Clustering and Proto-Clusters in the Early Universe

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Abstract. The clustering properties of clusters, galaxies and AGN as a function of redshift are briefly discussed. It appears that extremely red objects at \( z \approx 1 \), and objects with \( J - K > 1.7 \) and photometric redshifts \( 2 < z_{\text{phot}} < 4 \) are highly clustered, indicating that a majority of these objects constitutes the progenitors of nearby ellipticals. Similarly clustered seem luminous radio galaxies at \( z \approx 1 \), indicating that these objects comprise a short lived phase in the lifetime of these red objects. The high level of clustering furthermore suggests that distant powerful radio galaxies (e.g. \( z > 2 \)) might be residing in the progenitors of nearby clusters – proto-clusters. A number of observational projects targeting fields with distant radio galaxies, including studies of Ly\( \alpha \) and H\( \alpha \) emitters, Lyman break galaxies and (sub)mm and X-ray emitters, all confirm that such radio galaxies are indeed located in proto-clusters. Estimates of the total mass of the proto-clusters are similar to the masses of local clusters. If the total star formation rate which we estimate for the entire proto-clusters is sustained up to \( z \approx 1 \), the metals in the hot cluster gas of local clusters can easily be accounted for.

1 Introduction

An important theme in astrophysics is to understand the nature of clustering of galaxies, active galaxies and even clusters of galaxies. Observationally, two different methods have been employed to measure clustering and its evolution with redshift.

A first method is to measure the level of clustering in various distinct populations of objects. A number of statistical methods have been used to quantify clustering including counts in cells, nearest-neighbor statistics and the two-point correlation function. By introducing the “bias parameter”, which basically measures the clustering of light compared to the underlying clustering of dark matter, the clustering of objects in the “local” universe can be directly linked to the measured fluctuations in the cosmic microwave background. For the art of understanding how galaxies and AGN form, an interesting way to rephrase aspects of this problem is to understand the evolution of this bias parameter for various classes of galaxies and AGN. In this contribution we will consider measurements of clustering of a number of different classes of galaxies and AGN and how these evolve as a function of redshift. Briefly, some implication for the understanding of the nature of these objects will be discussed.
A second method is to actually find and study ensembles of galaxies in the early Universe for which the case can be made that they will evolve into present day clusters. This will not only constrain the formation and evolution of clusters, but will also allow detailed studies of how the environment in which galaxies are born influences their subsequent evolution. To find such early clusters, “proto-clusters”, we have a number of programmes to observe fields centered on extremely luminous radio galaxies with redshifts in the range $2 < z < 5$. In all the well studied fields, it seems that there are significant excesses of galaxies compared to the field, suggesting masses of the proto-clusters in the range of $10^{14} - 10^{15} M_\odot$.

2 Clustering of galaxies and AGN

A well established way of characterizing the clustering of objects is through measuring their spatial two-point correlation function (e.g. Peebles 1980). In the usual case of a limited number of objects with well determined distances for which clustering is being assessed, only the correlation length $r_0$ can be constrained. This parameter indicates the spatial scale at which the chance of detecting an object at a distance from a given object is a factor of two more than for random distribution. Often, as in the case of new imaging surveys, the distances to the objects are not known and only the angular clustering can be determined. If the redshift distribution of such a population is known, the spatial correlation length can be derived using the well known Limber’s equation (e.g. Daddi et al. 2000 and references therein).

A consideration of the correlation length for a number of samples at different redshifts of galaxies and AGN can be found in Overzier et al. (2003) and Röttgering et al. (2003). At low redshift, the most clustered objects are clusters of galaxies, followed by elliptical galaxies and spirals. Detailed measurements of the local correlation functions have recently been carried out on the basis of the 2dF survey (Hawkins et al. 2003). In the last few years, a number of interesting results have been obtained which constrain the correlation length of various types of objects at $z \sim 1$.

A major achievement of the VLA was the production of the NVSS radio catalogue, which now contains 2 million radio sources observed at 1.4 GHz (Condon et al. 1998). Recently, two groups have measured the angular correlation function of NVSS sources (Overzier et al. 2003, Blake and Wall 2002), and determined the correlation lengths using the redshift distribution from Dunlop and Peacock (1990). In their analysis Overzier et al. concluded that the most luminous radio sources at $z \sim 1$ are clustered at about a level approaching that of local clusters. This may indicate that these sources are preferentially located in the progenitors of nearby massive clusters, while the less luminous sources would then be associated with a field population.

The availability of large area infrared surveys made it possible to study the clustering of extremely red objects (EROs). The definition of the color cut that distinguishes EROs from the general population is often taken to be $R - K > 5$. 
The main two reasons that these objects are so red are that (i) they straddle the 4000 Å break of a $z \sim 1$ elliptical, or that (ii) the dust in a starburst galaxy has absorbed most of the optical light (see Cimatti et al. 2003 and references therein). Various clustering measurements for EROs gave correlation lengths of similar magnitude as found for the luminous radio sources (Daddi et al. 2000, Roche et al. 2002, Firth et al. 2002). Taking into account that the lifetime of radio sources is relatively small ($\sim 10^7$ years), the inferred space density of both EROs and radio galaxies are similar (Mohan et al. 2002; Willott et al. 2001). This all has the interesting implication that luminous radio sources and EROs might be similar objects at a different stage of their evolution.

Measurements of clustering of optical quasars at $z \sim 1$ has been done to an unprecedented accuracy by the 2dF team (Croom et al. 2001). Interestingly, the correlation lengths that are found ($\sim 4 - 5$ Mpc) are significantly smaller than that for the powerful radio galaxies. This has the immediate implication that these optical quasars can not evolve into or descend from luminous radio sources. Optical quasars are therefore probably associated with a field population of objects with modest mass black holes as supposed to the clustered radio galaxies with very massive black holes.

With the availability of wide and deep surveys conducted with 10-m class optical telescopes, large numbers of Lyman break galaxies (LBGs) have been detected. With these samples of LBGs it was found that $r_0$ was constant over the measured redshift range of $3 < z < 5$ (Hamana et al. 2004). This is in agreement with hierarchical models of galaxy formation that state that the highest redshift galaxies are the very biased tracers of the underlying dark matter distribution.

The FIRES survey (Franx et al. 2000) is a very deep survey with the VLT that is designed to obtain a sample of high redshift galaxies selected in the rest-frame optical rather than the restframe UV, like the LBGs. For this programme, in total 100 hours were spent on observing the Hubble Deep Field South, reaching in each of the infrared bands $J$, $H$ and $K$, limiting magnitudes of 26.0, 24.9, and 24.5, respectively (Labbé et al. 2003). One of the interesting discoveries was the presence of a population of galaxies with $J - K > 2.3$. Although these objects had photometric redshifts $z > 2$, in general there was only limited overlap with the LBG population (Franx et al. 2003). This is because these objects are too faint in the optical to detect the Lyman break according to the usual criteria and/or are too red. Although the number of such galaxies is limited, an attempt to measure the clustering was presented by Daddi et al. 2003. Down to $K > 24$, it was found that the galaxies with a $2 < z_{\text{phot}} < 4$ and $J - K > 1.7$ had a correlation length a factor of 2-3 larger than LBG galaxies. Although the statistics are clearly somewhat limited, the objects with $J - K > 2.3$ seem to be even more clustered. Models of the evolution of the clustering of ellipticals by for example Kauffmann et al. (1999) predicted that the correlation length for local elliptical and their progenitors should be at the same high level. Since this is what we observe, this is an important indication that these red objects are indeed the progenitors of local ellipticals. Further evidence for this comes from
considerations related to their number density, masses and sizes (van Dokkum et al. 2004, submitted).

3 Radio galaxies at the centers of proto-clusters

As already noted, the powerful radio galaxies at $z \sim 1$ seems to have large correlation lengths, suggesting that they are located in progenitors of local clusters. This suggests that proto-clusters could be found in fields containing distant and powerful radio galaxies. There is significant additional supporting evidence that radio galaxies can be associated with proto-clusters, including (i) they are amongst the most massive objects at high redshifts, (ii) they have large Ly$\alpha$ halo’s whose outer regions are consistent with originating from a cooling flow, (iii) 20% have high rotation measures as measured with the VLA, indicating the presence of a dense medium. We therefore started a project to study fields centered at distant powerful radio galaxies with the aim of finding proto-clusters at a range of redshifts. A second aim was to study the various classes of galaxies in these proto-clusters.

4 The proto-cluster associated with 1138-262 at $z = 2.2$

The first radio galaxy for which we studied its associated proto-cluster in great detail was 1138-262 at $z = 2.2$ (Kurk et al. 2003 and references therein) For a number of reasons this was among the very best objects to study. It is among the brightest object both at K-band and at radio wavelength. It has the highest rotation measure (6200 rad/m$^2$) of a well studied sample of 80 $z > 2$ radio galaxies. The morphology both in the radio, optical and near infrared is very clumpy, consistent with simulation of forming brightest cluster galaxy in which many star forming regions are merging together to ultimately form a massive galaxy. With a size of almost 200 kpc, the very luminous Ly$\alpha$ halo represents a significant reservoir of gas from which part of the stars that will make up the final system can be formed. The first programme was to carry out deep narrow band imaging to obtain candidate Ly$\alpha$ emitting galaxies. This resulted in 70 candidates. As compared to the field the overdensity was derived to be at least a factor of two. Subsequent spectroscopy resulted in 14 confirmed galaxies at the redshift of the radio galaxy. Deep narrow band imaging in the infrared combined with infrared spectroscopy resulted in the detection of 7 confirmed H$\alpha$ emitting galaxies. The K-band imaging data combined with the optical contained 44 galaxies with $I - K > 4.3$. Unfortunately, these objects have no measured redshift – this is notoriously difficult –, but their surface density peaks at the location of the radio sources. Finally, we looked at the X-ray emitting galaxies using a deep Chandra image. On the basis of either spectroscopy or colour information, for 6 objects the case could be made that they are at the redshift of the proto-cluster. The spatial distribution of the various classes is given in Figure 1. In Figure 2, the surface density of these classes as a function of distance from the radio galaxy is given. An important point apparent from these two figures, is that
the distribution of Hα galaxies seems much more concentrated than the Lyα emitting galaxies. Further differences are that the population of Hα emitters on average have brighter K-band magnitudes and as a whole have a lower velocity dispersion. We interpreted this as the population of Hα emitting galaxies being older and dustier and further in the process of having their orbits virialized in the “proto-cluster” potential. It seems that the seeds of the morphology-density relation are already in place at \( z = 2.2 \). Following the analysis of Steidel et al. (1998) as they carried out for the high “redshift spike” at \( z = 3.1 \), the mass associated with the over density is in the range \( 10^{14} - 10^{15} M_\odot \). And indeed this is what is expected for a progenitor of a nearby massive cluster.

![Fig. 1. The spatial distribution of candidate cluster galaxies in the field of the powerful radio galaxy 1138-262 (\( z = 2.2 \)). Indicated are the candidate Hα emitters with downward pointing triangles, candidate Lyα emitters with upward pointing triangles and extremely red objects with squares. The X-ray emitters are indicated with stars. The radio galaxy is located at the origin. The dotted line indicates the boundaries of the two fields of the IR observations with ISAAC/VLT within which Hα emitters and EROs have been searched for. Note that spectroscopy yielded 15 confirmed Lyα and 7 confirmed Hα emitters.](image-url)
Fig. 2. The surface density of candidate cluster galaxies as a function of distance from the powerful radio galaxy 1138-262 (z = 2.2). Indicated are candidate Ly$\alpha$ emitters with black lines, candidate H$\alpha$ emitters with dotted lines, and extremely red objects with dashed lines.

5 Towards a sample of proto-clusters

The results on the proto-cluster of 1138-262 prompted us to extend this study to more objects. We initiated an ESO large programme to search for Ly$\alpha$ emitting galaxies in potential proto-clusters around radio galaxies with redshifts in the range 2 < z < 5. An account of the results of this programme has been presented in this conference by Venemans et al. The main conclusion is that all of the 7 radio galaxies that have been studied in sufficient detail show over densities and resulting masses similar to that found for 1138-262.
6 Hubble Space Telescope ACS imaging

In the course of our ESO large programme, we studied the region of the powerful radio galaxy 1338-193 at $z = 4.1$ and subsequently found the highest redshift group of galaxies. In total we have 50 candidate Ly$\alpha$ emitters distributed over two partly overlapping $7 \times 7$ arcminute field of views of the FORS instrument of the VLT. Of these, 32 are spectroscopically confirmed. This field was studied in detail using data from the new Advanced Camera for Surveys on the Hubble space telescope (Miley et al. 2004). It was observed in three filters (F475m, F625m, F775m), for optimum sensitivity for detecting LBG galaxies at $z \sim 4$. Comparisons with the surface densities in the Hubble Deep Field and the Subaru deep field led us to conclude that there are a factor of 2 more $z \sim 4$ LBGs than in a random field. Given that the three filters in principle select objects over the entire redshift range of $3.5 < z < 4.5$, the actual spatial over density compared to the field is likely to be well in excess of ten.

7 mm/submm imaging with JCMT and IRAM

Both the LB galaxies and the Ly$\alpha$ emitters are discovered at optical wavelengths, which naturally biases the obtained samples to galaxies that are relatively unobscured. With (sub)mm telescopes, a number of galaxy fields have been observed with the aim of detecting very dusty and potentially very obscured galaxies located in the proto-cluster. Using the SCUBA array mounted on the JCMT, 7 radio galaxy fields have been observed. An excess of dusty galaxies of about a factor of two compared to the field has been found (Stevens et al. 2003). De Breuck et al. (2004, submitted) carried out a detailed investigation of the field of the radio galaxy 1338–192 at a redshift of $z = 4.1$ using MAMBO at the IRAM 30m. Combined with deep optical and radio data 5 dusty objects were found with properties consistent with being located at the distance of the proto-cluster. This is further evidence for the reality of an excess of starburst galaxies in distant radio galaxy fields.

8 Discussion

Both from the analysis of the correlation function of galaxies and AGN and the observational data, it seems that the evidence is now very convincing that distant powerful radio galaxies are located in “proto-clusters”. It is even plausible that every proto-cluster has gone through a radio-active phase as it turns out that the space density of powerful radio galaxies is comparable to the space density of local clusters, taking into account the short lifetime of the radio activity ($10^6 - 10^7$ years). Again following the analysis of Steidel et al., the associated masses of the structures are in the range of $10^{14} - 10^{15}$ $M_\odot$. A simple estimate of the total star formation rate of all the galaxies combined in the proto-clusters is in excess of 20,000 $M_\odot$ yr$^{-1}$. If such a high rate is sustained, then the high metal content in the hot gas in $z < 1$ clusters can be easily accounted for.
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