Kinematics of quasars and AGN

K.I. Kellermann\textsuperscript{a}, R.C. Vermeulen\textsuperscript{b}, J.A. Zensus\textsuperscript{c}, M.H. Cohen\textsuperscript{d}, A. West\textsuperscript{a}

\textsuperscript{a}NRAO, Edgemont Rd., Charlottesville, VA 22903, USA
\textsuperscript{b}NFRA, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
\textsuperscript{c}MPIfR, Auf dem Hügel 69, D-53121 Bonn, Germany
\textsuperscript{d}Department of Astronomy, Mail-Stop 105-24, Caltech, Pasadena, CA 91125, USA

Abstract

The VLBA has been used over a period of four years to study the internal motions within a sample of quasars and AGN. In most sources, features appear to propagate away from the central engine along a well collimated radio jet with apparent transverse velocities between zero and $10c$, with some evidence for apparent accelerations and decelerations. The distribution of apparent velocity is not consistent with any simple ballistic model and appears to require either a spread in intrinsic velocity or a difference between the bulk velocity and pattern velocity. The dependence of apparent angular velocity with redshift is consistent with standard Friedmann world models. Further observations of a larger source sample, especially at large redshift may lead to meaningful constraints on world models. © 1999 Elsevier Science B.V. All rights reserved.

PACS: 98.54.-h; 98.54.Cm; 98.70.Dk

Keywords: Galaxies: active; Galaxies: jets; Galaxies: kinematics; Galaxies: nuclei; Quasars: general

1. Introduction

One of the driving forces behind the construction of the VLBA was to facilitate frequent observations of quasars and AGN in order to determine their internal motions. Understanding of the kinematics of quasars and AGN are important for two reasons: first, it is only at radio wavelengths that it is possible to directly observe the outflow of relativistic plasma close to the central engine where the plasma is accelerated and collimated into the narrow jet which feeds the outer radio lobes. Detailed observations of jet kinematics close to their origin may lead to a better understanding of jet physics and clues to the nature of the central engine. Second, an accurate determination of the distribution of apparent angular velocities and their dependence on redshift, may lead to significant constraints on world models (e.g., Vermeulen & Cohen, 1994).

2. The observations

Since the beginning of routine observations with the VLBA in 1994 we have been making multi-epoch observations of a sample of about 150 quasars and AGN at 15 GHz (2 cm). Single epoch images showing the best image obtained for 132 sources along with a description of our observing technique have already been published (Kellermann et al., 1998). Images obtained at all epochs may be found...
at our web site www.cv.nrao.edu/2cmsurvey which will be updated as future observations become available.

As there are no 2 cm sky surveys available, we have based our source list on the 6 cm all sky catalogue of Kühr et al. (1981) as updated by Stickel et al. (1994) by selecting sources on the basis of their spectra that are expected to have compact structure stronger than 1 Jy for declinations north of 10 degrees, and greater than 2 Jy for declinations between −30 and +10 degrees. A few sources of special interest were also included which do not fulfill this criteria. However, uncertainties in the radio spectra and time variations in the flux density lead to incompleteness in our source list. Starting in 1997, we began to supplement our source list based on single epoch spectra observed by Kovalev & Kovalev (1998) at the RATAN-600 radio telescope, as well as other VLBA and VLBI observations (e.g., Moellenbrock et al., 1996).

We have so far, made observations at a total of 8 epochs between 1994 and the present. For each source in our sample we have obtained up to 7 observations over the four year period. By the end of 1999 we expect to have at least three epochs on about 150 sources. Our images typically have an rms noise of ∼250 μJy and a resolution of 1 × 0.5 mas with the major axis oriented roughly in the north-south direction. Thus, for unresolved and slightly resolved components stronger than 100 mJy we are generally able to measure the component velocity to an accuracy better than 0.01 mas/year. We are therefore able to accurately determine component velocities even for sources with subluminal motions.

Our observations complement the 6 cm global VLBI observations of CJF sources reported by Britzen et al. (1998) in several ways. Our resolution is better by a factor of 2 to 2.5. This allows us to achieve a comparable accuracy to observed motions in half the time. Moreover, with superior resolution, we are better able to resolve the individual jet features. This leads to improved accuracy as small changes in the intensity of blended features lead to uncertainties in the measured positions and corresponding errors in the determination of component velocities. On the other hand, our sensitivity is poorer at 2 cm than at 6 cm, and as the jet decays faster at 2 cm, we are able to follow the motion of individual components for a shorter time.

3. Kinematics

In Fig. 1, we show the observed distribution of apparent linear velocities for 72 sources with asymmetric structure and well determined motions. Low luminosity sources, with $P_b < 10^{25.5}$ W/Hz appear to move more slowly. However, as these low luminosity sources are all at low redshift, we cannot break the degeneracy in our current sample between redshift and luminosity. Moreover, we note that the low luminosity sources are mostly AGN rather than quasars. For a given luminosity and redshift, we find no clear difference in the apparent motions of one-sided quasars, AGN, or BL Lac objects. This is perhaps surprising, since with unified schemes AGN, BL Lac and quasars are expected to be increasingly oriented along the line of sight, so that the observed kinematics should differ among these different populations. We note however, that in two-sided sources which presumably lie close to the plane of the sky, the apparent velocity is smaller than in one sided sources. We find some evidence for accelerations and decelerations along the jet, but it is not clear if this represents real changes in velocity, or is just the effect of motion along a curved trajectory with a changing inclination to the line of sight. Our new observations confirm the previously reported superluminal motion in the cores of the FR II radio galaxies 3C 111 (0415 + 379) reported by Alef et al. (1998) and 3C 390.3 (Alef et al., 1996).

We base our discussion on the twin ejection relativistic beaming model, (e.g., Blandford & Rees, 1974; Blandford & Konigl, 1979). We assume that material is ejected with an intrinsic velocity near the speed of light. Relativistic motion of the radiating plasma has three observational consequences. (i) Owing to the Doppler shift, the observed emission from the approaching (receding) component is emitted at a longer (shorter) wavelength in the source rest frame. (ii) Due to differential Doppler boosting, the approaching component will appear brighter than the receding component. (iii) Since the approaching component is nearly catching up with its own radiation, an observer located close to the direction of motion sees apparent superluminal motion. In a randomly oriented sample, one expects that most sources lie close to the plane of the sky, so that the apparent observed velocities should peak near $c$ or $2c$. On the other hand, in a flux limited sample,
differential Doppler boosting gives a bias toward components moving close to the line of sight. The observed distribution of apparent velocities depends in detail on the intrinsic value of the Lorentz factor, γ, the spectral index, and the slope of the radio source count. Vermeulen (1995) has shown that for a wide range of parameters, the observed distribution of apparent velocities should be closely peaked near γc. However, the observed distribution is not consistent with any simple ballistic model and appears to require either a large dispersion in intrinsic velocity or a difference between the bulk flow velocity and the pattern velocity.

4. Gamma-ray sources

Many of the sources in our sample are known sources of powerful gamma-ray emission (Mattox et al., 1997). We find that for a sample of 15 observed gamma-ray sources, the mean observed apparent velocity (v/c) = 5.7±0.6. This may be compared with a value of (v/c) = 3.9±0.4 for 48 non gamma-ray sources with comparable radio luminosity and structure. It is widely supposed that the gamma-ray emission originate deep within the relativistic jet close to the central engine. Strong gamma-ray emission may reflect an extreme case of relativistic beaming with an unusually large Lorentz factor and/or with the relativistic jet oriented unusually close to the line of sight. Alternatively, the gamma-ray emission may be inverse Compton scattered radiation from lower energy photons. Since large Doppler factors are often invoked in order to avoid catastrophic inverse Compton losses, our observations suggest that the observed gamma-ray luminosity is not primarily the result of inverse Compton scattering.

5. The angular velocity–redshift test of world models

Kellermann (1993) and Gurvits (1994) have ar-
gued that compact radio sources may be used as probes to distinguish among world models as their properties should be mostly determined by the local environment close to the central engine. Moreover, the parsec-scale radio jets have characteristic ages of only a few tens of years and so are, at any epoch, young compared with the age of the Universe. Thus, unlike the extended radio sources, compact radio sources associated with quasars and AGN may be free of the systematic effects of cosmic evolution. Gurvits et al. (1999) have shown that the angular size–redshift relation for compact radio sources is consistent with Friedmann world models with $q_0 = 0.21 \pm 0.30$. This is in contrast the corresponding relation for extended double lobe radio sources which is dominated by evolutionary and selection effects.

Nevertheless, for several reasons it has proven difficult to use the angular size–redshift test for compact sources to make a definitive distinction between world models. First, there is no unique definition for the size of a parsec scale radio jet. The greater the sensitivity and dynamic range, the longer the jet appears to extend. Second, because the jet features have steeper spectra than the optically thick core, sources at high redshift, which are observed at a higher rest frequency, appear systematically shorter when observed at a fixed frequency.

The angular velocity–redshift test is similar to the angular size–redshift test, except that the apparent angular velocity is reduced by an additional factor of $(1 + z)^{3/2}$ due to relativistic time dilation. However, the angular velocity test has several attractions compared with the angular size test. One advantage is that it is possible to choose any two well defined features in the source and to measure their apparent rate of separation. Second, as the distribution of apparent velocities depends on the intrinsic value of $\gamma$, whereas the mean value depends also on the geometry of the Universe, the comparison of the distribution of apparent velocities as a function of redshift is a test of the evolution of $\gamma$. So, given a sufficiently large data set, unlike any other cosmological test known to us, the angular velocity–redshift test can distinguish between evolutionary effects and geometry. But the required data involves repeated observations of source structure of a moderately large sample over a wide range of redshift and over an extended period of time to obtain an accurate rate of separation. This is particularly true for sources at high redshift where the distinction among cosmological models is greatest, but where the apparent angular velocity is low.

Our data are not yet adequate to distinguish among world models or to provide a meaningful check on cosmic evolution. But, the observed angular velocity–redshift relation, like the angular size–redshift relation is consistent with standard Friedmann world models which slightly favour a cosmic mass density somewhat smaller than the critical value.

We plan to continue these observations with emphasis on sources at high redshift where the distinction among world models is greatest.

References