Estimates of Doppler Factors, Outflow Angles, and Bulk Lorentz Factors for a Sample of Compact Radio Sources

R. A. Daly, E. J. Guerra, & A. Guijosa
Department of Physics, Princeton University, Princeton, NJ 08544

Abstract. Compact radio sources can be strongly affected by relativistic motion. The relativistic motion is characterized by 2 quantities: the speed or bulk Lorentz factor of the outflow, and the angle subtended by the outflow direction and the line of sight to the observer. One combination of these yields the Doppler factor of the outflow, and a different combination yields the apparent (sometimes superluminal) speed with which a feature moves away from the core. Since there are two observed quantities, the Doppler factor and the apparent velocity, the two unknowns, the bulk Lorentz factor and the outflow angle, can be estimated separately. Thus, the bulk Lorentz factor and the outflow angle can be estimated separately for a source that has an estimate of both the Doppler factor and an apparent velocity, assuming that the apparent velocity is due to physical motion rather than a pattern speed.

Two key results are presented in this paper. First, equipartition Doppler factors have been estimated for a sample of 105 sources with previously estimated inverse Compton Doppler factors. The different categories of active galactic nuclei (AGN) have different ranges and typical values of the Doppler factor; lobe dominated AGN tend to have low Doppler factors, core-dominated quasars tend to have large Doppler factors, and BL Lacertae objects span the full range of Doppler factors. These results support the “orientation unified model” for different categories of AGN.

The second key result comes from combining equipartition Doppler factors and apparent velocities from superluminal motion studies. There are 43 sources for which apparent speeds and equipartition Doppler factors are available. The bulk Lorentz factor and outflow angle are estimated for each of these 43 sources. Again, typical parameter values for different categories of AGN are quite interesting, and generally agree with expectations based on the orientation unified model.

1. Introduction

Relativistic motion in compact radio sources is indicated by apparent superluminal motion, one-sidedness of jets, rapid flux variations, and a deficit of synchrotron self-Compton X-rays. The relativistic motion is characterized by
2 quantities: the angle \( \theta \) subtended by the direction of outflow and the line of sight to the observer, and the bulk Lorentz factor of the outflow \( \gamma \), where \( \gamma = 1/\sqrt{1 - \beta^2} \), and \( \beta \) is the speed of the outflow relative to the speed of light.

The Doppler factor \( \delta \) of the outflow is a combination of these 2 parameters: 
\[
\delta = \gamma^{-1}(1 - \beta \cos \theta)^{-1}.
\]

If a source has an estimate of both \( \delta \) and \( \beta_{\text{app}} \), then there are 2 observations to constrain the 2 unknowns, so the bulk Lorentz factor \( \gamma \) and the outflow angle \( \theta \) may be estimated separately for the source. Combining the equations for \( \beta_{\text{app}} \) and \( \delta \), we obtain:

\[
\gamma = (2\delta)^{-1}(\beta_{\text{app}}^2 + \delta^2 + 1) \tag{1}
\]

and

\[
\cos \theta = \left(\frac{1}{\sqrt{\gamma^2 - 1}}\right)(\gamma - \delta^{-1}) \tag{2}.
\]

Equipartition Doppler factors for 105 sources are discussed in §2, bulk Lorentz factors and outflow angles for 43 sources are discussed in §3. The results are summarized in §4.

2. Equipartition Doppler Factors

Bulk relativistic motion can strongly alter the appearance of the emitter. In order to be able to study intrinsic source properties, and selection effects that determine which subset of the parent population make it into a radio catalogue, it is necessary to understand and correct for relativistic effects.

The Doppler factor may be estimated from single epoch radio observations using the “equipartition Doppler factor,” first introduced by Readhead (1994), and computed for a sample of 105 radio sources by Guijosa and Daly (1996) using the sample compiled and studied by Ghisellini et al. (1993). Guijosa and Daly (1996) compare the equipartition Doppler factor with the inverse Compton Doppler factor, and find that the two are strongly correlated. The appropriate error bar for each of these quantities is presently under investigation (Guerra and Daly 1995), and we plan to investigate in detail whether the fact that the ratio of equipartition to inverse Compton Doppler factor is about 1 ± 0.1 indicates that both are reliable estimators of the true Doppler factor.

It is quite interesting to note that the range and typical value of the Doppler factor are different for each of the categories of AGN studied. The 8 radio galaxies in the sample all have equipartition Doppler factors \( \delta_{eq} \) less than or on the order of 1, as do most of the 11 lobe-dominated quasars (except for one quasar with \( \delta_{eq} \approx 65 \)). The 24 core-dominated high-polarization and 29 core-dominated low-polarization quasars are quite similar and have \( \delta_{eq} \) that range from about 1 to 30; the only apparent difference between the populations is that the core-dominated low-polarization quasars seem to have a cluster of points with \( \delta_{eq} < 1 \) that is not present in the high-polarization population. And, the 33 BL Lacertae objects have \( \delta_{eq} \) that span the full range, with \( \delta_{eq} \) much less than one up to about relatively large values of about 30 (see figure 1 and the figures of Guijosa and Daly 1996).
Figure 1. Equipartition Doppler Factor as a Function of (1+z)

The range of $\delta_{eq}$ for each category of source is evident on figure 1, which shows the redshift behavior of $\delta_{eq}$ for the sample of 105 sources discussed by Guijosa and Daly (1996). The Doppler factor appears to increase with redshift, as expected from selection effects; more distant sources must be more strongly Doppler boosted to make it into the sample. Note, however, that a large part of the effect is due to low-redshift BL Lacs, and the redshift behavior of $\delta_{eq}$ may be different for different categories of AGN; this is presently under investigation.

3. Bulk Lorentz Factors and Outflow Angles

It would be fascinating and enlightening to be able to study the bulk Lorentz factor and outflow angle for different categories of AGN. This would shed light on the relationships between different categories of AGN, and allow an estimate of selection effects for different types of AGN as a function of redshift. As mentioned in §1, it is possible to estimate $\gamma$ and $\theta$ separately for sources with an estimate of both $\beta_{app}$ and $\delta_{eq}$. Two important assumptions are: (1) that the apparent velocity is due to a physical motion of the emitter rather than a pattern speed of the flow, and (2) that the equipartition Doppler factor provides a good rough estimate of the true Doppler factor. Both of these assumptions are presently under investigation by Guerra and Daly (1995), who discuss the uncertainty on estimates of $\delta_{eq}$, $\gamma$, and $\theta$. Although error bars are not included here, some obvious trends are indicated by the data that are likely to stand the test of time.

Figure 2. Outflow Angle $\theta$ as a Function of Bulk Lorentz Factor $\gamma$

Figure 2 shows the values of $\theta$ and $\gamma$ obtained by applying equations (1) and (2) to the 43 sources studied by both Vermeulen and Cohen (1994), who investigate $\beta_{app}$ for a large number of sources, and by Guijosa and Daly (1996), who investigate $\delta_{eq}$ for a large number of sources. Radio galaxies have Lorentz factors that are typically close to unity, and tend to have very large angles to the line of sight. Specifically, 6 of the 7 radio galaxies have values of $\gamma$ between about 1 and 2, and the seventh has $\gamma \sim 10$; all of the sources have $\theta$ between 45° and 180°, and about half of the radio galaxies in the sample have $\theta$ greater than 90°. If these values are accurate, they indicate that these radio galaxies have a relatively slow, one-sided jet that is pointing away from the observer about half the time.

Six of the 7 lobe-dominated quasars in the sample have $\theta$ between 20° and 60°, and one has $\theta \sim 0°$; the Lorentz factors range from 2 to 30, with an apparent peak at $\gamma \sim 10$.

Nine of the 10 low-polarization core-dominated quasars have $\theta$ between 0° and 20°, and one has $\theta \sim 45°$; the $\gamma$ factors range from 2 to 20 with an apparent peak at $\gamma \sim 10$. The range of Lorentz factors for the high-polarization core-dominated quasars seems to be larger than that for the low-polarization quasars,
with $\gamma$ ranging from about 1 to 200 (it is not clear if this apparent difference is significant), and 4 of the 8 high-polarization core-dominated quasars have $\gamma \sim 10$. All of the 8 high-polarization core-dominated quasars in the sample have $\theta$ between $0^\circ$ and $20^\circ$. The 3 core-dominated quasars without polarization information have values of $\theta$ between about $30^\circ$ and $60^\circ$, and $\gamma$ between about 1 and 10.

The 8 BL Lacertae objects seem to have a relatively broad range of $\theta$ and $\gamma$, and sources with large $\theta$ tend to have small $\gamma$. Two BL Lacs have $\theta$ between $40^\circ$ and $60^\circ$ and $\gamma$ between 1 and 2, and 6 BL Lacs have $\theta$ between about zero and $20^\circ$ and $\gamma$ between about 2 and 30.

Figure 3. Outflow Angle $\theta$ as a Function of $(1+z)$

Figure 4. Bulk Lorentz Factor as a Function of $(1+z)$

Figures 3 and 4 show $\theta$ and $\gamma$ as a function of $(1+z)$. Both appear to exhibit the type of selection effect seen in figure 1 and expected if the intrinsic luminosity of the sources is nonevolving, since in this case higher redshift sources must be more strongly Doppler boosted to make it into the sample. Thus, figures 3 and 4 suggest that $\theta$ decreases and $\gamma$ increases with redshift. This is not a result of the adopted cosmology; similar results are obtained when different cosmological parameters are assumed. However, it is not clear if the effect is significant, or if it is operating for each category of AGN separately; this point is presently under investigation. Generally speaking, the results presented here are consistent with those presented by Vermeulen and Cohen (1994).

4. Summary

It is striking that the different categories of AGN have different typical values and ranges of $\delta_{eq}$, $\gamma$, and $\theta$. Generally, different categories of AGN have values of these parameters that are consistent with expectations based on the orientation unified model. It is quite interesting to note that radio galaxies, lobe-dominated quasars, and some BL Lacs have very similar values of the equipartition Doppler factor $\delta_{eq}$, but clearly separate out on the $\theta$-$\gamma$ diagram. The radio galaxies studied here appear to lie in a region of the diagram that is separate from the other types of AGN. Further, the radio galaxies have relatively slow outflow velocities, and about half of the sources are pointing away from the observer, suggesting one-sided slow jets; note that radio galaxies are the only category of source with $\theta > 90^\circ$. Lobe-dominated quasars, most BL Lacs, and core-dominated high- and low-polarization quasars fill in the rest of the $\theta$-$\gamma$ diagram.

Lobe-dominated quasars have relatively large $\theta$ and small $\gamma$ compared with other types of quasars, but lie in a region of the diagram distinct from radio galaxies. Core-dominated quasars tend to have the largest values of $\gamma$ and smallest values of $\theta$. BL Lacertae objects appear to span the full range of parameters between lobe-dominated quasars and core-dominated quasars on the
Similar conclusions are indicated by $\delta_{eq}$. It is clear from figure 1 that radio galaxies and lobe-dominated quasars tend to have low values of the equipartition Doppler factor, typically $\delta_{eq} < 1$. Core-dominated high- and low-polarization quasars tend to have high values of the Doppler factor, with $\delta_{eq}$ between about 1 and 30, with a few sources having a value less than 1. And, the BL Lacertae objects seem to span the full range of $\delta_{eq}$ from values much less than one to values over 10. Again, we see that BL Lacs span the full range, with values similar to lobe-dominated quasars and core-dominated quasars, though now with a much larger sample.

The large range of $\theta$ and $\delta_{eq}$ seen for BL Lacs may suggest either that we are looking so close to the central engine that the full collimation is not complete, so we see a “spray” and thus a broad range of $\theta$ and $\delta_{eq}$, or that the opening angle that allows an observer to see into the heart of the AGN and classify it as a BL Lac is larger than previously thought, or perhaps some sources have been mistakenly classified as BL Lacs.

It is important to keep in mind that the $\theta$-$\gamma$ diagram has been constructed assuming that $\delta_{eq}$ is a good measure of the true Doppler factor, and that $\beta_{app}$ reflects a bulk flow rather than a pattern speed. Both of these assumptions are presently under investigation (Guerra & Daly 1995).

Acknowledgments. It is a pleasure to thank the participants of this meeting and other colleagues for interesting discussions, especially Marshall Cohen, Ed Groth, Alan Marscher, Tim Pearson, Tony Readhead, Larry Rudnick, Peter Scheuer, Rene Vermeulen, and Paul Wiita. This work was supported in part by the US National Science Foundation through a Graduate Student Fellowship and a National Young Investigator Award, by the Independent College Fund of New Jersey, and by a grant from W. M. Wheeler III.

References

Ghisellini, G., Padovani, P., Celotti, A., & Maraschi, L. 1993, ApJ, 407, 65
Guerra, E. J., & Daly, R. A. 1995, in preparation
Guijosa, A., & Daly, R. A. 1996, ApJ, 461, in press
Readhead, A. C. S. 1994, ApJ,
Vermeulen, R. C. & Cohen, M. H. 1994, ApJ, 430, 467
All Classes ($q=0.05, h=1$)
All Classes (q=0.05, h=1)

Theta (deg)

1+z

BL Lac ×
CDHPQ ▲
CDLPQ □
CDQ(NPI) ◊
LDQ ★
RG +
All Classes (q=0.05, h=1)

- BL Lac
- CDHPQ
- CDLPQ
- CDQ(NPI)
- LDQ
- RG

Gamma vs. (1+z) graph.