Astrophysical Phenomena Revealed by Space VLBI
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Observations of Relativistic Outflow in AGN and the Brightness Temperature of Synchrotron Sources

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Abstract

VLBA observations over a five year period are used to discuss the outflow of relativistic plasma from the center of quasars and AGN. The distribution of apparent linear velocity has a tail indicating pattern velocities up to $20c$, but there is little evidence for corresponding Doppler boosting of the flux density.

1 Introduction

We are using the VLBA to investigate the flow of relativistic plasma from the center of quasars and AGN. Our goals are to describe and understand source kinematics. We wish to know: a) Do components move along straight or curved trajectories? b) Do all components in an individual source follow the same trajectory or have the same velocity? c) Are there accelerations or decelerations of individual components? d) Does the apparent velocity depend on luminosity or other parameters? e) Can the time of component ejection be related to flux density changes at radio, optical, or high-energy wavelengths? We also wish to compare the kinematic properties of AGN, quasars, and BL Lac objects with the systematic differences expected from unified models, and we also want to compare the observed motions of strong gamma-ray sources with those that are not.

We interpret our observations in terms of relativistic beaming models with the ultimate goal of understanding the process of acceleration and collimation of relativistic jets. We want to know if simple ballistic models are correct or whether there are differences between the bulk flow velocity and the pattern velocity. Finally, we are interested in exploring the use of the angular velocity–redshift (μ–z) relation to test

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world models. We are mainly interested in statistical properties, so our investigation complements other programs designed to study individual sources in more detail including multiwavelength polarization observations (e.g., Marscher, these proceedings) or studies of particular classes of source such as BL Lac objects.

We have chosen to observe at a wavelength of 2 cm as a compromise between getting the best angular resolution and good image quality. At shorter wavelengths the resolution is better, but the sensitivity is worse; individual features may decay with time before their motion can be determined, and tropospheric fluctuations degrade the image quality. At longer wavelengths the data are more robust, but the resolution is often inadequate to separate closely spaced components.

We have observed approximately 150 sources over a period of five years. Two to three 48-hour observing runs per year allow 60 sources to be observed in each session. There are 4–18 month intervals between observations of individual sources, depending on the apparent rate of change in the structure. Up to ten epochs have been obtained for the fastest sources. The observing procedure is described in more detail by Kellermann et al. (1998). Typically each image has an rms noise of 200 to 300 μJy and the resolution is 0.5×1 mas. Assuming a minimum SNR of 10:1 for individual components, we should be able to measure component locations to within about 0.1 mas; therefore, after 5 years we might expect to determine the rate of motion with an accuracy of only a few hundredths of a mas/yr. However, in practice our accuracy is considerably poorer, owing in part to changes in component structure and/or changes in the synthesized beam shape resulting from the loss of one or more antennas.

Single-epoch images for 132 sources have already been published (Kellermann et al. 1998). Images from other epochs are available at http://www.cv.nrao.edu/2cmsurvey. As our resolution at 2 cm is similar to that of VSOP at 6 cm, our program provides good matched resolution images for studies of the spectral distribution across compact sources.

2 The Distribution of Apparent Velocity

We interpret our observations in terms of relativistic twin-ejection models. For a given intrinsic value of velocity, v, $\beta = (v/c)$ where c is the velocity of light; $\gamma = (1-\beta^2)^{-1/2}$; and the Doppler factor, $\delta = 1/(1-\beta_b \cos\theta)$; and where θ is the angle between the beam and the

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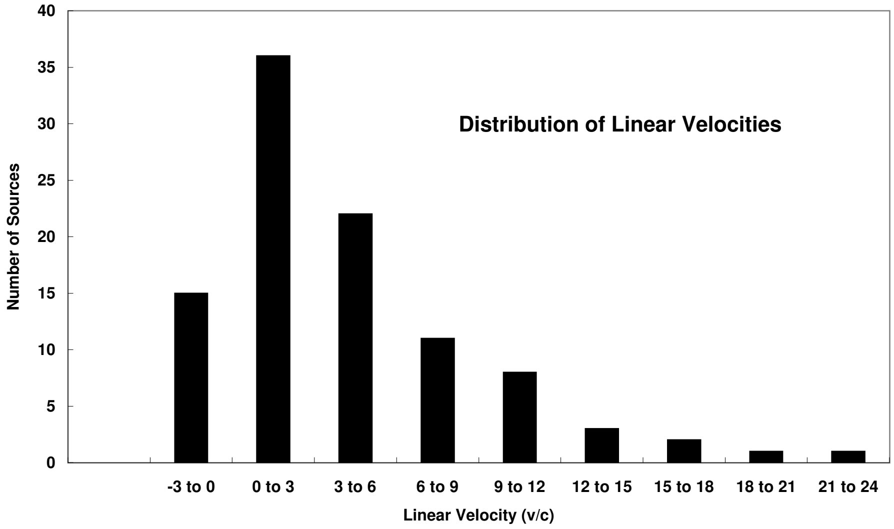

Figure 1: The observed apparent velocity distribution

line of sight and β_b is the bulk velocity of the plasma flow. For numerical calculations we assume $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 1/2$.

There are three observable effects of relativistic motion.

a) The Doppler shift, which moves the rest frame frequency, ν_r, to $\nu_{obs} = \delta\nu_r$ in the observer's frame.

b) The apparent transverse motion $\beta_a = \sin\theta/(1 - \beta_p\cos\theta)$ where β_p is the intrinsic velocity of the pattern flow.

c) Relativistic or Doppler boosting of the intrinsic luminosity, S_i to give an observed luminosity, $S_{obs} = S_i\delta^3$.

Assuming that the ejection of relativistic beams is randomly oriented in space, in the absence of Doppler boosting the probability, that a source lies within an angle θ to the line of sight is proportional to $1/(1 - \cos\theta)$ and most sources will lie close to the plane of the sky. However, due to Doppler boosting, flux-limited samples are dominated by sources oriented close to the critical angle $1/\gamma$.

Figure 1 shows the observed distribution of β_a, defined as the separation rate of the two brightest components for each source in our sample where we have adequate data to define the apparent velocity. In every

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case where the core can be unambiguously identified at the end of a one-sided structure, the observed flow is outward. The few cases shown in Fig. 1 with negative velocity are not significant, or occur in complex, often symmetric sources, where we have probably not properly identified the core. The distribution of observed velocity is concentrated at low velocities, with a median value of $\beta_a = 2.9$. This is in sharp contrast to early studies which appear to have been biased by observers' selection to study and report only sources with large apparent velocity, but it is consistent with the more recent studies reported by Vermeulen (1995) based on observations at 6 cm. The observed distribution appears to require either a large spread in γ (Lister and Marsher 1997) or that the bulk velocity is much less than the pattern velocity so that there is little or no Doppler bias toward observing sources near the critical orientation $\theta = 1/\gamma$. Indeed the observed distribution is not unlike the simple *light echo model* discussed by Ekers & Laing (1990).

It is tempting to consider interpretations which do not invoke the usual Doppler bias. However, it is then hard to understand the apparent one-sidedness of the observed structures (e.g., Kellermann et al. 1998). The low-luminosity sources, which often have two-sided jets, appear to move more slowly, consistent with the simple Doppler boosting picture. It will be important, in future observations of the more rapidly moving sources, to obtain sufficient dynamic range and sensitivity to detect any counter-jet, thus providing additional constraints on models which invoke Doppler boosting. Interestingly, we find a very slow velocity in the jet of M87 where the brightest jet component located about one parsec from the core has an apparent velocity of only $0.1c$, although HST and VLA observations further along the jet show velocities closer to c (Junor, these proceedings). In other sources as well, such as 3C84 (Dhawan et al. 1998), where there is a clear observed difference between the flow velocity and pattern velocity, there is an apparent increase in velocity along the jet.

Of course, this does not necessarily mean that components actually accelerate as they move outward from the core. In fact, we do not find significant evidence for changes in the speed or direction of any individual component. Instead, the observed increase in apparent velocity may be the result of bending, although this should produce apparent decelerations in addition to accelerations. Alternately, we may simply be seeing the consequence of the fact that the faster components have propagated further from the core. This may be tested by checking if the

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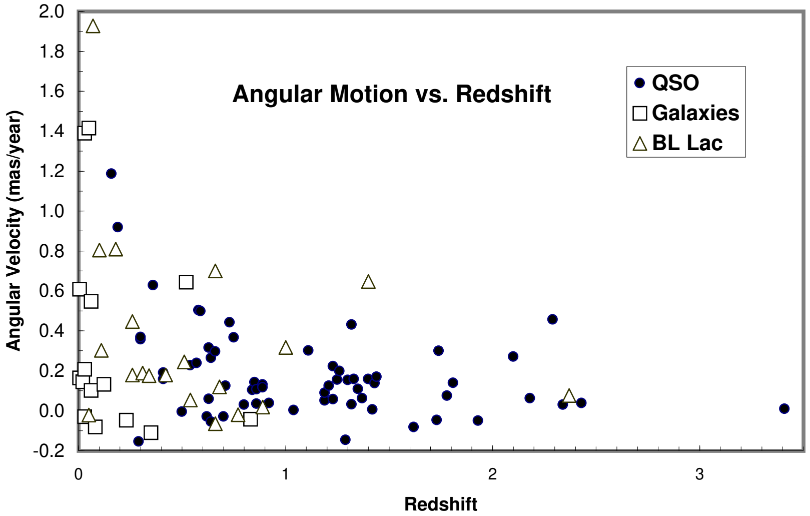

Figure 2: Apparent angular velocity for quasars, BL Lacs and radio galaxies as a function of redshift.

observed velocities are proportional to their distance from the core.

In sources with multiple components, the apparent velocities are similar, but not identical. In those cases where we have been able to follow the two-dimensional trajectory, there is some evidence that the different components do not follow the same trajectories, but further observations will be required to confirm this (e.g., Zensus et al. 1995)

It is widely assumed that the observed gamma-ray emission from quasars originates at the base of the jet, close to the accretion disk of a supermassive black hole. Radio VLBI observations image the region closer to the central engine than is possible in any other wavelength band and may provide some insight into the generation of the gamma-ray emission. We have examined the distribution of apparent velocities for sources which have been detected by the EGRET facility aboard GRO. Taking only radio loud quasars with $P_{5GHz} \geq 10^{25.5}\ W/Hz$, the EGRET sources appear to have a median value of $\beta = 5.7 \pm 0.6$ compared with the non EGRET sources of 3.9 ± 0.4. We note however, that unlike the radio observations of QSO's which have a well defined radio-loud and radio-quiet population, the range of gamma-ray flux sensitivity is currently

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very limited so that there is not a well defined class of gamma-ray loud and gamma-ray quiet quasars. Future observations with GLAST will better define the relationship, if any, between gamma-ray luminosity and apparent velocity as well as determine if the onset of a component ejection corresponds to a gamma-ray flare.

3 Applications To Unified Models and Cosmology

Figure 2 shows the dependence of apparent angular velocity on redshift for the brightest jet component in each source. We note two important things. First, there appears to be no obvious difference in observed velocity among quasars, the cores of FR II radio galaxies, and BL Lacs, contrary to what might be expected from unified models which predict systematic differences in orientation among sources classified as quasars, radio galaxies, or BL Lacs. In particular, we confirm the previously reported superluminal motion for the cores of the FR II radio galaxies, 3C 111 (Preuss et al. 1990) and 3C 390.3 (Alef et al. 1996).

Second, we note the apparent angular velocity is greatest for sources at low redshift, as expected if the redshift is a measure of distance. Vermeulen & Cohen (1994) have discussed the use of the angular velocity–redshift, or μ–z, relation to distinguish among cosmological models. Unlike these earlier studies which considered the upper envelope of the distribution appropriate to a Doppler-boosted sample, we have considered the binned median velocity distribution which may be more appropriate to the apparent lack of Doppler induced bias in our sample. While the dispersion is too great to meaningfully distinguish among world models, it is encouraging that the median angular velocity does appear to decrease with increasing redshift in a manner consistent with standard world models. Future observations of component motions for high-redshift quasars may offer the possibility of better defining the cosmological parameters.

4 Inverse Compton Limits and Brightness Temperature

Although there are no unresolved sources in our sample, there are ten sources, 0007+106, 0048−097, 0235+164, 0642+449, 0808+019, 1308+326, 1638+398, 1741−038, 1758+388, and 2145+067 which consist of a single barely resolved component with apparent brightness temperatures in the range 10^{11-12} K. These sources will be useful as

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calibrators for centimeter wavelength VLBI. In addition, the strong millimeter source 1921−293 which has a diffuse cocoon-like extended feature is dominated by a single component with brightness temperature comparable to the above sources. Kellermann and Pauliny-Toth (1969) have pointed out that owing to inverse Compton cooling, brightness temperatures in excess of 10^{11-12} K cannot be maintained for long periods. However, Readhead (1994) has argued that if there is equipartition between the magnetic energy density and relativistic particle density, then the peak brightness temperatures are nearly an order of magnitude lower. It seems to us, however, that it is unlikely that such equipartition conditions will exist in sources where there is clearly a sudden highly collimated violent release of relativistic plasma.

These sources, therefore, do not necessarily require a Doppler boosting factor to reduce the rest frame brightness temperature to the equipartition value. Moreover, Slysh (1992) has argued that a non-equilibrium situation may exist for months to years following the turn-on of an electron energy distribution initially extending to very high energy. This is consistent with the observed variability time scales, even in the case of the rapid intraday variables (e.g., Wagner 1998). However, it is not clear if the analysis of Slysh properly includes the effect of second order scattering which greatly reduces the lifetime to inverse compton cooling.

Thus, Doppler factors deduced from observed brightness temperatures and measurements of inverse Compton scattered X-ray emission, may not be as large as previously discussed, consistent with the low apparent velocities which we have observed, and the apparent absence of strong Doppler boosting.

5 Summary

Although most theoretical models of AGN and jets involve infall on a massive central engine, only outflows are observed. The typical apparent observed velocity is about $3c$ and ranges up to about $20c$ corresponding to real velocities of 95 and 99.7 percent of the speed of light, respectively. As previously reported in other studies, low-luminosity sources, lobe dominated quasars, and compact symmetric objects appear to show smaller velocities. Quasars associated with powerful gamma-ray emission appear to have somewhat faster ejection velocities.

Individual components appear to move with constant velocity. We find no convincing evidence for acceleration or deceleration of individual

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components, although more detailed studies of some strong sources do show changes in component velocity (e.g. Zensus et al. 1995). In any individual source, different components appear to move with similar velocity possibly along somewhat different trajectories. The distribution of linear velocity shows surprising little evidence for Doppler bias.

There is no clear difference in the kinematics of quasars, BL Lacs and AGN. The median angular velocity decreases with increasing redshift consistent with standard cosmological models, but the data are not yet sufficiently precise to distinguish among currently discussed models.

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