Angular clustering of photometrically classified quasar candidates from SDSS NBCKDE

Ivashchenko G.1⋆, Vasylchenko O.2†, Tugay A. V.2‡

1 Astronomical Observatory of the Taras Shevchenko National University of Kyiv, Observatorna str., 3, 04058, Kyiv, Ukraine
2 Faculty of Physics of the Taras Shevchenko National University of Kyiv, Glushkova ave., 4, 03127, Kyiv, Ukraine

ABSTRACT

The angular clustering of 230,829 photometrically selected quasar candidates from SDSS NBCKDE catalogue with photometric redshifts within the range $0.8 \lesssim z_{\text{phot}} \lesssim 2.2$ is studied with the help of the angular two-point correlation function. For this purpose own technique of the random catalogue generation was investigated and used. The obtained angular 2pCF of photometrically selected quasars within $0.6' - 40'$ scales is fitted well with the power-low $w(\theta) = (\theta_0/\theta)^\alpha$ with parameters $\theta_0 = 2.3^{+0.9}_{-1.0}$ arcsec and $\alpha = 0.87 \pm 0.06$, that agree well with previous studies of earlier releases of this catalogue, as well as with the results on clustering of X-ray point sources which are mostly active galactic nuclei. Investigation of the sample showed that except the well-known stellar contamination of photometrically selected quasar candidates there is also a small (about 0.1%) contamination by artifacts of the automatic selection technique of point-like sources, like star formation regions in spiral galaxies or parts of interference crosses of bright stars.

Key words: cosmology: observations – large-scale structure, surveys

1 INTRODUCTION

Quasars as the brightest extragalactic objects play an important role in study of the large-scale structure of the Universe. They are the only observational source of information about inhomogeneity and clustering of matter (including the dark matter) at cosmological redshifts. The most powerful results on quasars clustering were obtained using two largest quasar surveys up to date: the 2-degree Field (2dF) Quasar Survey1 with 2QZ catalogue as a result (Croom et al. 1998) and the Sloan Digital Sky Survey (SDSS)2, the second stage of which has been completed with the 7th release (Abazajian et al. 2009). The two-point correlation functions (2pCF) (Peebles 1981) of quasars $\xi(r)$ are important characteristics of matter spatial inhomogeneity that may be compared to cosmological theories of structure formation. Development of 2dF and SDSS surveys gave a powerful incentive to investigation of various aspects of correlation functions of quasars (see, e.g., Croom et al. 2005; Ross et al. 2009) and references therein.

The study of the matter distribution with the help of extragalactic redshift surveys comprises two main problems. The first one is related to the fact that surveys of extragalactic objects give us an information only about distribution of the luminous matter which is biased relative to the dark matter (Dekel & Rees 1987). Moreover the biasing may depend on the physical peculiarities of extragalactic objects, i.e., on morphological type (Einasto et al. 2007; Ross et al. 2007), luminosity (Beisbart & Kerscher 2000; Sorrentino et al. 2004), color-index (Coil et al. 2008), star formation rate (Owers et al. 2007) etc. and evolves with redshift (Croom et al. 2007; Porciani et al. 2004; Myers et al. 2007; da Angela et al. 2008; Mountrichas et al. 2009).

The second problem of the 3-dimensional analysis of the distribution of extragalactic objects relates to the observed redshifts of these objects. These redshifts are the only tool for measuring distance between the objects on cosmological distances, but they are ‘contaminated’ by measurement errors and non-Hubble motions. This results in the so called redshift-space distortions, namely Kaiser (1987) and ‘Finger of God’ effects (see, e.g., Ross et al. 2009; da Angela et al. 2008; Mountrichas et al. 2009; Ivashchenko et al. 2010) and references therein.

To avoid the problem of the redshift-space distortion the projected, spatial $w(\sigma)$ and angular $w(\theta)$, 2pCF are usually used. In the first case the projections $\sigma$ of the 3-dimensional...
distances $r$ on the plane perpendicular to the line of sight are used, and the parameters of the 3-dimensional $2pCF\,\xi(r)$ can be reconstructed from the parameters of $w(\sigma)$. Here the assumption that the influence of redshift inexactness causes a negligible effect on $\sigma$ comparing to $r$ is usually made. In the second case only the angular distances on the sky plane are used, and the parameters of $\xi(\theta)$ can be reconstructed from $w(\theta)$ using Limber’s equation (Limber 1953). This process of deprojection of the $2pCF$ is much more complicated than in the first case because it comprises the usage of the redshift distribution function of objects and analytical functions describing the clustering evolution. Nevertheless, taking into account smaller sizes and larger volumes of quasar spectroscopic surveys comparing with the galaxy ones, the angular $2pCF$ is still appealing for quasars because it does not include redshift information and thus allows to use catalogues of photometrically classified quasars, which contain one order of magnitude larger number of objects than spectroscopic quasar catalogues.

The angular $2pCF$ of quasars was previously studied by Myers et al. (2006, 2007) on the catalogues of photometrically selected quasar candidates from SDSS NBCKDE (Richards et al. 2004, 2009) based on the Early and the 4th data releases of SDSS. They showed that the angular $2pCF$ of quasars is fitted well with a power low $w(\theta) = (\theta_0/\theta)^\alpha$ and noticed two breaks in this power low on scales $\sim 1'$ and $\sim 25'$, where $\alpha$ is the slope of the angular $2pCF$. Some studies were carried out also on the angular $2pCF$ of the luminous red galaxies (LRG) which are the farthest galaxies seen with a peak of distribution around $z \approx 0.5$ and 2-point cross-correlation function of quasars and LRG (Mountrichas et al. 2007; Ross et al. 2007; Sawangwit et al. 2011). It is also interesting to compare the results of the angular clustering of quasars with those of X-ray point-like sources, a sufficient part of which is supposed to be active galactic nuclei (AGN).

In this paper we present the results on our study of the angular $2pCF$ of photometrically selected quasar candidates from SDSS NBCKDE catalogue (Richards et al. 2009). The sample, its selection and properties, along with the technique of the angular $2pCF$ calculation and the random catalogue generation method are discribed in Sec. 2. The results together with their discussion are presented in Sec. 3. Finally, in Sec. 4 we sum up the results.

2 THE SAMPLES AND THE TECHNIQUE

2.1 Angular $2pCF$

According to Peebles (1980) the angular $2pCF\,w(\theta)$ of the objects distribution determines the probability $dP_3$ to find simultaneously two objects with positions inside small solid angles $d\Omega_1$ and $d\Omega_2$ on a unit sphere with the angular separation $\theta$ as

$$dP_3 = n^2 [1 + w(\theta)] d\Omega_1 d\Omega_2,$$

where $n$ is a number density of objects for a given sample. In practice the angular $2pCF$ of objects is calculated using the numbers of objects pairs with different separations. There are four estimators known in a literature:

$$w_{LS}(\theta) = \frac{n(n-1)\,DD(\theta)}{n(n-1)}\frac{RR(\theta)}{RR(\theta)} - \frac{2(n-1)\,DR(\theta)}{n}\frac{RR(\theta)}{RR(\theta)} + 1;$$

$$w_H(\theta) = \frac{4nn_r\,DD(\theta)}{(n-1)(n_r-1)}\frac{RR(\theta)}{DR(\theta)} DR(\theta) - 1;$$

$$w_{PH}(\theta) = \frac{DD(\theta)}{RR(\theta)} DR(\theta) - 1;$$

$$w_{DP}(\theta) = \frac{2nn_r\,DD(\theta)}{n-1}\frac{DR(\theta)}{DR(\theta)} - 1,$$

which are Landy-Szalay (Landy & Szalay 1993), Hamilton (Hamilton 1993), Peebles-Hauser (Peebles & Hauser 1974) and Davis-Peebles (Davis & Peebles 1983) estimators correspondingly. Here $DD(\theta)$ and $RR(\theta)$ are numbers of pairs with separations $\theta$ in initial (data-data) and random (random-random) samples correspondingly, and $DR(\theta)$ is a number of cross-pairs between initial and random samples (data-random). Normalizing coefficients containing values $n$ and $n_r$ are included in a case of different numbers of objects in initial, $n$, and random, $n_r$, samples. The random sample is a sample, which should reproduce a random distribution of objects with the same redshift and angular distributions inherent to the initial sample as much as possible.

2.2 SDSS NBCKDE data

Our sample is taken from the SDSS NBCKDE Catalogue of Photometrically Classified Quasar Candidates (Richards et al. 2009) that contains 1,015,082 quasar candidates selected from the photometric imaging data of SDSS using a non-parametric Bayesian classification kernel density estimator (NBC-KDE). The objects are all point sources to a limiting magnitude of $i = 21.3$ from 8417 deg$^2$ of imaging from SDSS Data Release 6. According to authors the overall efficiency (quasars/quasar candidates) of the catalog is $\sim 95\%$.

For our study we selected only the objects with photometric redshifts within the range $0.8 \leq z_{phot} \leq 2.2$ and photometric redshift range probability $z_{phot,prob} > 0.5$. This redshift range is known as ‘SDSS window’ (Weinstein et al. 2004), i.e. the redshift range where the algorithm for photometric selection of quasar candidates is the most efficient. As the sky coverage of SDSS contains one big ‘piece’ and three narrow near-equatorial ‘strips’, we excluded these stripes to reduce boundary effects, thus our right ascension range is $100^\circ \leq \alpha \leq 270^\circ$. The resulting sample (we call it full sample throughout the paper) contains 320,761 object. Its sky coverage and photometric redshift distribution are presented in Fig. 1 and Fig. 2 (solid line) correspondingly.

The KDE photometrical selection algorithm for quasar candidates has its limitations. Based on classifying simulated quasars, Richards et al. 2004 found that the KDE technique is 95% efficient, where the rest 5% is assigned to contamination by stars. Beside this, there could be other sources of contamination caused by the errors of automatic survey. To check these effects we selected first 30,000 objects from our sample (about 10% of the sample) and examined them by eye using the SDSS SkyServer web-service. Among these 30,000 objects, 28 appeared to be bright blue parts of spiral galaxies, probably star formation regions, I is a faint

http://cas.sdss.org/
extended object, possibly a galaxy or nebula, misclassified as a point-like source ('STAR' according to SDSS nomenclature), and 4 are parts of interference crosses from bright stars. Thus a contamination of the sample by misclassified point-like sources is only $\sim 0.1\%$, which can be neglected in comparison with the stellar contamination.

As the main criterion of the KDE photometrical selection algorithm is based on quasar magnitudes and colors, that have been corrected for Galactic extinction using the maps of Schlegel et al. (1998), any systematic errors in the reddening model can induce additional effects on clustering results (see Ross et al. (2009) for discussion of possible effects). That is why following Ross et al. (2009); Ivashchenko et al. (2010) we divided our sample into low-reddening ($E(B-V) \leq 0.0217$) sample and high-reddening ($E(B-V) > 0.0217$) sample. The numbers of objects in these samples are 128,757 and 192,004 for low and high reddening correspondingly, and the sky coverage by them are presented in Fig. 3 and 4. As one can see from Fig. 2, the redshift distribution of both samples is similar to that of the full sample, and the relative distribution of low- and high-reddening regions around the sky plane is clearly seen in Fig. 3 and 4.

### 2.3 Initial and random samples

The random catalogues were generated with the help of the following technique. Firstly the sky area covered by the sample was divided into ‘squared’ cells and then filled with the same number of random points (random $\alpha$ and $\delta$) as in the initial sample with homogeneous distribution along $\alpha$ and $\cos \delta$-distribution along $\delta$. The ‘squared’ cell means a quadrangle with similar number of degrees in $\alpha$ and $\delta$, which is a trapezoid indeed. This technique has the same idea of preserving the original inhomogeneity of the sky coverage by the sample as the usage of the imaging mask (see e.g. Myers et al. (2006)), but unlike that technique it does not require any information about conditions of observations. An important aspect of our technique lies in a choice of the cell size. It should be small enough to reproduce all the sample density fluctuations and large enough not to smooth the physical clustering of objects. To choose the appropriate cell size we checked different possible sizes from $1^\circ \times 1^\circ$ up to about $17^\circ \times 17^\circ$. In Fig. 5 the relative fluctuations (rms) of the number density from cell to cell as a function of the cell side size is presented. As one can see, for small sizes fluctuations grow with decrease of the cell size as it is expected due to clustering, but on some scales about $10^\circ$ these fluctuations become constant, that means that these scales are larger than the scales of inhomogeneity. Fluctuations around constant on the largest scales are the result of
2.4 Errors estimation

To avoid the effects which can occur due to usage of the samples with sky coverage like in Fig. 3-4, especially related to the specific technique of random samples generation described above, for studying the angular 2pCF and possible influence of the different reddening on the results we selected three subsamples from the initial sample. The first full subsample is a patch of the sky with $130^\circ < \alpha < 240^\circ$, $0^\circ < \delta < 60^\circ$, containing 230,829 objects. The second subsample is a patch of the sky with $140^\circ < \alpha < 230^\circ$, $30^\circ < \delta < 60^\circ$, containing 80,107 objects (71,190 objects, or 89\%), of which are ‘low-reddening’ quasars. We formally call these last two subsamples low-reddening and high-reddening correspondingly.

Using the technique described above we generated 20 random catalogues for each of our 3 samples. Thus in each case the values of $RR$ and $DR$ were calculated as the arithmetic mean of 20 corresponding values.

3 RESULTS AND DISCUSSION

In Table 2 the slopes of the angular 2pCF from previous studies by Myers et al. (2006, 2007) of the photometrically classified quasars from the previous releases of SDSS NBCKDE catalogue are presented. For comparison we also presented here the results on LRG (Sawangwit et al. 2011), which are the most distant galaxies seen with large redshift surveys, the cross-correlation function of them with dependences of $w(\theta)$ on $DD$, $RR$ and $DR$ for different estimators and limitation of their usage), could be a result of peculiarities of the random samples generation technique, namely the fact, that the cell size is only about 6 times larger than the scales where the discrepancy occurs.

For further calculations we used Landy-Szalay estimator as the most conventional one and fitted the 2pCF with a power-law

$$w(\theta) = \left(\frac{\theta_0}{\theta}\right)^\alpha,$$

where $\theta_0$ is the angular correlation length and $\alpha$ is the slope, related to the slope of 3D 2pCF correlation function, $\gamma$, as $\gamma = 1 + \alpha$.

In Fig. 7 the 2pCF for the full subsample (Landy-Szalay estimator) together with the best fits within the whole range $0.06' - 40'$ and separately for ranges $< 1'$ and $> 1'$ are shown. The 1, 2, and 3$\sigma$ levels of likelihood function for these fits on the plane $\{\theta_0, \alpha\}$ are shown on the bottom panel. In Fig. 7 the 2pCF for the low- and high-reddening subsamples are presented together with 1, 2, and 3$\sigma$ levels of the likelihood function for best fits on the plane $\{\theta_0, \alpha\}$ for the same angular ranges are shown. The values of parameters $\alpha$ and $\theta_0$ are presented in Table 1. As one can see the values of the slopes for three subsamples agree within $3\sigma$-levels, thus one can neglect possible selection effects caused by different galactic extinction in different parts of survey, moreover the redshift distribution of quasars (as it is shown in Fig. 2) are similar for different reddening.

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Angular clustering of photometrically classified quasar candidates from SDSS NBCKDE

4 CONCLUSIONS

We calculated the angular 2pCF for the subsample of 230,829 photometrically classified quasar candidates from the largest catalogue of these objects up to date, SDSS NBCKDE (Richards et al. 2009), with photometric redshifts within the range $0.8 \leq z_{\text{phot}} \leq 2.2$, known as ‘SDSS window’ (Weinstein et al. 2004), and photometric redshift range probability $z_{\text{phot prob}} > 0.5$. For this purpose own technique of the random catalogue generation was investigated and used.

The obtained angular 2pCF of photometrically selected quasars within $0.6' - 40'$ is fitted well with the power-low $w(\theta) = (\theta_0/\theta)^{\alpha}$ with parameters $\theta_0 = 2.3^{+1.0}_{-0.9}$ arcsec and $\alpha = 0.87 \pm 0.06$, that agree well with previous studies of earlier releases of this catalogue by Myers et al. (2006, 2007) for photometrically classified quasars from the earlier release of same SDSS NBCKDE catalogue, as well as with X-ray point sources by Eliv et al. (2011).

We also investigated our sample and found that except the well-known stellar contamination of photometrically selected quasar candidates there is also a small (about 0.1%) contamination by artifacts of the automatic selection technique of point sources, like bright blue regions in spiral galaxies or parts of interference crosses of bright stars. The subsamples with high and low Galactic extinction (reddening) showed similar results on 2pCF, that means that one can neglect the selection effects of the catalogue caused by varying reddening when studying quasar clustering.

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Table 1. The slopes \( \alpha \) and correlation lengths \( \theta_0 \) for the full, low-reddening and high-reddening subsamples for Landy-Szalay estimator within the ranges 0.06' - 1', 1' - 40' and 0.06' - 40'.

|          | full     | low-reddening | high-reddening |
|----------|----------|---------------|----------------|
| \( \alpha \) | \( \theta_0 \), arcsec | \( \alpha \) | \( \theta_0 \), arcsec | \( \alpha \) | \( \theta_0 \), arcsec |
| 0.06' - 1' | 0.9 ± 0.3 | 2.6^{+1.6}_{-2.9} | 0.9^{+0.3}_{-0.2} | 3.2^{+2.1}_{-1.4} | 1.2 ± 0.4 | 4.7^{+1.3}_{-2.9} |
| 1' - 40'  | 0.93 ± 0.10 | 4.1^{+2.4}_{-1.9} | 1.17^{+0.17}_{-0.15} | 8.3^{+4.2}_{-3.6} | 0.93 ± 0.14 | 5.5^{+1.2}_{-2.2} |
| 0.06' - 40' | 0.87 ± 0.06 | 2.3^{+1.0}_{-0.9} | 1.02^{+0.08}_{-0.07} | 4.5 ± 1.3 | 0.86^{+0.08}_{-0.09} | 3.6^{+1.6}_{-1.5} |

Table 2. The slopes \( \alpha \) of the angular 2pCF of quasars, LRG, and X-ray sources from previous studies by other authors. Here ‘phot.’ stands for photometrically classified objects.

| objects                  | \( \theta \) range | \( \bar{z} \) | method       | slope \( \alpha \) | source                  |
|--------------------------|---------------------|-------------|--------------|------------------|-------------------------|
| phot. quasars (SDSS NBCKDE DR1) | 0.04' - 1'          | 0.35        | 0.92 ± 0.055 | 0.9 ± 0.02       | Myers et al. (2007)     |
| phot. LRG (SDSS DR5)      | 0.1' - 60'          | 0.55        | 1.01 ± 0.01  | 0.96 ± 0.01      | Sawangwit et al. (2011) |
| phot. LRG (2SLAQ)         | 0.68                | 0.04        | 1.07 ± 0.04  | 0.7 ± 0.2        | Mountrichas et al. (2009) |
| quasars (2SLAQ)-LRG (2SLAQ) | 0.1' - 100'        | 0.43        | 1.12 ± 0.04  | 0.8 ± 0.1        | Ebrero et al. (2009)    |
| quasars (2QZ)-LRG (2SLAQ) | 0.5                 | 1.09 ± 0.10 | 0.33 ± 0.23  | 1.47 ± 0.57      | Eliviv et al. (2011)    |
| quasars (2SLAQ)-LRG (2SLAQ) | 0.6                 | 1.33 ± 0.10 | 0.13 ± 0.07  | 1.17 ± 0.04      | Ebrero et al. (2009)    |
| XMM 0.5-2 keV sources     | 0.0                 | 1.33 ± 0.10 | 0.13 ± 0.07  | 1.17 ± 0.04      | Ebrero et al. (2009)    |
| XMM 2-10 keV sources      | 0.4                 | 0.81 ± 0.02 | 1.90 ± 0.04  | 1.33 ± 0.10      | Ebrero et al. (2009)    |
| XMM-LSS 0.5-2 keV sources | 0.7                 | 0.81 ± 0.02 | 1.90 ± 0.04  | 1.33 ± 0.10      | Ebrero et al. (2009)    |
| XMM-LSS 2-10 keV sources  | 1.0                 | 0.81 ± 0.02 | 1.90 ± 0.04  | 1.33 ± 0.10      | Ebrero et al. (2009)    |

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Angular clustering of photometrically classified quasar candidates from SDSS NBCKDE

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