The Cosmological Application of the VLBI Technique at Ultimate Resolutions

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Abstract. The behaviour of the milliarcsecond structures of AGN is analyzed as a function of redshift (z). Such a dependence contains a well known feature, a dependence of the apparent angular size of a "standard rod" on cosmological distance. A nonlinear regression model was applied for observational data of the VLBI survey at 2.3 GHz (PRESTON *et al.*, 1985). Results of the regression models are discussed from the perspective of apparent and intrinsic properties of milliarcsecond structures of AGN. In the particular case of the universe with the Robertson-Walker metric and zero cosmological constant the estimated value q_o = 0.16 ± 0.71 is somewhat favorable for the open cosmological models.

1. Introduction

Measuring the sizes of objects at cosmological distances is a long-standing problem. It contains two aspects of astrophysical interest: (i) an application to defining source properties, and (ii) a utility in cosmological tests and the estimation of the parameters of the cosmological model. Among the approaches to estimating cosmological parameters, and especially the deceleration parameter q_o, and the dimensionless average density of the Universe Ω, the most direct are associated with searches for a "standard rod" or a "standard candle". The recent progress in Very Long Baseline Interferometry (VLBI) promises a breakthrough in the use of this approach by studying the milliarcsecond angular scale of radio sources, which corresponds to parsecs in linear measure. Recently KELLERMANN (1993) provides the first direct evidence of the behavior of a hypothetical "standard rod" predicted by Friedmann cosmology. Analogous evidence for a "Friedmann-like" dependence in the "ϑ-z" relation are shown by GURVITS (1993a, b) by interpreting the data from a VLBI survey. Moreover, KRAUSS and SCHRAMM (1993) indicate a potential use of such approaches for estimating the most uncertain cosmological parameter of all — the cosmological constant Λ.

This contribution presents a brief interpretation of VLBI survey data for estimating of the cosmological deceleration parameter and some intrinsic properties of extragalactic radio sources.

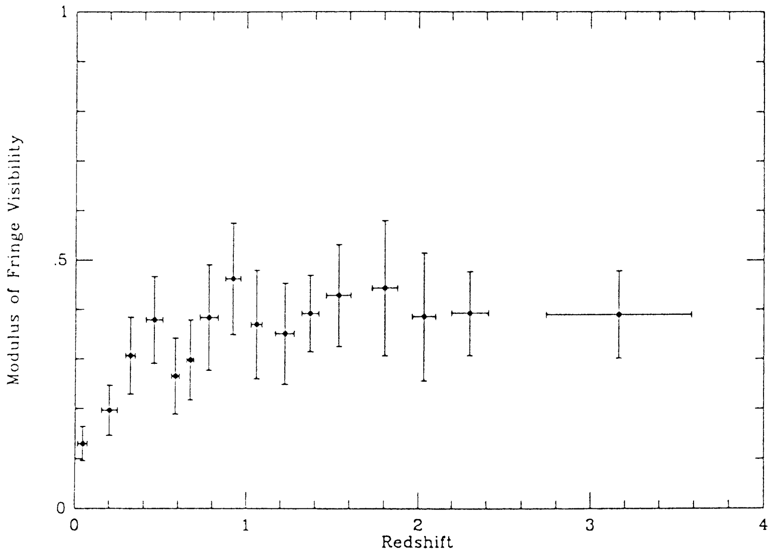

Fig. 1. Averaged within 16 redshift bins values of the modulus of visibility Γ versus redshift z. Error bars correspond to a standard deviation value for a group of sources within a redshift bin.

2. Observational Data

We have used the 2.3-GHz VLBI survey of extragalactic sources (PRESTON *et al.*, 1985). The survey has been carried out with five antennas located in Spain (Madrid), California (Goldstone), Australia (Parkes and Tidbinbilla), and South Africa (Hartebeesthoek). A typical angular resolution of the survey data is $\simeq$3 mas. The experiment was not aimed to reconstruct source images, so each source is presented in the data by one *uv*-point (i.e. by a measurement at the longest baseline). The sample of our interest is composed of the 337 sources from this survey, having known redshifts, and measured total (S_t) and correlated (S_c) flux densities. Our sample of 337 sources consists almost exclusively of active galaxies nuclei (AGN) in the redshift range of $0.003 \leq z \leq 3.8$.

Figure 1 shows a dependence of the modulus of visibility $\Gamma = S_c/S_t$ on the redshift z. The growth of Γ with redshift to $z \simeq 0.5$, and the following plateau at greater redshifts, is best fitted to cosmological models with $q_o < 0.5$ (cf. GURVITS, 1993a).

3. The Characteristic Angular Size as a Standard Rod

One can use Γ to calculate a characteristic angular size for a source

$$\theta = \frac{2\sqrt{-\ln\Gamma \cdot \ln 2}}{\pi B} \tag{1}$$

where B is the interferometer baseline, measured in wavelengths (THOMPSON *et al.*, 1986, p. 13). This value represents a single parameter Gaussian, which can be assumed to be a rough representation of source structure. In practice, it may be rather far from the true source size due to the complications of the actual brightness distribution. However, θ provides an angular measure, which can be used to represent source sizes statistically.

Consider a source of a projected linear size x at a redshift z. It's corresponding angular size is

$$\vartheta = x\frac{(1+z)^2}{D_L(z)} \tag{2}$$

where

$$D_L(z) = \frac{c}{H_o h q_o^2}\left[q_o z + (q_o - 1)\left(\sqrt{2q_o z + 1} - 1\right)\right] \tag{3}$$

is the luminosity distance (WEINBERG, 1972, p. 485) in "standard cosmological model", i.e. a homogeneous, isotropic universe with the cosmological constant $\Lambda = 0$. Here the Hubble constant is presented by a product $H_o h$, where $H_o = 100$ km·s^{-1}·Mpc^{-1} and the dimensionless Hubble constant h.

Generally $x \neq \text{const}(z)$. A number of studies have investigated the "x-z" relation for various classes of extragalactic sources at arcsecond and larger angular scales (SINGAL, 1993, and references therein). The following phenomenological formula connecting the projected linear size of a source x at the arcsecond angular scale with its luminosity L_c and redshift z

$$x = l \cdot \left(\frac{L_c}{L_o}\right)^{\beta} \cdot (1+z)^n \tag{4}$$

where l and L_o are a normalizing linear size and luminosity respectively. For convenience, we assume $l = l_o h$, where l_o is the normalizing metric size. There is no reason not to extend the use of such a phenomenological formula to our case of three orders of magnitude smaller linear scale than in its initial use for sources of arcsecond angular sizes. We note that formula (2) is correct for the angular size ϑ as well as for the characteristic angular size θ. So, substituting (4) into (2), and using θ instead of ϑ gives

$$\theta = \frac{H_o}{c} l \cdot \left(\frac{L_c}{L_o}\right)^{\beta} \cdot (1+z)^n \cdot D \tag{5}$$

where

$$D = \frac{c}{H_o}\frac{(1+z)^2}{D_L(z)} = \frac{q_o^2(1+z)^2}{q_o z + (q_o - 1)\left(\sqrt{1+2q_o z} - 1\right)}. \quad (6)$$

We can now apply a multiple regression analysis using these formulae for the characteristic angular sizes of the sample of 337 sources. The regresion parameters are l, q_o, β, and n.

4. Discussion of Regression Model Results

Details of the computational algorithm for multiple nonlinear regression could be found in GURVITS (1994). The best fit obtained for the following regression parameters

$$l = 4.79 \pm 0.92 \text{ pc},\ q_o = 0.16 \pm 0.71,\ \beta = 0.26 \pm 0.03,\ n = -0.30 \pm 0.90.$$

The results of this work are based on two main assumptions:

(i) the mean characteristic angular size of a group of sources, defined as a width of a single-parameter Gaussian brightness distribution, is a representative value of a standard source size;

(ii) the dependence of source linear size on its luminosity and redshift is represented by the power law (formula (4)).

The reason to use in this work these two assumptions is that they both are practically the simplest possible relevant assumptions. Some further development of the described approach could be based on more sophisticated assumptions.

Our results can be summarized as follows:

(1) Although the estimate of the first parameter, l, is an *ad-hoc* result, it is not without interest. In principle, it could be useful for any kind of study of the physical parameters of AGN. It gives some feeling for the typical size of the emitting volume $l_o = l/h$ (pc). Similar estimates obtained at different frequencies could be used for modeling physical conditions in AGN. Furthermore, such multi-frequency data on l could help in estimating the Hubble constant h for any given physical model of AGN.

(2) The linear size, l of an AGN on the milliarcsecond angular scales shows a dependence on radio luminosity as $l \propto L_c^{0.26\pm0.03}$. If there is any difference in the "luminosity-size" behavior of quasars and nuclei of radio galaxies on the parsec scale, then this difference is not the same on the kiloparsec scale.

(3) VLBI survey data at 2.3 GHz provide evidence for the apparent dependence of AGN linear sizes on redshift $l \propto (1+z)^{-0.3\pm0.9}$. This dependence may incorporate three different physical phenomena:

i) an intrinsic cosmological evolution of source metric sizes;

ii) a dependence of the metric size on emitted frequency;

iii) a scattering broadening effect.

Our result indicates the existence of the effect. The distinction between the above three explanations requires specially designed VLBI experiment.

(4) We estimate the deceleration parameter as $q_o = 0.16 \pm 0.71$ assuming the model with the Robertson-Walker metric and with a zero cosmological constant. The large uncertainty of this estimate is due to the sparse intrinsic distribution of the data over four regression parameters. However, it indicates a preference for open models of the Universe. Our approach could provide better accuracy with a specially composed source sample, with a narrow range of either luminosity or redshift. This will allow to eliminate one parameter from the regression model to improve the statistical confidence of the remaining parameters. A sample with a narrow range of redshift is preferable since it gives a possibility of searching within a narrow range of the parameter β, to take into account its dependence on $(1 + z)$. This sample could be applied to the test, proposed by KRAUSS and SCHRAMM (1993) to distinguish between cosmological models with zero and non-zero cosmological constant Λ.

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