Black Holes from Stars to Galaxies – Across the Range of Masses
Proceedings IAU Symposium No. 238, 2006
V. Karas & G. Matt, eds.

doi:10.1017/S174392130700470X

Cosmological evolution of the AGN kinetic luminosity function

Andrea Merloni[1] **and Sebastian Heinz**[2]

[1] Max Planck Institut für Astrophysik, Garching, Germany
[2] Department of Astronomy, University of Wisconsin, Madison, WI, USA
email: am@mpa-garching.mpg.de, heinzs@astro.wisc.edu

Abstract. We present a first attempt to derive the cosmological evolution of the kinetic luminosity function of AGN based on the joint evolution of the flat spectrum radio and hard X-ray selected AGN luminosity functions. An empirical correlation between jet power and radio core luminosity is found, which is consistent with the theoretical assumption that, below a certain Eddington ratio, SMBH accrete in a radiatively inefficient way, while most of the energy output is in the form of kinetic energy.

We show how the redshift evolution of the kinetic power density from such a low-$\dot{m}$ mode of accretion makes it a good candidate to explain the so-called "radio mode" of AGN feedback as outlined in many galaxy formation schemes.

Keywords. black hole physics – galaxies: active – galaxies: jets

1. Introduction: the radio mode of AGN

Supermassive black holes in the nuclei of many nearby bulges are fundamental constituents of their parent galaxies. The observed correlations between black hole mass and large scale bulge properties (Marconi & Hunt 2003, and references therein) suggest there must have been an epoch in which the central black hole had a direct impact on the galaxy's structure. Recent sustained theoretical efforts have indeed identified the period of most rapid black hole growth as the most likely epoch when such an impact was more dramatically felt. As it is now well established that most of this growth is to be identified with episodes of accretion, when galactic nuclei become "active" (Yu and Tremaine 2002; Marconi *et al.* 2004), AGN feedback is regarded as a necessary ingredient in all models of galaxy formation and evolution.

In particular, numerical simulations of merging galaxies with SMBH growth and radiative feedback (Di Matteo *et al.* 2005) demonstrated the effectiveness of quasars in quenching subsequent episodes of star formation. However, semi-analytic schemes of galaxy formation (Croton *et al.* 2006; Bower *et al.* 2006) as well as indirect evidence of AGN-induced heating in clusters of galaxies both seem to indicate that a different mode of accretion onto SMBH, not directly linked to bright quasar phases (and therefore termed "radio mode") must be effective in the most massive system at late times in order not to over-predict the observed abundances of high mass galaxies as well as to explain the absence of vigorous cooling flows in the center of clusters.

2. A simple scaling for the jet kinetic energy

A mode of AGN feedback dominated by kinetic energy is in fact expected on theoretical grounds (Rees *et al.* 1982) in black holes of low luminosity (in units of the Eddington one $L_{\rm Edd} = 1.3 \times 10^{38} M/M_{\odot}$ erg s^{-1}). Observational evidence for such "jet dominated" modes of accretion come from either black holes of stellar mass in the so-called low/hard or quiescent states (Fender, Gallo & Jonker 2003; Gallo *et al.* 2006) and low-luminosity AGN (Merloni, Heinz and Di Matteo 2003 (MHD03); Falcke, Körding & Markoff 2004). In both cases, the observed correlation between the (unresolved) radio luminosity of the jet core and its X-ray luminosity can be interpreted as a by-product of the coupling between a radiatively inefficient accretion flow and a self-absorbed (quasi-conical) jet, provided that the kinetic luminosity of the jet obeys $L_{\rm kin} \propto \dot{M}_{\rm out} c^2$, where $\dot{M}_{\rm out}$ is the accretion rate at the outer boundary of the accretion flow, roughly coincident with the Bondi radius in the case of AGN. The constant of proportionality in the above relationship cannot be directly inferred from the observed radio-X-ray correlations, but has to be determined by direct measurements of jet kinetic energy. On the basis of a very sparse collection of measurements of this sort, Heinz and Grimm (2005) originally proposed the following scaling:

$$L_{\rm kin} = 6 \times 10^{37} (L_{\rm R}/10^{30})^{0.7} {\rm erg/s}, \tag{2.1}$$

where $L_{\rm R}$ is the radio luminosity of the core at 5 GHz measured in ergs $\rm s^{-1}$. In fact, it can be shown that such a normalization corresponds to an extreme case in which essentially all accretion power $\eta \dot{M}_{\rm out} c^2$, for $\eta \simeq 0.1$, is released as kinetic energy, on the basis of the observed "fundamental plane" relation of MHD03.

One way to test the above relation is to look for alternative, indirect ways to estimate the kinetic power of the AGN jet. This has been done recently by Allen *et al.* (2006) and Rafferty *et al.* (2006) by measuring PdV work done by the jet on the intracluster gas. In Figure 1 we show these observational data points, together with a few estimates of kinetic power from direct modeling of the radio lobe emission (stars) plotted as a function of the radio core luminosity, either measured directly or, preferentially, from the black hole mass and 2–10 keV nuclear luminosity and the MHD03 relation (see Heinz & Grimm 2005 for references). In the same figure we also plot relation (2.1). Indeed, the observational points do not scatter too far away from the predicted relation, even more so if one considers that the kinetic power measurements from X-ray cavities (circles and squares), although averages, are most likely lower limit to the intrinsic jet power, due to the additional presence of weak shocks and low-contrast cavities (Nulsen 2006).

3. The kinetic luminosity evolution

With the aid of eq. (2.1), we are now in the position to attempt a measurement of the kinetic luminosity function of AGN. First, we need to derive the intrinsic 5GHz jet core luminosity function of AGN. This can be done by analytically de-beaming the observed luminosity function of flat spectrum radio quasars and blazars (dominated by relativistically beamed sources), via the formalism described in detail in Urry and Padovani (1991). The analysis is greatly simplified if a narrow distribution of Lorentz factor is assumed for the jets, and, for the sake of simplicity, we assume this holds true here.

One can then use the technique developed in Merloni (2004) to unveil the accretion history of SMBH based on the combined evolution of the hard X-ray and radio cores luminosity function coupled with the fundamental plane relationship. Here, differently from Merloni (2004), we adopt an intrinsic radio core luminosity function evolution, based on the observed FSRQ/Blazar luminosity function of De Zotti *et al.* (2005), to which we added local constraints on the faint-end slope from Filho, Barthel & Ho (2006). We adopt the scaling (2.1) for all sources accreting below a critical Eddington fraction, that we have fixed at about 3% (see Merloni 2004). Such objects, by construction, will lie on the fundamental plane of black hole activity and represent the majority of radio sources

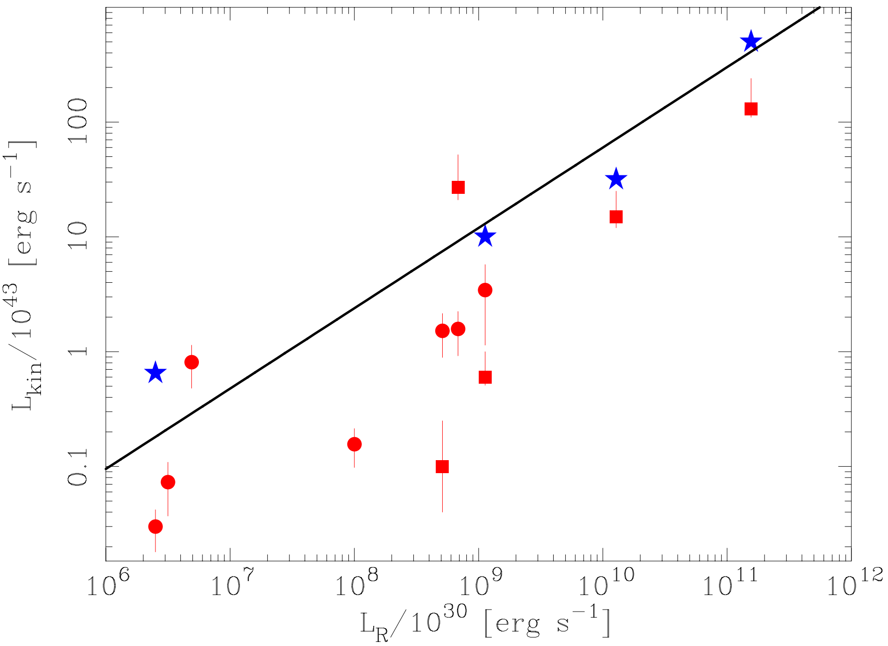


Figure 1. Estimated jet kinetic luminosity as a function of the 5GHz core radio luminosity. Stars represent direct kinetic energy estimates based on radio lobe modeling for NGC 4636, M87, Per A and Cyg A, in order of increasing power. Filled circles are the kinetic energy estimates from Allen *et al.* (2006), filled squares those from Rafferty *et al.* (2006). The solid line is the theoretical scaling $L_{\rm Kin} = 6 \times 10^{37} (L_{\rm R}/10^{30})^{0.7}$.

below the FRI/FRII divide. We assume here that only a small fraction of the accreting matter (powering the jet) makes its way onto the central black holes, i.e. we assume that black holes are always radiatively efficient (*with respect to the accreted gas*, rather than to the liberated energy; see the discussion in Gallo *et al.* 2006). For object whose accretion rate is above 3%, we assume that the vast majority (90%) are radio quiet and radiatively efficient (with $\epsilon_{\rm rad} = \eta = 0.1$), while for the remaining 10% the liberated energy is equally divided into radiative and kinetic. Those powerful radio loud quasar dominate the high end of the radio luminosity function (FR II). It is worth noticing here that the above recipe to include powerful radio sources is highly arbitrary, pending a more complete knowledge of the physical nature of powerful radio loud quasars. Therefore, all our conclusions regarding the evolution of this class of sources, and of their kinetic energy output, should be considered as indicative only.

Given such a recipe for the accretion modes (or, equivalently, for the radiative and kinetic efficiencies as functions of $\dot{m}$), the local SMBH mass function is evolved backwards in time according to the corresponding accretion rate distribution, and the procedure is reiterated until acceptable fits to the observed hard X-ray and radio core luminosity functions are found.

Figure 2 shows, on the left panel, the evolution of the computed kinetic luminosity function of AGN at four different redshifts. By integrating these luminosity functions one can obtain the redshift evolution of the kinetic energy density, $\rho_{\rm kin}$, provided by SMBH. This is shown in the right panel of fig. 2. Here the uncertainties in $\rho_{\rm kin}$ include not only the jets' Lorentz factor distribution, but also uncertainties on the faint end slope of the radio core luminosity function. The redshift evolution of $\rho_{\rm kin}$ differs substantially from that of the accretion rate (BHAR) density, strongly resembling instead the required

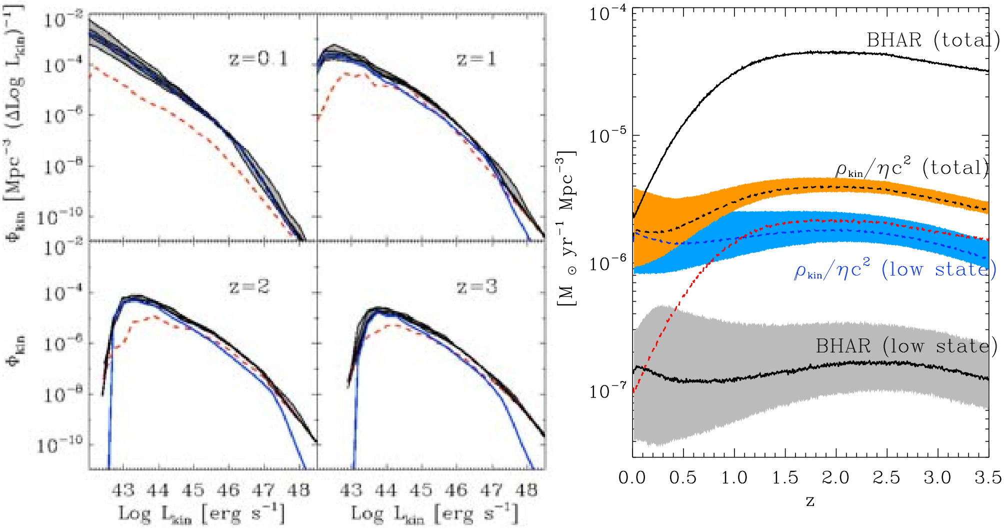


Figure 2. Left panel: total kinetic luminosity function (solid lines) at various redshifts as the sum of low- and high-$\dot{m}$ modes (solid blue and dashed red, respectively). The shaded areas highlight the uncertainties due to variation of the average jets' Lorenz factors ($2 < \Gamma < 10$, black solid line corresponds to $\Gamma = 5$). The low luminosity downturns are due to incompleteness in the high-redshift radio and X-ray luminosity functions adopted here. Right panel: redshift evolution of the kinetic energy density mass equivalent (calculated assuming a energy conversion efficiency of $\eta = 0.1$; black dashed line, orange shaded area), decomposed into the sum of the low- (blue dashed line, cyan shaded area) and high-$\dot{m}$ (red dashed line) modes, and compared with the mass accretion rate onto the black holes (black solid lines).

"radio mode" evolution of galaxy formation models (Croton *et al.* 2006; Bower *et al.* 2006). A more detailed study of these results is underway and will be presented elsewhere (Heinz *et al.*, Merloni *et al.*, in preparation).

4. Conclusions

A separate mode of SMBH growth in which most of the energy is released in kinetic form is postulated both on theoretical grounds and from very general arguments of galaxy formation theory. Here we have discussed how direct observational evidence of such a mode emerging from recent studies of X-ray binary black holes can be generalized to the case of SMBH, when the accretion rate (in Eddington units) is low (less than a few percent).

We have then presented a scaling that provides a simple method to estimate the kinetic energy output of black holes growing at sub-Eddington rates. Using such a scaling, we have derived the kinetic luminosity function of AGN and its redshift evolution. Overall, we show conclusively that the kinetic power output of the low-$\dot{m}$ mode of SMBH growth has a very different redshift dependency from the radiative one, and matches the phenomenological requirements put forward by semi-analytic schemes of galaxy formation: it is in fact more effective at late times (and for the more massive systems).

Our results suggest that the so-called "radio mode" of AGN feedback is simply a jet-dominated *accretion mode*, and that its physical and evolutionary properties are dictated by the physics of accretion in the vicinity of the SMBH.

References

Allen S. W., Dunn R. J. H., Fabian A. C., Taylor G. B. & Reynolds C. S. 2006, MNRAS, 372, 21

Bower R., Benson A. J., Malbon R., Helly J. C., Frenk C. S., Baugh C. M., Cole S. & Lacey C. G. 2006, MNRAS, 370, 645

Croton D. J., Springel V., White S. D. M., De Lucia G., Frenk C. S. & Gao L. *et al.* 2006, MNRAS, 365, 11

De Zotti G., Ricci R., Mesa D., Silva L., Mazzotta P., Toffolatti L. & González-Nuevo J. 2005, A&A, 431, 893

Di Matteo T., Springel L. & Hernquist L. 2005, Nature, 433, 604

Falcke H., Körding E. & Markoff S. 2004, A&A, 414, 895

Fender R. P., Gallo E. & Jonker P. 2003, MNRAS (Letters), 343, L99

Filho M. E., Barthel P. D. & Ho L. C. 2006, A&A, 451, 71

Gallo E., Fender R. P., Miller-Jones J. C. A., Merloni A., Jonker P. G. & Heinz S. *et al.* 2006, MNRAS, 370, 1351

Heinz S., Grimm H.-J. 2005, ApJ, 633, 384

Marconi A., Hunt L. K. 2003, ApJL 589, L21

Marconi A., Risaliti G., Gilli R., Hunt L. K., Maiolino R. & Salvati M. 2004, MNRAS, 351, 169

Merloni A., Heinz S. & Di Matteo T. 2003, MNRAS, 345, 1057 (MHD03)

Nulsen P. E. J. 2006, Proceedings of “Heating and Cooling in Clusters of Galaxies”, H. Boehringer, P. Schuecker, G. W. Pratt, A. Finoguenov (eds.)

Rafferty D. A., Mc Namara B. R., Nulsen P. E. J. & Wise M. W. 2006, ApJ, astro-ph/0605323

Rees M. J., Begelman M. C., Blandford R. D. & Phinney E. S. 1982, Nature, 295, 17

Urry M., Padovani P. 1991, ApJ, 371, 60

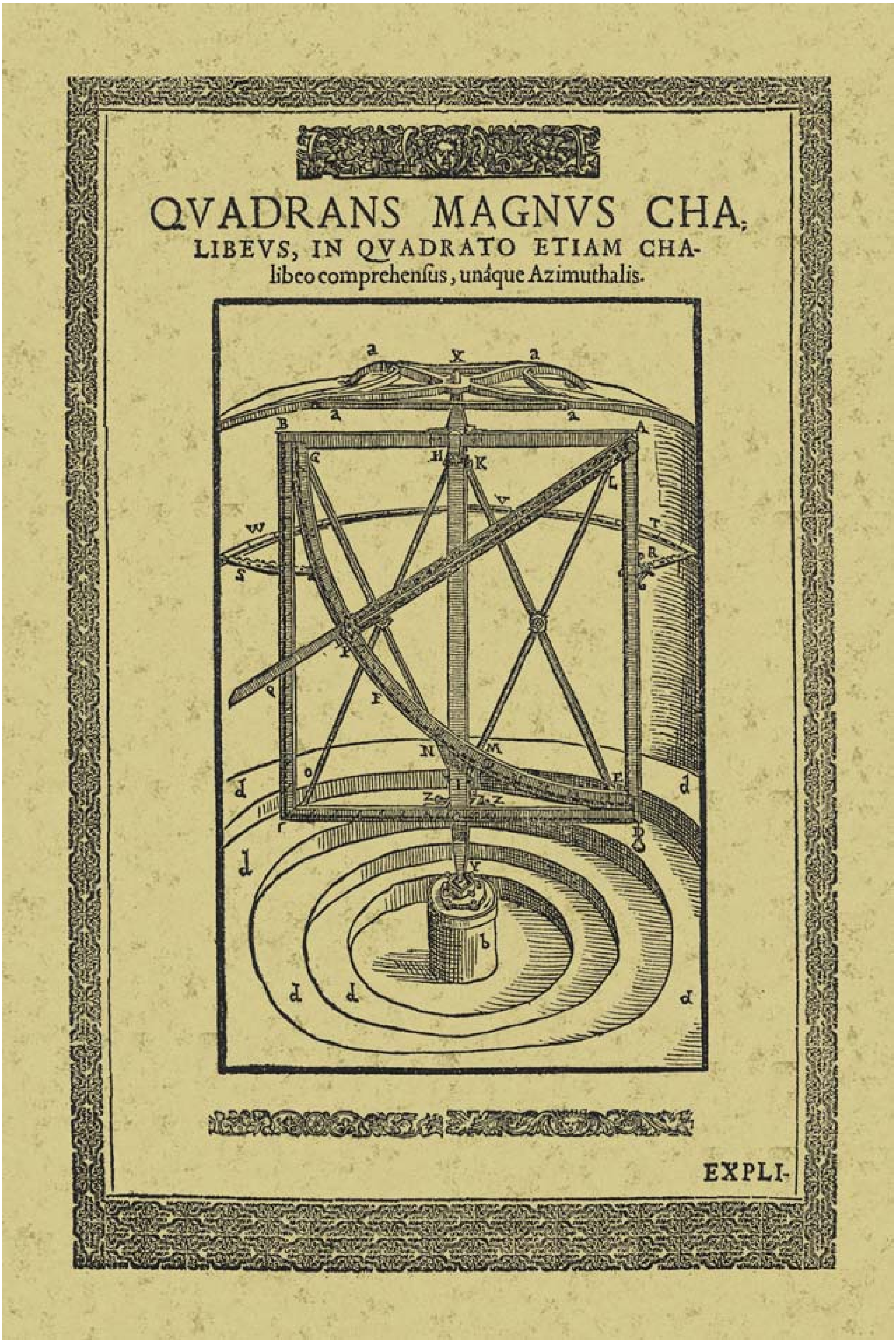
Yu Q., Tremaine S. 2002, MNRAS, 335, 965

Günther Hasinger: There is a upper limit to the kinetic feedback given by the efficiency of the black hole accretion. Since radiation is already at the level of 10% (see my talk), kinetic energy can not be much higher then that.

Andrea Merloni: Indeed, taking into account the average accretion efficiency of the evolving supermassive black hole population, the results I presented here would suggest that the efficiency with which the rest-mass energy of the black hole is used to power the kinetic feedback does not exceed ~ 1.6–2%.

Felix Mirabel: Where in your picture stand the high soft state sources?

Andrea Merloni: If one wishes to push the analogy between AGN and X-ray binaries one step forward, one should take into account the complex phenomenology of bright (near-Eddington) stellar-mass accretors. In particular, we know that they can launch powerful relativistic jets episodically, and they can even launch strong winds. This occurs predominantly in the so-called very high state. Such a transient phase is probably related to violent disc instabilities close to the Eddington rate and it might be the origin of radio loud quasars.



QVADRANS MAGNVS CHALIBEVS,
IN QVADRATO ETIAM CHALIBEO
comprehenſus, unáque Azimuthalis.

EXPLI-