COSMOLOGICAL APPLICATION OF MULTI-FREQUENCY VLBI OBSERVATIONS OF ULTRA-COMPACT STRUCTURE IN Z \sim 3 RADIO QUASARS

Shuo Cao\textsuperscript{1}, Marek Biesiada\textsuperscript{1,2}, Xiaogang Zheng\textsuperscript{1,2}, Jingzhao Qi\textsuperscript{1}, Tengpeng Xu\textsuperscript{1} and Zong-Hong Zhu\textsuperscript{1*}

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\begin{abstract}
In this paper, we use multi-frequency angular size measurements of 58 intermediate-luminosity quasars reaching the redshifts \( z \sim 3 \) and demonstrate that they can be used as standard rulers for cosmological inference. In particular, we use the value of the intrinsic metric size of compact milliarcsecond radio quasars derived in a cosmology independent manner from survey conducted at 2 GHz and rescale it properly according to predictions of the conical jet model. This approach turns out to work well and produce quite stringent constraints on the matter density parameter \( \Omega_m \) in the flat \( \Lambda \)CDM model and Dvali-Gabadadze-Porrati braneworld model. The results presented in this paper pave the way for the follow up engaging multi-frequency VLBI observations of more compact radio quasars with higher sensitivity and angular resolution. Samples of high redshift standard rulers expected from this approach, would make it possible to eventually constrain the dynamical dark energy.

\textbf{Keywords:} cosmological parameters - galaxies: active - quasars: general
\end{abstract}

1. INTRODUCTION

For some time, radio sources (extended FRIIb radio galaxies, radio loud quasars, etc.) have been proposed as standard rulers \citep{Buchalter1998, Guerra1998, Guerra2000, Daly2003} and hence as alternative cosmological probes complementary to standard candles (SN Ia) and anisotropies in the cosmic microwave background radiation (CMBR). One important class of such objects are ultra-compact radio-sources whose cores have angular sizes of order of milliarcseconds (\textit{mas}) which could be measured by very-long-baseline interferometry (VLBI) \citep{Kellerman1993, Gurvits1994}. In the VLBI images, the core is usually identified with the most compact (often unresolved) feature with a substantial flux and flat spectrum across the radio band. More importantly, radio sources (especially quasars) can be observed up to very high redshifts, well beyond the observed redshift range of SNIa \citep{Amanullah2010} limited to \( z < 2 \). First attempts to constrain cosmological models using such kind of sources were due to \citep{Gurvits1999}, who compiled a data-set of 330 milliarcsecond radio sources containing various optical counterparts (radio galaxies, quasars, BL Lac etc.). A sub-sample containing 145 compact sources with little dependence of angular size on spectral index \(( -0.38 \leq \alpha \leq 0.18 \) and luminosity \( Lh^2 \geq 10^{26} \text{WHz}^{-1} \)) was also derived in their analysis, based on which all data points were distributed into twelve redshift bins and were extensively discussed in the literature \citep{Chen2001, Zhu2002, Vishwakarma2003} as cosmological probes. However, the determination of the typical value of the linear size \( l_m \) for this standard ruler (or even whether compact radio sources are indeed “true” standard rulers) was remaining an important problem to be solved \citep{Vishwakarma2001}.

\begin{equation}
\theta(z) = \frac{l_m}{D_A(z)}
\end{equation}

between the intrinsic metric length \( l_m \) of the standard ruler located at the redshift \( z \), its observed angular size \( \theta(z) \) and its angular diameter distance \( D_A(z) \). The main problem here is to find a convincing population of standardizable rulers. In particular, metric sizes \( l_m \) of compact radio sources may depend on their luminosity \( L \) (i.e. on the central engine) and display evolutionary effects, i.e. may depend on \( z \). As already mentioned, \citep{Cao2017d} using the parametrization \( l_m = Lh^{3}(1+z)^{p} \) capturing these effects, demonstrated that the linear size \( l_m \) of compact structure in 120 intermediate-luminosity...
Table 1
Compilation of intermediate-luminosity quasars from Pushkarev & Kovalev (2015) included also in the sample of Cao et al. (2017b). Column (1): source (name); Column (2): redshift; Column (3)-(8): angular size in milliarcseconds at 2, 5, 8, 15, 24, and 43 GHz, respectively.

| Source               | z   | θ_2 | θ_5 | θ_8 | θ_15 | θ_24 | θ_43 |
|----------------------|-----|-----|-----|-----|-----|------|------|
| J1256-0547           | 0.536 | 2.56 | 0.59 | 0.37 | 0.23 | 0.13 | 0.07 |
| J0407+1211           | 0.573 | 1.82 | 0.33 |     |     |     |      |
| J0922-3959           | 0.591 | 2    | 0.38 |     |     |     |      |
| J1642+3948           | 0.593 | 1.29 | 1.28 | 0.54 | 0.24 | 0.19 |      |
| J2332-4118           | 0.671 | 1.89 | 0.45 |     |     |     |      |
| J1800+7828           | 0.68  | 0.55 | 0.27 | 0.23 | 0.16 | 0.1  | 0.09 |
| J1357+1919           | 0.72  | 1.4  | 0.75 | 0.41 | 0.14 | 0.43 |      |
| J1637+4717           | 0.74  | 0.72 | 0.23 | 0.08 |     |     |      |
| J1239-1023           | 0.752 | 2.25 | 1.37 | 0.7  |     |     |      |
| J0728+6748           | 0.846 | 0.99 | 0.26 |     |     |     |      |
| J0917-2131           | 0.847 | 1.72 | 0.2  |     |     |     |      |
| J1215+3448           | 0.857 | 1.31 | 0.82 | 0.51 |     |     |      |
| J0538-4405           | 0.894 | 1.41 | 0.43 |     |     |     |      |
| J0539-1550           | 0.947 | 1.59 | 0.38 |     |     |     |      |
| J1937-3958           | 0.965 | 1.49 | 0.34 |     |     |     |      |
| J0239+0416           | 0.978 | 0.89 | 0.23 | 0.05 |     |     |      |
| J0132-1654           | 1.02  | 1.44 | 0.59 | 0.91 | 0.25 |     |      |
| J1516+1932           | 1.07  | 0.88 | 0.16 | 0.09 | 0.11 |     |      |
| J1337+5501           | 1.1   | 1.22 | 0.45 | 0.47 |     |     |      |
| J1213-1307           | 1.14  | 1.53 |     |     |     |     |      |
| J1231-1556           | 1.153 | 1.156| 1.15 | 0.5  | 0.45 |     |      |
| J1441-3456           | 1.159 | 1.9  |     |     |     |     |      |
| J1955+5131           | 1.22  | 1.05 | 0.66 | 0.23 | 0.2  |     |      |
| J1153+8058           | 1.25  | 1.19 | 0.31 | 0.27 | 0.15 |     |      |
| J1023+3948           | 1.254 | 1.03 | 0.69 | 0.26 | 0.21 |     |      |
| J0516-1603           | 1.278 | 1.69 | 0.73 |     |     |     |      |
| J0406-3826           | 1.285 | 0.96 | 0.45 |     |     |     |      |
| J0710+4732           | 1.292 | 0.79 | 0.75 | 0.16 | 0.12 | 0.07 |      |
| J2314-3138           | 1.323 | 0.91 | 0.36 |     |     |     |      |

Quasars observed at 2.29 GHz (later on we will denote this frequency as 2 GHz for short) displays negligible dependence both on redshift and luminosity (|n| ≃ 10^{-3}, |β| ≃ 10^{-4}). In extragalactic jets, however, the apparent position of a bright narrow end depends on the observing frequency, owing to synchrotron self-absorption and external absorption. Considering that 10 pc is a typical radius at which AGN jets are apparently generated (Blandford & Rees 1978), it is very important to investigate the relation between the observing frequency and the apparent linear size of compact structure. To be more specific, at any given frequency, the core is believed to be located in the region of the jet where the optical depth is τ = 1. In the conical jet model proposed by Blandford & Königl (1979), if we observe a given milliarcsecond source at different observing frequencies ν, its observed size falls as the frequency increases (Marscher & Shaffer 1980, O’Sullivan & Gabuzda 2009), being proportional to ν^{-1}.

In our analysis, we turn to the more recent VLBI imaging observations based on better uv-coverage. Pushkarev & Kovalev (2015) presented the VLBI data of more than 3000 compact extragalactic radio sources observed at different frequencies, ν = 2 – 43 GHz. This sample, however, contains a wide class of extragalactic objects, belonging to different luminosity categories, including quasars, radio galaxies, and BL Lac objects. We identified 58 intermediate-luminosity quasars from the sub-sample constructed in Cao et al. (2017a), which have also been included in the Pushkarev & Kovalev (2015) sample. Fig. 1 displays observed angular size against redshift in this sample. This way, we obtained a set of data – summarized in Table 1 – comprising angular sizes of flat spectrum cores in intermediate luminosity radio quasars at six different radio frequencies: 2, 5, 8, 15, 24 and 43 GHz.

In order to use Eq. (1) for cosmological inference one needs to calibrate l_{\nu}. According to Blandford & Königl (1979), calibrated metric size of such standard ruler should depend on observing frequency in the same way as the observed angular size, i.e. decrease as ν^{-1}. We checked that frequency dependence of angular sizes in our sample is compatible with Blandford & Königl (1979) conical jet model. This is illustrated in Fig. 2 for selected four quasars. Therefore, in the context of multifrequency data, one can use the characteristic linear size at 2 GHz

\[ l_{m,2} = 11.03 \pm 0.25 \text{pc}, \]  

calibrated in Cao et al. (2017a) and scale it according to l_{\nu} \propto ν^{-1} to any other frequency at which angular size θ has been observed. Let us remind and emphasize that calibration underlying the Eq. (2) has been performed using a cosmological-model-independent method (Li et al. 2015), by constructing angular diameter distances D_A by means of GP-processed H(z) measurements (Moresco et al. 2012, Zheng et al. 2016) from cosmic chronometers (Jimenez & Loeb 2002) using publicly available GaPP code (Seikel et al. 2012). See Cao et al. (2017a) for detailed description of this procedure.

In order to demonstrate how the above described ap-
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proach works we have constrained two simple cosmological models using the multi-frequency quasar data from Table 1. The models we chose were: the ΛCDM and Dvali-Gabadadze-Porrati (DGP) models under assumption of spatially flat Universe. The cosmological model parameters \( p \) were determined by a \( \chi^2 \) function minimization, where:

\[
\chi^2 = \sum_{j=1}^{6} \sum_{i=1}^{58} \frac{[\theta_{ij}^{th}(l_{mj}, p) - \theta_{ij}^{obs}]^2}{\sigma_{ij}^2}
\]

and summation is over different quasars at redshifts \( z_i \) observed at different frequencies \( \nu_j \), \( \theta_{ij}^{th} = l_{mj}/D_{A,i} \) is the theoretical value of the angular size of an object of proper length \( l_{mj} \) at observing frequency \( \nu_j \), while \( \theta_{ij}^{obs} \) is the corresponding observed value with total uncertainty \( \sigma_{ij} \). We have assumed 10% uncertainties in the observed angular sizes.

3. RESULTS AND DISCUSSION

In our analysis we assumed flatness of the FRW metric, which is strongly indicated by the location of the first acoustic peak in the CMBR (Ade et al. 2014). This conclusion is also independently supported by the quasar data at \( z \sim 3.0 \) as demonstrated in (Cao et al. 2017a). Cosmological models we considered, i.e. the ΛCDM and DGP have two free parameters: the Hubble constant \( H_0 \) and mass density parameter \( \Omega_m \). It is a well known fact for the ΛCDM model while the DGP model requires a few words of reminder. This model is one of the simplest modified gravity models based on the concept of braneworld theory (Dvali & Porrati 2000), in which gravity leaks out into the bulk above a certain cosmological scale \( r_c \). Hence this scale is a free parameter of the theory which in the flat DGP model can be associated with the density parameter: \( \Omega_c = 1/(4r_c^2H_0^2) \). It is then easy to see that the relation \( \Omega_c = 4(1 - \Omega_m)^2 \) is valid.

On the other hand, strong geometric degeneracy between the Hubble constant \( H_0 \) and other parameters is also very well known. Therefore in our analysis we estimated only matter density parameter \( \Omega_m \) assuming three different priors for the Hubble constant. To be specific, we used three recent measurements: \( H_0 = 67.3 \pm 1.2 \) km s\(^{-1}\) Mpc\(^{-1}\) with 1.8% uncertainty (Ade et al. 2014), \( H_0 = 69.6 \pm 0.7 \) km s\(^{-1}\) Mpc\(^{-1}\) with 1% uncertainty (Bennett et al. 2014), and \( H_0 = 73.24 \pm 1.74 \) km s\(^{-1}\) Mpc\(^{-1}\) with 2.4% uncertainty (Riess et al. 2016). Such choice enables us to see the influence of the Hubble constant on the constraining power of our multi-frequency quasar data. One can consider it as a consistency between the same type of probes – standard rulers – acoustic peaks revealed by CMBR anisotropy measurements at the redshift of \( z \sim 1000 \) and our quasar sample reaching the redshift of \( z \sim 3.0 \). Finally, the value of matter density obtained with the prior on \( H_0 \) taken after (Riess et al. 2016) is generally lower than that given by most of other types of cosmological observations. This illustrates the importance of measuring the Hubble constant accurately with independent techniques and better understanding the nature of discrepancy between \( H_0 \) inferred from CMBR or BAO and from local measurements based on cosmic distance ladder.

Concerning the DGP models, marginalized distribution of the model parameter \( \Omega_m \) is shown in Fig. 3. The best fit values of the mass density parameter in DGP model, corresponding to three different priors on \( H_0 \) are the following: \( \Omega_m = 0.291 \pm 0.063 \), \( \Omega_m = 0.258 \pm 0.063 \), and \( \Omega_m = 0.213 \pm 0.049 \). The last constraint is by them at \( H_0 = 70.0 \pm 2.2 \) km s\(^{-1}\) Mpc\(^{-1}\). One can see that our results are consistent with these estimates. One can consider it as a consistency between the same type of probes – standard rulers – acoustic peaks revealed by CMBR anisotropy measurements at the redshift of \( z \sim 1000 \) and our quasar sample reaching the redshift of \( z \sim 3.0 \). We demonstrated that the approach initiated in (Cao et al. 2017a) i.e. calibrating intermediate luminosity milliarcseconds compact radio quasars in sufficiently big sample obtained even at a single frequency is promising. Namely,
Figure 2. Angular size versus frequency for four quasars from the Pushkarev & Kovalev (2014) sample. The curve is fitted to the data according to the Blandford & Königl (1979) jet model.

Figure 3. Cosmological constraint on the flat $\Lambda$CDM model (upper panel) and DGP model (lower panel) from multi-frequency P15 sample.
the intrinsic metric size $l_m$, identified at some observing frequency, when properly rescaled, can be used in objects observed in other surveys performed at other frequencies. For this purpose known for long, simple conical jet model of [Blandford & Königl (1979)] works quite well. Theoretical improvements of [Blandford & Königl (1979)] model leading to more accurate and realistic models would be very important. Secondly, even with a relatively small sample of 58 sources we were able to demonstrate that combined multi-frequency data concerning compact radio quasars gives quite stringent cosmographic constraints and is able to differentiate between different cosmological models like ΛCDM and DGP. The value of density parameter in ΛCDM model is perfectly consistent with values obtained in an independent manner. Moreover when confronted with alternative methods of determining Ω_\text{m} like from the peculiar velocities of galaxies [Feldman et al. (2003)] our fits obtained for the DGP model are accurate enough to falsify this model. However, strong degeneracy between $H_0$ and $Ω_m$, illustrated in our study in the spirit of sensitivity analysis, emphasizes the importance of independent and more direct determinations of $H_0$. In this respect the approach of strong lensing time delays is promising. Recent results of the H0LiCOW project [Bonvin et al. (2017)] already demonstrated that a few percent accuracy in $H_0$ determination is feasible.

Finally, the results presented in this paper pave the way for the follow up engaging multi-frequency VLBI observations of more compact radio quasars with higher sensitivity and angular resolution, which may make it less susceptible to systematic errors. The approach, introduced in this paper, would make it possible to build a significantly larger sample of standard rulers at much higher redshifts. With such a sample, we can further investigate constraints on the cosmic evolution and eventually probe the evidence for dynamical dark energy.

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