THE KINETIC LUMINOSITY FUNCTION AND THE JET PRODUCTION EFFICIENCY OF GROWING BLACK HOLES

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Abstract

We derive the kinetic luminosity function for flat spectrum radio jets, using the empirical and theoretical scaling relation between jet power and radio core luminosity. The normalization for this relation is derived from a sample of flat spectrum cores in galaxy clusters with jet-driven X-ray cavities. The total integrated jet power at \( z = 0 \) is \( W_{\text{tot}} \approx 3 \times 10^{40} \text{ ergs s}^{-1} \text{ Mpc}^{-3} \). By integrating \( W_{\text{tot}} \) over red-shift, we determine the total energy density deposited by jets as \( \epsilon_{\text{tot}} \approx 2 \times 10^{38} \text{ ergs Mpc}^{-3} \). Both \( W_{\text{tot}} \) and \( \epsilon_{\text{tot}} \) are dominated by low luminosity sources. Comparing \( \epsilon_{\text{tot}} \) to the local black hole mass density \( \rho_{\text{BH}} \) gives an average jet production efficiency of \( \epsilon_{\text{jet}} = \epsilon_{\text{tot}}/\rho_{\text{BH}}c^2 \approx 3\% \). Since black hole mass is accreted mainly during high luminosity states, \( \epsilon_{\text{jet}} \) is likely much higher during low luminosity states.

Subject headings: galaxies: jets — black hole physics — accretion

1. INTRODUCTION

The \( M - \sigma \) relation between black hole mass and the velocity dispersion of the host galaxy’s bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2000) shows that the growth of black holes and large scale structure is intimately linked. X-ray observations of galaxy clusters show that black holes deposit large amounts of energy into their environment in response to radiative losses of the cluster gas (e.g. Birzan et al. 2004). Finally, mechanical feedback from black holes is believed to be responsible for halting star formation in massive elliptical galaxies (Springel et al. 2005).

These arguments hinge on the unknown efficiency \( \epsilon_{\text{jet}} \), with which growing black holes convert accreted rest mass into jet power. Constraints on \( \epsilon_{\text{jet}} \) are vital for all models of black hole feedback. Efficiencies of 1% are typically assumed, but this number is derived for phases of powerful jet outbursts and velocity dispersion of the host galaxy’s bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2000). The discovery of a tight correlation between core radio and X-ray luminosity in accreting black hole X-ray binaries (Gallo et al. 2003) in low luminosity states inspired a number of theoretical investigations of how jet radio emission relates to the accretion state and rate of the black hole. In the classical model by Blandford & Koepig (1979), the flat spectrum radio synchrotron emission of a compact jet core is produced by superposition of self-absorbed synchrotron spectra, each from a different region in the jet. The model predicts a dependence of the radio luminosity \( L_{\nu} \) on jet power \( W_{\text{jet}} \) of the form \( L_{\nu} \propto W_{\text{jet}}^{17/12} \). More generally, Heinz & Sunyaev (2003) showed that any scale invariant jet model producing a powerlaw synchrotron spectrum with index \( \alpha_{\nu} \) must obey the relation \( L_{\nu} \propto W_{\text{jet}}^{(17+8\alpha_{\nu})/12} M^{-\alpha_{\nu}} \). With \( \alpha_{\nu} = 0 \) for flat spectrum jet cores, we can write

\[
W_{\text{jet}} = W_{0} \left( \frac{L_{\nu}}{L_{0}} \right)^{12/17} \quad (1)
\]

1.1. The Kinetic Luminosity Function

Given a measurement of \( L_{\nu} \), we can thus estimate a jet’s kinetic power, up to a multiplicative constant \( W_{0} \) (which we determine in §2.2). In §2 we will use this relation to construct the kinetic jet luminosity function from the observed flat spectrum radio luminosity function \( \Phi_{L}(L_{\nu}) \) (abbreviated as FSLF below). In §3 we will derive the current mean jet power per cubic Mpc and the jet production efficiency \( \epsilon_{\text{jet}} \) of black holes. Section 4 summarizes our results. Throughout the paper we will use concordance cosmological parameters of \( \Omega_{M} = 0.3, \Omega_{\Lambda} = 0.7, H_{0} = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. THE AGN-JET KINETIC LUMINOSITY FUNCTION

As pointed out in Merloni (2004) and Heinz et al. (2004), we can use eq. 1 and the observed FSLF to derive the underlying kinetic luminosity function \( \Phi_{W}(W) \) of flat spectrum jets:

\[
\Phi_{W}(W) = \Phi_{L}(L_{\nu}(W)) \frac{dL_{\nu}}{dW} = \Phi_{L} \left( \frac{W}{W_{0}} \right)^{17/12} \frac{17}{12} \frac{L_{0}}{W_{0}} \left( \frac{W}{W_{0}} \right)^{28/17} \quad (2)
\]

We will follow Dunlop & Peacock (1990, DP90) in using a broken powerlaw to describe \( \Phi_{L}(L_{\nu}) \):

\[
\Phi_{L}(L_{\nu}) = \rho_{0}(z) \left( \frac{L_{\nu}}{L_{c}(z)} \right)^{a_{1}} + \left( \frac{L_{\nu}}{L_{c}(z)} \right)^{a_{2}} \quad (3)
\]

From DP90, we adopt \( a_{1} = 1.85 \) and \( a_{2} = 3 \). \( a_{1} \) is well determined at low \( z \), but at higher \( z \), the flux limit of the DP90 sample approaches \( L_{c} \) and an accurate determination of \( a_{1} \) is not possible anymore. In fact, within the anti-hierarchical scenario for SMBH growth (e.g. Merloni 2004) a change in slope at high redshifts is expected, as more powerful black holes were more common at high redshift, as indeed observed in X-ray and optically selected AGN samples (Hopkins et al. 2006). For lack of better information, we will assume a constant \( a_{1} \) below. It is reasonable and, in fact, necessary that \( \Phi_{L} \) has a low-luminosity cutoff at some minimum luminosity \( L_{\text{min}} \) (see §2.2).

The red-shift dependence of \( L_{c} \) and \( \rho_{0}(z) \) varies with cosmology. DP90 adopted a \( \Omega_{m} = 1, \Omega_{\Lambda} = 0 \) cosmology with \( H_{0} = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \), which gave \( L_{c}(1,0,50) = 6.7 \times 10^{32} \text{ ergs Hz}^{-1} \text{ s}^{-1} \times 10^{2.35[1-(1+z)^{-1}]^{37}} \). DP90 param-
eterized $\rho_0(z)$ as $\rho_0(1.0, 50) = 0.43 \, \text{Mpc}^{-3} \times 10^5 \Sigma_i (c_{\text{min}}(0.12)^{5})$ with $c_{\text{min}} = \{-7.87, -5.74, 93.06, -738.9, 2248, -2399\}$.

2.1. Correcting for relativistic boosting

Since jets are relativistic, the observed FSLF is affected by Doppler boosting. The Doppler-correction of luminosity functions has been discussed in a number of publications, most notably Urry & Shaffer (1984), Urry & Padovani (1991). Following these authors, we will neglect the contribution from the receding jet. The error introduced by this approximation is small compared to the other sources of uncertainty. The Doppler factor for a jet with Lorentz factor $\Gamma = \sqrt{1/(1-\beta^2)}$, velocity $\beta = v/c$ and viewing angle $\theta_{\text{LOS}}$ is then given by $\delta = 1/\Gamma (1-\beta \cos (\theta_{\text{LOS}}))$, with a maximum of $\delta_{\text{max}} = \sqrt{1+\beta}/(1-\beta)$. The jet luminosity for a flat spectrum source is then boosted by a factor $\delta^2$.

Without knowledge of the underlying jet four-velocity distribution, exact Doppler correction is impossible. However, for sensible distributions that show a clear peak at some $\Gamma_{\text{mean}}$, it is sufficient to approximate the distribution as a delta function, allowing decomposition. We will assume that the velocity distribution is well behaved in such a way.

A rest-frame (i.e., intrinsic) FSLF of the form of eq. (3), subject to Doppler boosting, will still be observed as a broken powerlaw with the same indices, but with an additional powerlaw regime with slope of $-3/2$ (Urry & Shaffer 1984). At low $z$, the low luminosity slope of the observed FSLF is well determined to be steeper than $-3/2$, indicating that the $-3/2$ Doppler tail must lie at luminosities below the DP90 flux limit. There are indications of a turnover to $-3/2$ slope at luminosities below $L_{\text{min}} = 10^{27} \, \text{ergs Hz}^{-1} \, \text{s}^{-1}$ in the low red-shift, low luminosity sample of (Nagar et al. 2005, NFW), indicating that the rest frame FSLF becomes shallower than $-3/2$ below $L_{\text{min}} = L_{\text{noobs}}/\delta_{\text{max}}^2$. At high $z$, $a_1$ is not well enough determined to draw this conclusion.

Following Urry & Shaffer (1984), the rest frame (i.e., Doppler corrected) FSLF must be of the form of eq. (3), with the observed break luminosity $L_{\text{obs}}$ and the low-luminosity cutoff/turnover $L_{\text{obs}}$ each Doppler boosted by a factor $(\delta_{\text{max}})^2$ and the normalization corrected by a factor

$$\Delta = \frac{\Gamma^2-2a_1}{2} \left[ (1-\beta)^{2-2a_1} - 1 \right] \beta^{(2a_1-3)}.$$

2.2. Estimating the kinetic power normalization $W_0$

To estimate the normalization $W_0$ of the radio—jet-power relation in eq. (1), Heinz et al. (2004) and Heinz & Grinn (2005) used information from three well studied radio galaxies, M87, Cygnus A, and Perseus A, for which estimates of the kinetic power from large scales (and kpc jet-scales in the case of M87) exist, along with measured flat spectrum fluxes for the jet core.

Given the recent X-ray surveys of galaxy clusters with central radio sources (Birzan et al. 2004, Allen et al. 2000), a more sophisticated estimate of $W_0$ is now possible. Taking all radio sources with robust kinetic power estimates based on X-ray cavities and with observed nuclear flat spectrum fluxes, we composed a sample of 15 sources. Whenever more than one measurement of the jet kinetic power was available we have taken the logarithmic average of the available data. Fig. 1 plots the core flux against the kinetic power for the 13 sources considered. Other estimators for jet power are available in the literature (e.g. Willott et al. 1998), based on total steep spectrum radio power. Since, unlike cavity based measurements of $W$, these estimates are rather model dependent, we will not employ them here.

Eq. (1) predicts that the two quantities $W_0$ and $L_\nu$ should be related by a power-law with index 12/17. To derive the constant of proportionality $W_0$ we performed a least-squares fit to the data in Fig. 1 fixing the slope at 12/17. The best fit for $W_0$ is shown as a thick solid line, along with two lines for the 1-sigma uncertainty derived from the scatter in the plot. Arbitrarily fixing $L_0$ at

$$L_{0, \text{obs}} = 7 \times 10^{29} \, \text{ergs Hz}^{-1} \, \text{s}^{-1} \tag{5}$$

and introducing the parameter $w_{44} = W_0/10^{44} \, \text{ergs s}^{-1}$ for convenience, the best fit for $W_0$ is

$$W_0 = 1^{+1.3}_{-0.6} \times 10^{44} \, \text{ergs s}^{-1} \equiv w_{44} \times 10^{44} \, \text{ergs s}^{-1} \tag{6}$$

The observed core luminosity $L_{0, \text{obs}}$ must be corrected for Doppler boosting. For an unbiased sample of sources, the core luminosity will, on average, be de-boosted by a factor $\delta_{60}^2 = 4/(\Gamma^2(2-\beta^2))$, corresponding to an average viewing angle of 60$^\circ$. However, we cannot assess what selection biases affect the sample of sources contributing to this estimate (e.g., X-ray sensitivity to detect jet–induced cavities selects against beamed sources, Enßlin & Heinz 2002). We will write $L_0 = L_{0, \text{obs}}/\delta_{60}^2$ with the implicit understanding that $\delta_{60}$ subsumes the unknown effects of any line-of-sight bias in the sample from Fig. 1.

After taking all corrections into account, the un-boosted kinetic luminosity function is

$$\Phi_W = \frac{17}{{\rho_{0, \text{obs}}}} \frac{12W_c\Delta_\delta_{\text{max}}^{2a_1}}{(W/W_c)^{17a_1-3} + (W/W_c)^{17a_1+3}} \tag{7}$$

where we defined the critical power $W_c$ as

$$W_c = W_0 \left( \frac{L_{0, \text{obs}}\delta_{60}^2}{L_{0, \text{obs}}\delta_{\text{max}}^2} \right)^{12} \tag{8}$$

$\Phi_W$ has a low luminosity slope of $\Phi(W) \propto W^{(5-17a_1)/12}$. This implies that the total integrated kinetic power is dominated by the lowest power sources for values of $a_1$ steeper than $a_1 > 29/17 \sim 1.7$. Given that DP90 measured $a_1 \approx$...
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1.85, the luminosity function must have a break or cutoff at some \( L_{\text{min}} \) somewhere below the flux limit of DP90 (possibly given by the value of \( L_{\text{min,obs}} \) indicated by NFW), since otherwise the total kinetic luminosity would diverge.

3. DISCUSSION

The total power released by jets from all sources under the FSLF (i.e., all black holes except those contributing to the observed steep–spectrnum luminosity function, abbreviated as SSLF), per comoving Mpc\(^3\), is simply the first moment of the kinetic luminosity function:

\[
W_{\text{tot}}(z) = \frac{17\rho_{0,\text{obs}}(z) W_c}{12 \Delta \delta_{\text{max}}^{a_1}} \int_{x_0}^\infty dx \frac{dx}{x^{2(a_1-1)} + x^{2(a_2-1)}}
\]

where \( x_0 \equiv (L_{\text{min,obs}}(z)/L_{c,\text{obs}}(z))^{\frac{3}{2}} \). For \( L_{\text{min}} \approx 10^{27} \text{ergs} \text{s}^{-1} \) (NFW), this yields

\[
W_{\text{tot}}(z = 0) \approx 2.8 \times 10^{40} \text{ergs} \text{s}^{-1} \text{Mpc}^{-3} \mathcal{D} w_{44}
\]

where \( \mathcal{D} \equiv \frac{\delta_{60}}{\delta_{\text{max}}^{a_2}} \approx \frac{1}{\Delta \delta_{\text{max}}^{a_1}} \)

This is the estimated total power released per Mpc\(^3\) by flat spectrum jets today. The main sources of uncertainty in \( W_{\text{tot}} \) are \( W_0, a_1, \Gamma_{\text{mean}}, \) and, for large values of \( a_1 \), the estimate of \( L_{\text{min}} \). Fig. 2 shows \( W_{\text{tot}}/w_{44} \) as a function of \( \Gamma_{\text{mean}} \) for different values of \( L_{\text{min}} \) and \( a_1 \).

To put this value of \( W_{\text{tot}} \) in context, it is useful to compare it to the average stellar luminosity density \( L_* \approx 2 \times 10^{41} \text{ergs} \text{s}^{-1} \text{Mpc}^{-3} \) (Ellis et al. 1996) and to the current supernova power \( L_{\text{SN}} \approx 10^{39} \text{ergs} \text{s}^{-1} \text{Mpc}^{-3} \) (Madau et al. 1998), which is well below the integrated jet power.

The estimate of \( W_{\text{tot}} \) is dominated by low luminosity sources (which is why \( L_{\text{min}} \) is critical for \( W_{\text{tot}} \)). This suggests that AGN make a much bigger contribution to feedback in regular galaxies than commonly assumed. It also implies that low luminosity AGN dominate the global kinetic energy output of black holes in a quasi-steady state, rather than short, energetic bursts of individual black holes. This picture agrees well with the concept of slow, "effervescent" feedback envisioned to be responsible for AGN heating in galaxy clusters (Begelman 2001; Churazov et al. 2002).

In order to derive the total energy density released by jets, we can integrate \( W_{\text{tot}} \) from eq. (5) over redshift, taking the proper cosmological corrections into account. We will use an upper limit of \( z_{\text{max}} = 5 \) for the redshift integral, but the results are not sensitive to the exact value of \( z_{\text{max}} \). Taking the most conservative approach by using the observed radio flux limit from DP90 as a solid upper limit on the low-luminosity cutoff \( L_{\text{min}} \), we find a lower limit of

\[
e_{\text{tot}} = \int_0^\infty dz \frac{dt}{dz} W_{\text{tot}} > 1.5 \times 10^{57} \text{ergs} \text{Mpc}^{-3} \mathcal{D} w_{44}
\]

on the total integrated jet energy density. A more realistic assumption would be to adopt the low-redshift value of \( L_{\text{min}} \) from NFW and assume the same redshift evolution for \( L_{\text{min}} \) as that of \( L_* \). This gives an estimated value of

\[
e_{\text{tot}} \approx 1.7 \times 10^{58} \text{ergs} \text{Mpc}^{-3} \mathcal{D} w_{44}
\]

Keeping \( L_{\text{min}} \) fixed at the \( z = 0 \) value from NFW at all redshifts provides a robust upper limit of \( e_{\text{tot}} < 2.5 \times 10^{58} \text{ergs} \text{Mpc}^{-3} \mathcal{D} w_{44} \).

Comparing \( e_{\text{tot}} \) to the mean cosmic black hole mass density of \( \rho_{BH} \approx 3.3 \times 10^5 M_\odot \text{Mpc}^{-3} h_7^2 \) (Yu & Tremaine 2002) finally yields the average conversion efficiency of accreted rest mass to jet power for supermassive black holes:

\[
\epsilon_{\text{jet}} = \frac{e_{\text{tot}}}{\rho_{BH} c^2} \approx 3\% \mathcal{D} w_{44}
\]

for the same assumptions that went into eq. (13). Assuming that \( L_{\text{min}}(z) \) is smaller than the survey flux limit and larger or equal to \( L_{\text{min,NFW}} \), gives limits of 0.25% \( \mathcal{D} w_{44} \), \( \epsilon_{\text{jet}} \) is negligible. This estimate of \( \epsilon_{\text{jet}} \) is broadly consistent with previous best-guess estimates of the jet conversion efficiency, typically believed to be of the order of 1% - 10%.

Note, however, that the estimate of \( \rho_{BH} \) from Yu & Tremaine (2002) includes mass accreted in all phases of black hole growth. Black holes grow predominantly through radiatively efficient accretion: The observed amount of X-ray background radiation is equivalent to about 10% of the total black hole rest mass energy measured today, implying that, for typical radiative efficiencies of order 10%, most of the accreted mass must have contributed to the production of the X-ray background in a radiatively efficient mode (Soltan 1982). Radiatively efficient accretion flows are typically radio quiet (i.e., inefficient at producing jets). Thus, the conversion efficiency during low-luminosity accretion phases must be significantly higher than the average \( \epsilon \) implied by eq. (14). Given that about 10% of AGN are radio loud, the average black hole accumulates a fraction of \( f_m = 90\% f_{90} \) of its mass during radio quiet, radiatively efficient accretion. Thus, the jet conversion efficiency \( \epsilon_{\text{jet}} \) during radio loud phases must be at least a factor of \( (1 - f_m)^{-1} \sim 10 \) larger than shown in eq. (13), of order 30%.

Efficiencies of several tens of percent are not implausible, however: If black hole spin is important in jet launching (Blandford & Znajek 1977) and if black holes accrete large amounts of angular momentum (i.e., are close to maximally rotating for a significant fraction of their life, as suggested by recent merger-tree models Volonteri et al. 2005), they can liberate up to 30% of the accreted rest mass energy by black hole spin extraction alone, implying \( \epsilon_{\text{jet}} \) of up to 42%.

Finally, we will briefly discuss the possible contribution of steep–spectrum sources to \( \epsilon_{\text{jet}} \). By definition, the FSLF
contains all black holes except those included in the SSLF (which are dominated by optically thin synchrotron emission). The scaling relation from eq. (1) does not hold for steep-spectrum sources. We can, however, derive an upper limit on the contribution from steep spectrum sources. Assuming a typical optically thin synchrotron spectral index of 0.65, any underlying flat spectrum component would have to fall below 20% of the observed 5GHz luminosity, otherwise the source would become too flat to qualify as a steep-spectrum source. Using the SSLF from DP90, the same redshift integral that yielded eq. (12) provides an upper limit on the contribution from the flat spectrum sources underneath the SSLF of \( \epsilon_{\text{steep}} < 6\% \, D \, w_{44} \), where \( D \) is the Doppler correction for the steeper spectral index. Since the SSLF is shallow at low luminosities, \( \epsilon_{\text{steep}} \) is dominated by sources around \( L_c \) and not affect by the uncertainty in \( L_{\text{min}} \).

4. SUMMARY

Starting from the relation between kinetic jet power and flat spectrum core radio luminosity, we derived the kinetic luminosity function of flat spectrum radio sources. We found that the kinetic luminosity density is dominated by the lowest luminosity sources, indicating that constant, low level effervescent type heating is important in black hole feedback. Integrating the kinetic luminosity density over redshift and comparing it to the estimate of the current black hole mass density showed that the efficiency of jet production by black holes is of the order of a few percent and smaller than 10%. However, since most of the power comes from low luminosity sources, which are not believed to contribute much to the total mass accretion of the black hole, the efficiency of jet production during low luminosity, jet-driven phases must be significantly higher.

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