

Constraints on relativistic beaming from estimators of the unbeamed flux

S. Heinz^{1,2} & A. Merloni³

¹ Center for Space research, MIT, 77 Mass. Ave., Cambridge, MA 02139

² Chandra Fellow

³ Max-Planck-Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85743 Garching, Germany

1 October 2004

ABSTRACT

We review the statistical properties of relativistic Doppler boosting relevant for studies of relativistic jets from compact objects based on radio–X-ray(–mass) correlations, such as that found in black-hole X-ray binaries in the low/hard state, or the “fundamental plane” of Merloni, Heinz, & DiMatteo. We show that the presence of only moderate scatter in such relations does not necessarily imply low Lorentz factors of the jets producing the radio emission in the samples under consideration. Applying Doppler beaming statistics to a large sample of XRBs and AGN, we derive a limit on the width of the Lorentz factor distribution of black holes with relativistic jets: If the X-rays are unbeamed (e.g., if they originate in the accretion disk or in the slower, innermost part of the jet), the width of the $\beta\Gamma$ distribution should be about one order of magnitude or less. If the scatter about the “fundamental plane” is entirely dominated by relativistic beaming, a lower limit on the mean Lorentz factor $\langle\beta\Gamma\rangle > 5$ can be derived. On the other hand, if the X-rays are boosted by the same factor as the radio emission, we show that the observed scatter cannot be reasonably explained by Doppler boosting alone.

Key words:

1 INTRODUCTION

Astrophysical jets from black holes in active galactic Nuclei (AGNs) and X-ray binaries (XRBs) are known to propagate with velocities close to the speed of light. Evidence for relativistic bulk motion stems from variability and compactness limits in compact cores (Jones et al. 1974), from superluminal motions of knots (Whitney et al. 1971; Cohen et al. 1971), and from doppler boosted jet-to-counter jet flux ratios (e.g. Perley et al. 1982). While proper motion measurements typically only constrain pattern speeds, the body of evidence points towards a range of mildly to ultra-relativistic jet speeds. As a result, the observed flux densities from these jets can be affected by strong Doppler boosting, which must be corrected for if one wants to infer the intrinsic luminosity of the jet, emitted in the rest frame of the plasma, which is important when calculating the physical parameters of the jet.

Recently, a correlation between the radio emission from steady jets and the hard (2–10 keV) X-ray emission has been found in black hole XRBs (Corbel et al. 2003; Gallo et al. 2003). This relation implies that in a given XRB in the low/hard state (see McClintock & Remillard 2004, for a review of the state classification in XRBs), the radio flux is proportional to the X-ray flux to the 0.7th power. This trend has been observed for different sources. The normalisation of the relation differs only by factors of a few for different XRBs. Since the radio emission stems from the jet, it will be affected by Doppler boosting and its brightness will differ strongly for different viewing angles. In the standard scenario, the

X-rays come from the disk (or alternatively the inner, slow moving part of the jet) and are thus not significantly beamed. The lack of strong scatter in the radio–X-ray relation has been interpreted as an indication that Doppler boosting is weak in the steady jets of XRBs in the low/hard state and that they must therefore move with only mildly relativistic speeds (Gallo et al. 2003).

Furthermore, Merloni et al. (2003) and (Falcke et al. 2004) have found a strong correlation between radio luminosity, X-ray luminosity, and black hole mass for samples of black holes spanning a wide range in black hole masses and accretion rates (called the “fundamental plane of black hole activity”, FP for short). Again, this relation shows a certain amount of intrinsic scatter, part of which might be contributed by Doppler boosting. Thus, studying this scatter can provide constraints on the presence or absence of Doppler boosting in the jets that produce the radio emission.

The nature of Doppler boosting has been studied exhaustively in the literature, specifically in regard to its statistical effects on samples of objects emitting beamed radiation (Orr & Browne 1982; Urry & Shafer 1984; Urry & Padovani 1991, 1995; Morganti et al. 1995; Lister & Marscher 1997; Lister 2003). Typically, one deals with a sample of radio sources that have been selected in the radio band and consider the effects of Doppler boosting on their luminosity function and on possible selection effects, not knowing what the unboosted flux of any particular source in the sample is.

What makes the situation considered in this paper different is that we actually *have* an unbiased estimator of the unbeamed

radiation: in the case of XRBs it is the X-ray luminosity, in the more general case of black holes of all masses it is the FP relation that links radio luminosity, X-ray luminosity, and black hole mass. It is therefore worth considering the statistical properties of relativistic Doppler boosting under those conditions.

In §2 we will review the basic properties of Doppler boosting and define the statistical integrals necessary for the remainder of the paper. In §3 we will apply these results to individual pairs of XRBs and argue that the observed moderate amount of scatter in the XRB radio-X-ray relation alone cannot be used to argue for low jet velocities. In §4 we apply the same method to the FP sample to derive constraints on the Lorentz factor distribution of the source in the sample. Section 5 presents our conclusions.

2 THE BEAMING PROBABILITY DISTRIBUTION

In the following we will consider radio emission from two-sided jets. We will assume that the approaching jet is identical to the receding jet. We will further assume that the spectrum emitted by the jet is a powerlaw with index α_r such that the jet flux is $F_\nu \propto \nu^{-\alpha_r}$. We will use a fiducial value of $\alpha_r = 0$, appropriate for the cores of jets observed in AGNs and XRBs, which show a roughly flat spectrum emitted from a *continuous* jet. For a review on jet properties and relativistic beaming, see, e.g., Begelman et al. (1984).

We are interested in situations where we have an independent estimator of the relative radio flux of different sources in the sample from observables like the X-ray flux, the distance, and the black hole mass, such as were proposed by Corbel et al. (2003); Gallo et al. (2003); Merloni et al. (2003); Falcke et al. (2004). Furthermore, we are interested in situations where the set of independent measurements is drawn from a sample of sources that are not selected in the spectral band where beaming is important and can thus be assumed to be oriented randomly. That is, the orientation of the approaching jet is random on a hemisphere of 2π steradian. This implies that $\cos\theta$ is randomly distributed between 0 and 1, where θ is the angle between the line of sight and the approaching jet. It does *not* imply that θ is randomly distributed between 0 and $\pi/2$.

For a given jet Lorentz factor Γ and four-velocity $\beta\Gamma = \sqrt{\Gamma^2 - 1}$, the relativistic Doppler boosting formula for the observed flux F_ν relative to the flux emitted in the rest frame of the plasma $F_{\nu,\text{jet}}$ is:

$$F_\nu = \frac{F_{\nu,\text{jet}}}{\Gamma^{k+\alpha_r}} \left[\frac{1}{(1 + \beta \cos\theta)^{k+\alpha_r}} + \frac{1}{(1 - \beta \cos\theta)^{k+\alpha_r}} \right] \quad (1)$$

where k varies from 2 for continuous jets to 3 for discrete ejections (e.g. Urry & Padovani 1995). Since we are considering steady, quasi-continuous jets, we will take $k = 2$ as our fiducial value.

Since the sources are randomly oriented, the fraction $P(> \theta)$ of sources with line of sight angle larger than θ is simply

$$P(> \theta) = \int_0^\theta d\theta \sin\theta = \cos\theta \quad (2)$$

(note that $0^\circ \leq \theta \leq 90^\circ$) and eq. (1) becomes

$$F_\nu(P, \Gamma) = \frac{F_{\text{jet}}(\nu)}{\Gamma^{k+\alpha_r}} \left[\frac{1}{(1 + \beta P)^{k+\alpha_r}} + \frac{1}{(1 - \beta P)^{k+\alpha_r}} \right] \quad (3)$$

$F(P, \Gamma)$ is monotonic in P for $0 \leq P \leq 1$. For a given Γ , P is the probability to observe a source at boosted flux lower than $F_\nu(P)$.

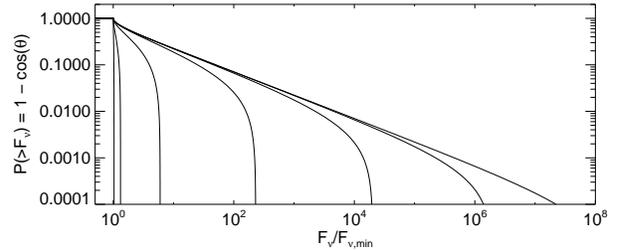


Figure 1. Probability for Doppler boosted flux to lie above a given value (relative to the maximally de-boosted flux F_{min} at 90° viewing angle). Curves are for increasing 4-velocity $\beta\Gamma$ from $\beta\Gamma = 0.1$ (leftmost) to $\beta\Gamma = 100$ (rightmost), in logarithmic intervals increasing by factors of $\sqrt{10}$.

Assuming the fiducial values of $\alpha_r = 0$ and $k = 2$, we can invert eq. (3) to find the cumulative probability of observing a source at a flux lower than F_ν (plotted in Fig. 1):

$$P(< F_\nu) = \frac{1}{\beta} \sqrt{1 + \frac{1}{F\Gamma^2} - \sqrt{\left(1 + \frac{1}{F\Gamma^2}\right)^2 + \frac{2}{F\Gamma^2}}} - 1 \quad (4)$$

and, conversely, $P(> F_\nu) = 1 - P(< F_\nu)$.

It is clear from eq.(4) that, in a randomly oriented sample of jets with identical Γ , most of the sources fall into a relatively narrow flux range: Using $0 \leq \beta \leq 1$, we can see that 50% of the sources fall within the range

$$\frac{2}{\Gamma^{k+\alpha_r}} \leq F_\nu \leq \frac{1}{\Gamma^{k+\alpha_r}} \left(2^{k+\alpha_r} + \left(\frac{2}{3}\right)^{k+\alpha_r} \right) \quad (5)$$

For the fiducial parameters, these two limits fall within a factor of ≤ 2.2 . Thus, *independent* of the actual Lorentz factor, the fluxes of 50% of the sources in a randomly oriented sample of flat spectrum jets with identical Γ fall within a factor of ≤ 2.2 . The remaining sources are distributed in a tail to larger observed fluxes, cutting off at the maximum flux, $F_\nu \leq \Gamma^2 (2 + 2\beta^2)$ (see Fig. 1). The curves for $\Gamma = 10$ and $\Gamma = 100$ differ only below $P(> F_\nu) < 3\%$, i.e., for 3 out of 100 sources.

Well below this cutoff, the probability distribution is very similar for different Γ , but shifted to lower fluxes (i.e., deboosted) by a factor of $\zeta_0 \equiv 1/\Gamma^{k+\alpha_r}$. Thus, measuring the width of the flux distribution (FWHM) of randomly oriented sources *with identical* Γ is not sufficient to determine Γ if the width is larger than about a factor of 2.2. A proper determination would require sampling the cutoff. For a measured width of $\delta \equiv F_{\text{max}}/F_{\text{min}} \gg 2.2$, to be able to say that the upper limit corresponds to the cutoff would require a total number of sources well in excess of

$$N(\delta) = \left[1 - \sqrt{\frac{2\delta + 1 - \sqrt{8\delta + 1}}{2\delta}} \right]^{-1} \quad (6)$$

where we used eq. (3) and $\alpha = 0$ and $k = 2$.

However, it is rather unlikely that the bulk Lorentz factors of all the sources are identical. Instead, $\beta\Gamma$ will follow some distribution $f(\beta\Gamma)$ around a mean $\beta\Gamma_{\text{mean}} = \langle \beta\Gamma \rangle$. Because of the strong dependence of the shift ζ_0 of the flux distribution on Γ and because the flux distribution for a given Γ is strongly concentrated around the minimum value, the spread δ in the flux distribution of a *randomly oriented sample* is typically dominated by the spread in Γ , not by viewing angle effects.

Thus, for flux distributions significantly wider than $\delta \sim 2.2$, we cannot determine the maximum or mean $\beta\Gamma$ simply by measuring the width of the flux distribution, assuming an inherently

uniform flux, or by imposing a universal radio-X-ray relation (Gallo et al. 2003; Merloni et al. 2003; Falcke et al. 2004) and measuring the spread against this relation. Only if the distribution contains a total number of sources well in excess of the value of eq. (6) and if the upper cutoff of the flux distribution is well sampled can one derive an upper limit on $\beta\Gamma$. Otherwise, the only conclusion that can be reached from a relatively narrow distribution in fluxes around a radio-X-ray relation is that *the spread* in Γ around $\beta\Gamma_{\text{mean}}$ is small.

3 CONSTRAINTS FOR A SINGLE PAIR OF RADIO JETS

For situations where a tight relation between the beamed radio jet emission with some unbeamed observables (e.g., the X-ray flux) is observed over a large range in the secondary observables but for a small number of sources, one can derive constraints on the Lorentz factors of individual pairs of sources from the difference in normalisation of the observed relation, assuming that it reflects only differences in orientation and Lorentz factor.

One such example is the XRB radio-X-ray relation (Corbel et al. 2003; Gallo et al. 2003), where the number of sources contributing is rather small — between 2 and 4 on the low luminosity end, where the relation holds most firmly. The two most significant sources in the sample are V404 Cyg and GX339-4. Following Gallo et al. (2003), the radio flux in V404 is a factor of about 2.5 to 5 larger than that of GX339-4 for the same X-ray flux. Allowing for some uncertainty in the mass of the black hole in GX339-4 (Hynes et al. 2004) and of the distances to GX339-4 and V404 (Hynes et al. 2004; Jonker & Nelemans 2004), the rough confidence limits on this ratio fall between 1.5 and 5. We can then ask what constraints on beaming can be derived from this observation.

We assume that, at the same X-ray luminosity, both sources have the same comoving (i.e., unbeamed) radio luminosity, i.e., they fall on the same X-ray-radio relation when corrected for beaming. In other words, we assume that the X-rays are not affected by beaming (see §4 for more discussion of this assumption). If the jets have Lorentz factors of Γ_{404} and Γ_{339} , the probability that the observed radio flux from V404 is larger than that of GX339 by a factor δ is

$$P(F_{404} > \delta F_{339}) = 1 - \int_0^1 dp P(\delta F_\nu(p, \Gamma_{339}), \Gamma_{404}) \quad (7)$$

where $F_\nu(p, \Gamma)$ follows eq. (3) and $P(F, \Gamma)$ is taken from eq. (4).

Fig. 2 shows the one-, two-, and three-sigma contours on $\beta\Gamma$ of both jets for the range in normalisation offsets allowed by the observations (Gallo et al. 2003) $1.5 \lesssim F_{404}/F_{339} \lesssim 5$. The fact that the ratio of F_{404}/F_{339} is close to unity implies that the Lorentz factors of both sources fall within roughly a factor of 2 and that the jet in GX339-4 likely has a higher Lorentz factor than that of V404. The possible presence of larger uncertainties in black hole mass and distance to both objects that are unaccounted for in our estimate of δ imply that the confidence contours in Fig. 2 will be widened and the constraints on $\beta\Gamma_{404}/\beta\Gamma_{339}$ will be less stringent, thus allowing the Γ of both objects to be more different than otherwise implied.

While it is not possible to extend this graphical analysis to more than 2 sources, the formalism can easily be adapted to N sources, in which case the confidence contours turn into $N-1$ dimensional hyper-surfaces in an N dimensional $\log \beta\Gamma_n$ space. Asymptotically (at large $\beta\Gamma_n$), the surfaces will describe hyper-cylinders around an axis parallel to the diagonal vector $(1, 1, \dots, 1)$, shifted

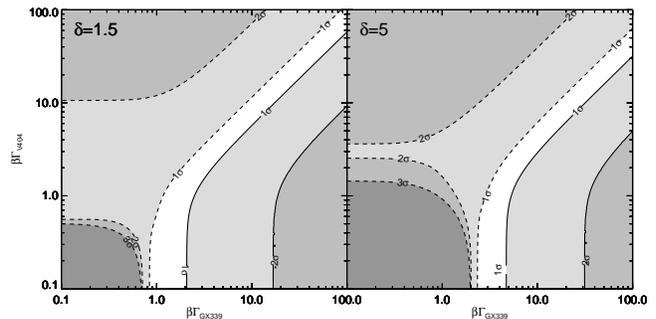


Figure 2. Chisquare maps of the jet Lorentz factors of GX339-4 (bottom axis) and V404 Cyg (left axis), given the observed difference in radio luminosity $1.5 \lesssim \delta \lesssim 5$ (left and right panel respectively). Shown are the contours outside of which the probability of observing a flux ratio larger or smaller than δ are 68%, 95%, 99.5% (i.e., 1, 2, and 3 sigma).

along each axis by the square root of the flux ratio of the reference source relative to source n . For large N , this distribution of shifts is then a representation of the distribution of Γ_n .

The formal conclusion we reach from this analysis is that the relative similarity in the normalisation of the radio-X-ray relations for GX339-4 and V404 Cyg does not imply that the Lorentz factors of both jets are small, but rather that they are similar. From the constraints on the scatter about the radio-X-ray relation, we cannot put any upper limit on Γ of either source. However, because for large Γ , the observed radiation is severely de-boosted, other physical limitations can provide such limits. E.g., at very large Γ , the implied kinetic power would vastly exceed any reasonable limits (Fender et al. 2004). Also, radio timing constraints from Cyg X-1 indicate that its jet is only moderately relativistic (Gleissner et al. 2004).

4 THE SPREAD IN THE FUNDAMENTAL PLANE

We will now use the scatter observed in the radio-X-ray-mass “fundamental plane” (FP) correlation found by Merloni et al. (2003) and Falcke et al. (2004) to constrain the Lorentz factor distribution of the jets in the sample. These limits will be based on the assumption that the orientation of the sources is random and that the scatter in the distribution is at least partly due to relativistic beaming. Clearly, other sources of scatter will enter (e.g., uncertainty in black hole mass, spin, variations in α_r), so the observed scatter cannot be *solely* due to relativistic boosting. This implies that any constraints derived here will be upper limits. We will show that the observed scatter can only be used to constrain the width of the Lorentz factor distribution.

4.1 Unbeamed X-rays

If the X-ray emission of the sources in the sample stems from the accretion disk, the X-rays will not be affected by relativistic beaming. It should be noted that the disk X-ray emission can still be anisotropic simply due to the nature of the accretion flow (e.g., Shakura & Sunyaev 1973; Beloborodov 1999), however, the scatter produced by the differences in viewing angle is a relatively mild effect and small compared to the scatter due to boosting, and we will neglect this effect in the following. We can estimate the radio Doppler boosting factor from eq. (3) using $k = 2$ and $\alpha_r = 0$. We can then relate this expression to the scatter about the FP,

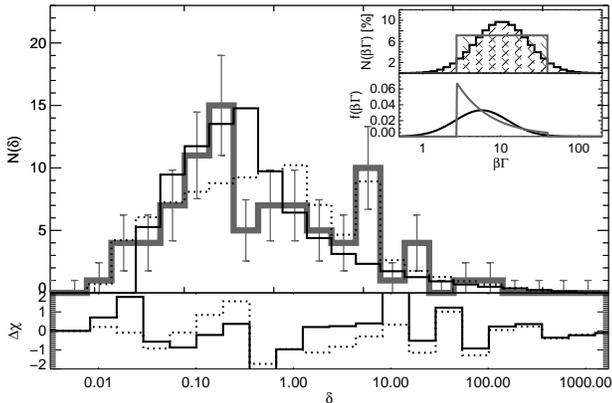


Figure 3. Upper panel: *thick grey curve*: Histogram of the scatter of all individual sources of the FP sample (excluding upper limits and averaging over the different data sets for different XRBs); *solid black curve*: fit of log-normal distribution with $\beta\Gamma_{\text{mean}} = 10.5$, $\sigma = 0.78$; *dotted black curve*: fit of log-flat $\beta\Gamma$ distribution with $\beta\Gamma_{\text{mean}} = 10.5$, $\sigma = 1.34$. Lower panel: residuals. Insert: *Upper panel*: histogram of $\beta\Gamma$ -distributions corresponding to fits in Fig. 3 (*black*: log-normal, *grey*: log-flat). *Lower panel*: corresponding $\beta\Gamma$ distributions.

$$\delta = F_r / (10^{7.33} F_x^{0.6} M^{0.78}) \quad (8)$$

Since we have no information about the distribution of Γ , we will take two simple functional forms as templates. First, we will use a log-normal distribution of the form (see Fig. 3):

$$f(\beta\Gamma) = \frac{N \exp \left[-(\log \beta\Gamma / \beta\Gamma_{\text{mean}})^2 / (2\sigma^2) \right]}{\beta\Gamma \sigma \sqrt{2\pi}} \quad (9)$$

Since the un-beamed normalization of the radio flux is unknown (the mean in the FP distribution corresponds to an average over all angles and Γ 's), we have to allow for an arbitrary re-normalisation of the flux δ_0 . We can then produce a histogram of the scatter δ of all the sources in the FP relation. This is shown in Fig. 3. We have used Poisson errors for the histogram bins. Also shown is a fit of a log-normal distribution in $\beta\Gamma$ to this histogram (fit parameters: $\beta\Gamma_{\text{mean}} = 7$, $\sigma = 0.78$, $\delta_0 = 0.74$), which can reproduce the range and shape of the scatter distribution rather well.

Fitting a log-flat distribution of the form $f(\beta\Gamma) = N / (\ln(\sigma^2)\beta\Gamma)$ for $\frac{\beta\Gamma_{\text{mean}}}{\sigma} \leq \beta\Gamma \leq \sigma\beta\Gamma_{\text{mean}}$ and $f(\beta\Gamma) = 0$ elsewhere, provides a marginally better fit, which can be understood by the fact that it is a decent approximation to eq. (9) to lowest order. This shows that we cannot constrain the shape of the $\beta\Gamma$ distribution very well. For the purpose of this letter, we shall limit ourselves to constraining the width of this distribution. A better determination of the shape of the distribution will only be possible when a larger, more carefully selected sample is available.

In §1 we argued that the width of the scatter distribution about a radio–X-ray(–mass) relation can only be used to constrain the width σ of the distribution, not $\beta\Gamma_{\text{mean}}$ itself. To demonstrate this point quantitatively, Fig.4 shows the chi-square distribution of the two interesting parameters $\beta\Gamma_{\text{mean}}$ and σ (marginalising over the unknown radio flux normalisation ζ_0 of the underlying, unbeamed FP relation) of the assumed lognormal distribution in $\beta\Gamma$ used to fit the δ histogram in Fig. 3. The 1, 2, and 3 sigma confidence contours show that σ is constrained much better than $\beta\Gamma_{\text{mean}}$. In fact, the fit only provides a *lower limit* on $\beta\Gamma_{\text{mean}}$, similar to the result in Fig. 2. However, since other sources of scatter will render all mea-

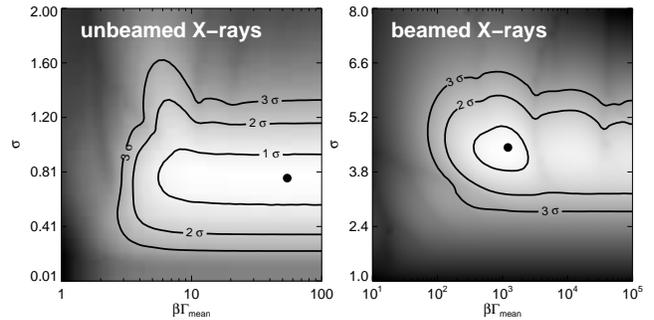


Figure 4. Chisquare maps of the two interesting parameters $\beta\Gamma_{\text{mean}}$ and σ , fitting a log-normal distribution in Γ to the δ -histogram in Fig. 3. The curves show the formal 1, 2, and 3 sigma confidence contours. Left panel: unbeamed X-rays, right panel: beamed X-rays.

surements derived from the scatter about the FP upper limits, we cannot make any statements about the mean $\beta\Gamma_{\text{mean}}$ in the sample, while we can safely state that $\sigma \leq 0.8_{-0.6}^{+0.8}$ (3-sigma limits).

In this context, it is interesting to note the recent claim of limits $0.43 \lesssim \beta\Gamma \lesssim 1$ for the jet in Cyg X-1 (Gleissner et al. 2004), which is part of the FP sample. Given the upper limit on σ , this would place a 3-sigma upper limit on $\beta\Gamma_{\text{mean}} \leq 250$ and put Cyg X-1 at the low end of $\beta\Gamma$ distribution. In other words, if most of the scatter in the distribution is indeed due to relativistic beaming, then most of the jets in the sample should have faster velocities than Cyg X-1. The limit on $\beta\Gamma$ for Cyg X-1 is based on the lack of correlations between radio and X-ray emission above a given frequency. If other XRB jet source are indeed significantly faster, this should manifest itself correlations between radio and X-rays on shorter timescales than in Cyg X-1, which can be tested observationally.

The sample used to derive the FP contains some steep spectrum sources and some sources without measured α_r . As discussed in Merloni et al. (2003), this can be an additional source of scatter. In order to assess the influence of the presence of steep spectrum sources on the scatter about the fundamental plane and on the limits we can place on the $\beta\Gamma$ distribution, we repeated the same analysis as above limited to sources that are known to have flat radio spectra. We find that the scatter is slightly reduced and that the 1-sigma confidence contour moves downward to lower values of σ , while the 2- and 3-sigma confidence contours are expanded in all directions. This is because the number of sources in the sample is reduced significantly, thus reducing the statistical significance of the result. The overall shape of the contours is not changed, and the main conclusion that one can only place an upper limit of $\sigma \leq 0.4_{-0.4}^{+1.2}$ from these considerations remains.

4.2 Beamed X-rays

If we try to reproduce the scatter about the FP in a model where the X-rays are produced in the jet at the same Γ as the radio (e.g., as synchrotron or synchrotron-self-Compton radiation), the formalism changes: Assuming the X-ray and radio fluxes are emitted with the same Γ and the same viewing angle, and taking the X-ray flux to follow a powerlaw of the form $F_x \propto \nu^{-\alpha_x}$, the observed deviation of the radio flux from the FP defined in eq. (8) is

$$\delta(P, \Gamma) = \frac{\Gamma^{0.6\alpha_x - \alpha_r - 0.4k} \left[\frac{1}{(1+\beta P)^{k+\alpha_r}} + \frac{1}{(1-\beta P)^{k+\alpha_r}} \right]}{\left[\frac{1}{(1+\beta P)^{k+\alpha_x}} + \frac{1}{(1-\beta P)^{k+\alpha_x}} \right]^{0.6}} \quad (10)$$

For $k \sim 2$, $\alpha_r \sim 0$, and $\alpha_x \sim 1/2$ (typical for optically thin synchrotron emission), it turns out that eq. (10) requires unrealistically large values of Γ to obtain the observed scatter about the FP, as plotted in the right panel of Fig. 4. The range in Γ implied by the 1-sigma contours on $\beta\Gamma_{\text{mean}}$ and σ would reach from Γ of order unity to $\Gamma \sim 10^5$ or higher. Furthermore, in many sources the X-ray spectra are steeper than $\alpha_x = 1/2$. As can be seen from eq. (10), the effectiveness of beaming to produce scatter about the FP is reduced further when α_x is increased from 0.5 to 1 (in the latter case, values of $\beta\Gamma_{\text{mean}} \sim 10^8$ and $\sigma \sim 10$ are required to produce the observed amount of scatter).

Two possible conclusions arise from this result: If the X-rays are produced by the jet, then either a) some other source of statistical uncertainty must be present to dominate the observed scatter about the FP, and/or b) the X-ray emission must arise from a region of the jet that suffers less relativistic beaming. Most jet acceleration models actually accelerate the jet over several decades in distance to the core. The latter scenario would therefore be compatible with the general notion that the optically thin X-ray synchrotron emission is dominated by the innermost region of the jet, closest to the core, while the optically thick radio emission stems from a region further out that might have been accelerated to larger Γ .

Simple direct synchrotron models do present other challenges (Heinz 2004). More realistic scenarios include a combination of synchrotron plus synchrotron-self-Compton and inverse Compton scattering of disk radiation (Markoff & Nowak 2004). It is not clear whether the X-ray emitting region in this scenario would be co-spatial with the radio emitting region or not. Certainly, however, the modest amount of scatter in the XRB radio-X-ray relation and in the FP relation cannot be used to argue in favor of a jet origin of the X-ray - both disk X-rays and X-rays from the base of the jet can easily produce the observed amount of scatter.

4.3 Blazars and highly beamed sources

As mentioned in §2, in the absence of velocity constraints on individual source (like those on Cyg X-1 used above), the only way to obtain an upper limit on $\beta\Gamma$ from this method is to observe the cutoff at high luminosities where the sources fall into the beaming angle and no further amplification is possible. However, in those sources the X-rays almost certainly contain a beamed component from the jet, as observed in blazars and BL-Lacs. Thus, the source of the X-rays is possibly not the same as in the unbeamed sources and the upper cutoff will not adequately sample the maximum Γ . Furthermore, the sample used here was selected to exclude blazars and BL-Lac objects (with the exception of 3C279) since they are almost strongly selection biased and because the X-rays most likely come from a different source. Thus we have specifically eliminated the possibility to sample the upper cutoff even if it were observable.

Following eq. (10), the effect of an additional, strongly beamed X-ray component is to *reduce* the deviation from the regular FP relation that would otherwise be measured for a large positive beaming of the radio flux alone. For a truly randomly oriented, unbiased sample, the large majority of the sources will not be stringly affected by this, because at high $\beta\Gamma$, a very small fraction of sources falls into the beaming cone, while at low $\beta\Gamma$, beaming is unimportant. Since we cannot be sure that the FP sample is free of bias, a note of caution is in order regarding possible selection effects. Still, because the conclusions reached in this paper are not based on claims about the upper cutoff in the flux distribution, the results should be robust even if the contribution from highly beamed sources is not treated entirely self-consistently.

5 CONCLUSIONS

We showed that the scatter in the radio-X-ray relation in XRBs and in the “fundamental plane” relation in accreting black holes can be used to constrain the width of the Lorentz factors distribution of the jets in these sources. It cannot be used to put an upper limit on the mean Lorentz factor $\langle\Gamma\rangle$ of the jets in the sample. However, if all of the scatter is indeed due to relativistic Doppler boosting, we show that a lower limit can be put on $\langle\beta\Gamma\rangle$. Both log-normal and log-flat distributions in $\beta\Gamma$ fit the observed scatter well. We show that, if the X-rays are produced in the jet, they either have to originate in an unbeamed portion of the jet (close to the base) or other sources of scatter must dominate in the “fundamental plane” relation.

We would like to thank Rob Fender, Sera Markoff, Mike Nowak, and the anonymous referee for helpful insights and discussions. Support for this work was provided by the National Aeronautics and Space Administration through Chandra Postdoctoral Fellowship Award Number PF3-40026 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-39073.

REFERENCES

- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, *Rev. Mod. Phys.*, 56, 255
- Beloborodov, A. M. 1999, *ApJL*, 510, L123
- Cohen, M. H., Cannon, W., Purcell, G. H., et al. 1971, *ApJ*, 170, 207
- Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, *A&A*, 400, 1007
- Falcke, H., Körding, E., & Markoff, S. 2004, *A&A*, 414, 895
- Fender, R., Gallo, E., & Belloni, T. 2004, submitted to *MNRAS*
- Gallo, E., Fender, R. P., & Pooley, G. G. 2003, *MNRAS*, 344, 60
- Gleissner, T., Wilms, J., Pooley, G. G., et al. 2004, accepted for publication in *A&A*, astro-ph/0407070
- Heinz, S. 2004, *MNRAS*, in press, astro-ph/0409029
- Hynes, R. I., Steeghs, D., Casares, J., Charles, P. A., & O’Brien, K. 2004, *ApJ*, 609, 317
- Jones, T. W., O’dell, S. L., & Stein, W. A. 1974, *ApJ*, 192, 261
- Jonker, P. G. & Nelemans, G. 2004, *MNRAS*, 344
- Lister, M. L. 2003, *ApJ*, 599, 105
- Lister, M. L. & Marscher, A. P. 1997, *ApJ*, 476, 572
- Maccarone, T. J., Gallo, E., & Fender, R. 2003, *MNRAS*, 345, L19
- Markoff, S. & Nowak, M. 2004, *ApJ*, 609, 972
- McClintock, J. & Remillard, R. 2004, in *Compact Stellar X-ray Sources*, ed. W. Lewin & M. van der Klis, Vol. in press, astro-ph/0306213
- Merloni, A., Heinz, S., & di Matteo, T. 2003, *MNRAS*, 345, 1057
- Morganti, R., Oosterloo, T. A., Fosbury, R. A. E., & Tadhunter, C. N. 1995, *MNRAS*, 274, 393
- Orr, M. J. L. & Browne, I. W. A. 1982, *MNRAS*, 200, 1067
- Perley, R. A., Fomalont, E. B., & Johnston, K. J. 1982, *ApJL*, 255, L93
- Shakura, N. I. & Sunyaev, R. A. 1973, *A&A*, 24, 337
- Urry, C. M. & Padovani, P. 1991, *ApJ*, 371, 60
- Urry, C. M. & Padovani, P. 1995, *PASP*, 107, 803
- Urry, C. M. & Shafer, R. A. 1984, *ApJ*, 280, 569
- Whitney, D. A., Shapiro, I. I., Rogers, A. E. E., et al. 1971, *Science*, 173, 225