Spatial clustering of USS sources and galaxies*

Carlos G. Bornancini¹, Nelson D. Padilla², Diego G. Lambas¹,³ Carlos De Breuck⁴

¹ Grupo de Investigaciones en Astronomía Teórica y Experimental, IATE
Observatorio Astronómico, Universidad Nacional de Córdoba
Laprida 854, X5000BGR, Córdoba, Argentina.
² Department of Astronomy, Pontificia Universidad Católica
Vicuña Mackenna 4860, Casilla 306 Santiago 22, Chile
³ Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Avenida Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina.
⁴ European Southern Observatory, Karl Schwarzschild Straße 2, D-85748 Garching, Germany.

ABSTRACT
We present measurements of the clustering properties of galaxies in the field of redshift range $0.5 \lesssim z \lesssim 1.5$ Ultra Steep Spectrum (USS) radio sources selected from Sydney University Molonglo Sky Survey and NRAO VLA Sky Survey. Galaxies in these USS fields were identified in deep near-IR observations, complete down to $K_s = 20$, using IRIS2 instrument at the AAT telescope. We used the redshift distribution of $K_s < 20$ galaxies taken from Cimatti et al. (2002) to constrain the correlation length $r_0$. We find a strong correlation signal of galaxies with $K_s < 20$ around our USS sample. A comoving correlation length $r_0 = 14.0 \pm 2.8$ h$^{-1}$ Mpc and $\gamma = 1.98 \pm 0.15$ are derived in a flat cosmological model Universe.

We compare our findings with those obtained in a cosmological N–body simulation populated with GALFORM semi-analytic galaxies. We find that clusters of galaxies with masses in the range $M = 10^{14.4-14.2}$ h$^{-1}$ M$_\odot$ have a cluster–galaxy cross-correlation amplitude comparable to those found between USS hosts and galaxies. These results suggest that distant radio galaxies are excellent tracers of galaxy overdensities and pinpoint the progenitors of present day rich clusters of galaxies.

Key words: cosmology: large-scale structure of Universe–galaxies: galaxies: high-redshift.

1 INTRODUCTION
In hierarchical galaxy formation models, cosmic structures form by the gravitational amplification of small primordial fluctuations of matter density in the early Universe (White & Rees 1978). Studies of the clustering properties of galaxies at high redshift are essential for understanding galaxy and structure formation. One of the most commonly used statistics to measure the clustering of a population of sources is the two-point correlation function $\xi(r)$, which measures the excess probability of finding a pair of objects at a separation $r$ with respect to a random distribution.

High redshift radio galaxies are ideal targets for pinpointing massive systems. Radio galaxies follow a close relation in the Hubble $K–z$ diagram (Lilly & Longair 1984). The nature of this behavior in the $K–z$ diagram shows that the stellar luminosities of $z \gtrsim 1$ radio galaxies are more luminous than normal galaxies at these redshifts (De Breuck et al. 2002). At lower redshifts they are found frequently in moderately rich clusters (Hill & Lilly 1991; Yates et al. 1989). Recently, galaxy overdensities comparable to that expected for clusters of Abell class 0 richness are found near radio galaxies up to $z = 1.6$ (Best 2000; Best et al. 2002; Bornancini et al. 2004). There is increasing evidence that galaxy overdensities around radio galaxies existed at very high redshifts. Using Lyα and/or Hα techniques, Kurk et al. (2000); Venemans et al. (2002); Miley et al. (2004) found overdensities of companion galaxies around powerful $2 < z < 4$ radio galaxies.

In this paper we estimated the spatial correlation length for galaxies in the fields of USS targets selected from the 843 MHz Sydney University Molonglo sky Survey (SUMSS) and 1.4 GHz NRAO VLA Sky Survey (NVSS) in the redshift range $0.5 \lesssim z \lesssim 1.5$, through the Limber’s equation using an appropriate observed redshift distribution. We compared our results with those obtained in cosmological N–body sim-
ulations. This paper is organized as follows: Section 2 describes the sample analyzed, we investigate the USS-galaxy cross-correlation analysis in Section 3. In Section 4 we interpret our results with those obtained in a cosmological N-body simulation. Finally we discuss our results in Section 5.

Throughout this paper we will use a flat cosmology with density parameters $\Omega_M = 0.25$, $\Omega_\Lambda = 0.75$ and a Hubble constant $H_0 = 100 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$.

2 THE DATA

The USS sample selection, radio data and redshifts used for this analysis was presented and described by De Breuck et al. (2004, 2005). Detailed descriptions of the construction of the galaxy catalogue is given in Bornancini et al. (2005). In summary, we used 11 $K_s$-band images centered in Ultra Steep Spectrum (USS) radio sources selected from the Sydney University Molonglo sky Survey and NRAO VLA Sky Survey, obtained with the instrument IRIS2 at the AAT telescope. We selected the redshift of the USS sample in the range $0.5 \lesssim z \lesssim 1.5$. The redshift upper limit was adopted in order to assure that $K$-band images are sufficiently deep while the lower limit precludes the use of too close USS for which the field of view subtends too small linear scales.

Our sample sources is listed in Table 1 in IAU J2000 format, including the $K_s$ counterpart magnitude and the spectroscopic redshift (De Breuck et al. 2004, 2005). Detailed descriptions of the USS selection function of USS targets and galaxies and can be calculated by Lilie & Efstathiou (1988):

$$B = \frac{\sum_i N(y_i)}{\frac{1}{2} \int_{y_0}^{\infty} N(x) x^2 dx},$$

where $N(y_i)$ is the selection function of the galaxy survey, $y_i$ is the distance to USS target $i$ and the sum extends over all USS targets in the sample. Equation (4) can be easily solved analytically if we perform a linear interpolation of $\omega_{\mu_0}$ between its values at the measured $\sigma$’s. In order to calculate the constant $B$ we evaluated the selection function $N(y)$ using the redshift (spectroscopic and photometric) distribution of $K_s < 20$ galaxies published by Cimatti et al. (2002). We model the distance distribution using a Gaussian function. The upper small box shows the corresponding redshift distribution of the sample.

$\omega(\sigma) = B \sqrt{\frac{\pi}{\sigma}} \frac{\Gamma\left(\frac{\gamma-1}{2}\right)}{\Gamma\left(\frac{\gamma}{2}\right)} \frac{r_0^2}{\sigma^{\gamma+1}},$

where the constant $B$ regulates the amplitude of the correlation function taking into account the differences in the selection function of USS targets and galaxies and can be calculated by Lilie & Efstathiou (1988):

$B = \frac{\sum_i N(y_i)}{\frac{1}{2} \int_{y_0}^{\infty} N(x) x^2 dx},$

where $N(y_i)$ is the selection function of the galaxy survey, $y_i$ is the distance to USS target $i$ and the sum extends over all USS targets in the sample. Equation (4) can be easily solved analytically if we perform a linear interpolation of $\omega_{\mu_0}$ between its values at the measured $\sigma$’s. In order to calculate the constant $B$ we evaluated the selection function $N(y)$ using the redshift (spectroscopic and photometric) distribution of $K_s < 20$ galaxies published by Cimatti et al. (2002). We model the distance distribution using a Gaussian function, and find that $\bar{y} = 2000 \, \text{h}^{-1} \, \text{Mpc}$ (mean) and $\sigma_y = 635 \, \text{h}^{-1} \, \text{Mpc}$ (standard deviation) is a reasonable set of values that reproduces the distribution (See Figure 4). In Figure 4 we show the projected cross-correlation function $\omega_{\mu_0}(\sigma)$ for USS targets with spectroscopic redshifts in the range $0.6 \lesssim z \lesssim 1.5$ and galaxies with $K_s < 20$. We estimate cross-correlation function error bars using the jackknife technique (Efron 1982). We find a comoving correlation length $r_0 = 14.0 \pm 2.8 \, \text{h}^{-1} \, \text{Mpc}$ with slope $\gamma = 1.98 \pm 0.04$.

We tested the accuracy of this result by varying the $N(y_i)$ distribution over a reasonable range of values for $\bar{y}$ and

1 Data and further information available at http://www.arcetri.astro.it/~k20/releases

© 2005 RAS, MNRAS 000, 000–000
The error bars correspond to the 1σ uncertainty estimated using the jackknife technique.

σ_y. We find that the calculated r_0 is only weakly dependent on the y used, and is only affected at the 10% level.

4 COMPARISON WITH N–BODY SIMULATIONS

We interpret our results with the aid of a cosmological N-body simulation populated with GALFORM semi-analytic galaxies (Cole et al. 2000) at different outputs corresponding to different redshifts, z = 0, 1, and 3. This simulation was kindly provided by the Durham group. The cosmological model corresponds to matter and cosmological constant density parameters Ω_m = 0.25, Ω_Λ = 0.75, a power spectrum tilt n = 0.95, an amplitude of fluctuations of σ_8 = 0.8, and a Hubble constant of H_0 = 100 h km s^{-1} Mpc^{-1}, where h = 0.7. The total number of particles is 1080^3, the mass resolution is 5.05 × 10^{10} M⊙, and the number of dark matter haloes with masses greater than M = 10^{12} M⊙ ranges from ~ 400,000 at z = 3 to ~ 2,200,000 at z = 0. The number of GALFORM galaxies ranges from ~ 20,000,000 to 120,000,000 at z = 3 and z = 0 respectively.

We now briefly explain the procedure by which galaxies are assigned their properties in the Semi-analytic code. GALFORM is run for each halo in the numerical simulation, where galaxies are assigned to a randomly selected dark matter halo particle. The different galaxy properties such as magnitudes in different bands, including the K-band, depend on the dark matter halo merger tree. This merger tree is generated via Monte-Carlo modelling based on the extended Press-Schechter theory, and the evolution of the galaxy population in the halo is followed through time and different processes are considered in this evolution, including gas cooling, quiescent star formation and star formation bursts, mergers, galactic winds and super winds, metal enrichment, extinction by dust. For full details on the modelling the reader is referred to Cole et al. (2000).

We calculate the cross–correlation function using the simulation haloes with masses above a lower mass limit as centres, and as tracers, the GALFORM semi-analytic galaxies. By comparing these measurements to the results from the cross–correlation between USS and normal galaxies, we make the implicit assumption that USS galaxies reside at the centres of dark-matter haloes. This comparison will make it possible to infer the mass of the structures associated to the USS hosts.

Figure 2 shows the resulting real-space cross-correlation functions between haloes and semi-analytic galaxies at z = 1 (top panel) for different halo masses. The shaded area corresponds to the power law fit for the real-space correlation function inferred from the cross–correlation function for USS radio sources with spectroscopic redshifts in the range 0.6 ≤ z ≤ 1.5 (See Figure 2). In the middle panel of this figure, we compare the values of USS–galaxy cross-correlation length as a function of halo mass for three different redshift outputs from the numerical simulations; as can be seen, the observed values are consistent with cluster masses within M = 10^{13.4—14.2} M⊙ at redshift z = 1, indicating that our USS sample resides in massive clusters.

In order to check whether our observational estimate of r_0 is affected by systematic biases, we calculate the projected correlation function in the numerical simulation and recover the real-space correlation length using Eq. 4, setting B = 1; we consider the same range of separations available in the real data. The results for z = 1 are shown in filled circles in the middle panel. As can be seen, our conclusions on the mass of USS host haloes changes only slightly to M = 10^{13.2—13.8} h^{-1} M⊙, although we note that for lower and higher halo masses, the value of r_0 recovered from projected correlations is underestimated and overestimated, respectively. This test provides a useful check of our observational results which were derived from relatively small projected scales (r_p ≤ 1 Mpc). Our findings in the simulations indicate that reliable r_0 values are obtained using the power law approximation applied to projected correlations for r_p < 1 h^{-1} Mpc when the true correlation length is lesser than ~ 15 h^{-1} Mpc corresponding to host halo mass M ≤ 10^{14} M⊙.

A further indication of the mass of USS galaxy host haloes comes from the lower panel of this figure, where the lines correspond to the projected cross-correlation function measured in the GALFORM simulation for different masses (High to low masses from top to bottom lines at log_{10}(σ/h^{-1}Mpc) = −0.3). Ξ(σ) is calculated directly using,

\[
Ξ(σ) = \text{Norm.} \int_0^{\sigma_{max}} ξ(\sqrt{σ^2 + π^2})dσ,
\]

where we have used π_{max} = 80 h^{-1} Mpc, and the normalisation, Norm., is set so that Ξ(σ) and ω(σ) coincide at log_{10}(σ/h^{-1}Mpc) = −1. The gray area shows the measured values of ω(σ) from the USS sample; as can be seen the measured projected correlation function is in best agreement for M ≈ 10^{13.87} h^{-1} M⊙.
Figure 3. Top panel: cluster-galaxy cross-correlation functions from the simulation output at $z = 1$ for increasing halo masses $\log(M) = 12.35, 12.68, 13.2, 13.85$ and $14.57$ $h^{-1} M_\odot$ (bottom to top). The shaded area shows the real-space correlation function measured from the USS targets with spectroscopic redshift in the range $0.6 < z < 1.5$. Middle panel: the real-space correlation length, $r_0$, as a function of halo mass for three different redshift outputs; the open symbols show the values recovered from the real-space correlation function, whereas the filled symbols (shown only for $z = 1$) indicate the values of $r_0$ obtained from the projected correlation function following a similar procedure to that applied to the real data. The shaded area shows the allowed range of $r_0$ for the USS results. Bottom panel: the projected USS cross-correlation function (gray area) and $\Xi(\sigma)$ from the GALFORM simulation for the same halo masses as in the top panel; the normalisation is set so that $\Xi(\sigma)$ and $\omega(\sigma)$ coincide at $\log_{10}(\sigma/h^{-1}{\text{Mpc}}) = -1$.

5 CONCLUSIONS

We have analyzed the clustering properties of galaxies in the field of $0.5 < z < 1.5$ Ultra Steep Spectrum (USS) radio galaxies selected from the Sydney University Molonglo Sky Survey (SUMSS) and NRAO VLA Sky Survey (NVSS). We estimated the spatial clustering correlation length for galaxies in these fields, using the Limber equation using an appropriate observed redshift distribution, and we examined the dependence of galaxy clustering on USS targets luminosity. A comoving correlation length $r_0 = 14.0 \pm 2.8$ $h^{-1}$ Mpc is derived and a slope $\gamma = 1.98 \pm 0.15$.

From our comparison with numerical simulations, we find that clusters of galaxies with masses in the range $M = 10^{13.4 - 14.2}$ $h^{-1} M_\odot$ have a cluster-galaxy correlation amplitude comparable to that found between USS hosts and galaxies. Our testing with the numerical simulations also indicate that these observational results are not severely affected by the relatively small projected scales explored. We notice that for larger spatial correlation lengths, the power-law extrapolation for observed projected correlations in $\sim 1h^{-1}{\text{Mpc}}$ fields would not give confident results.

Previous studies have addressed the clustering of galaxies around radio sources. Wold et al. (2000), using different cosmological parameters obtained a radio quasar-galaxy cross-correlation length about twice as large as the local galaxy autocorrelation length in suitable agreement with our findings. The more recent work by Barr et al. (2003) also indicates a moderate galaxy density enhancement around radio loud quasars similar to Abell richness 0 clusters.

Our analysis suggest that distant luminous radio galaxies are excellent tracers of galaxy overdensities and may pinpoint the progenitors of present day rich and moderate rich clusters of galaxies.

6 ACKNOWLEDGEMENTS

The authors are specially grateful to C. Baugh and the Durham group for providing the GALFORM semi-analytic simulation output used in this work. C. Bornancini thanks to Julian Martínez for helpful comments and suggestions. This work was supported in part by the ESO-Chile Joint Committee, NDP was supported by a Proyecto Postdoctoral Fondecyt no. 3040038. This work was partially supported by the Consejo Nacional de Investigaciones Científicas y Técnicas, Agencia de Promoción de Ciencia y Tecnología, Fundación Antorchas and Secretaría de Ciencia y Técnica de la Universidad Nacional de Córdoba, and the European Union Alfa II Programme, through LENAC, the Latin American-European Network for Astrophysics and Cosmology.
Table 1. USS Sample characteristics. Designation in IAU J2000 format, together with the $K_s$ counterpart magnitude, and the spectroscopic redshift (De Breuck et al, in prep.).

| Name             | $K_s$-mag. | $z_{\text{spectroscopic}}$ |
|------------------|------------|----------------------------|
| NVSS J015232−333952 | 16.26±0.02 | 0.6148±0.001 |
| NVSS J015544−330633 | 16.93±0.05 | 1.048±0.002 |
| NVSS J021716−325121 | 18.75±0.20 | 1.384±0.002 |
| NVSS J030639−330432 | 17.88±0.11 | 1.201±0.001 |
| NVSS J202026−372823 | 18.56±0.15 | 1.431±0.001 |
| NVSS J204147−331731 | 16.86±0.05 | 0.871±0.001 |
| NVSS J225719−343954 | 16.53±0.02 | 0.726±0.001 |
| NVSS J230203−340932 | 17.34±0.07 | 1.159±0.001 |
| NVSS J231519−342710 | 18.10±0.13 | 0.970±0.001 |
| NVSS J234145−350624 | 15.94±0.04 | 0.641±0.001 |
| NVSS J234904−362451 | 17.63±0.14 | 1.520±0.003 |

REFERENCES

Barr, J. M., Bremer, M. N., Baker, J. C., & Lehnert, M. D. 2003, MNRAS, 346, 229
Best, P. N. 2000, MNRAS, 317, 720
Best, P. N., Lehnert, M. D., Miley, G. K., & Röttgering, H. J. A. 2003, MNRAS, 343, 1
Bornancini, C. G., Lambas, D. G., De Breuck, C., 2005, MNRAS, in press
Bornancini, C. G., Martínez, H. J., Lambas, D. G., de Vries, W., van Breugel, W., De Breuck, C., & Minniti, D. 2004, AJ, 127, 679
Cimatti, A., et al. 2002, A&A, 391, L1
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
De Breuck, C., Klamer, I., Johnston, H., Hunstead, R. W., Bryant, J., Rocca-Volmerange, B., & Sadler, E. M., 2005, MNRAS, in press
De Breuck, C., Hunstead, R. W., Sadler, E. M., Rocca-Volmerange, B., & Klamer, I. 2004, MNRAS, 347, 837
De Breuck, C., van Breugel, W., Stanford, S. A., Röttgering, H., Miley, G., & Stern, D. 2002, AJ, 123, 637
Efron, B., 1982, The Jackknife, the Bootstrap and Other Resampling Plans, Philadelphia: SIAM.
Hill, G. J., & Lilly, S. J. 1991, ApJ, 367, 1
Kurk, J. D., et al. 2000, A&A, 358, L1
Limber, D. N. 1953, ApJ, 117, 145
Lilje, P. B., & Efstathiou, G. 1988, MNRAS, 231, 635
Lilly, S & Longair, M. 1984, MNRAS, 211, 833
Mannucci, F., Basile, F., Poggianti, B. M., Cimatti, A., Daddi, E., Pozzetti, L., & Vanzi, L. 2001, MNRAS, 326, 745
Miley, G. K., et al. 2004, Nature, 427, 47
Peebles, P. J. E., 1980, “The Large-Scale Structure of the Universe”, Princeton University Press.
Venemans, B. P., et al. 2002, ApJ, 569, L11
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Wold, M., Lacy, M., Lilje, P. B., & Serjeant, S. 2000, MNRAS, 316, 267
Yates, M. G., Miller, L., & Peacock, J. A. 1989, MNRAS, 240, 129

© 2005 RAS, MNRAS 000, 000-000