Milliarcsecond compact structure in radio quasars and the geometry of the universe

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In this paper, by using the recent observations of 120 intermediate-luminosity quasar (QSO) observed by single-frequency VLBI survey, we propose an improved model-independent method to probe cosmic curvature parameter \( \Omega_k \) and make the first measurement of the cosmic curvature referring to a distant past, with redshifts up to \( z \sim 3.0 \). Compared with other model-independent methods testing the cosmic curvature, this method with quasar data achieves constraints with much higher precision. More importantly, our results indicate that the measured \( \Omega_k \) is in good agreement with zero cosmic curvature (\( |\Omega_k| \sim 10^{-3} \)), implying that there is no significant deviation from a flat Universe. Finally, we investigate the possibility of testing \( \Omega_k \) with a much higher accuracy using quasars discovered in the future VLBI surveys. It is shown that our method could provide a reliable and tight constraint on the prior \( \Omega_k \) and one can expect the zero cosmic curvature to be estimated at the precision of \( \Delta \Omega_k \sim 10^{-3} \) with 250 well-reserved radio quasars.

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Introduction.— As one of the fundamental issues in modern cosmology, whether the cosmic space is open, flat, or closed may help us investigate various important cosmological problems, including the homogeneous and isotropic Friedmann-Lemaître-Robertson-Walker (FLRW) metric, the evolution of our Universe, the nature of dark energy, etc. Possibilities for the deviation from the zero cosmic curvature may lead to far-reaching effects on our knowledge of fundamental physics (FLRW approximation) and our Universe (inflation theory, the observed late-time accelerated expansion, the reconstruction the state equation of dark energy). Although the zero cosmic curvature is supported by many astrophysical probes at the current observational data level, two potential problems should be taken into consideration. On the one hand, the most convincing evidence from the latest Planck 2015 results of Cosmic Microwave Background (CMB) observation at \( z \sim 1000 \) (Planck Collaboration et al. 2015), which failed to measure the curvature in any direct geometric way, is strongly dependent on the assumed cosmological model (the standard \( \Lambda \)CDM model). On the other hand, direct model-independent methods for determining the curvature from popular probes, which have been extensively studied in the literature, concentrate on the luminosity distance \( D_L(z) \) using SN Ia as standard rulers at lower redshifts \( (z \sim 1.40) \), combined with the measurements of Hubble parameter \( H(z) \) using passively evolving galaxies and baryon acoustic oscillation (BAO) as cosmic chronometers (or standard clocks). Results showed that no evidence was found for deviation from flatness (see also Mortsell & Jonsson, Sapone et al. (2007)). However, two main drawbacks should be taken into account when using SN Ia data to accurately determine the cosmic curvature. Firstly, this approach is heavily dependent on the nuisance parameters characterizing SN light-curves, which will introduce a large uncertainty to the final determination of \( \Omega_k \). More importantly, the SN Ia are commonly accepted standard candles in the Universe and from their observed distance moduli we are able to recover luminosity distances covering the lower redshift range \( z \leq 1.40 \) (12, 13), while the latest CMB measurements from Planck were obtained at high redshift \( z \sim 1000 \). The so-called redshift desert problem still remains a challenge for exploring the behavior of cosmic curvature.

Therefore, in order to avoid the shortcoming of SN Ia and CMB, we perform an improved model-independent method to achieve a reasonable and compelling test of the cosmic curvature with the QSO data. In fact, advances in cosmology over recent decades have been accompanied by intensive searches for reliable standard rulers at higher redshifts. More promising candidates in this context are ultra-compact structures in radio quasars that can be observed up to very high redshifts, with milliarcsecond angular sizes measured by the very-long-baseline interferometry (VLBI); for details regarding the respective definitions of angular size see Data. The angular diameter distance information obtained from quasars has helped us to bridge the redshift desert and extend our investigation of cosmic curvature to much higher redshifts \( (z \sim 3.0) \).

Data.— In the following, we describe the two data sets to be used in our analysis.

For the “angular size - redshift” observations, we use a sample of 120 intermediate-luminosity quasars compiled by by Cao et al. 10, 17. The observed angular size of
the compact structure in each quasar is given by 18

$$\theta(z) = \frac{l_m}{D_A(z)}$$ (1)

where \(l_m\) is the intrinsic metric linear size and \(D_A\) represents the angular diameter distance. Moreover, we include two parameters \(\beta\) and \(n\) to respectively consider the “angular size - redshift” and “angular size - luminosity” relations, \(l_m = IL^{\beta}(1+z)^n\). The \(\beta\) parameter, which captures the dependence of the linear size on source luminosity, is highly dependent on the physics of compact radio emitting regions 19, 20. Besides cosmological evolution of the linear size with redshift, the parameter \(n\) may also characterize the dependence of the linear size on image blurring due to scattering in the propagation medium. Considering that all VLBI images for our sample were observed at a frequency of 2.29 GHz, this effect is not important in the present analysis 16.

The quasar data used in this paper were derived from a well-known 2.29 GHz VLBI survey undertaken by Preston et al. 21 (hereafter called P85). By employing a world-wide array of dishes forming an interferometric system with an effective baseline of about \(8 \times 10^7\) wavelengths, this survey succeeded in detecting interference fringes from 917 radio sources out of a list of 1398 candidates selected mainly from the Parkes survey 22. This work was extended further by Jackson & Jannetta 23, who updated the P85/Gurvits 13 sample with respect to redshift, to include a total of 613 objects with redshifts \(0.0035 \leq z \leq 3.787\). The full listing is available in electronic form via http://nrl.northumbria.ac.uk/13109/, including source coordinates, redshift, angular size, uncertainty in the latter, and total flux density. This extended data set is the one used in the present paper. More recently, Cao et al. 16, 17 found that quasars with intermediate-luminosities meet the requirement for a standard rod: \(|n| \simeq 10^{-3}\), \(|\beta| \simeq 10^{-4}\). The best-fitted values of \(\beta\) and \(n\) for this sub-population are significantly different from the corresponding quantities for other sub-samples, which supports the scheme of using a distinct strategy for treating quasars with intermediate luminosities. The redshift of intermediate-luminosity quasars ranges between \(z = 0.462\) and \(z = 2.73\). In this case, there is only one nuisance parameter \(l_m\) in the distance estimate, which should be fitted simultaneously with the cosmic curvature parameter \(\Omega_k\). In this work, we firstly take \(l_m\) as a free parameter and justify whether the curvature has a dependence on this nuisance parameter. Then, different cosmological-model-independent method will then be applied to determine the linear size of this standard rod, which will help us to obtain a cosmology-independent constraint on the cosmic curvature \(\Omega_k\).

For the expansion rate measurements, we use the latest 41 \(H(z)\) data points obtained from the derivative of redshift with respect to cosmic time carried out in two approaches. One is inferred from 31 passively evolving galaxies 24, 30 and the other is derived from 10 radial baryon acoustic oscillation (BAO) measurements 31, 32. The redshift of Hubble parameter data ranges between \(z = 0.09\) and \(z = 2.34\).

**Method.** — It is well known that the angular diameter distance \(D_A\) from the \(H(z)\) data connects to the reconstructed proper distance \(D_P = \frac{H_0}{c} \int_0^{\frac{1}{H(z)}(1+z)} d\zeta\) via

$$D_A(z) = \left(\frac{H_0}{c}\right) z \frac{1}{\sqrt{\Omega_k}} \sin \left(\sqrt{\Theta_k} D_P(z) \frac{H_0}{c}\right)$$ (2)

for \(\Omega_k > 0\), \(\Omega_k = 0\) and \(\Omega_k < 0\), respectively. A model-independent Gaussian processes (GP) can be used to reconstruct proper distances through the Hubble parameter \(H(z)\) measurements, which is independent of any specific cosmological model. The readers may turn to Seikel et al. 38 for more details of the GP method and the python package of GP code. We remark here that, in order to explore the influence of Hubble constant on the reconstruction and then on the test of the curvature parameter \(\Omega_k\), two recent measurements of \(H_0 = 69.6 \pm 0.7\) km s\(^{-1}\) Mpc\(^{-1}\) with 1\% uncertainty 39 and \(H_0 = 73.24 \pm 1.74\) km s\(^{-1}\) Mpc\(^{-1}\) with 2.4\% uncertainty 40 are respectively used for distance estimation in the following analysis. Then the reconstructed angular-size of the compact structure in radio quasars \(\theta_H(\Omega_k; z)\) from the \(H(z)\) data can be obtained as \(\theta_H(\Omega_k; z) = l_m/D_A^H(\Omega_k; z)\).

Here two emphases should be made in the following analysis. Firstly, the spatial curvature \(\Omega_k\) directly enters the reconstructed theoretical angular-size of the compact structure in radio quasars, which makes it possible to investigate \(\Omega_k\) with observational value of \(\theta_QSO\). Secondly, compared with the SN Ia data extensively used in the literature 3, 4, there is only one nuisance parameter \(l_m\) in the distance estimate of quasars, which should be fitted simultaneously with the cosmic curvature parameter \(\Omega_k\). In this work, we firstly take \(l_m\) as a free parameter and justify whether the curvature has a dependence on this nuisance parameter. Then, different cosmological-model-independent method will then be applied to determine the linear size of this standard rod, which will help us to obtain a cosmology-independent constraint on the cosmic curvature \(\Omega_k\).

**Results and discussion.** — For the single-frequency VLBI observations of quasars, we determine cosmic curvature \(\Omega_k\) using a \(\chi^2\) minimization method

$$\chi^2(l_m, \Omega_k) = \sum_{i=1}^{120} \frac{[\theta_H(z_i; l_m, \Omega_k) - \theta_{QSO}(z_i)]^2}{\sigma_0(z_i)^2},$$ (3)

where \(\sigma_0^2 = \sigma_{\theta H}^2 + \sigma_{QSO}^2\) and \(\sigma_{QSO}^2\) is the statistical uncertainty for the ith data point in the sample. Considering both observational errors and the intrinsic spread
FIG. 1: Results from single-frequency VLBI observations: 1σ and 2σ constraint contours for Ω_k and l_m (upper panel), and constraint on the cosmic curvature with the corrected linear size of compact quasars derived in a cosmological model independent way (lower panel), corresponding to two priors of Hubble constant.

TABLE I: Best-fit values with 1σ standard error for the cosmic curvature Ω_k and the QSO nuisance parameter l_m, derived from current VLBI observations.

| QSO (S/M) | Cosmic curvature (Ω_k) | Linear size (l_m) |
|-----------|------------------------|------------------|
| H_0(I)    | Ω_k = 0.042 ± 0.293    | l_m = 11.16 ± 0.51 pc |
|           | Ω_k = -0.029 ± 0.081   | l_m = 11.04 pc |
| H_0(II)   | Ω_k = 0.068 ± 0.271    | l_m = 11.15 ± 0.51 pc |
|           | Ω_k = 0.008 ± 0.071    | l_m = 11.04 pc |

in linear sizes, we have added 10% uncertainties in the observed angular sizes in computing. Moreover, two priors of Hubble constant H_0 are taken into account in our test of the curvature parameter. Results are shown in Fig. 1 and summarized in Table 1.

To start with, by applying the above χ^2-minimization procedure, we obtain 1σ, 2σ contours for the joint distributions of Ω_k and l_m in Fig. 1. With the prior of H_0 = 69.6 ± 0.7 km s^{-1} Mpc^{-1}, the best-fit parameters are Ω_k = 0.042 ± 0.293 and l = 11.16 ± 0.51 pc, with the 1σ standard deviations. With the prior of H_0 = 73.24 ± 1.74 km s^{-1} Mpc^{-1}, the two parameters respectively constrained to be Ω_k = 0.068±0.271 and l_m = 11.15 ± 0.51 pc. One can easily see that, for both of the two H_0 priors, the model-independent estimation for the spatial curvature fully agrees with a flat Universe at the current quasar observational level.

Now a cosmological-model-independent method will be applied to calibrate the linear size of the compact structure in the intermediate-luminosity radio quasars. We turn to the well-measured angular diameter distances from Baryon Acoustic Oscillations (BAO) covering the redshift range 0.35 ≤ z ≤ 0.74. The detailed information about these data can be found in their references. Although the BAO samples is not sufficient to provide precise information of D_A, one can use a powerful reconstruction method based on Gaussian Processes (GPs). Applying the redshift-selection criterion, Δz = |z_{QSO} - z_{BAO}| ≤ 0.005, we obtain certain measurements of D_A, inferred from the BAO data, corresponding to the quasar redshifts. Next we perform a similar fitting procedure, so that the values of D_A inferred from quasars match the BAO ones. As a result, we obtain the following:

l_m = 11.04^{+0.40}_{-0.40} pc.  (4)

In order to check the constraining power of quasars with the corrected linear size, using the “θ−z” relation for the full quasar sample, we get stringent constraints on the cosmic curvature Ω_k = -0.029 ± 0.081 and Ω_k = 0.008 ± 0.071 corresponding to the priors of H_0 = 69.6 ± 0.7 km s^{-1} Mpc^{-1} and H_0 = 73.24 ± 1.74 km s^{-1} Mpc^{-1}, which are explicitly presented in Fig. 1. Therefore, a universe with zero curvature (spatially flat geometry) is strongly supported by the available observations. This is the most
unambiguous result of the current dataset. Moreover, in the framework of model-independent methods testing the cosmic curvature, quasars may achieve constraints with much higher precision at much higher redshifts, compared with other popular astrophysical probes including SN Ia. For instance, the error on the measured $\Omega_k$ is at the level of $\sigma_{\Omega_k} \simeq 0.08$ with our quasar data, which is significantly better than that of the Union2.1/JLA sample ($\sigma_{\Omega_k} \simeq 0.20$) [48]. The constraining power of the former is much obvious when the large size difference between the samples is taken into consideration.

In order to test the validity and efficiency of our method, we perform Monte Carlo simulation to create mock “$H(z) - z$” and “$\theta - z$” data sets. $\Lambda$CDM is chosen as the fiducial cosmology ($\Omega_m = 0.30, \Omega_{\Lambda} = 0.70$), while the linear size of quasars is fixed at $l_m = 11.04$ pc. Following the simulation method proposed in [44], there are 20 mock $H(z) - z$ data points in the Hubble parameter simulation, the redshifts of which are chosen equally in $\log(1+z)$ space in $0.1 \leq z \leq 3.0$. Note that the fractional uncertainty of these mock data is taken at a level of 1%. This reasonable assumption of the “$H(z)$” measurements will be realized by future observation [45]. The route of quasar simulation is carried out in the following way: I) When calculating the sampling distribution (number density) of quasars, we adopt the luminosity function constrained from the combination of the SDSS and 2dF (2SLAQ) [49]. Note that the bright and faint end slopes in this model agree very well with those obtained other luminosity functions including Hopkins et al. [47]. In each simulation, there are 500 intermediate-luminosity quasars covering the redshift range $0.50 \leq z \leq 6.00$ and 250 data points are located in the redshifts of $0.50 \leq z \leq 3.00$. II) We attribute the angular size of compact structure “$\theta$” to each quasar, the fractional uncertainty of which is taken at a level of 3%. This reasonable assumption of the “$\theta$” measurements will be realized from both current and future VLBI surveys based on better uv-coverage [48]. III) This process is repeated 100 times for each data set and then provides the distribution of determined average $\Omega_k$, therefore the final results are unbiased. An example of the simulations and the fitting results are shown Fig. 3. We demonstrate that with 250 well-observed radio quasars, one can expect the zero cosmic curvature to be estimated with the precision of $\Omega_k = -0.0001 \pm 0.0021$. Finally, We also pin our hope on multi-frequency VLBI observations of more compact radio quasars with higher angular resolution based on better uv-coverage [49], in which the dependency of linear size $l_m$ on frequency $\nu$ should be taken into account, i.e., following the conical jet model proposed by Blandford & Königl [50], the characteristic linear size at other frequencies can be modified as $l_m \propto \nu^{-1}$ [51]. Therefore, the prospects for constraining the cosmic curvature with quasars is very promising, with future multi-frequency VLBI surveys comprising much more sources with higher sensitivity and angular resolution.

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