The large-scale clustering of radio sources

M. Negrello,1⋆ M. Magliocchetti1,2 and G. De Zotti1,3

1SISSA, Via Beirut 4, I-34014 Trieste, Italy
2Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-32131, Trieste, Italy
3INAF – Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Accepted 2006 February 7. Received 2006 February 3; in original form 2005 December 13

ABSTRACT

The observed two-point angular correlation function, \( w(\theta) \), of milliJansky (mJy) radio sources exhibits the puzzling feature of a power-law behaviour up to very large (~\(10^6\)) angular scales which cannot be accounted for in the standard hierarchical clustering scenario for any realistic redshift distribution of such sources. After having discarded the possibility that the signal can be explained by a high-density local (\(z \lesssim 0.1\)) source population, we find no alternatives to assuming that – at variance with all the other extragalactic populations studied so far, and in particular with optically selected quasars – the radio sources responsible for the large-scale clustering signal were increasingly less clustered with increasing look-back time, up to at least \(z \simeq 1\). The data are accurately accounted for in terms of a bias function which decreases with increasing redshift, mirroring the evolution with cosmic time of the characteristic halo mass, \(M_*\), entering the non-linear regime. In the framework of the ‘concordance cosmology’, the effective halo mass controlling the bias parameter is found to decrease from about \(10^{15} M_{\odot} h^{-1}\) at \(z \simeq 0\) to the value appropriate for optically selected quasars, \(\simeq 10^{13} M_{\odot} h^{-1}\), at \(z \simeq 1.5\). This suggests that, in the redshift range probed by the data, the clustering evolution of radio sources is ruled by the growth of large-scale structure, and that they are associated with the densest environments virializing at any cosmic epoch. The data provide only loose constraints on the radio source clustering at \(z \gtrsim 1\) so that we cannot rule out the possibility that at these redshifts, the clustering evolution of radio sources enters a different regime, perhaps similar to that found for optically selected quasars. The dependence of the large-scale shape of \(w(\theta)\) on cosmological parameters is also discussed.

Key words: galaxies: evolution – cosmological parameters.

1 INTRODUCTION

Extragalactic radio sources are well suited to probe the large-scale structure of the Universe since they are detected over large cosmological distances (up to \(z \sim 6\)), are unaffected by dust extinction, and can thus provide an unbiased sampling of volumes larger than those usually probed by optical surveys. On the other hand, their 3D-space distribution can be recovered only in the very local Universe (\(z \lesssim 0.1\); see Peacock & Nicholson 1991; Magliocchetti et al. 2004) because the majority of radio galaxies detected in the available large area surveys, carried out at low frequencies, have very faint optical counterparts, so that measurements of their redshifts are a difficult task. As a result, only the angular clustering could be measured for the radio source population. Interestingly, high-frequency surveys have much higher identification rates (Ricci et al. 2004), suggesting that this difficulty may be overcome when such surveys will cover sufficiently large areas.

★E-mail: negrello@sissa.it

Even the detection of clustering in the 2D distribution of radio sources proved to be extremely difficult (see Webster 1976; Seldner & Peebles 1981; Shaver & Pierre 1989) since, when projected on to the sky, the space correlation is significantly diluted because of the broad-redshift distribution of radio sources. It was only with the advent of deep radio surveys covering large areas of the sky, such as the Faint Images of the Radio Sky at Twenty centimeters (FIRST; Becker, White & Helfand 1995), the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997), the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) and the Sydney University Molonglo Sky Survey (SUMSS; Bock, Large & Sadler 1999), that the angular clustering of this class of objects has been detected with a high statistical significance down to flux density limits of few mJy [see Cress et al. (1997) and Magliocchetti et al. (1998, 1999) for the FIRST survey; Blake & Wall (2002a,b) and Overzier et al. (2003) for the NVSS; Rengelink & Röttgering (1999) for the WENSS and Blake, Mauch & Sadler (2004) for the SUMSS]. Amongst all the cited surveys, the NVSS is characterized by the most extensive sky coverage and can thus...
take advantage of higher statistics despite its relatively higher flux limit (~3 mJy versus ~1 mJy of FIRST). The two-point angular correlation function, \( w(\theta) \), measured for the NVSS sources brighter than 10 mJy is well described by a power law, extending from \( \sim 0.1^\circ \) up to scales of almost 10\(^\circ\). A signal of comparable amplitude and shape was detected in the FIRST survey at the same flux density limit, on scales of up to 2–3\(^\circ\) (see e.g. Magliocchetti et al. 1999), while at larger angular separations any positive clustering signal – if present – was hidden by the noise.

Most analyses of the radio source clustering performed so far (see e.g. Blake & Wall 2002a,b; Overzier et al. 2003) assume a two-point spatial correlation function of the form \( \xi_{gg}(r) = (r/r_0)^{-\gamma} \). The power-law shape is in fact preserved when projected onto the sky (see Limber 1953), so that the observed behaviour of the angular correlation is well recovered. The studies summarized by Overzier et al. (2003) typically found correlation lengths \( r_0 \) in the range 5–15 h\(^{-1}\) Mpc. This large range may reflect on one hand real differences in the correlation properties of radio sources of different classes/luminosities, and, on the other hand, the large uncertainties on both the redshift distribution of the sources and the time-evolution of clustering, which are necessary ingredients to estimate \( \xi_{gg}(r) \) from the observed \( w(\theta) \).

Overzier et al. (2003) found that the data on clustering of powerful radio galaxies are consistent either with an essentially redshift independent comoving correlation length \( r_0 = 14 \pm 3 \ h^{-1} \) Mpc, close to that measured for extremely red objects (EROs) at \( z \approx 1 \) (Daddi et al. 2001) or with a galaxy conservation model, whereby the clustering evolution follows the cosmological growth of density perturbations. In the latter case, the present-day value of \( r_0 \) for the most powerful radio sources is comparable to that of local rich clusters.

A deeper examination of the power-law behaviour of the angular two-point correlation function up to scales of the order of \( \sim 10^\circ \) highlights some interesting issues. In fact, within the cold dark matter paradigm of structure formation, the spatial correlation function of matter displays a sharp cut-off around a comoving radius of \( r \sim 100 \) h\(^{-1}\) Mpc\(^1\) (see e.g. Matsubara 2004, fig. 1), which, at the average redshift for radio sources \( z \sim >1 \), corresponds to angular separations of only a few \( (\sim 1^\circ \) to \( 2^\circ \)\) degrees, in clear contrast with the observations. This opens the question of how to reconcile the clustering properties of these sources with the standard scenario of structure formation. Magliocchetti et al. (1999) claim that the large-scale positive tail of the angular correlation function \( w(\theta) \) can be reproduced by allowing for a suitable choice of the time-evolution of the bias parameter, characterizing the way radio galaxies trace the underlying mass distribution. Although promising, this approach suffers from a number of limitations due to both theoretical modelling and the quality of data then available.

The aim of the present work is therefore to investigate in better detail and to provide a self-consistent explanation of the puzzling behaviour of the angular correlation function of radio sources, especially on large angular scales. We will concentrate on the results from the NVSS survey (Blake & Wall 2002b; Overzier et al. 2003) as, thanks to the extremely good statistics, a clear detection of a positive clustering signal was obtained up to \( \sim 10^\circ \). We will exploit the available spectroscopic information on local radio sources to limit the uncertainties on their redshift distribution, and will mainly focus on the time-evolution of their clustering properties via the bias parameter. In this way, we will derive interesting constraints on the typical mass of dark matter haloes hosting the population of radio sources. We will also investigate the dependence of the predicted angular correlation function on cosmological parameters.

The layout of the paper is as follows. A short description of the NVSS survey is presented in Section 2. Section 3 illustrates the adopted model for the redshift distribution of milliJansky (mJy) radio sources, while in Section 4, we provide the formalism for the two-point angular correlation function. Results and discussions are presented in Section 5. In Section 6, we summarize our main conclusions.

### 2 THE NRAO VLA SKY SURVEY

The NVSS (Condon et al. 1998) is the largest radio survey that currently exists at 1.4 GHz. It was constructed between 1993 and 1998 and covers \( \sim 10.3 \) sr of the sky north of \( \delta = -40^\circ \). The survey was performed with the Very Large Array (VLA) in the D configuration and the full width at half-maximum (FWHM) of the synthesized beam is 45 arcsec. The source catalogue contains 1.8 \( \times 10^6 \) sources and it is claimed to be 99 per cent complete above the integrated flux density \( S_{1.4\text{GHz}} = 3.5 \) mJy.

The two-point angular correlation function, \( w(\theta) \), of NVSS sources has been measured by Blake & Wall (2002a,b) and Overzier et al. (2003) for different flux density thresholds between 3 and 500 mJy. The overall shape of \( w(\theta) \) is well reproduced by a double power law. On scales below \( \sim 0.1^\circ \), the steeper power law reflects the distribution of the resolved components of single-giant radio sources. On larger scales, the shallower power law describes the correlation between distinct radio sources. Since, the behaviour on small scales is mainly determined by the joint effect of the astrophysical properties of the sources and of the resolution of VLA in the various configurations, while that on larger scales is of cosmological origin, we will concentrate on the latter only. In fact, the clustering behaviour on scales \( \gtrsim 0.1^\circ \) provides insights on both the nature of the radio sources, through the way in which they trace the underlying dark matter distribution, and on the cosmological framework which determines the distribution of dark matter at each epoch.

We will consider the two-point angular correlation function as measured by Blake & Wall (2002b) for sources with \( S_{1.4\text{GHz}} \geq 10 \) mJy. Such a flux limit ensures the survey to be complete and, at the same time, provides good enough statistics to measure the angular clustering up to very large scales with small uncertainties. Moreover, this limit also represents the deepest flux density for which systematic surface density gradients are approximately negligible (Blake & Wall 2002a). The NVSS source surface density at this threshold is 16.9 deg\(^{-2}\).

The data corresponding to separations in the range \( 0.1^\circ \leq \theta \leq 0.3^\circ \) most likely suffer from a deficit of pairs probably due to an imperfect cleaning of bright side lobes (see Blake et al. 2004). Therefore in the following, we will only consider scales \( \theta > 0.3^\circ \). In this range of scales, the measured angular correlation function can be described as a power law, \( w(\theta) = 1.49 \times 10^{-3} \times \theta^{-1.05} \), with \( \theta \) in degrees (see Blake et al. 2004).

### 3 REDSHIFT DISTRIBUTION OF MILLIJANSKY RADIO SOURCES

In order to provide theoretical predictions for the angular two-point correlation function of a given class of objects, it is necessary to know their redshift distribution, \( N(z) \), that is, the number of objects per unit comoving volume as a function of redshift. Unfortunately, the redshift distribution of mJy radio sources is

---

\(^1\) We assume a flat universe with a cosmological constant and \( \Omega_0 = 0.7, \Omega_m = 0.27, \Omega_k = 0.045, \sigma_8 = 0.9, n = 1 \) and \( h = 0.72 \), in agreement with the first-year WMAP results (Spergel et al. 2003).
not yet accurately known as the majority of radio sources powered by active galactic nuclei (AGN)—which dominate the mJy population—are located at cosmological distances ($z \sim 1$) and are in general hosted by galaxies which are optically extremely faint.

A large set of models for the epoch-dependent radio luminosity function (hereafter RLF) are available in literature (see e.g. Dunlop & Peacock 1990; Rowan-Robinson et al. 1993; Toffolatti et al. 1998; Jackson & Wall 1999; Willott et al. 2001), but they all suffer from the fact that they are mainly based on, and constrained by data sets which include only bright sources ($S_{1.4 \text{GHz}} \gtrsim 100 \text{ mJy}$) so that any extrapolation of their predictions to lower fluxes is quite uncertain. Amongst all the available RLFs, those provided by (Dunlop & Peacock 1990, hereafter DP90) are the most commonly used to infer the redshift distribution of radio sources at the mJy level. DP90 derived their set of RLFs on the basis of spectroscopically complete samples from several radio surveys at different frequencies. By using a 'maximum entropy' analysis, they determined polynomial approximations to the luminosity function and its evolution with redshift which were all consistent with the data available at that time. In addition, they also proposed two models of a more physical nature, assuming either pure luminosity evolution (hereafter PLE) or luminosity/density evolution.

Recently, with the aim of determining the photometric and spectroscopic properties for at least the population of local (i.e. $z < 0.2$) radio sources at the mJy level, a number of studies have concentrated on samples obtained combining radiocatalogues like FIRST and NVSS with optical ones like Sloan Digital Sky Survey (SDSS) and 2dF Galaxy Redshift Survey (2dFGRS) (Ivezić et al. 2002; Magliocchetti et al. 2002, 2004; Sadler et al. 2002). The radio/optical samples obtained in this way provide a crucial constraint at $z \sim 0$ for any theoretical model aiming at describing the epoch-dependent RLF.

For instance, Magliocchetti et al. (2002, hereafter M02) have shown that the RLF at 1.4 GHz derived from all the objects in their spectroscopic sample having $S \geq 1 \text{ mJy}$ and $b_1 \leq 19.45$, is well reproduced at relatively high radio luminosities ($P_{1.4 \text{GHz}} > 10^{20.5} \text{ W Hz}^{-1} \text{ sr}^{-1}$) by the DP90’s PLE model for steep-spectrum FRI–FRII sources (Fanaroff & Riley 1974). At lower radio luminosities, where the radio population is dominated by star-forming galaxies, the measured RLF is better described by the one proposed by Saunders et al. (1990) for IRAS galaxies (see also Rowan-Robinson et al. 1993), although with a small adjustment of the parameters.

Following to M02, we adopt the DP90 PLE model to derive the redshift distribution of AGN-fuelled radio sources with $S_{1.4 \text{GHz}} \geq 10 \text{ mJy}$ (see Fig. 1, dashed line). We will not take into account the other DP90 models, since we have found them to be inconsistent with the local RLF. In fact, while the model assuming density/luminosity evolution overpredicts the number of steep-spectrum radio galaxies below $P_{1.4 \text{GHz}} \lesssim 10^{23} \text{ W Hz}^{-1} \text{ sr}^{-1}$, models using polynomial approximations for the RLF give an unrealistic overestimate of the number of local sources at every luminosity.

We will use the fit provided by M02 to the local RLF in order to estimate the redshift distribution of star-forming radio galaxies with $S_{1.4 \text{GHz}} \geq 10 \text{ mJy}$ (see Fig. 1, dotted line). Note that star-forming galaxies comprise less than 30 per cent of the $z \lesssim 0.1$ population of radio sources with $S_{1.4 \text{GHz}} \geq 10 \text{ mJy}$, and only $\lesssim 0.5$ per cent of the total counts at this flux limit. As we will show in Section 4, this result implies that the contribution of star-forming galaxies to the large-scale angular clustering of the NVSS sources is completely negligible.

Figure 1. Adopted redshift distribution per unit redshift interval, $N(z)$, for the radio source population with $S_{1.4 \text{GHz}} \geq 10 \text{ mJy}$. The dashed line represents the contribution of AGN-powered radio sources according to the PLE model of DP90, while the dotted line shows the contribution from star-forming galaxies obtained by Magliocchetti et al. (2002).

### 4 THE MODEL FOR THE ANGULAR CORRELATION FUNCTION

The two-point angular correlation function, $w(\theta)$, of a population of extragalactic sources is related to their spatial correlation function, $\xi(r, z)$, and to their redshift distribution by Limber’s (1953) equation:

$$w(\theta) = \int_{z} dz N^2(z) \int_{Z(z)} d(\delta z) \xi[r(\delta z, \theta), z] \times \left[ \int_{Z} dz N(z) \right]^{-2},$$

In this expression, $r(\delta z, \theta)$ is the comoving spatial distance between two objects located at redshifts $z$ and $z + \delta z$ and separated by an angle $\theta$ on the sky. For a flat universe and in the small angle approximation (which is still reasonably accurate for the scales of interest here, i.e. $0.3^\circ < \theta < 1^\circ$),

$$r^2 = \left[ \frac{c}{H(z)} \right]^2 \delta z^2 + d^2_0(z),$$

where $H(z) = H_0(z)$ is the time-dependent Hubble parameter and $d_0(z)$ is the comoving linear distance on the sky surface corresponding, at a the redshift $z$, to an angular separation $\theta$. Integrations in equation (1) are performed in the ranges $Z = [z_{\min}, z_{\max}]$ and $Z'(z) = [z_{\min} - z, z_{\max} - z]$, where $z_{\min} = 0$ and $z_{\max} = 6$ are, respectively, the minimum and the maximum redshift at which radio sources are observed.

On sufficiently large scales (e.g. $r \gtrsim 3 \text{ Mpc}$), where the clustering signal is produced by galaxies residing in distinct dark matter haloes and under the assumption of a one-to-one correspondence between sources and their host haloes, the spatial two-point correlation function can be written as the product of the correlation function of dark matter, $\xi_{DM}$, times the square of the bias parameter, $b$ (Matarrese et al. 1997; Moscardini et al. 1998):

$$\xi(r, z) = b^2(M_{\text{eff}}, z)\xi_{DM}(r, z).$$

Here, $M_{\text{eff}}$ represents the effective mass of the dark matter haloes in which the sources reside and $b$ is derived in the extended Press & Schechter (1974) formalism according to the prescriptions of Sheth & Tormen (1999).
The function $\xi_{DM}$ is determined by the power spectrum of primordial density perturbations as well as by the underlying cosmology. For the power spectrum of the primordial fluctuations, we adopt the fitting relations by Eisenstein & Hu (1998) which account for the effects of baryons on the matter transfer function. The initial power spectrum is assumed to be scale invariant with a slope $n = 1$. As already mentioned, we adopt a ‘concordance cosmology’, in agreement with the first-year WMAP results (Spergel et al. 2003).

In the range of scales of interest here the clustering evolves in the linear regime, so that $\xi_{DM}(r, z) = D^2(z)\xi_{DM}(r, 0)$, $D(z)$ being the linear density growth rate (Carroll, Press & Turner 1992).

Since the population of radio sources with $S_{1.4 \text{GHz}} \geq 10$ mJy is composed by two different types of objects, that is, AGNs and star-forming galaxies, which display different clustering properties (see Saunders, Rowan-Robinson & Lawrence 1992; Madgwick et al. 2003), the angular correlation function of the whole NVSS sample is given by (cf. e.g. Wilman et al. 2003, equation 9):

$$w(\theta) = f^2_{AGN}w_{AGN}(\theta) + f^2_{SF}w_{SF}(\theta) + 2f_{AGN}f_{SF}w_{\text{cross}}(\theta),$$

where $f_{AGN}$ and $f_{SF}$ are the fractions of AGNs and star-forming galaxies in the whole sample, respectively, that is,

$$f_{AGN/SF} = \frac{\int_{z} dz N_{AGN/SF}(z)}{\int_{z} dz N(z)},$$

where $N(z)$ being the global redshift distribution.

In equation (4), $w_{AGN}$ and $w_{SF}$ are the angular correlation functions of the two classes of radio sources, while $w_{\text{cross}}$ accounts for the cross-correlation between the two populations:

$$w_{\text{cross}}(\theta) = \int_{z} dz N_{AGN}(z)N_{SF}(z)$$

$$\times \left[ \int_{z} dz N_{AGN}(z) \int_{z} dz N_{SF}(z) \right]^{-1}.$$

We model $\xi_{\text{cross}}$ as (cf. e.g. Magliocchetti et al. 1999, equation 31):

$$\xi_{\text{cross}}(r, z) = \xi_{\text{cross}}(r, z) S_{\text{cross}}(r, z)$$

$$= b(M_{\text{eff}}^{AGN}, z) b(M_{\text{eff}}^{SF}, z) \xi_{DM}(r, z),$$

where $\xi_{\text{cross}}$ are the spatial correlation functions of AGNs and star-forming galaxies, respectively, while $M_{\text{eff}}^{AGN}$ and $M_{\text{eff}}^{SF}$ denote the effective masses of the corresponding dark matter haloes (cf. equation 3). Note that this definition likely overestimates the cross-correlation term, which may be close to zero, since AGN-powered radio sources are normally found in clusters while star-forming galaxies are in the field.

5 RESULTS

As a first step, we worked out estimates of the two-point angular correlation function, $w(\theta)$, assuming a redshift-independent effective mass for the host haloes of AGN-powered radio sources, $M_{\text{eff}}^{AGN}$, consistent with clustering properties of optically selected quasars (Porciani, Magliocchetti & Norberg 2004; Croom et al. 2005). The value of $M_{\text{eff}}^{AGN}$ is taken as a free parameter. The observationally determined spatial correlation length of star-forming galaxies, $r_{\delta}(z = 0) \sim 3–4 \text{ Mpc} h^{-1}$ (Saunders et al. 1992; see also Wilman et al. 2003) is consistent with an effective halo mass not exceeding $M_{\text{eff}}^{SF} = 10^{11} M_{\odot} h^{-1}$. We adopt this value in our analysis. Any dependence of $M_{\text{eff}}^{SF}$ on redshift can be ignored because of the small range in redshift covered by star-forming galaxies with $S_{1.4 \text{GHz}} \geq 10$ mJy.

In the top panel of Fig. 2, we show the contributions to $w(\theta)$ for the NVSS sources with $S_{1.4 \text{GHz}} \geq 10$ mJy arising (see equation 4) from the clustering of AGNs with $M_{\text{eff}}^{AGN} = 10^{13}, 10^{14}$ and $10^{15} M_{\odot} h^{-1}$ (short-dashed curves), and of star-forming galaxies (long-dashed curve), and from the cross-correlation between the two populations (dotted curves). As noted above, the cross-correlation term, computed from equation (7) for the three values of $M_{\text{eff}}^{AGN}$, is likely overestimated. Such contributions are compared with the observational determination of Blake & Wall (2002b). In the lower panel of the same figure, the redshift evolution of the bias parameter for AGNs (short-dashed curves) and star-forming galaxies (long-dashed curves).
The large-scale clustering of radio sources...
Increasing $\sigma_8$ is almost negligible. This is because the decrease of this quantity contributes to the overall normalization of the spatial clustering pattern on the rms mass fluctuation, $\sigma$. In principle, this quantity contributes to the overall normalization of the spatial clustering, but we have checked that in our case the effect of changing it is almost negligible. This is because the decrease of $b$ with increasing $\sigma_8$ is compensated by the corresponding increase of the effective mass [assumed to be proportional to $M_{\star}(z)$]. Therefore, we also keep $\sigma_8 = 0.9$.

The parameters in our analysis are then: $M_{\text{eff}}(0)$, $\Omega_{0,m}$, and $\Omega_b$. In Fig. 5, we show the predicted two-point angular correlation function for different choices of these parameters. In each panel, the dashed curves correspond (from bottom to top) to $\Omega_{0,m} = 0.03, 0.045$ and 0.06. The values adopted for both $M_{\text{eff}}(0)$ and $\Omega_{0,m}$ are given in each panel: $M_{\text{eff}}(0)$ increases from the top to the bottom panels, while $\Omega_{0,m}$ increases from the left- to the right-hand panels.

We note that variations of these parameters within the allowed ranges mainly translate into changes of the normalization of $w(\theta)$, although $\Omega_b$ also affect its slope on scales $\theta \lesssim 2^\circ$, while $\Omega_{0,m}$ affects the slope on large scales. In general, the amplitude of $w(\theta)$ increases with increasing $M_{\text{eff}}(0)$ or $\Omega_b$, and decreases with decreasing $\Omega_{0,m}$. From Fig. 5, we can deduce that for the given $w(\theta)$, smaller values of $M_{\text{eff}}(0)$ are favoured for lower values of $\Omega_{0,m}$.

Fixing the baryonic content to the reference value $\Omega_b = 0.045$, we have then investigated the $\Omega_{0,m}$-$M_{\text{eff}}(0)$ interdependence by constructing $\chi^2$ contours on the $\Omega_{0,m}$-$M_{\text{eff}}(0)$ plane. The results are shown in Fig. 6 where the curves represent, from the innermost to the outermost, contours corresponding to the 68.3, 95.4 and 99.7 per cent confidence intervals, respectively. The filled square corresponds to the best-fitting set of parameters: $\Omega_{0,m} = 0.105$, $M_{\text{eff}}(z = 0) = 10^{13.15} M_\odot h^{-1}$. The resulting angular two-point correlation function, the redshift evolution of both the bias parameter and the effective mass are represented by the dotted line in Fig. 4. We note that the effect of a change in the baryonic content is just that of smearing the relation between $\Omega_{0,b}$ and $M_{\text{eff}}(0)$ (in particular for $\Omega_{0,m} \lesssim 0.2$), since there is a whole set of $\Omega_b - M_{\text{eff}}(0)$ pairs which can provide the same best fit to the data.

The fit obtained for a zero offset $\epsilon$ is really good, but is obtained for a local matter density parameter $\Omega_{0,m}$ substantially smaller than indicated by other data sets (see e.g. Spergel et al. 2003), although the difference is significant to less than $3\sigma$. The degeneracy between the host halo mass and the matter density parameter indicates that large-area radio surveys without redshift information can hardly provide significant constraints on cosmological parameters, unless independent information on $M_{\text{eff}}$ is available. On the other hand, for a given set of cosmological parameters, such surveys yield important information on masses of hosting haloes.

Taken at face value, our results indicate that, within the standard cosmological framework, in the local universe radio sources are as strongly clustered as rich clusters of galaxies, in excellent agreement with the findings of Peacock & Nicholson (1991) and Magliocchetti et al. (2004).
The large-scale clustering of radio sources

6 DISCUSSION AND CONCLUSIONS

The observed angular two-point correlation function of mJy radio sources exhibits the puzzling feature of a power-law behaviour up to very large (∼10°) angular scales. Standard models for clustering, which successfully account for the clustering properties of optically selected quasars, turn out to be unable to explain the long positive tail of the \( w(\theta) \), even when ‘extreme’ values for the parameters are invoked. This is because – according to the standard scenario for biased galaxy formation in which extragalactic sources are more strongly clustered at higher redshifts – the clustering signal of radio sources at \( z \gtrsim 1 \), which is negative on large scales, overwhelms that of more local sources, yielding a sharp cut-off in the angular two-point correlation function on scales of ∼1° to 2°.

The only way out we could find is that the clustering strength of radio sources was weaker in the past. The data can be accounted for if we assume that the characteristic mass of the haloes in which these objects reside, \( M_{\text{eff}}(z) \), is proportional to \( M_\star(z) \), the typical mass scale at which the matter density fluctuations collapse to form bound structures (see Mo & White 1996).

A good fit of the observed \( w(\theta) \) up to scales of at least 4° is obtained for \( M_{\text{eff}}(z = 0) = 10^{14.96 \pm 0.04} M_\odot h^{-1} \). The data on larger scales can be accurately reproduced if the measured values of \( w(\theta) \) are slightly enhanced by small systematic variations in the source surface density due to calibration problems at low flux densities (Blake & Wall 2002a). In the absence of such systematic offset, the data might indicate a lower value of the mean cosmic matter density than indicated by other data sets. The best fit is obtained for \( M_{\text{eff}}(z = 0) = 10^{13.15} M_\odot h^{-1} \), with rather large uncertainties on both parameters, as shown by Fig. 6. In particular, the best-fitting value of \( Q_{\odot, m} \) is less than 3σ away from the ‘concordance’ value. This shows that current large-scale radio surveys, without redshift measurements, cannot provide strong constraints on cosmological parameters, but are informative on the evolution of dark matter haloes hosting radio sources.

Taken at face value, the above results point to different evolutionary properties for different types of AGNs as the decreasing trend for the effective mass ruling the clustering of radio sources found in this work strongly differs from the behaviour of optically selected quasars. For the latter sources, the data are consistent with a constant \( M_{\text{eff}} \sim 10^{13} M_\odot h^{-1} \), at least up to the highest probed redshift, \( z \gtrsim 2.5 \) (see e.g. Grazian et al. 2004; Porciani et al. 2004; Croom et al. 2005). This different behaviour is illustrated in Fig. 7, where the values of the bias inferred for optically selected quasars have been scaled to the values of \( \sigma_8 \) and \( Q_{\odot, m} \) used here.

It must be noted, however, that the data provide very weak constraints on clustering properties of radio sources at \( z \gtrsim 1 \). For example, we have directly checked that the predicted \( w(\theta) \) does not change significantly over the range of angular scales considered here if we assume \( M_{\text{eff}} \propto M_\star(z) \) for \( z \lesssim 1.5 \) and \( M_{\text{eff}} \sim 10^{13} M_\odot h^{-1} \) at higher redshifts. It is thus possible that the difference in the clustering evolution between AGN-powered radio sources and optically selected quasars is limited to \( z \lesssim 1 \) consistent with observational indications that, at higher redshifts, the environment of radio-quiet and radio-loud quasi-stellar objects (QSOs) is almost the same (Russell, Ellison & Benn 2006).

Interestingly, our analysis indicates that, at \( z \simeq 1 \), the effective halo mass associated to radio sources is consistent with being essentially equal to that associated to optical quasars (Croom et al. 2005). This suggests that, at least at this redshift, the bias parameter is similar for radio-loud and radio-quiet AGNs.

On the other hand, our analysis suggests that at least for \( z \lesssim 1 \), at variance with what found for optical quasars, the clustering of radio sources reflects that of the largest haloes which collapse at any given cosmic epoch. This conclusion is in keeping with results of previous studies showing that, locally, radio sources are preferentially associated with clusters of galaxies (e.g. Peacock & Nicholson 1991; Magliocchetti et al. 2004), and, at higher redshift, are often associated with very massive galaxies and very massive galaxy environments (e.g. Carilli et al. 1997; Best, Longair & Röttgering 1998;
The major intriguing point that remains unsolved is the link with the population of optical QSOs. The clustering properties of the latter objects seems to reflect that of elliptical galaxies. But why this difference? Clearly, more observations are crucial to shed light on this issue. So far, the main limitation to our understanding of the environmental properties of radio sources has been due to selection effects that allow identifications of mostly radio galaxies in the local universe and exclusively quasars (regardless of their radio activity) at higher redshifts. Therefore, it would be of uttermost importance to consider a redshift range in which the clustering properties of both radio galaxies and radio-active quasars can be measured with good precision. We plan to tackle this issue in a forthcoming paper.

ACKNOWLEDGMENTS

We warmly thank C. Blake and J. Wall for having provided, in a tabular form, their estimates of the two-point angular correlation function of NVSS sources and for clarifications on their analysis. We acknowledge useful suggestions from the anonymous referee, which helped to improve this paper. Work supported in part by MIUR and ASI.

REFERENCES


This paper has been typeset from a TeX/LaTeX file prepared by the author.