CLUSTERING OF GALAXIES ABOUT EXTRAGALACTIC RADIO SOURCES-IMPLICATIONS FOR OBSERVATIONS WITH THE EINSTEIN X-RAY OBSERVATORY

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The question which we have addressed is "what is the clustering of galaxies about extragalactic radio sources and how does it vary with the properties of the sources such as radio luminosity, optical spectral properties, radio morphology, etc". Only a small fraction of strong radio sources belong to rich clusters and most of the work on weaker associations is of a somewhat subjective nature. Our approach has been to work with complete, statistically defined samples of bright radio sources and to cross-correlate the positions of the sources with the Lick counts of galaxies. In this approach, we never define exactly what we mean by a cluster as group of galaxies - clustering is simply defined as the amplitude of a correlation function. This approach is only possible because the Lick counts of galaxies have been studied in detail by Seldner et al. (1977) who calibrated the Lick counts over the whole of the sky.

The analysis is performed in terms of standard angular correlation functions

$$N(\theta)\, d\Omega = N_g\ (1 + W_{gg*}\ (\theta))\ d\Omega$$

where N_g is the average surface density of galaxies and W_{gg*} (θ) is the angular correlation function. In all galaxies, $W_{gg}(\theta)$ has the form $A_{gg}\theta^{-0.77}$ on angular scales $\theta \lesssim 3^o$. Summing the angular correlation functions for all 3CR radio galaxies, we find that W_{gg*} tends to zero at redshift $z > 0.1$ but for smaller redshifts has the same form as for galaxies in general on angular scales $\theta < 2^o$. This is consistent with the fact that the limiting magnitude of the Lick counts, $m \gtrsim 19.5$, corresponds to the break in the optical luminosity function at a redshift of about 0.08. Our analysis of the clustering of galaxies about 3CR radio sources is therefore restricted to a statistically defined sample of 46 sources with $z < 0.1$ for all of which redshifts have been measured.

For each source, we convert the amplitude of the angular correlation function to a spatial correlation function

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$$n(r)dV = \rho_g \ (1 + \xi(r)) \ dV$$

where $\xi(r) = B_{gg*} r^{-1.77}$ describes the enhancement in the volume density of galaxies about the source. The relation between A_{gg*} and B_{gg*} depends upon the redshift of the radio galaxy and the optical luminosity function because fewer "cluster" galaxies are observed for sources close to the limit of the survey. It can be shown (Longair and Seldner, 1979) that

$$A_{gg*} = H(z) \ B_{gg*}$$

where

$$H(z) = \frac{I_\gamma}{N_g} \left(\frac{D_i}{(1 + z)}\right)^{3-\gamma} \phi(m_o, z).$$

I_γ is a constant, $\gamma = 1.77$ and $\phi(M) \equiv \phi(m_o, z)$ is the integrated optical luminosity function.

The results are presented in terms of the average values of B_{gg*} relative to the value of B_{gg} for galaxies selected at random. For Abell clusters we find $<B_{gg*}/ B_{gg}> \gtrsim 13$, consistent with Abell's definitions, whilst for galaxies selected at random, by definition, $<B_{gg*}/B_{gg}> = 1$. This provides a linear scale of clustering from randomly selected galaxies to the richest of clusters. The results for a standard Abell luminosity function are shown in Table 1 which includes the results of a survey of intrinsically weak 4C radio galaxies.

Table 1

$<B_{gg*}/B_{gg}>$

4C Zwicky galaxies - Zwicky galaxies	4C Zwicky galaxies - Lick counts	3CR radio galaxies - Lick counts
1.5 ± 1.7	1.1 ± 0.6	3.8 ± 0.7
$(0.73 \pm 0.54)^1$	$(0.42 \pm 0.48)^2$	
Very low radio luminosities		Strong radio sources
$10^{20} \lesssim P_{178} \lesssim 10^{23.5}$ W Hz^{-1} sr^{-1}		$P_{178} \gtrsim 10^{23.5}$ W Hz^{-1} sr^{-1}

1 - removing 2 sources with implausibly large and small values of B_{gg*}

2 - removing 3CR sources with $P_{178} \gtrsim 10^{24}$ W Hz^{-1} sr^{-1}

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Clearly, on average 3CR radio sources lie in regions of higher galaxy density than galaxies selected at random. On the other hand, very weak radio galaxies seem to be randomly selected members of the population of galaxies. This makes sense because in very weak radio galaxies the radio emission lies within the galaxy itself whereas the powerful sources are almost all extended radio sources which are more sensitive to the intergalactic environment.

Table 2 shows the values of $\langle B_{gg*}/B_{gg} \rangle$ for various sub-samples of the 3CR sample.

Table 2

		Number of sources	$\langle B_{gg*}/B_{gg} \rangle$	
Optical spectral Class	A	12	2.3 ± 0.7	Strong emission line spectrum
	B	24	4.5 ± 0.9	No strong emission lines
Fanaroff-Riley Class	I	12	4.6 ± 1.3	Complex sources
	II	15	2.2 ± 0.8	Double sources
Fanaroff-Riley Class II	"Classical" doubles	8	0.7 ± 0.8	
	Others	7	4.0 ± 1.2	

It can be seen that radio galaxies with strong emission line spectra and of Fanaroff-Riley Class II lie in regions of lower galaxy density than those without strong emission line spectra and complex radio structure. These properties of radio galaxies are already known to be strongly correlated (Hine and Longair, 1979). The Fanaroff-Riley classification was designed to discriminate between double and complex radio structures but not all F-R II galaxies are what we term "classical doubles". Not all F-R II radio sources contain compact "hot-spots" at the leading edges of the double sources - we call those which do "classical" doubles and those which do not "others" (see Riley and Longair, 1979).

The interesting result is that the "classical" double sources seem to lie in no richer associations of galaxies than galaxies selected at random. The significance of this result may be understood by considering 3C390.3 which is isolated according to our analysis. The galaxy must have a hot gaseous halo in order to confine the radio components which extend 200 kpc from the nucleus. The total mass of gas is $\sim 10^{11-12}\ M_\odot$ and consequently the galaxy itself must be massive. We infer that the radio galaxies which become strong double sources are isolated massive galaxies which can hold onto their own hot gaseous atmospheres. We note that this is precisely what must be happening in the case of those quasars which are double radio sources. It is well known that such quasars are "classical" double sources and are not members of clusters of galaxies.

There are however at least two classical double radio sources, Cygnus A and 3C 295, which belong to rich clusters. In our view, because both of these radio galaxies are dominant members of Bautz-Morgan I clusters. They are galaxies which hold onto their own atmospheres. Because they are stationary within the cluster, the beams responsible for the energy supply to the "hot-spots" are not wrecked by the motion of the galaxies and their envelopes through the intergalactic gas. This process is likely to be responsible for the "complex" radio morphologies observed in most clusters, particularly Bautz-Morgan class III where all the massive galaxies should be in relative motion. Thus, we believe that classical double sources should either be isolated or dominant members of Bautz-Morgan class I clusters. In both cases, the galaxy holds on to its own atmosphere which must be hot.

We predict that the classical double sources should all possess hot haloes which extend out at least to the position of the hot-spots in the radio lobes. These haloes should be detectable as X-ray haloes, similar to that of M87, around all radio galaxies and quasars which are classical doubles. This experiment is well within the capabilities of the Einstein X-ray observatory.

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