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WHY THE FUNDAMENTAL PLANE OF BLACK HOLE ACTIVITY IS NOT A DISTANCE ARTIFACT

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RESUMEN

El plano fundamental de actividad en agujeros negros es una correlación no lineal entre la luminosidad nuclear en radio, la luminosidad en rayos X y la masa de los agujeros negros en acreción (tanto estelares como supermasivos). Fue identificada independientemente por Merloni, Heinz y Di Matteo (2003) y por Falcke, Körding y Markoff (2004). En este trabajo se analizan en detalle diversas cuestiones estadísticas relacionadas con esta correlación. En particular, se cuantifica el sesgo introducido por la distancia a las fuentes, y se discute el problema de seleccionar una muestra. Mostramos que la relación del plano fundamental no es sencillamente un artefacto de la distancia, y que su carácter no lineal es un indicador fiel de las propiedades intrínsecas de agujeros negros en acreción. Asimismo, discutimos maneras de mejorar nuestro entendimiento a futuro de esta correlación por medio de observaciones.

ABSTRACT

The fundamental plane of black hole activity is a non-linear correlation among radio core luminosity, X-ray luminosity and mass of all accreting black holes, both of stellar mass and supermassive, discovered by Merloni, Heinz, & Di Matteo (2003) and, independently, by Falcke, Körding, & Markoff (2004). Here we discuss with greater detail a number of statistical issues related to the above correlation. In particular, we discuss the issue of sample selection and quantify the bias introduced by the effect of distance. We demonstrate that the fundamental plane relation is not simply a distance artifact, and that its non-linear slope represents a genuine intrinsic characteristics of accreting black holes. We also discuss possible future observational strategies to improve our understanding of this correlation.

Key Words: **BLACK HOLE PHYSICS — GALAXIES: NUCLEI — X-RAYS: BINARIES**

1. INTRODUCTION

The search for statistical associations between the X-rays and radio core emission in Quasars and AGN is about as old as X-ray astronomy itself. Very early on, a number of statistical issues related to the search of correlations between radio and X-ray luminosities in actively accreting black holes was already under discussion. In fact, they stimulated the formulation and the wider recognition of a set statistical methods specifically targeted to astrophysical problems (for a discussion of distance bias in astrophysical correlation analyses, including an introduction to partial correlation analyses to address such biases, see, e.g., Feigelson & Berg 1983; Kembhavi, Feigelson, & Singh 1986; for a more comprehensive discussion of statistical methods in astrophysics, see Babu & Feigelson 1996 and references therein).

In particular, the fundamental question was raised (see e.g. Elvis et al. 1981; Feigelson & Berg 1983) of whether correlations are more accurately measured by comparing observed flux densities or intrinsic luminosities, as it is obvious that in flux limited samples spanning large ranges in redshift (i.e. distance) spurious correlations can be inferred in luminosity-luminosity plots if only detected points are considered. On the other hand, as clearly discussed in Feigelson & Berg (1983) and in Kembhavi et al. (1986), flux-flux correlations can themselves lead to spurious results, whenever there exists any non-linear intrinsic correlation between luminosities. The most statistically sound way to deal with the aforementioned biases has been formalized in terms of partial correlation analysis capable to handle censored data (upper limits), as discussed in Akritas & Siebert (1996). With such a method, not only can a correlation coefficient be calculated for

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any luminosity-luminosity relationship in flux limited samples, but also a significance level can be assigned to it.

1.1. *The fundamental plane of black hole activity*

Black holes as mathematical entities are extremely simple, being fully described by just three quantities: mass, spin and charge. For astrophysical black holes, necessarily uncharged, little is known so far about their spin distribution. However, it is well established observationally that black holes do span a wide range in masses, from the $\sim 10 M_{\odot}$ ones in X-ray Binaries (XRB) to the supermassive ($\sim 10^6 - 10^9 M_{\odot}$) ones in the nuclei of nearby galaxies and in Active Galactic Nuclei (AGN). In Merloni, Heinz, & Di Matteo (2003, hereafter MHD03), we posed the following question: is the mathematical simplicity of black holes also manifest in their observational properties? More specifically: which observed black hole characteristics do scale with mass?

To answer such a question, we searched for a common relation between X-ray luminosity, radio core luminosity and black hole masses among X-ray binaries and AGN. This necessarily imposes a set of complications for any statistical analysis. These are essentially twofold. On the one hand, as already pointed out in the original papers on the subject (MHD03; Falcke, Körding, & Markoff 2004), there is a vastly differing distance scale between the two populations that should at some level induce spurious (linear) correlations between the observed luminosities even for a *completely* random distribution of fluxes.

On the other hand, the inclusion of black hole mass in the analysis imposes a very complex selection criterion on any sample: mass can be estimated in a number of different ways, with different degrees of uncertainties, and different degrees of observational difficulty, so that it is almost impossible, at least with the current data, to estimate the degree of incompleteness of any black hole mass sample.

In what follows, it is also important to keep in mind that the original sample studied in MHD03 was *neither* a flux limited sample, *nor* a combination of flux limited samples, but rather a combination of flux and volume limited samples, observed in both X-ray and radio bands with different sensitivities (see Figure 1). For example, we considered all known Low-Luminosity AGN within 19 Mpc observed by Nagar et al. (2002) with the VLA. Upper limits were recorded as far as possible, whenever the information regarding a source with reasonably well measured/estimated black hole mass was available from radio or X-ray surveys, but no effort was

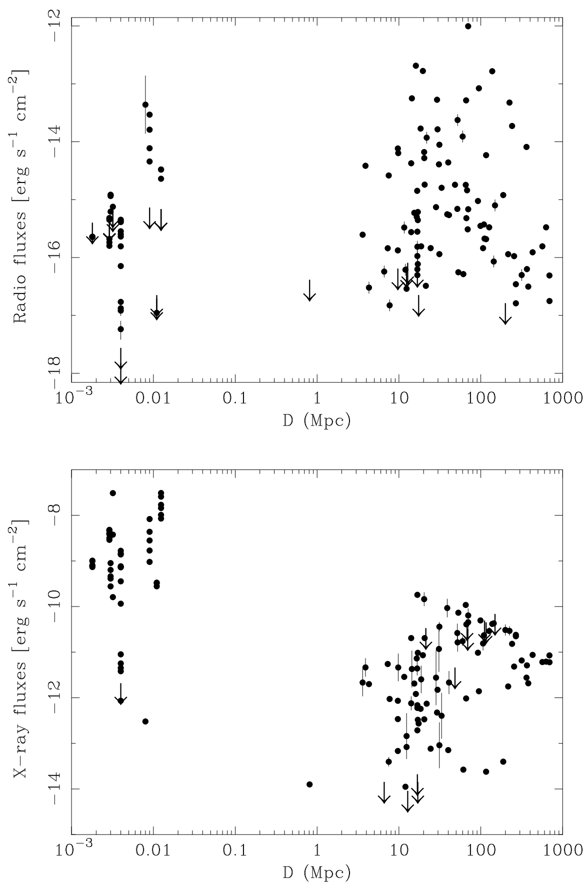

Fig. 1. Radio (upper panel) and X-ray (lower panel) fluxes for the sources in the original sample of MHD03 vs. distance (in Mpc). Upper limits are marked by green arrows.

made to account for the incompleteness derived from the requirement of a source having a measured black hole mass itself. The heterogeneity of the resulting sample may well introduce biases which are hard to account for in a luminosity-luminosity correlation; however, it is also a safeguard against systematic effects that might arise from any one technique of estimating black hole masses.

For the specific example we are interested in, a relationship is posited between the radio core luminosity (at 5GHz) $L_{\rm R}$ of a black hole, its X-ray luminosity $L_{\rm X}$, and its mass M. $L_{\rm R}$ and $L_{\rm X}$ are derived quantities, each carrying, in addition to the respective flux, a factor of D^2 (where D is the luminosity distance to the source).

As discussed in the introduction, statistical tools exist to test whether a correlation is, in fact, an artifact of distance, or whether it reflects an underlying luminosity-luminosity relation, even in flux limited samples (Feigelson & Berg 1983). In MHD03 (section 3) a partial correlation analysis was performed (including all upper limits in the sample using the algorithm for performing Kendall's τ test in the presence of censored data proposed by Akritas & Siebert 1996), which showed unequivocally that, even after the large range of distances in the sample was taken into account, the radio core luminosity was correlated with *both* X-ray luminosity both for the entire sample (XRB plus AGN) and for the sample of supermassive black holes only[5].

Motivated by the findings of the partial correlation analysis, MHD03 proceeded in performing a linear regression fit to the data and found them to be well described by the following expression:

$$LogL_{\rm R} = 0.6LogL_{\rm X} + 0.78LogM + 7.33, \qquad (1)$$

with a substantial residual scatter ($\sigma \simeq 0.88$). A very similar result was obtained independently, from a different but largely congruent sample of sources, at essentially the same time by Falcke, Körding, & Markoff (2004).

In the following, we review some of the original arguments presented in MHD03 that address the following question: is the multivariate correlation of Eq.(1) a spurious result due to the effect of plotting distance vs. distance in flux limited samples? Moreover, we present further evidence that a strong *non-linear* correlation among $L_{\rm R}$, $L_{\rm X}$ and M indeed exists, which is *not* affected by the range of distance and the heterogeneity of the sample selection criteria.

2. FUNDAMENTAL PLANE VS. DISTANCE DRIVEN ARTIFACT

Apart from the traditional partial correlation analysis, different tests can be performed regarding the extent to which the range in distances in a sample may be responsible for inducing the observed correlation. For example, one can randomize the the observed fluxes in any one band, and compare the correlation strengths of the original and the randomized ("scrambled") data[6]. The reason for this is obvious: if the observed correlation is just an artifact introduced by the range of distances in a sample of otherwise uncorrelated luminosities, then the randomized datasets (the fluxes of which are guaranteed to be intrinsically non correlated) should show the same degree of correlation as the real dataset from which the fundamental plane was derived. Below, we will present a thourough, comparative statistical analysis of the original sample with the randomized ones.

2.1. *SMBH only*

We will first consider the extragalactic supermassive black holes (SMBH) in the sample[7]. If we consider only the detections (79 objects) and exclude the upper and lower 5% in radio luminosity, the sample spans a 90% range of $\log F_{\rm R,max} - \log F_{\rm R,min} \simeq 3.6$ orders of magnitude in radio luminosity and of $\log F_{\rm X,max} - \log F_{\rm X,min} \simeq 3.3$ in X-ray luminosity (see Figure 1). On the other hand, the range of distances spanned by the SMBH sample is also significant. The 90% range in the distances of the detected objects is 85, so that the factor distance squared, that enters in the luminosity has a range of about 7.2×10^3, which is of the same order as the range in fluxes. As argued by Kembhavi, Feigelson, & Singh (1986), a comparable spread in distance should prevent a spurious luminosity-luminosity correlation from dominating a strong, underlying correlation signal. However, it is clear that care has to be taken when studying luminosity-luminosity correlations and that distances effects should always be accounted for.

To test how the claim of a dominant distance bias holds up against the flux-scrambling test we took the radio fluxes of the detected sources and randomized them by assigning radio fluxes to objects in the sample via random permutations.

To construct our Monte Carlo test, we repeated this procedure 10^6 times and calculated the Pearson correlation coefficient between $L_{\rm R}$ and $0.6L_{\rm X} + 0.78M$ for each of the randomized datasets (using the code `slopes`, developed by M. Akritas & M. Bershady `http://astrostatistics.psu.edu/statcodes`). The upper left panel of Figure 2 shows the distribution of the correlation coefficients obtained from the randomized datasets. For comparison, the correlation coefficient ($R \simeq 0.7775$) of the *real*, observed SMBH sample is marked by a vertical line.

The figure shows that, as expected, the range of distances in the sample does induce some degree of spurious correlation, as the distribution of R is peaked at positive values. However, if the correlation seen in the real dataset were purely due to this spurious effect, its Pearson correlation coefficient would lie within the distribution of the scrambled

[5]The partial correlation analysis carried on in MHD03 further demonstrated that the radio core luminosity is correlated with black hole mass after the common dependence on X-ray luminosity is taken into account, and vice versa, thus not only justifying, but statistically *mandating* the multivariate linear regression, rather than just a bivariate one.

[6]This specific test was proposed by Bregman (2005).

[7]Unlike the original sample by MHD03, we remove the only genuinely beamed source (3C 273) for consistency.

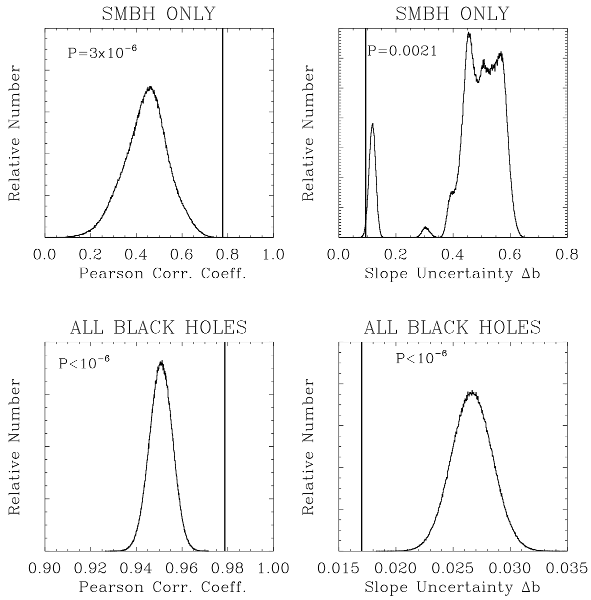

Fig. 2. Results of the Monte Carlo simulation of scrambled radio fluxes. *Upper panels*: extragalactic supermassive black holes only; *lower panels*: entire sample of detected sources, including XRBs; *left hand panels*: distributions of the Pearson's correlation coefficients for randomized fluxes (curve), compared to correlation coefficient of the original dataset (vertical line) — larger is better; *right hand panels*: distributions of the uncertainties in the regression slope for the randomized fluxes (curve), compared to the value for the original data (vertical line) — smaller is better. Also shown are the Monte Carlo likelihoods for the observed values as random chance realizations of the randomized sample (upper left corners). All plots show clearly that the randomized sample is not as strongly correlated as the real one.

data, which is clearly excluded by our Monte Carlo simulation. Out of a million realizations of the randomized radio flux distribution, only 3 had a larger correlation coefficient than the real data. Clearly, the real data are much more strongly correlated than the scrambled data.

We also performed a linear regression on the scrambled data, with slope b and intercept a, using a "symmetric" fitting algorithm (see MHD03, §3.1)[8]. The upper right hand panel of Figure 2 shows the uncertainty in the derived value for the slope b, which can itself be regarded as a measure of the intrinsic scatter of the fitted data. Only in about 0.2% of the scrambled datasets was this uncertainty smaller than that obtained for the real sample. This confirms the statement made in MHD03 (derived from partial correlation analysis), that the degree of correlation among L_{R}, L_{X} and M cannot be dominated by the effect of distances.

2.2. *SMBHs and XRBs*

Next, we consider the entire sample of detected sources, including XRBs, bringing the sample up to 117 points in total. It is obvious that when the XRB in our own Galaxy are included the range of distances spanned by the sample increases dramatically. The 90% ranges in $\log F_{\mathrm{R}}$, $\log F_{\mathrm{X}}$ and D^2 are now, respectively, 4, 5.7 and 4.6×10^{10}.

As for the SMBH sample discussed above, we performed a Monte Carlo simulation by randomizing the radio fluxes of the entire sample 10^6 times. The distribution of the resulting correlation coefficients for the scrambled dataset (including XRB) is shown in the lower right panel of Figure 2.

As expected, this distribution is now peaked at very high values of R, demonstrating that indeed the large range in distances can induce a spurious, strong correlation. This effect is unavoidable when comparing SMBH and XRB, and it is not going to improve with any volume limited sample of extragalactic sources, as telescopes with a large enough dynamic range to allow observations of XRB down to low luminosities in nearby AGN hosts do not exist (see below).

What is striking about the Monte Carlo results derived from the combined sample is that the Pearson correlation coefficient (R=0.9786) is even *more* inconsistent with the randomized data than in the SMBH-only case. Out of a million realizations of the randomized data sets, *not even one* showed a stronger correlation than the real data. In other words, the probability that the correlation found by MHD03 is entirely due to distance effects is less than 10^{-6}. This statement is confirmed by the distribution of the uncertainties in the regression slope, shown in the lower right panel.

This is partly due to the fact that in the XRB sample radio and X-ray luminosities are correlated quite tightly, over a range of luminosities much larger than the range in distances out of which they are observed (see e.g. Gallo, Fender, & Pooley 2003). More importantly, the X-ray fluxes of the XRBs are systematically enhanced compared to the AGN X-ray fluxes, while the radio fluxes of both samples are

[8]In particular, we have used here both the OLS bisector and the reduced major axis method as described in Isobe et al. (1990) and in Feigelson & Babu (1992), and implemented in the code `slopes`; Figure 2 shows only the results for the reduced major axis, but the results are consistent in the two cases.

comparable. In other words, the correlation is *non linear* ($L_{\rm R} \propto L_{\rm X}^{0.7}$) and the *slope* of the XRB correlation is, within the errors, consistent with being *the same* as that derived from the best fit of the SMBH only sample. It is thus *a fortiori* consistent (within the uncertainties imposed by the significant residual scatter) with the correlation that is derived for the entire sample.

If the effect were purely distance driven, one would expect to find a correlation that is significantly more linear (see §2.5). This non-linearity between $L_{\rm R}$ and $L_{\rm X}$ and the fact that the power is the same for XRBs and SMBHs produces a very strong signal in the correlation analysis, much stronger that the spurious one induced by the distance effects (only the latter can be recovered from a sample with scrambled radio fluxes), at greater than the 99.9999% level.

This leaves little room for arguing that the "fundamental plane" correlation between radio luminosity, X-ray luminosity, and black hole mass does not exist at all and instead is induced entirely by distance bias, consistent with the partial correlation analysis by MHD03, which is using non-parametric tests capable of handling censored data.

The fact that the correlation is stronger when XRB are included, *even after the effect of distances is considered*, although extremely statistically significant, can be hard to visualize when plotting the entire fundamental plane. Such a difficulty amounts to that of distinguishing two correlations, one with a Pearson correlation coefficient of $R \approx 0.94$, another with $R \approx 0.98$, extending over more than 12 orders of magnitude[9]. We believe this difficulty in visualizing this very statistically significant difference may lie at the origin of some of the criticisms (Bregman 2005) of the fundamental plane correlation. It is obvious that only an accurate statistical analysis can reveal this difference.

This also explains why the few upper limits in the MHD03 sample when plotted against the entire fundamental plane will follow the same correlation. A better test in this case would be to *quantify* the degree of such a correlation. The scrambled data analysis suggests that they will indeed be correlated, but not as strongly as the real dataset. There are, however, too few upper limits in the SMBH sample to allow a meaningful statistical test.

[9]If two samples of 117 data each have two measured Pearson correlation coefficients of 0.94 and 0.98 respectively, then it is possible to show that the probability of the former being intrinsically a better correlation than the latter, is of the order of 10^{-5}, see Numerical Recipes chapter 14.

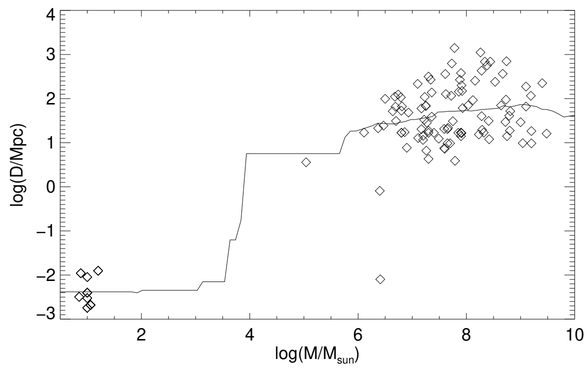

Fig. 3. Distance vs. black hole mass for the objects in the MHD03 sample. the solid line is the sliding mean. This shows that the AGN sample is homogeneous in distance with mass and therefore any $L_{\rm R}/L_{\rm X}^{\xi_{\rm RX}}$ vs. M relation in the AGN sample cannot be driven by distance.

2.3. *Distance independent plots*

Obviously, it is possible to remove the distance effect entirely from plots. If one were to expect a linear relation between $L_{\rm R}$ and $L_{\rm X}$, and some combined dependence of both on M, one could, for example, plot $L_{\rm R}/L_{\rm X}$ vs. M, in which case the common distance dependence of $L_{\rm R}$ and $L_{\rm X}$ is removed.

However, as was explained at length in MHD03, and as should be apparent from the well known radio/X-ray relation in XRBs, one should *not* expect a priori that the relation between the two is linear. Rather, it is reasonable to expect that, to lowest order, the two will follow a non-linear relation of the form $L_{\rm R} \propto L_{\rm X}^{\xi_{\rm RX}}$ (though the exact power-law index $\xi_{\rm RX}$ of this non-linearity depends on model assumptions).

This suggests that a better variable to plot would be $L_{\rm R}/L_{\rm R}^{\xi_{\rm RX}}$ vs. M. Using the best fit value of $\xi_{\rm RX} = 0.6$ from MHD03, this is shown in Figure 4, compared to the same plot if a linear relation between $L_{\rm R}$ and $L_{\rm X}$ is assumed. Clearly, the non-linear plot is significantly more correlated than the linear plot. Note that this plot removes the distance bias up to the level that black hole mass is only very slightly correlated with distance within the extragalactic SMBH sample (this can be seen from Figure 3). This statement can be quantified: The correlation coefficient for the two variables $L_{\rm R}/L_{\rm X}^{\xi_{\rm RX}}$ and M has a maximum of 0.65 at $\xi_{\rm RX} \sim 0.5$, compared to the value of $P = 0.4$ reached at $\xi_{\rm RX} = 1$ (note that this correlation does not use a symmetric method, thus resulting in a different value than the $\xi_{\rm RX} \sim 0.6$ found in the regression analysis of MHD03). This difference is significant to the 99.99% level.

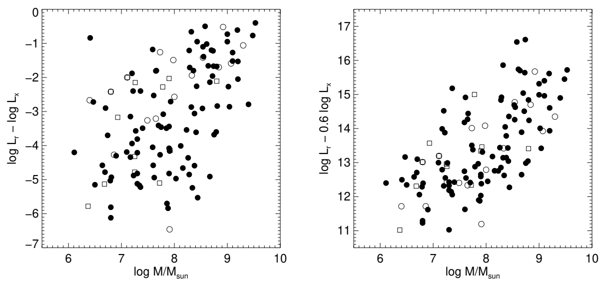

Fig. 4. The left panel shows the logarithm of the ratio of radio to X-ray luminosity, $logL_{\mathrm{R}} - logL_{\mathrm{X}}$ vs. the logarithm of black hole mass for the SMBH in the sample. The right panel shows instead the ratio $L_{\mathrm{R}}/L_{\mathrm{X}}^{0.6}$. The latter shows clearly a stronger correlation with black hole mass than the former. Note that this plot removes the distance bias up to the level that black hole mass is only very slightly correlated with distance within the extragalactic SMBH sample (this can be seen from Figure 3). Open symbols are upper limits.

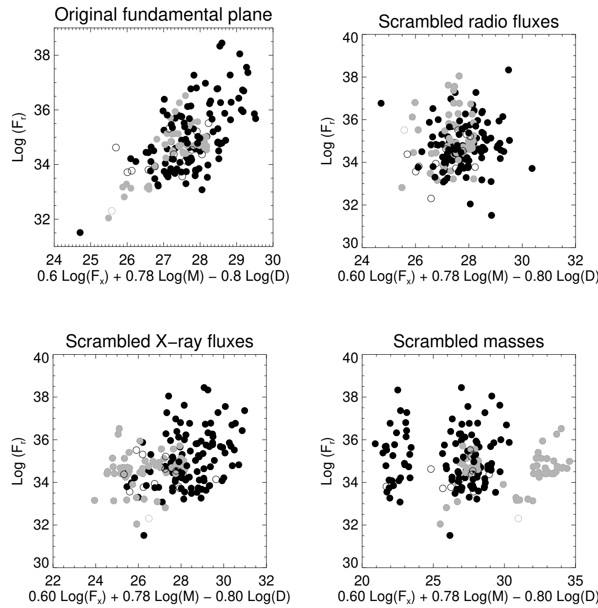

Fig. 5. The upper left panel shows the fundamental plane relation in a flux-flux-distance, rather than luminosity-luminosity plot (fluxes are calculated measuring distances in Mpc). The other three show the same dataset in which either radio flux, or X-ray flux or mass has been randomized. Grey dots are points from Galactic X-ray binaries, open symbols correspond to upper limits.

A related, more visually clear, illustration of the fact that the fundamental plane correlation is much stronger than any distance induced bias can be shown by plotting the data in the flux-flux-mass space. Figure 5 shows in the upper left panel the data viewed across the fundamental plane relationship expressed in fluxes and with the distance as a fourth variable. The correlation found in MHD03, expressed this way, reads:

$$LogF_{\mathrm{R}} = 0.6LogF_{\mathrm{X}} + 0.78LogM - 0.8D + 7.33 \quad (2)$$

The other three panels of Figure 5 show the data points after a randomization of radio fluxes (upper right panel), of X-ray fluxes (lower left panel) and of black hole mass (lower right panel). A visual inspection is sufficient to show that the correlation in the original data is much stronger than the residual correlation in the lower left panel (scrambled X-ray fluxes - note that a residual correlation should be expected in this case, as the radio luminosity should be related to black hole mass even for a random set of X-ray luminosities) and that no correlation is present in the other two panels. By construction, this correlation cannot be a spurious distance effect.

2.4. *Volume limited samples*

Clearly, the plots in Figure 5, as well as the confidence in the regression slopes, could be improved by a more carefully crafted, more complete sample. We shall briefly address the question of whether a volume limited sample would, in fact, the best way to treat this problem.

As discussed above, the entire sample including both XRBs and SMBHs is neither volume nor flux limited. Furthermore, the two populations have vastly different distances, masses, and luminosities. Clearly, these distinct regions of parameter space are largely responsible for stretching out the original plot of the fundamental plane over fifteen orders of magnitude on each axis. The question then arises whether a volume limited sample could address some of the concerns that a large part of the strong correlation is simply due to this distance bias (after all, even the randomized data show a correlation coefficient of 0.94).

Before addressing that question, it is important to note that it is not at all unreasonable to compare X-ray binaries and AGNs in the same flux range, and that a volume limited sample including both XRBs and SMBHs would, in fact, not make much sense. Physical intuition suggests that, when comparing black holes of vastly different mass, one should restrict the analysis to a similar range in dimensionless accretion rate, $\dot{m} \equiv \dot{M}/M$. By coincidence, the roughly seven orders of magnitude difference in M between XRBs and SMBHs are almost exactly canceled out by the roughly 3.5 orders of magnitude larger distance to the SMBH sample, making the flux ranges spanned by XRBs at least comparable. As it turns out, comparing the volume limited XRB sample with flux limited AGN sample puts both classes in roughly the same range of $\dot{m}$ (individual sources like GX 339-4 and Sgr A* representing a small percentage of outliers).

In a volume limited sample that includes both AGNs and XRBs, one would be forced to compare objects at vastly different accretion rates, which would not be very meaningful from a physical point of view. In this sense, one could also argue that the distance bias that is invariably introduced when correlating XRBs and AGNs is in reality an accretion rate bias, which is warranted on physical grounds.

Furthermore, due to the cosmological evolution of the accreting black holes population, a volume limited sample would be strongly dominated by quiescent sources for AGNs. For fitting regression slopes, a sample crafted to have roughly equal density of points throughout the parameter space spanned by the sources in the sample would presumably be much better suited for determining the slopes. While the MHD03 sample is certainly far from reaching that goal, it is another argument against a broad brush call for volume limited samples.

2.5. *The slope of the fundamental plane*

Fitting a regression through the data requires the *assumption* that one single underlying relation drives the data. Within that context, the regression will produce the correct slopes no matter what the sample. The same is true for including XRBs - whether the fact that they have comparable slope to the AGNs and that the AGNs lie on the extrapolation of the XRB slope with the mass correction is truly an expression of the same accretion physics at work must be posited as an ansatz (see MHD03).

The fact that a correlation can be found in sample that contains both classes of sources, either in luminosity-luminosity, or flux-flux (with slaved distance) space that are consistent with each other within the uncertainties then supports the ansatz, and the correctness of the idea of fitting *one* correlation. Within those limits, the slopes we derived are an accurate representation of the putative relation. This is, in fact, the customary and correct way to proceed. First one should test that the available data are indeed correlated, taking all possible biases (as those induced, for example, by distance, sample selection, etc.) into account. If, and only if, any such correlation is found to be statistically significant, then a linear (possible multivariate) regression fit to the data can be looked for.

Within the present context, the clear nonlinearity of the correlation between radio and X-ray luminosity for XRB and the apparent non-linearity of such correlation for the SMBH sample (with the slope consistent with being the same in the two separate samples), not only reinforce strongly the validity of our approach, but also suggest that only by working in the luminosity-luminosity space can one recover the intrinsic properties of the objects under scrutiny (Feigelson & Berg 1983; Kembhavi, Feigelson, & Singh 1986).

3. CONCLUSIONS

We have presented further statistical evidence that the fundamental plane of black hole activity(i.e. the non-linear correlation between radio core luminosity, X-ray luminosity and mass of accreting black holes) is not an artifact due to an overlooked bias introduced by the range of distances out of which sources in our sample are observed.

Partial correlation analysis techniques capable of handling censored data were already used in the original work of MHD03, following a decades long tradition in the multiwavelength study of AGN and QSOs. Here we have extended this analysis performing Monte Carlo simulations of randomized radio fluxes and found results consistent with the partial correlation analysis.

Distance-independent tests also demonstrate that the fundamental plane correlation is real and has a non-linear slope, which further suggests that studying flux-flux relations only is *not* appropriate when dealing with the data.

With respect to the traditional studies of correlations between luminosities of AGN in different bands, the inclusion of a mass term in the analysis imposes a very complex selection criterion on any sample: mass can be estimated in a number of different ways, with different degrees of uncertainties, and different degrees of observational difficulty, so that it is almost impossible, at least with the current data, to estimate the degree of incompleteness of any black hole mass sample. With respect to this crucial aspect, we argue that volume limited samples are not necessarily the best tools to study and understand the physical origin of such a correlation, as the cosmological evolution of the population of accreting black holes introduces severe biases in the (M, $\dot{m}$) parameter space, which also have to be taken into account.

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