the radio LF is not a major source of uncertainty when it comes to determining the mechanical LF of AGN. This is true both at low and at high z.

Finally, we have repeated the same calculation using only low-frequency data: we have taken the Willott et al. (2001) LF, we have converted it into a 327 MHz LF assuming $\alpha_{\rm s} = -0.8$ and we have convolved it with the mechanical luminosity estimated from equation (5). The result of this third determination, shown by the dark-purple dashes in Fig. 1, lies in between the results obtained from equations (2) and (4) over most of the plotted luminosity range. This is not surprising because the exponent of equation (5) is intermediate between those of equations (2) and (4).

The mechanical power per unit volume obtained integrating equation (2) over the LF of Dunlop & Peacock (1990), $\rho^{\rm synchro}_{\rm mech}$, is shown as a function of redshift in Fig. 3 (dashed line) and compared to

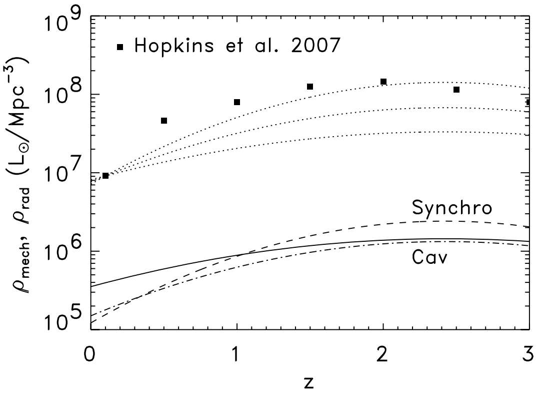

Figure 3. The mechanical (lines) and radiative (symbols) power of AGN per unit cosmic volume as a function of redshift. The mechanical power per unit volume $\rho_{\rm mech}^{\rm synchro}$ (dashed line) is computed by inserting equation (2) into equation (8) and using the radio LF of Dunlop & Peacock (1990). The solid line shows the redshift dependence of $\rho_{\rm mech}^{\rm cav}$. The vertical normalization of this line depends upon the lower luminosity limit of the radio LF adopted for the integration interval in equation (8), but the redshift dependence does not. The plotted solid line uses a normalization that corresponds to $L_{\rm min} = 10^{21}$ W Hz^{-1} at $z = 0$. The dot–dashed line is computed in the same way as the solid line but uses equation (6) instead of equation (4). The radiative power per unit volume $\rho_{\rm rad}$ is computed from equation (9) using the bolometric LF of Hopkins et al. (2007). The dotted lines correspond to the dashed line, the dot–dshed line and the solid line scaled to match the radiative power at redshift zero. They have been added to ease the comparison of these lines with the symbols.

the radiative power per unit volume from equation (9) (symbols). The upper dotted line in Fig. 3 is simply $57\rho_{\rm mech}^{\rm synchro}$. It shows that the cosmic evolution of the mechanical power density traces that of the radiative power density, at least for equation (2). It also shows that throughout cosmic time jets contribute to a small fraction (∼2 per cent) of the AGN energy budget. This fraction goes up by a factor of ∼4–5 at low redshifts, if we believe that equation (4) is a more accurate determination of $L_{\rm mech}$ (solid line in Fig. 3). Moreover, the LF by Dunlop & Peacock (1990) gives a local mechanical energy density that is ∼30 per cent lower than the more accurate value determined from the LF by Best et al. (2005a; compare Fig. 3 with the values quoted in Section 3). Even when this is taken into account, it is unlikely that the mechanical energy accounts for much more than ∼15 per cent of the AGN cosmic energy budget locally. In addition, the cosmic evolution of the jet mechanical energy estimated by equation (4) is weaker than that of the radiative power, and so in this case the fraction of the AGN energy budget associated with jet mechanical power falls with increasing redshift, being well below 10 per cent at $z \gtrsim 1$.

The trend with redshift derived combining equation (6) with the LF by Dunlop & Peacock (1990) is shown by the dot–dashed line in Fig. 3. The mechanical energy density found with this determination is intermediate between that derived from equation (2) and that derived from equation (4) at $z \sim 0$ but is lower than both of them at higher redshifts reinforcing the notion that the importance of mechanical energy decreases at high z.

5 DISCUSSION AND CONCLUSION

Fig. 1 suggests that the radio LF is not a major source of uncertainty when it comes to determining the mechanical LF of radio sources. It should be cautioned that constraints on the evolution of the faint end of the radio LF beyond $z \sim 1$ remain quite poor. The uncertainties are almost certainly larger than the variations between the different determinations of the radio LF evolution suggested. Nevertheless, it is also clear that the main source of uncertainty is the exponent of the $L_{\rm mech} \propto L_{\rm radio}^{\beta}$ relation.

The argument based on X-ray cavities suggests that the importance of the mechanical energy output decreases in luminous high-accretion-rate objects. On the contrary, the argument based on the minimum energy to produce the observed radio emission suggests that the mechanical energy output traces the luminous output. It is not surprising that the latter conclusion follows from equation (2) since Willott et al. (2001), from which equations (1) and (2) are derived, find that the jet mechanical luminosity is proportional to the optical narrow-line luminosity. We speculate that the results obtained with the two methods may be different because the jets in powerful radio sources advance supersonically and often pierce through the ambient hot gas. In that case, the cavities are not inflated gently, therefore the work done to inflate the cavities is much larger than pV. Important progress is beginning to come from observational studies comparing the mechanical luminosities derived with the two methods for the same objects (e.g. Bîrzan et al. 2008). The 327 MHz relation derived by Bîrzan et al. (2008), equation (5), combined with the LF at 151 MHz derived by Willott et al. (2001) suggests that the mechanical LF of AGN is likely to lie in between those derived from equations (2) and (4) at $L_{\rm mech} \gtrsim 10^{10.5}$–$10^{11}$ $L_\odot$ and below both of them at luminosities that are just below this value (Fig. 1).

Independent of whether one favours equations (2), (4) or (5), Fig. 1 shows clearly that the bolometric LF is larger than the mechanical LF by at least one order of magnitude at all luminosities. Equation (2) establishes a ∼2 per cent value at all redshifts for the mechanical contribution to the AGN cosmic energy budget (Fig. 3). Equation (4) gives a higher value, which depends on the minimum luminosity at which the radio LF levels off (Fig. 2). While this luminosity is uncertain, we can reasonably estimate that the contribution inferred from equation (4) is larger than the contribution inferred from equation (2) by a factor of ∼3–10. It is thus unlikely that mechanical energy accounts for much more than 10 per cent of the AGN cosmic energy budget with 20 per cent as a firm upper limit. This is in broad agreement with previous studies (Merloni & Heinz 2008; Shankar et al. 2008), which is encouraging given the different methods that we have used in our analyses.

This result implies that radiatively inefficient accretion is unlikely to contribute to much more than 10 per cent of the BH mass in the Universe unless the overall energy efficiency of accretion in this mode is substantially lower than the energy efficiency in the radiatively efficient mode, i.e. unless a substantial fraction of the energy is advected on to the BH, rather than coming out as either photons or jets. Based on an advection-dominated accretion flow (ADAF; Narayan & Yi 1994) model, Merloni & Heinz (2008) suggested a kinetic efficiency for the production of jets of $\epsilon_k \simeq 0.005$ (where $L_{\rm mech} = \epsilon_k \dot{M}_\bullet c^2$) in low-accretion-rate AGN, and thus concluded that ∼18–27 per cent of the BH growth occurs in a radio-jet-producing mode. Shankar et al. (2008) found a similar value (∼20–30 per cent) by deriving a kinetic efficiency of $\epsilon_k \sim 0.01$ for the production of radio jets in radiatively efficient radio-loud AGN and by adopting this value for all radio sources. However, it is not clear whether such a low value for ϵ_k is appropriate for radiatively inefficient AGN, which may channel most of the accretion power into jets (Blandford & Begelman 1999).

How do our results fit in the emergent scenario, in which jet heating plays a major role in the evolution of early-type galaxies and galaxy clusters? The energy released by the formation of a supermassive BHs is two orders of magnitude larger than the host galaxy's binding energy, so the issue is not the energy but the efficiency with which it can absorbed by the ambient gas. Photoionization of the inner orbitals of metals and Compton scattering are the main processes by which AGN radiation heats the surrounding gas. In nearby massive elliptical galaxies such as the systems studied by Allen et al. (2006), the gas on a galactic and group or cluster scale is hot and highly transparent, having $n_H \sim 10^{21}\,\mathrm{cm}^{-2}$. This column density is only a 100th the column density σ_T^{-1} above which the gas becomes Thomson thick (σ_T is Thomson cross-section for electron scattering), meaning that only ∼1 photon in 10^3 is scattered by an electron before leaving the galaxy. Even discounting any inefficiencies in the transfer of the photon energy to the gas in the scattering process (i.e. Compton scattering transfers $\frac{h\nu}{m_\mathrm{e}c^2} < 1$ per cent of the photon energy to a free electron per scattering event), the fraction of the luminous energy that would be absorbed by the gas if a quasar switched on in a nearby massive elliptical galaxy would be $\lesssim$0.1 per cent. Therefore, based on this argument, mechanical heating could be >10 times more important than radiative heating even if the mechanical power were 100 times smaller than the radiative power.

There is broad observational evidence that mechanical heating by jets plays an important role in solving the cooling-flow problem in galaxy clusters. The evidence that the same solution can be applied to individual galaxies is much weaker because jets may be collimated on kiloparsec scales and transport most of the energy to beyond the gaseous halo of the host galaxy. However, the bulk of the jet mechanical power is produced in low-luminosity radio sources, most of which have small radio sizes. Even in larger sources, jet–interstellar-medium interactions may also occur on subkiloparsec scales (the knots in the jets of M87 may be evidence for this). Therefore, in individual ellipticals the role of weak radio sources versus episodic quasar heating (e.g. Ciotti & Ostriker 2007) remains an open problem.

ACKNOWLEDGMENTS

AC acknowledges discussion with A. Merloni. We should also like to thank an anonymous referee for comments on the manuscript.

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