RELATIVISTIC DOPPLER BEAMING AND MISALIGNMENTS IN AGN JETS

ASHOK K. SINGAL

Astronomy & Astrophysics Division, Physical Research Laboratory, Navrangpura, Ahmedabad-380 009, India; asingal@prl.res.in

ABSTRACT

Radio maps of active galactic nuclei often show linear features, called jets, on both parsec and kiloparsec scales. These jets supposedly possess relativistic motion and are oriented close to the line of sight of the observer, and accordingly the relativistic Doppler beaming makes them look much brighter than they really are in their respective rest frames. The flux boosting due to the relativistic beaming is a very sensitive function of the jet orientation angle, as seen by the observer. Sometimes, large bends are seen in these jets, with misalignments being 90° or more, which might imply a change in the orientation angle that should cause a large change in the relativistic beaming factor. Hence, if relativistic beaming does play an important role in these jets such large bends should usually show high contrast in the brightness of the jets before and after the bend. It needs to be kept in mind that sometimes a small intrinsic change in the jet angle might appear as a much larger misalignment due to the effects of geometrical projection, especially when seen close to the line of sight. What really matters are the initial and final orientation angles of the jet with respect to the observer’s line of sight. Taking the geometrical projection effects properly into account, we calculate the consequences of the presumed relativistic beaming and demonstrate that there ought to be large brightness ratios in jets before and after the observed misalignments.

Key words: galaxies: active – radiation mechanisms: non-thermal – radio continuum: general

1. INTRODUCTION

Radio galaxies and quasars, which are essentially active galactic nuclei (AGNs), often show linear features called jets, which presumably are the channels of relativistic plasma through which energy is continually transported to outer parts of these AGNs. There is plenty of evidence that these jets are relativistic, at least in quasars and radio galaxies of type FR II (Fanaroff & Riley 1974), and relativistic Doppler beaming could be an important factor in their appearance to the observer. The Lorentz factors could be high, $\gamma \sim 5-40$, as estimated from the observed superluminal motion (Cohen et al. 1977; Kellermann et al. 2003; Jorstad et al. 2005; Marscher 2006). There is other, independent, evidence for relativistic Doppler beaming, from the high brightness temperatures ($T_b$) inferred from the short-period variability. The estimated $T_b$ values exceed the theoretical limit of $\sim 10^{12}$ K, initially thought to be set by the large inverse Compton losses at still higher $T_b$ (Kellermann & Pauliny-Toth 1969) and therefore long known in the literature as an inverse Compton limit, though of late a somewhat stricter limit of $\sim 10^{11.3}$ K has instead been shown to be set by the diamagnetic effects in a synchrotron source, which lead to the condition of equipartition among radiating charges and the magnetic field—a condition that is also the configuration of minimum energy for the source (Singal 1986, 2009). But much larger brightness temperatures, violating the above limit on incoherent brightness temperature, have been inferred for the variable sources at centimeter wavelengths. This excess in brightness temperatures has been explained in terms of a bulk relativistic motion of the emitting component (Rees 1966; Blandford & Königl 1979).

The relativistic Doppler factors required to explain the excessively high temperatures of up to $\sim 10^{19}$ K (Quirrenbach et al. 1992; Wagner & Witzel 1995) for the intra-day variables are $\delta > 10^2$. Thus the evidence for relativistic flows and relativistic beaming in AGNs is quite strong. The flux boosting due to relativistic beaming is a very sensitive function of the orientation angle $\theta$ of the jet with respect to the line of sight to the observer. A slight change in $\theta$ could cause a very large change in the observed flux density. The onesidedness of jets seen in many AGNs is explained by the difference in the relativistic beaming on the two sides because of their different orientations with respect to the observer’s line of sight.

Now what appears mysterious is that quite often large bends are seen in these jets, with misalignments being 90° or even more (Pearson & Readhead 1988; Conway & Murphy 1993; Appl et al. 1996; Kharb et al. 2010). Though most misalignments quoted are between jet directions on parsec and kiloparsec scales, their large values led us to consider the brightness ratio of jets before and after the misalignment on particular scales. There are examples of such bends without much change in brightness on both parsec and kiloparsec scales. Some examples are: 3C66A, 0528+134, 1803+784, BL Lac (Jorstad et al. 2005) and S5 0716+714 (Rani et al. 2015).

As we will show, if only modest brightness contrasts on either side of a bend are seen, they may not be consistent with the relativistic beaming models. However, no systematic statistical study has been made of the changes in brightness in the jet after a misalignment so as to make an unambiguous statement. In fact there is no statistically unbiased study available about the absolute frequency of occurrence of bending in a complete sample.

It needs to be kept in mind, however, that sometimes a small bending angle might appear as a much larger misalignment due to the effects of geometrical projection, especially when seen close to the line of sight. The argument goes like this. Let $\theta$ be the angle that the jet initially makes with the line of sight and let $\eta$ be the misalignment angle as seen by the observer in the sky plane (perpendicular to the line of sight). Then the misalignment must have a component perpendicular to the initial direction of the jet (if not then no misalignment would be noticed in the jet). If $\zeta$ is the change in angle at the source, then because of foreshortening of the parallel component by $\sin \theta$
when projected in the sky plane, we get

$$\tan \eta = \tan \zeta / \sin \theta \sim \gamma \tan \zeta,$$

for $\sin \theta \sim 1/\gamma$ (assuming a relativistic beaming with $\gamma$ as the Lorentz factor). Thus the misalignment of the jets will appear enhanced by a factor $1/\sin \theta \sim \gamma$ in cases of relativistic beaming. As an example, a 3° bend could appear as a 30° misalignment if $\gamma = 10$. However, because much larger misalignments ($\eta \gtrsim 90°$) have been seen, one would still need reasonably large $\zeta$ in order to explain the observations (unless $\theta \sim 0$). Of course, what really matters is the final orientation angle $\theta_f$ of the jet with respect to the observer’s line of sight. For that, one has to evaluate the projection effects in a more precise and rigorous manner, and we shall endeavor to do so here. Accordingly, we shall explore the question of what the relativistic beaming models predict about the expected contrast in the jet brightness before and after the observed misalignments, taking into account effects of proper geometrical projection.

2. GEOMETRY OF THE JET BENDING

Following Conway & Murphy (1993), we assume a simple model of jet bending where there is a change only in the direction of the jet motion (for simplicity we take the bending to be a sudden discontinuous change and not a gradual turning of the jet). The speed of the jet material is assumed to remain constant during the bending and we further assume that there is no change in the intrinsic properties (in particular the intrinsic emissivity of the jet material) before and after the bending. This is to keep the number of free variables required to explain the observations to a minimum. A change in the jet speed alone, with a corresponding change in the relativistic Lorentz factor, would not cause any change in the apparent direction of the jet seen by the observer, though the brightness could change substantially depending upon the change in the jet speed. A change in the direction of jet motion is essential for the appearance of a misalignment in the jet direction, projected in the sky plane, as seen by the observer.

Figure 1 shows the geometry of the bend in the jet. Originally the jet is along OA, lying in the plane ZOX, making an angle $\theta$ to the observer’s line of sight, assumed to be along OZ. The sky plane is defined by YOX. The jet undergoes a bend at point A and is moving thereafter along AB, making an angle $\zeta$ to the original direction OAC. The plane ABC is defined by the azimuth angle $\phi$ with respect to the plane ZOC (which is the same as the plane ZOX). Our goal here is to determine $\theta_f$, the angle between AP and AB, because it is $\theta_f$ that would determine the relativistic beaming factor of the jet after the bending.

To the observer, the original direction of the jet in the sky plane YOX will appear to be along OX. The misalignment $\eta$ will be the angle that the projection of vector AB on the sky plane makes with OX. Vector AB is broken into a component of length $d \cos \zeta$ along AC and a perpendicular component along BC of length $d \sin \zeta$, the latter in turn giving components $d \sin \zeta \cos \phi$ along CL and $d \sin \zeta \sin \phi$ along BL. The component of AB along OX therefore is $d (\cos \zeta \sin \theta + \sin \zeta \cos \phi \cos \theta)$ while that along OY is $d \sin \zeta \sin \phi$. Therefore the misalignment in the jet direction, as seen by the observer (with line of sight along PA) is given by

$$\tan \eta = \frac{\sin \zeta \sin \phi}{\cos \zeta \sin \theta + \sin \zeta \cos \phi \cos \theta}.$$  

(2)

This expression for jet misalignment is the same as that derived by Conway & Murphy (1993).

Of course what decides the post-bend jet brightness is the orientation angle $\theta$ between the observer’s line of sight and the intrinsic direction of jet motion after the misalignment. From Figure 1, we need to determine the projection of AB along AP. The two components along AC and CL give the projection along AP as $d \cos \zeta \cos \theta$ and $-d \sin \zeta \cos \phi \sin \theta$ respectively. Thus angle $\theta_f$ as a function of $\zeta$, $\phi$, and $\theta$ is given by the expression

$$\cos \theta_f = \cos \zeta \cos \theta - \sin \zeta \cos \phi \sin \theta.$$  

(3)

From Equation (2) we can express the intrinsic bending angle $\zeta$ in terms of $\eta$, $\theta$, and $\phi$ as

$$\tan \zeta = \frac{\tan \eta \sin \theta}{\sin \phi - \tan \eta \cos \phi \cos \theta}.$$  

(4)

Then using Equation (3), one can compute the corresponding $\theta_f$ for this bending angle.

3. CHANGES IN BRIGHTNESS WITH ORIENTATION ANGLE

A relativistic jet with a velocity $v = \beta c$ (and a corresponding Lorentz factor $\gamma = 1/\sqrt{1 - \beta^2}$), moving in a direction at an angle $\theta$ with respect to the line of sight in the observer’s frame, has a beaming $\delta^{\alpha+\beta}$ with Doppler factor $\delta = 1/(\gamma (1 - \beta \cos \theta))$ where $\alpha$ is the spectral index defined by $I_\nu \propto \nu^{-\alpha}$ with $I_\nu$ the specific intensity. Beaming becomes large as $\theta$ becomes small; $\delta = \gamma$ when $\sin \theta = 1/\gamma$. As for the index $n$, one should use $n = 2$ if one is considering the integrated jet emission. This is because, due to the time
compression for the approaching component, a lifetime $\tau$ in the intrinsic frame will have a shorter duration $\tau/\delta$ in the observer’s frame. Thus with a smaller number of components visible at any time, the integrated emission will also be less. However, if one is considering the jet brightness (i.e., flux density per unit solid angle), then one should use $n = 3$ in the beaming formula, as we shall be doing here.

It is to be noted that the beaming factor becomes unity when $\sin \theta = \sqrt{2}/(1 + \gamma)$, and in fact for still larger $\theta$ it becomes less than unity, with $\delta = 1/\gamma$ for $\theta = \pi/2$. Therefore for, say, $\gamma = 10$, the brightness will be reduced for observers seeing the jet at right angles by a factor $10^{3+\alpha}$. Thus for relativistic jets lying in the sky plane, the observed jet brightness may be many orders of magnitude weaker than its intrinsic brightness in the rest frame.

If a jet is observed to be heavily beamed, then, being close to the line of sight ($\sin \theta \approx 1/\gamma$), we do not normally expect it to show large changes in the orientation angle $\theta$ because that would change the beaming by a large factor, usually causing a large drop in the jet brightness. Therefore, if anything, large changes in $\theta$ should appear more like gaps in the jet. Here we are neither going into the physics of jet formation nor entertaining the question of what might cause such large bends in a highly relativistic flow (see Appl et al. 1996); we are only examining expected changes in its apparent brightness if such large misalignments do take place. For brightness comparison it does not matter whether the bend is sharp or gradual; what matter are the initial and final values of orientation angle ($\theta$ versus $\theta_1$).

If bending shifts the orientation of the jet to a different value $\theta_1$, then the Doppler beaming factor would change to $\delta^{3+\alpha}$ where $\delta_1$ is the Doppler factor corresponding to $\theta_1$, i.e., $\delta_1 = 1/(\gamma (1 - \beta \cos \theta_1))$. That means the observed brightness of the jet will change by a factor $(\delta_1/\delta)^{3+\alpha}$. Actually the observed brightness of the jet would change by another factor, $\sin \theta/\sin \theta_1$, which is purely an effect of geometric projection. This projection factor is not accounted for in the relativistic beaming formula and is independent of the motion of the jet. The assumption here is that the jet is an optically thin linear feature, and when observed at an angle $\theta$, the length perceived will be foreshortened due to geometric projection by a factor $\sin \theta$, and therefore its apparent brightness will be higher by a factor $1/\sin \theta$. The ratio of the jet brightness after the misalignment to that before is then given by

$$B = \left[ \frac{1 - \beta \cos \theta}{1 - \beta \cos \theta_1} \right]^{3+\alpha} \frac{\sin \theta}{\sin \theta_1}. \tag{5}$$

Now the brightness ratio is unity ($B = 1$) if $\theta_1 = \theta$, which from Equation (3) will happen when

$$\tan(\zeta/2) = -\tan \theta \cos \phi. \tag{6}$$

4. RESULTS AND DISCUSSION

Pearson & Readhead (1988) noted that the distribution of misalignment angles in a core-dominated sample is bimodal with one peak near $0^0$ (aligned sources) and another peak around $90^0$ (misaligned or orthogonal sources). Conway & Murphy (1993) as well as Appl et al. (1996) also found the distribution of misalignment angles to be bimodal, with the secondary peak again around $90^0$. More recently Kharb et al. (2010), in an independent sample, found the distribution to be a smooth one with only a marginal peak around $90^0$. In any case misalignments of $60^0$ or more are found in $\sim$45%-50% of all these cases, and these large misalignments are often seen without any large changes in jet brightness.

Could such misalignments appear largely as a result of projection effects? The prevalent notion in the literature is that even though we see large misalignments in the jets, actual bendings ($\zeta$) may be small, and because the observer’s line of sight is at a small angle to the jet (a prerequisite for large relativistic beaming), even small intrinsic bending may appear as a large misalignment because of the geometry of projection (cf. Equation (1)). It is thought that since actual bending of the jets is very small, any changes in the relativistic beaming effects may also be small and large changes in brightness would not occur. We shall show the fallacy of this notion. For one thing, arguments leading to Equation (1) are true only for the specific case of $\phi = 90^0$, but in reality $\phi$ has an equal probability of taking any value between $0^0$ and $180^0$. Even otherwise, what really determines the beamed intensity is the orientation angle $\theta_1$ that the misaligned part of the jet makes with the line of sight of the observer, where even a small change from the erstwhile orientation angle $\theta$ could make a huge difference in the jet brightness.

The problem is actually twofold. First, it is difficult to get a population that will give a peak in the misalignment angle $\eta$ at around $\sim 90^0$. Conway & Murphy (1993) showed that if $\phi$ is randomly distributed (as it should be because it is the angle between two completely independent planes) then for no distribution of $\zeta$, $\theta$, and $\gamma$ could one get a peak in the misalignment angle $\eta \sim 90^0$. Thus the observed misalignments are difficult to obtain. Second, even if we ignore the difficulty of getting the observed distribution from any viable statistical distribution, and concentrate on individual cases of large misalignment angles (which after all can be obtained for some specific chosen values of $\zeta$, $\phi$, $\theta$ etc.), we may still have to match the observed relative brightness of the jets before and after the bending with the values expected from relativistic boosting, and this might be an equally daunting task.

The bending geometry is particularly simple for a misalignment $\eta = 90^0$, where the distribution shows a second peak. From Equation (4) we can write, $\tan \zeta = -\tan \theta \cos \phi$, the negative sign implying $\phi > 90^0$ since $\theta$ and $\zeta$ are presumably small. Then from Equation (3) we get a simple relation, $\cos \theta_1 = \cos \zeta \cos \phi$. If $\zeta_c$ denotes the critical value of the bending angle where $B = 1$ (or $\theta_1 = \theta$), then for $\eta = 90^0$ we get $\zeta_c \approx \sqrt{2} \theta$ (for a small $\theta$). Thus for $\gamma = 10$, $\theta \approx 5.7^0$, and we have $\zeta_c \approx 8^0$ for a $90^0$ misalignment. Even for a small change in bending, e.g., $\zeta \approx 6^0$, it can be easily calculated from Equation (5) that the jet would brighten by more than an order of magnitude ($B \approx 10^{4.7}$). A smaller $\zeta$ does not necessarily imply no change in the jet brightness.

In a more general case, assuming the jet has an initial orientation $\theta$ with respect to the observer’s line of sight, any particular misalignment seen by the observer is determined by a set of ($\zeta$, $\phi$) pairs in the $\zeta$-$\phi$ plane. Figure 2 shows such a diagram for an orientation angle $\theta = \sin^{-1}(1/\gamma)$ with $\gamma = 10$. Different solid curves plotted are for different misalignment angles ($\eta$). The dashed curve represents no change in brightness after a misalignment (i.e., $B = 1$ or $\theta_1 = \theta$), and its intersection with any given misalignment curve gives the critical bending angles ($\zeta_c$, $\phi_c$) corresponding to no change in brightness after that misalignment. Any departures from the critical ($\zeta_c$, $\phi_c$)
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The results are summarized in Table 1, where the three columns show (1) misalignment angle ($\eta$), (2) bending angle ($\zeta$), and the corresponding fraction of the azimuth angle ($\Delta\phi/2\pi$) for $0.5 \leq B \leq 2$. The chance of no change in the brightness is very unlikely to happen.

It is not possible to calculate the exact probabilities as we have no idea about the values that $\zeta$ in a jet could take. However, from observed $\eta$ one can get some constraints on the possible values of $\zeta$. From Figures 2 and 3 it can be seen that there will hardly be any change in the brightness for $\zeta \leq \theta$, due actually to a very small change in the orientation angle $\theta_1 \approx \theta$. But then the misalignment angle seen in the jet also cannot be large, i.e., $\eta \leq \theta$. However, with large misalignments ($\eta \sim 90^\circ$ or higher) often seen in jets, the bending angle $\zeta \geq \theta$, as also noted by Conway & Murphy (1993). From Figures 2 and 3 we see that the brightness ratio of the jet could be much below unity ($B \ll 1$) for large bending angles ($\zeta > 2\theta$), and this could very well happen because $\zeta$ and $\theta$ are quantities completely independent of each other. As for the azimuth angle $\phi$, we can be sure that $\phi$ is a random variable between 0 and $\pi$ because it is an angle between two independent planes, one determined by the intrinsic bending of the jet and the other determined by the observer’s line of sight. A small range of $\phi$ between the two dotted lines in Figures 2 and 3 means that in only a small percentage of cases does one expect to see changes in brightness within a factor of two, and that in the remaining cases changes in brightness after the misalignments would be much larger, even if we assume the range of $\zeta$ to be the most favorable, i.e., $\zeta$ does not go beyond $2\theta$.

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(ζ), and (3) the fraction of the azimuth angle (Δφ/2π) for 0.5 ≤ B ≤ 2. We may point out that most entries are approximate numbers, to indicate trends. Although we have no inkling of the distribution of possible values that ζ might take, it is still possible to get some idea of (N( |B| > 2))/N( |B| < 2)) for different ranges of ζ, expressed in terms of θ, irrespective of the misalignments. This is displayed in Table 2, where the three columns show (1) bending angle (ζ), (2) the fraction of the azimuth angle (Δφ/2π) for 0.5 ≤ B ≤ 2, and (3) the number of sources with brightness contrast larger than two as compared to those with contrast smaller than two (N( |B| > 2))/N( |B| < 2)). Of course it also has to be kept in mind that ζ and θ are otherwise completely independent quantities: while ζ is something intrinsic to the jet and its value may be determined by the jet physics or local circumstances near the location of the bend, θ is a pure chance value determined by the line of sight of the observer and the jet axis.

Figure 5 shows a plot of change in brightness as a function of ζ for the misalignment angles η = 90° and η = 60°, for θ = sin⁻¹(1/γ) for various γ values. What one again sees is that a small change in the bending angle (from ζ to ζ ≈ θ) can make the jet after the bending brighter by many orders of magnitude. Figure 6 shows a plot of beaming factor against azimuth angle φ for the misalignment angles η = 90° and η = 60°, for θ = sin⁻¹(1/γ) for various γ values. We see that while the critical value of φ does depend upon the misalignment angle, it is more or less independent of the Lorentz factor γ of the jet motion, and we see that our overall conclusions do not change for different but small misalignment angles, i.e., for ζ ≈ θ.

Of course, we assumed no change in the intrinsic brightness and we also assumed no change in the speed of the jet material; the only change assumed is in the direction of the jet. This was done to keep the problem simple and the number of free parameters to a minimum. Even otherwise, to assume changes in the intrinsic properties of the jet or in its relativistic speed of just the right amount so as to cancel neatly any variation in the relativistic beaming factor due to the change in the orientation angle, and thus for it to appear as a result with a similar brightness after the bending as it was before, would be a rather contrived scenario.

The question of comparison of the observed jet brightness on either side of misalignments has not been systematically explored in the literature. A quantitative comparison of the flux ratios on either side of the bend may, however, need to be corrected for numerous selection effects. As we discussed above, there would be many more large misalignments with large flux ratios that could be missed because of difficulties due to dynamic range limitations in measuring flux ratios of jets differing in brightness by more than an order of magnitude. In a proper, carefully selected sample of bending angles, observed with sufficiently good resolution and sensitivity, the distributions of the brightness ratios on either side of the bends would need to be consistent with the predictions made here, if relativistic beaming is true. At present, such data are either not yet available or not in a form to directly test or resolve the issues raised here. We may point out that there are independent, convincing arguments in the literature (Bell 2012) that Doppler boosting may have played no significant role in the finding surveys of radio-loud quasars.

### Table 2

| ζ (deg) | Δφ/2π | N2/N1 |
|---------|-------|-------|
| ζ < θ   | ≥0.8  | <1    |
| 0.2θ ≤ ζ < θ | ~0.2–0.5 | ~1–5 |
| θ ≤ ζ ≤ 2θ | ~0.03–0.1 | ~10–30 |
| ζ > 2θ  | <0.01 | >10²  |

#### Figure 5

Change expected in the jet brightness after an observed misalignment as a function of the intrinsic jet bending angle ζ, for various γ values. The initial orientation angle θ of the jet with respect to observer’s line of sight is assumed to be sin⁻¹(1/γ). The family of curves plotted are for two different misalignment angles: η = 90°—solid curves, η = 60°—dot-dash curves. The horizontal dashed line represents no change in the brightness while the horizontal dotted lines mark the boundary where brightness changes by a factor of two.

#### Figure 6

Same as Figure 5, but now the change expected in the jet brightness after an observed misalignment is plotted as a function of the azimuth angle φ, for various γ values.

### 5. CONCLUSIONS

We have shown that the relativistic beaming models, along with the observed large misalignments seen in the jets of AGNs, predict large contrasts in the brightness observed before and after the misalignments. It was also shown that for every large misalignment (ζ ≥ 60°) detected, there might be an order-
of-magnitude larger number of similar misalignments that might not have been seen because of high brightness ratios. That would also imply that large misalignments occur at least an order of magnitude more often than what has been inferred observationally. Carefully selected samples of jet misalignments, with measured ratios of the jet brightness on either side of the bends would be needed to test the consistency of the relativistic beaming hypothesis observationally.

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