A fundamental plane of black hole activity: pushing forward the unification scheme

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Abstract. We examine the disc–jet connection in stellar mass and supermassive black holes by investigating the properties of their compact emission in the hard X-ray and radio bands. We compile a sample of \( \sim 100 \) active galactic nuclei with measured mass, 5 GHz core emission, and 2-10 keV luminosity, together with 8 galactic black holes with a total of \( \sim 50 \) simultaneous observations in the radio and X-ray bands. Using this sample, we study the correlations between the radio (\( L_R \)) and the X-ray (\( L_X \)) luminosity and the black hole mass (\( M \)). We find that the radio luminosity is correlated with both \( M \) and \( L_X \), at a highly significant level. We show how this result can be used to extend the standard unification by orientation scheme to encompass unification by mass and accretion rate.

1. Introduction: unified pictures

Some galaxies are known to emit radiation with extremely high luminosities in the \( \gamma \)-ray, X-ray, UV and radio continuum from a very concentrated volume in the nuclear region. Such active cores are the so-called Active Galactic Nuclei (AGN) and their radiation is believed to be produced by accretion onto a supermassive black hole.

The intrinsically complex nature of such systems and the differences in the terminology among different scientific communities (radio, optical, X-ray astronomers) has led to an extremely complicated nomenclature for the AGN zoo. As the wealth of observations piled up, and with them the number of different AGN types, the opposite enterprise of finding unification schemes has progressively gained support. The basic idea behind the standard unification scheme is that AGN are asymmetric and anisotropic systems. This is natural, as all rotating systems necessarily single out a preferential axis in space and break the full spherical symmetry of non-rotating bodies. Therefore, the orientation of the AGN rotation axis with respect to our line of sight becomes another important parameter that can cause apparent
observational differences in two sources that are intrinsically identical (unification by orientation).

According to the current widely accepted paradigm (Urry and Padovani 1995), there are two principal causes of anisotropic radiation: obscuration and relativistic beaming. The former is usually associated with a torus of gas and dust obscuring the optical, UV and (sometimes) soft X-ray radiation along some line of sights, the latter with outflows of energetic particles (jets) along the symmetry axis: the high velocity plasma in the jet beams radiation relativistically in the forward direction. The powerful source of radiation and the launching site of the collimated jet lies in the center of the system.

Observationally, jet morphologies and spectral properties of both radio and X-ray cores are remarkably similar in the case of black holes of stellar mass (Galactic black holes, hereafter GBH) and of their supermassive counterparts in the nuclei of galaxies (hereafter SMBH). If jets are launched in the innermost parts of the accretion flows, as commonly assumed, then these similarities suggest that it should be possible to extend the unification scheme further and to understand the physics of both black hole accretion and jet production by studying all those systems as a single class (unification by mass). Furthermore, the recent discovery that SMBH lie at the center of the majority (possibly all) galactic nuclei, even in apparently inactive ones (Kormendy and Richstone 1995; Magorrian et al. 1998), naturally leads to the idea that a grand unification is possible by taking into account the differences in fueling rates among different objects (unification by accretion rate).

In the following, we will show how to proceed quantitatively towards a grand unification of active black holes by studying the multivariate correlation among masses, radio luminosities and hard X-ray luminosities of objects traditionally classified in the more diverse ways. The underlying theoretical assumption is that both accretion and jet production are fundamental manifestation of black hole activity, and are somehow physically connected (Begelman et al. 1984; Rawlings and Saunders 1991; Falcke and Biermann 1995; Heinz and Sunyaev 2003).

2. Unification by mass and accretion rate

Here we briefly describe the main results of the correlation analysis carried on in Merloni, Heinz and Di Matteo (2003, hereafter MHD03). A more detailed description of the sample used, of the selection effects and of the statistical analysis can be found there, together with a comprehensive list of references to the observational data. For future reference, we define the dimensionless black hole mass $M = M_{\text{BH}}/M_\odot$.
Figure 1. Radio core luminosity at 5 GHz versus black hole mass of SMBH only. Upper limits are marked with arrows, different symbols indicate objects belonging to different spectral classes. The dot-dashed line gives the regression fit proposed by Franceschini et al. (1998), the dashed line that proposed by Nagar et al. (2002), both obtained using different samples of SMBH only. The thick solid upper line gives the maximum core radio power as calculated by Ho (2002) for sources accreting at the Eddington rate.

and accretion rate $\dot{m} \equiv (L_{\text{bol}}/\epsilon)/L_{\text{Edd}} = \dot{M}c^2/L_{\text{Edd}} \propto \dot{M}/M$, where $\epsilon$ is the accretion efficiency.

We have selected from the existing literature a sample of black hole-powered systems with measured masses, the nuclei of which have been observed both at 5 GHz (mostly with arcsecond resolution with the VLA) and in the 2-10 keV band. The main obvious advantage of this choice lies in the fact that obscuration is unimportant, or easily accounted for, in these spectral bands.

We first considered the full sample of $\sim 40$ nearby inactive, or weakly active galaxies with existing nuclear black hole mass measurements from observations of spatially resolved kinematics. To these we have added a comparable number of bright AGNs (and QSOs) with nuclear black hole mass measured from reverberation mapping of their broad line region. From this sample we selected all objects which have been observed in both the radio and X-ray bands. In order to obtain a more statistically representative sample, we also searched the existing literature for both nearby low-luminosity galactic nuclei and for relatively bright Seyfert nuclei (either type 1, type 2 or Narrow
Figure 2. Radio core luminosity at 5GHz vs. the ratio $L_X/L_{Edd}$ of X-ray to Eddington luminosity. Upper limits are marked with arrows, different symbols indicate objects belonging to different spectral classes and different colors objects in different mass bins. The color-coding of the different mass bins makes the mass segregation more evident.

Line Seyfert 1) and radio galaxies with available radio and X-ray flux measurements. We assign black hole masses to these systems using the observed correlation between black hole masses and stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese and Merritt 2000).

Relativistically beamed sources (i.e. those whose jet axis points towards our line of sight) are dominated by the boosted jet emission, and cannot be used to test the disc-jet coupling. We therefore excluded from our sample BL Lac objects. Among the Quasars in our sample, only 3C 273, which has an extremely high radio loudness and a blazar-like spectrum, is likely to suffer from strong Doppler boosting of the radio jet. On the other hand, according to the unification scheme, Seyfert 2 nuclei should not be preferentially viewed pole on, while for all the other sources (mainly low-luminosity AGN and Seyfert 1), for which the nature of the (relatively faint) radio emission is not well established, we have assumed that the orientation of their jets with respect to line of sight is randomly distributed.

The Galactic X-ray binaries included in our sample have been selected to have (a) simultaneous X-ray and radio observations, or RXTE All-Sky-Monitor (ASM) X-ray data in conjunction with radio fluxes available from the literature, and (b) publicly available RXTE-ASM
X-ray and Green-Bank Interferometer (GBI) radio lightcurves (from which we estimated the 5 GHz fluxes by interpolating between the 2.25 GHz and the 8.3 GHz channels).

The final sample consists of \(\sim 100\) active galactic nuclei with measured mass, 5 GHz core emission, and 2-10 keV luminosity, together with 8 galactic black holes with a total of \(\sim 50\) simultaneous observations in the radio and X-ray bands (see MHD03 for a full list of the sample sources).

In Figure 1 we show the radio core luminosity versus the black hole mass for objects of different spectral classes. We concentrate on the SMBH only in order to show how, at a fixed black hole mass, sources which are classically regarded as powerful accretors (QSOs, Narrow Line Seyfert 1, Seyfert 1) tend to lie above the so-called Low-Luminosity AGN (here represented by LINERs), with Seyfert 2 galaxies spanning a large area in the vertical direction. Figure 2 shows instead the core radio luminosity versus the ratio of the X-ray nuclear luminosity to the Eddington luminosity (probably a good estimator of \(\dot{m}\), see below). We represent objects in different mass bins with different colors. It is clear that, when the data points are grouped into mass bins, objects in different bins tend to lie on parallel tracks. The presence of a mass segregation suggests that the radio luminosity of an object likely depends both on its accretion rate and on its mass.

We can proceed to quantify the degree of correlation between our three observables (radio luminosity at 5 GHz, \(L_R\), X-ray luminosity in the 2-10 keV band, \(L_X\) and black hole mass). We fit the data with the function

\[
\log L_R = \xi_{RX} \log L_X + \xi_{RM} \log M + b_R,
\]

and obtain well constrained values for the correlation coefficients, meaning that, if we define the instantaneous state of activity of a black hole of mass \(M\), by the radio and hard X-ray luminosity of its compact core, and represent such an object as a point in the three-dimensional space \((\log L_R, \log L_X, \log M)\), all black holes (either of stellar mass or supermassive) will lie preferentially on a plane (the “fundamental plane” of black hole activity, see Figure 3), described by the following equation:

\[
\log L_R = (0.60^{+0.11}_{-0.11}) \log L_X + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07},
\]

with a dispersion \(\sigma_R = 0.88\) (see Figure 3).

The value we obtain for the \(\xi_{RX}\) correlation coefficient is consistent, within the errors, with that found in low/hard state GBH (\(\xi_{RX} \approx 0.7\)) by Gallo et al. (2003). This also means that individual GBH sources for which the correlation between radio and X-ray luminosities is well established (GX 339-4 and V404 Cyg) do indeed follow the same global trend defined by black holes of all masses included in our sample.
3. Scale invariance and jet dominance in black hole accretors

In a recent paper, Heinz & Sunyaev (2003) have demonstrated that, under the general assumption that the jet formation process is not qualitatively different among SMBH of different mass or between SMBH and GBH, it is in fact possible to derive a universal scaling between the jet (radio) luminosity at a given frequency and both mass and accretion rate. The derived relation is independent of the jet model and has scaling indices that depend only on the (observable) spectral slope of the synchrotron emission in the radio band ($\alpha_r$), and on the accretion model. In particular, it was shown that, if the magnetic field $B_0$ at the base of the jet is in equipartition with the particles pressure and the total jet power scales as $W_{\text{jet}} \propto B_0^2 M^2 \propto M$ (see also Falcke & Biermann 1995; Heinz et al., this proceedings), and under the standard assumption that the electrons responsible for the jet synchrotron emission follow a power-law distribution in energy, with index $p = 2$, then $L_R \propto M^{17/12-\alpha_r/3}\dot{m}^{17/12+2\alpha_r/3}$. For the optically thick, flat spectrum cores we are mostly interested in ($\alpha_r \simeq 0$), then:

$$L_R \propto (\dot{M}\dot{m})^{1.42}. \quad (2)$$
To compare this prediction with the observed fundamental plane correlation, one needs to explicate the dependence of the hard X-ray luminosity on the accretion rate, $L_X \propto \dot{m}^q$. In MHD03 it was shown how indeed the prediction of standard synchrotron theory for the radio-X-ray-mass correlation of Heinz & Sunyaev (2003) are verified if, and only if, $q \approx 2$, i.e. if the accretion process is radiatively inefficient. Detailed models for the X-ray emission from such flows do indeed show that $q = 2.3$ (MHD03), and in this case $L_{R,q=2.3} \propto \dot{m}^{1.38} M^{1.38} = \dot{M}^{1.38}$, i.e., $L_R$ scales with the physical accretion rate only. This is tantalizingly close to the predicted dependence of eq. (2), and such a result can be interpreted in the following way: 1) the scale invariance hypothesis at the heart of the Heinz and Sunyaev (2003) calculations is correct, and black holes can indeed be further unified by considering their masses and accretion rates, and 2) the largest area of the fundamental plane is covered by radiatively inefficient sources.

The total power released by the accretion/jet system may be written as $W_{\text{tot}} \simeq \dot{M}c^2 = L_{\text{bol}} + W_{\text{jet}} + W_{\text{adv,conv}}$, where the first term on the right hand side is the total radiated luminosity and the last one include contributions from the energy advected and/or stored in the convective motions. Our results suggest that the flow must be radiatively inefficient, therefore, for small enough accretion rates we have $L_{\text{bol}} \simeq \dot{M}c^2 \ll \dot{M}c^2 \sim W_{\text{jet}} + W_{\text{adv,conv}}$. On the other hand, $W_{\text{jet}} \propto W_{\text{adv,conv}} \propto \dot{M}c^2$. Therefore, the issue of what the relative fraction of the total accretion energy dissipated into the jet is (or, alternatively, of when a source is “jet dominated”; Fender, Gallo & Jonker 2003; Falcke, Körding & Markoff 2004) reduces to the determination of the value of the constant $W_{\text{jet}}/W_{\text{adv,conv}}$. This requires the specification of a jet model or the direct measure of the total kinetic power carried by the jet (see, e.g. Heinz et al. 2004), together with a dynamical model for the disc-jet coupling.

4. Accretion mode changes

It is well accepted, both from theory and observations, that accretion can proceed in different modes (or states), with different radiative efficiencies and spectral properties. By fitting the whole dataset at our disposal with a single linear relationship (1), we have implicitly neglected the possibility of a global accretion mode change. This is clearly implausible, as the QSOs and the bright Seyferts in our sample, which occupy the region of high accretion rates, are independently known to have spectral characteristics inconsistent with models of low radiative efficiency. They should therefore depart from the observed
correlations. For GBHs, it has indeed been shown that the correlation between radio and X-ray luminosity breaks down as the sources switch to their high states (Maccarone 2003; Gallo, Fender and Pooley 2003). However, because both such modes of accretion are expected to occur only above accretion rates about a few percent of Eddington, and because another advective accretion mode is expected to ensue at around the Eddington limit (due to efficient radiation trapping, see e.g. Abramowicz et al. 1995), we would expect the log $M - \log L_R - \log L_X$ correlation to break down only in a limited range of $\dot{m}$. In other words, independently on the actual number of radiatively efficient sources, the area of the fundamental plane covered by them will always be limited, and the overall orientation of the plane will always be dominated by the radiatively inefficient ones. This also means that any (statistically significant) departure from the fundamental plane relation could be used to identify different modes of accretion. In fact, Maccarone, Gallo & Fender (2003) have already shown how is possible to use the fundamental plane relation as a baseline against which identify AGN in a High/Soft State (HSS) analogous to that of X-ray binaries.

The analogy with GBH can indeed be very useful to classify and understand the properties of bright AGN. Let us consider, for example, a recent paper by Fender, Belloni and Gallo (2004), where it was shown that the intermittent, powerful radio flares from the so-called microquasars, associated with the rapid variability in the Very High State (VHS), seem to follow a similar radio-X-ray correlation as the low/hard state sources, albeit with a much larger scatter. Can we extend this result to the larger family of radio loud AGN?

In Figure 4 we plot, as a function of the ratio $L_X/L_{Edd}$, the radio luminosity divided by $M^{1.38}$ of all the sources in our sample. As expected, by rescaling the radio luminosity in such a way all the different tracks corresponding to different mass bins in Fig. 2 collapse into a single one, with some residual scatter. The region between the two vertical lines corresponds to the theoretically expected values of $L_X/L_{Edd}$ above which a change of accretion mode, from radiatively inefficient to standard radiatively efficient is expected to occur. To the left of these lines, GBH are in the low/hard state and SMBH are mostly FR I, or low-luminosity, radio loud AGN. To the right, GBH are in the Very-High state (VHS) and SMBH are mostly FR II. In between, possibly lies the restricted region of the parameter space where pure discs accretion is allowed (HSS). Interestingly, it appears as if both low and high luminosity sources at the two sides of the HSS region obey a similar scaling $W_{jet} \propto \dot{M}c^2$. 
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Figure 4. The radio luminosity log $L_R$, divided by $M^{1.38}$ as a function of the ratio $L_X/L_{Edd}$. Upper limits are marked with arrows, different symbols indicate objects belonging to different spectral classes and different colors objects in different mass bins. Two vertical lines mark the boundary of the region where we expect the critical luminosity for the mode change between radiatively inefficient and efficient accretion. To the left of these lines, GBH are in the low/hard state and SMBH are mostly FR I. To the right, GBH are in the Very-High state (VHS) and SMBH are mostly FR II. In between, possibly the restricted region of the parameter space where pure discs accretion is allowed (High/Soft State, HSS).

We may thus speculate that the famous (and still much debated) radio loud/radio quiet dichotomy of quasars will appear only at the highest values of $\dot{m}$, and be caused mainly by a switch of accretion mode analogous to the high/very high transition in GBH. At low accretion rates, black holes seem to follow the more regular behavior circumscribed by the fundamental plane of eq. (1). Such sources not only tend to be radio loud (Ho & Peng 2001; Ho 2002), but also their radio loudness parameter, $R_X$ (here defined as the ratio of radio to X-ray luminosity), obeys the following scaling: $R_X \equiv L_R/L_X \propto L_X^{-2/5}M^{4/5}$. Therefore, the smaller the X-ray luminosity, the more radio loud these sources are. In this regime, no dichotomy need be expected, as already suggested by Nagar et al. (2002).
We have argued that the fundamental plane analysis presented here is a powerful tool to extend the unified scheme of accreting black holes. Such a relation between mass, radio and hard X-ray luminosity is affected very little by obscuration and beaming, provided that sources whose relativistic jets are in our line of sight can be effectively identified and excluded. Thus, the fundamental plane relation does not depend on orientation, and as such is complementary to the standard unification scheme. Moreover, the relation itself is perfectly consistent with the scaling relations predicted by standard synchrotron theory under a scale invariance assumption. The main scaling parameters are the mass of the black hole and its accretion rate. Finally, we have shown how the observed correlation can be effectively used to classify objects on the basis of their mode of accretion (and/or accretion/ejection coupling) rather than just on specific observational characteristics, as in the true spirit of unification models.

References

Abramowicz, M. A., X. Chen, S. Kato, J.-P. Lasota, O. Regev, 1995, ApJ, 438, L37
Begelman, M. C., R. D. Blandford and M. J. Rees, 1984, Rev. Mod. Phys., 56, 255
Falcke, H. and P. L. Biermann, 1995, A&A, 293, 665
Falcke, H., E. Kording and S. Markoff, 2004, A&A, 414, 895
Fender, R. P., E. Gallo and P. Jonker, 2003, MNRAS, 343, L99
Fender, R. P., T. Belloni and E. Gallo, 2004, MNRAS in press, astro-ph/0409360
Franceschini, A., S. Vercellone, A. C. Fabian, 1998, MNRAS, 297, 817
Gallo, E., R. P. Fender and G. G. Pooley, 2003, MNRAS, 344, 60
Heinz, S. and R. A. Sunyaev, 2003, MNRAS, 343, L59
Heinz, S., R. A. Sunyaev, A. Merloni, T. Di Matteo, 2004, to appear in the Proceedings of “Growing Black Holes”, Garching, Germany, June 21-25, 2004. Eds. A. Merloni, S. Nayakshin and R. Sunyaev, Springer-Verlag series of “ESO Astrophysics Symposia”.
Ho, L. C., 2002, ApJ, 564, 120
Ho, L. C. and C. Y. Peng, 2001, ApJ, 555, 650
Kormendy, J. and D. Richstone, 1995, ARA&A, 33, 581
Maccarone, T., 2003, A&A, 409, 697
Maccarone, T., E. Gallo and R. P. Fender, 2003, MNRAS, 345, L19
Magorrian, J. et al., 1998, AJ, 115, 2285
Merloni, A., S. Heinz and T. Di Matteo, 2003, MNRAS, 345, 1057 (MHD03)
Nagar N. M., A. S. Wilson, H. Falcke, J. S. Ulvestad, 2002, A&A, 392, 53
Rawlings, S. and R. Saunders, 1991, Nature, 349, 138
Urry, C. M. and P. Padovani, 1995, PASP, 107, 803