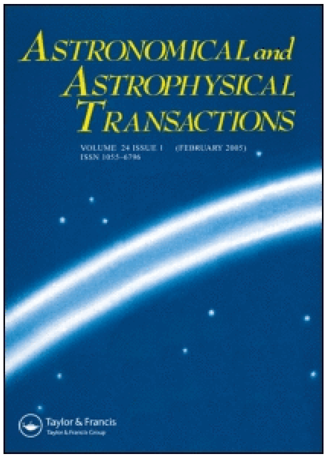

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THE SKY DISTRIBUTION OF RADIO SOURCES WITH FLAT SPECTRA

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Extragalactic radio sources with flat spectra ($\alpha < 0.5$) from two NRAO surveys at 4.85 and 1.4 GHz covering most of the northern hemisphere (about 6 sr) have been analysed by the angular correlation function versus flux densities. Excesses over the random expectation were concentrated in supergalactic plane in the range of $400 \div 800$ mJy and high ($> 10°$) supergalactic latitudes in the range of $150 \div 400$ mJy. The shift of the correlation interval for the sources which are away from the supergalactic plane to fainter flux densities as well as the shift of the distribution of correlation pairs to less angular sizes for these sources probably reflect the sky distribution of radio sources for more distant rich clusters.

KEY WORDS Cosmology, large-scale structure, extragalactic radio sources, radio surveys

1 INTRODUCTION

The Local Supercluster of galaxies is well known as a flattened system consisting of field galaxies, groups and clusters of galaxies. The coordinates of this system (supergalactic plane) have been determined by de Vaucouleurs *et al.* (1976). An analysis of the Molonglo catalogue (Large *et al.*, 1981) with strong ($S > 1$ Jy) radio sources at 408 MHz shows a local large-scale structure in low ($< 10°$) supergalactic latitudes (Shaver and Pierre, 1989; Shaver, 1991). In the supergalactic plane (SGP) the surface density is higher (1030 sr^{-1} compared to 910 sr^{-1}), the slope of the source counts is flatter (-1.54 ± 0.11 compared to -1.91 ± 0.06) and the amplitude of the angular two-point correlation function may also be greater (1.40 ± 0.50 compared to 0.46 ± 0.21), which makes it possible to estimate the characteristic scale of the Local Supercluster. There is an estimation of the depth of this supercluster in this paper: $z \sim 0.02$. The choice of a low frequency survey for investigation of the large-scale anisotropy, as has been mentioned, was discriminated in favour of local objects (steep spectrum radio galaxies) against distant objects (flat spectrum quasars).

Is this picture typical for objects with a steep spectrum, or is some part of the distribution anisotropy due to the sources with a flat spectrum? The latter is in agreement with the fact that flat spectrum sources are identified not only with quasars but also with normal spiral and elliptical galaxies (Kellermann and Pauliny–Toth, 1981).

To verify the phenomenon added by the flat spectrum sources located in the SGP, let us use the sample of objects from the centimeter survey. The centimeter surveys are less contaminated by selection effects connected with the flux limited ensemble from the high fluxes and include most of the flat spectra objects compared with surveys in the metre range.

2 ANALYSIS

To obtain a sample of the flat spectra sources, we shall use two NRAO surveys on Green Bank 91 m radio telescope covering the greater part of the northern hemisphere at the frequency 4.85 and 1.4 GHz (Condon *et al.*, 1985, 1986 and 1989). Radio maps of these surveys provided by Condon were used to obtain a list of sources at 4.85 GHz (Zhuravlev and Larionov, 1992) and spectral indices in the range 1.4–4.85 GHz. The threshold of the sources detected on the level 5σ was supposed equal to 25 mJy at 4.85 GHz and 150 mJy at 1.4 GHz. The sources spectra were approximated by the power law $S \sim \nu^{-\alpha}$. The sample was limited by the flux level $S_{4.85} = 150$ mJy, and the spectral index was $\alpha < 0.5$. We suppose that sources with indefinite identification at 1.4 GHz have a flux lower than the threshold detected at this frequency and that is why the spectral index $\alpha < 0$ can be ascribed to these sources and they can be included in the attributed list. This approach allows one to decrease selection effects, following from natural restrictions on the flux. It is easy to calculate a possible maximum restriction of flux at 4.85 GHz at which the sources still could be used in our analysis with $\alpha < 0.5$ and $S_{1.4} = 150$ mJy. This condition is fulfilled by $S_{4.85} = 80$ mJy. Nevertheless it should be taken into account that a completeness of the survey is destroyed for these fluxes due to a decrease in the sensibility of the Green Bank 91 m telescope in low declinations ($\delta < 20°$). Besides in high declinations ($74° < \delta < 75°$) a certain excess of the sources can be observed due to boundary effects by radio mapping (Kooiman *et al.*, 1995). Then we excluded from observation the sources which belong to the Galactic plane ($|b^{II}| < 10°$). The sample of radio sources with flat spectra ($\alpha < 0.5$) contain 1577 objects with flux $S_{4.85} > 150$ mJy in the range $0° < \delta < 75°$ and $|b^{II}| > 10°$, except the region $12^h40^m < \alpha \lesssim 14^h40^m$ and $0° < \delta < 5°$, where the observation data at 4.85 GHz unaffected by a sufficient interference from the Sun, were finally obtained. Figure 1 shows a distribution of the sources in the supergalactic coordinates and boundaries of the investigated region.

The most convenient method of defining a possible inhomogeneity in a complicated form of investigated region is the correlation method used in some papers on source distribution analysis (Peebles, 1980). This method allows one to analyse statistically the distribution of objects on the celestial sphere according to the

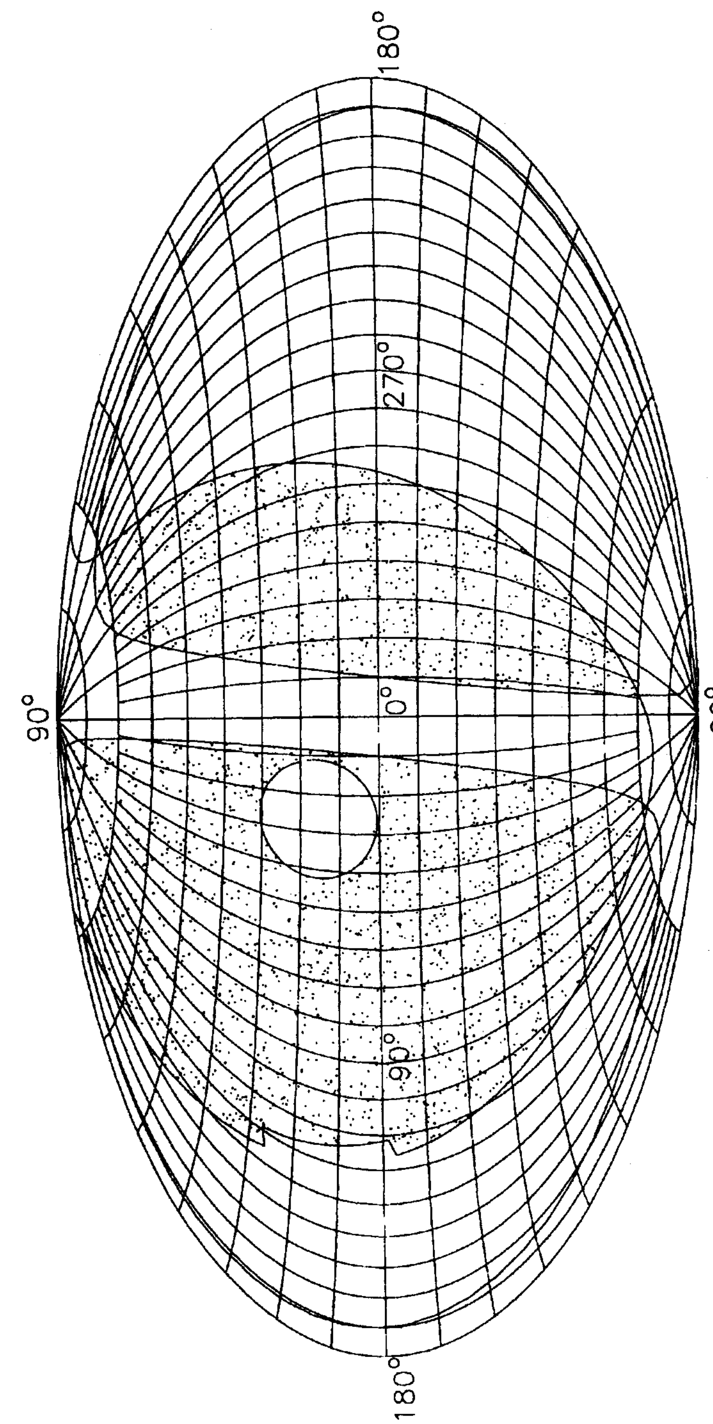

Figure 1 Sky distribution of 1577 extragalactic radio sources ($|b^{II}| > 10°$) with the flux density $S > 150$ mJy at 4.85 GHz and flat spectra ($\alpha < 0.5$) in supergalactic coordinates.

behaviour of the angular two-point correlation function:

$$w(v) = \frac{N(\vartheta)}{N_p(\vartheta)} - 1 \quad (1)$$

where $N(\vartheta)$ is the observable number of pairs of objects laying at the angular distance in the range from ϑ to $\vartheta + \Delta\vartheta$, $N_p(\vartheta)$ is the corresponding number of pairs in the Poisson distribution inside the same region.

Two coordinates were set by a random number generator independently and uniformly located inside the region investigated. The point occupied inside the region was included in the accidental list. The average over one hundred catalogues with the number of sources identical to the number in the investigated one was taken for the calculation of $N_p(\vartheta)$. For each calculation of the correlation function one hundred catalogues were generated once again. If the sources are located on the celestial sphere occasionally, then $w(\vartheta) = 0$, but if their locations correlate, then $w(\vartheta) > 0$.

According to Seldner and Peebles (1978), the mutual correlation can be estimated by the simple power law:

$$w(\vartheta) = A\vartheta^{-0.77} \quad (2)$$

where A is the amplitude of correlation function (ACF), ϑ is the angular distance.

To reveal the excess of correlation pairs in SGP, let us calculate $w(\vartheta)$ according to (1) for different flux intervals. An estimation for ACF can be obtained from (2) using the method of least squares. One can calculate $w(\vartheta)$ for all sources with the flux exceeding a certain value S_n, with a gradual decrease in S_n (as was realized by the analysis of radio sources of 4C (Seldner and Peebles, 1978)). Nevertheless we consider the preference of the calculated $w(\vartheta)$ when the investigated sources are located on a certain flux interval (S_i, S_j). In the second case we can reveal more effectively details of $w(\vartheta)$ for different fluxes, and the fluctuation of correlating pairs of close objects does not influence a further behaviour of the curve.

The statistical significance of deviation η of the investigated value from the average of the angular function on the interval of approximation is determinated by σ as follows:

$$\eta = \frac{N(\vartheta) - N_p(\vartheta)}{\sigma} \quad (3)$$

where σ is the root mean square of the random number of the pair N_{pk} from the average in the random distribution, $\sigma = \sqrt{\frac{\sum_{k=1}^{100}(N_p(\vartheta) - N_{pk}(\vartheta))^2}{99}}$. While approximating the positive values of the angular function $w(\vartheta)$ amplitudes by power law (2), only the values satisfying the confidence interval 95% for one hundred Poisson catalogues with artificial clusterization were used. The infinum of approximation is limited by the value of $0\overset{\circ}{.}2$. For the angle less then $0\overset{\circ}{.}2$ there takes place a negative correlation following from the limited size of the direction diagram of the antenna in the coordinates $(3\overset{\prime}{.}7 \times 3\overset{\prime}{.}3)$. The supremum of approximation is 3°.

From the estimation of reasonable flux intervals for the calculation of the angular correlation function we used a subsample containing 425 objects. The calculation ACF was held with the gliding interval containing ten sources in the whole region of the investigated flux range. ACF as a function of the mount flux of subsample was averaged on the intervals 50 mJy with determination of the root mean square.

3 DISCUSSION

Figure 2 demonstrates the results of processing the sources investigated. The open circles curve shows a dependence of ACF upon the flux for the sources ($|b^{II}| > 10°$), and the filled circles curve shows a similar dependence for the sources in high supergalactic latitudes ($|b_{\rm SGL}| > 10°$). Comparison of these dependencies shows that they coincide quite well in two flux ranges of ACF. For $S > 800$ mJy the function is close to zero, that is the angle distribution is close to random one, and for $150 < S < 400$ mJy the function increases which means that an excess of correlation pairs takes place. It testifies lack of a sufficient influence of SGP upon the distribution of sources in the range mentioned above. Otherwise for $400 < S < 800$ mJy the peak near SGP is observed for the function calculated for the sample of all objects, while it is not observed in the sample excluding SGP.

If the analysed structure is limited by depth $z = 0.02$, where a sufficient part of investigated objects of the Local Supercluster (Shaver, 1991) is concentrated, it is possible to estimate a radio luminosity P of the sources. The radio luminosity is connected with the flux S for the sources with the power spectrum ($S \sim \nu^{-\alpha}$) by the well-known formula (Zeldovich and Novikov, 1975):

$$P = SD^2(z)(1+z)^{1+\alpha} \tag{4}$$

where $D(z)$ is the distance, $D(z) = \frac{2c}{H}(1-(z+1)^{-0.5})$; z is the redshift, $H = 100h$ km c^{-1} Mpc^{-1} is the Hubble constant. Thus, for the average spectral index of the sources with a flat spectrum $\alpha = 0$ and the corresponding estimation z, the value $P = 1.3 \div 2.6 \times 10^{22} h^{-2}$ W Hz^{-1} sr^{-1} for the correlating pairs is obtained. Bahcall and Chokshi (1992) emphasize clusterization of the radio galaxies in groups and clusters of galaxies in the neighbourhood of $\log P = 22.5 \div 24.5$.

A statistical analusis of the Abell catalogue (Abell *et al.*, 1989) does not show an appreciable concentration of superclusters near SGP but comparison of the distribution of close clusters (distance class ≤ 4, average redshift ~ 0.06) with more distant ones, for which the selective effects are similar, demonstrates a possible excess (2σ) for $|b_{\rm SGL}| < 10°$. At these distances the supergalactic forms projected onto the celestial sphere can represent similar structures in high latitudes (Kopylov *et al.*, 1988). The observed excess of correlation pairs outside SGP in the range $150 \div 400$ mJy is likely due to similar structures. For the discovered correlation fluxes outside SGP and with a small spread of luminisity from (4), $z = 0.04$ is obtained. Estimation of the redshift coincides precisely enough with the typical sizes of voids 20 h^{-1}$\div$50 h^{-1} Mpc (de Lapparent *et al.*, 1986).

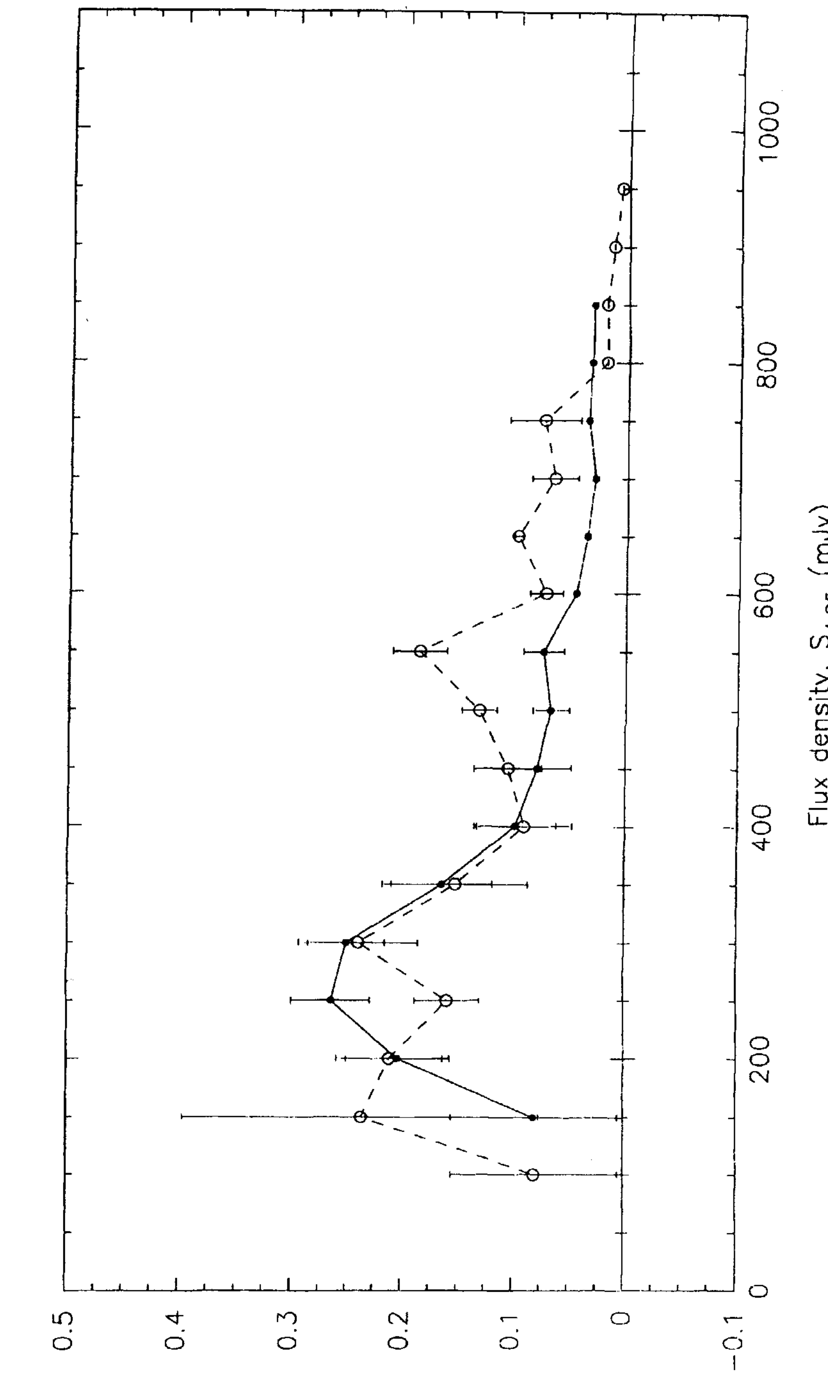

Figure 2 Comparison of the amplitude of the correlation function $A(S)$ for all radio sources (the open circles) and $A(S)$ for radio sources in high ($|b_{SGL}| > 10°$) supergalactic latitudes (the filled circles). The rms is shown.

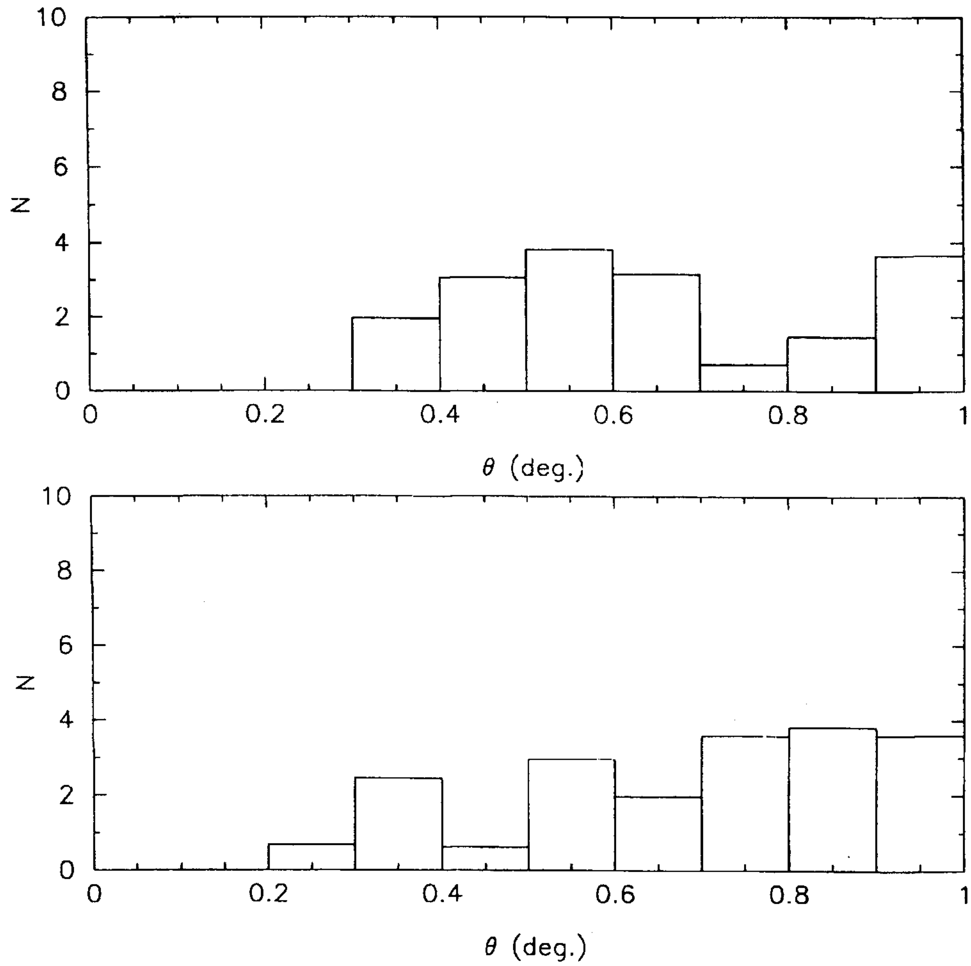

Figure 3 The distribution of the nearest neighbour subsample containing 425 sources. The upper plot, for all radio sources with $S = 400 \div 800$ mJy; the lower one, for radio sources in high ($|b_{\rm SGL}| > 10^\circ$) supergalactic latitudes with $S = 150 \div 400$ mJy.

Figure 3 demonstrates comparison of the distributions of the nearest neighbour subsamples from the flux intervals where an excess of the correlation pairs inside SGP ($400 \div 800$ mJy) and outside it ($150 \div 400$ mJy) is observed. The figure shows that if SGP has a peak due to calculating the correlation pairs at the angles $\sim 0\overset{\circ}{.}55$ then outside SGP it is smooth. The angle scale of the peak roughly corresponds to the cluster size at the distances $z \sim 0.02$. One should pay attention to decrease in the limiting value of the correlation distance from $0\overset{\circ}{.}3$ inside SGP to $0\overset{\circ}{.}2$ outside. This commutates with a supposition of higher distance objects and those outside SGP. A further decrease in the angular correlation diatances should be surely suppressed due to the limitation connected with the telescope resolution.

In conclusion we suggest a brief formulation of the main results obtained from the correlation analysis of the sources with the flat spectrum.

1. The analysis allows one to detect an excess of the correlation pairs of sources in the Local Superclusters ($z < 0.02$) in the flux range $400 \div 800$ mJy. This confirms a supposition of the sources with flat spectrum contribution to anisotropy of the objects distribution in SGP.

2. An excess of correlation pairs by less fluxes ($150 \div 400$ mJy) in supergalactic latitudes $> 10°$ is demonstrated. The source of these effects is hypothetically connected with other close superclusters with $z > 0.02$.

It is essential that there is no agreement between a simple model and observation data in the estimation of spatial scales using the luminosity function at long distances ($z \leq 5$) without including the selection effects (Kooiman *et al.*, 1995). We do not rule evolution of sources out at long distances but mention that it is necessary to take into account a local population in model calculations.

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