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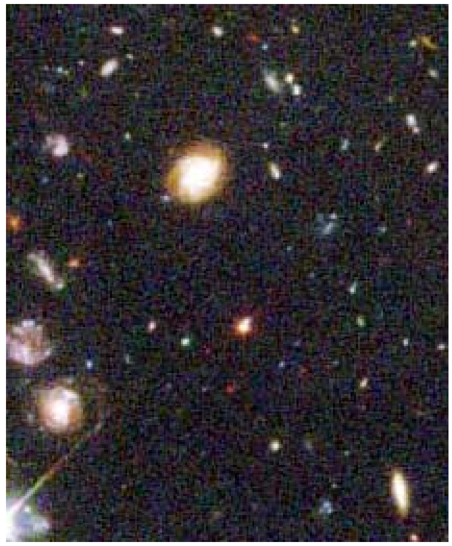
GALAXY CLUSTERS AND CLUSTERING AT $Z > 1$



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Our knowledge of galaxy clusters and clustering at redshifts greater than one is thin but has been growing steadily. "Blank field" X–ray and infrared surveys have recently identified a small but growing number of galaxy clusters with $z > 1$. However, the observational challenges for detecting and confirming such clusters remain formidable. As an alternative, targeted surveys of the environments of known, massive galaxies such as those hosting powerful radio sources provide an alternative method of "pre–selecting" likely sites for rich clusters, and have proven to be an efficient method of finding such systems at high redshift. I review the results of various targeted searches for high redshift clusters, and then go on to discuss galaxy *clustering* at $z \approx 3$ and its possible relation to virialized galaxy *clusters* at lower redshifts.

1 Introduction

For many years, $z = 1$ stood as a *de facto* upper redshift boundary for studies of galaxy clusters and clustering. In part, at least, this has been due to practical, observational limitations which make detecting, recognizing, and studying clusters at $z > 1$ quite difficult. As far as optically–based surveys and spectroscopic follow–up are concerned, galaxies at $z > 1$ are simply much harder to observe: their optical rest–frame light, including strong absorption and emission lines, are redshifted through and beyond the I–band into the near–infrared. For the red, early–type cluster galaxies which dominate the population of rich clusters out to at least $z \approx 0.9$ (cf. Stanford, Eisenhardt & Dickinson[61]) this wavelength shift has profound effects on optical visibility: the combination of distance modulus plus a fierce k–correction makes even bright red cluster galaxies all but invisible at optical wavelengths. This, combined with the steeply rising number counts of foreground and background field galaxies, dramatically reduces the surface number density contrast of even a rich galaxy cluster at optical wavelengths, making it very difficult to recognize. Near–infrared imaging can "take us where the light is," observing the redshifted cluster galaxies where they are brightest, but despite great advances in infrared array technology, it is still prohibitively expensive to survey large enough solid angles to faint enough limits in the near–IR in order to identify enough (rare) galaxy clusters to constitute a statistically useful sample.[a] Wide–angle X–ray surveys from *Einstein* and ROSAT have now produced large, complete, and well–characterized cluster samples out to $z = 0.9$, but the nature of the X–ray luminosity function is such that these surveys largely fade out past $z = 1$, with only a handful of X–ray clusters at higher redshifts known to date (see, e.g., contributions from Stanford and Borgani at this meeting). Finally, even if $z > 1$ cluster candidates are found in optical, infrared or X–ray surveys, obtaining spectroscopy to measure their redshifts and confirm cluster association is largely beyond the limits of 4m–class telescopes, and has had to await routine access to 8–10m telescopes, a relatively recent development. Even with those large–aperture facilities, the redshift range $1.3 < z < 2$ remains a "redshift desert," where galaxies have few strong absorption or emission lines in the optical window available for measuring redshifts. Thus even today, when several clusters at $z > 1$ have now been identified and confirmed from "blind" surveys (Stanford et al.;[60] Rosati et al.[53]), the upper redshift bound still remains at $z \approx 1.3$.

Because Isabella Gioia and others at this meeting have reviewed cluster surveys at $z < 1.3$, I will take a different approach here. First, I will review "desperate tactics" for cluster hunting at $z > 1$: targeted surveys to identify clusters where they are most likely to be found. Second, I will discuss what we know now about galaxy *clustering* at $z > 2$. This latter is a topic where progress has been very rapid in the last few years, and while we have not yet identified and confirmed anything at $z > 2$ that most people would recognize as a massive, virialized cluster like those found at $z \leq 1.3$, it is almost certainly the case that the clustering that we see at $z > 2$ traces the "proto–cluster" environment out of which modern–day rich clusters eventually form.

2 Targeted cluster searches at $z > 1$

Rather than blindly search the sky for contrast enhancements in the galaxy density or extended X–ray emission, targeted searches select likely sites of distant clusters and concentrate their efforts there. Because galaxies cluster, if one already knows where one high–z object is, then that is a good place to start looking for more. High redshift AGN are thus a natural place to begin searching for fainter cluster companions. In particular, various surveys (e.g., Yee & Green;[72,73] Yates et al.;[71] Hill & Lilly;[36], Ellingson, Yee & Green;[25] Allington–Smith et al.;[2] Wold et al.;[68] Blanton et al.[6]) found that radio–loud AGN at $z \approx 0.5$ are frequently (but not always) situated in rich galaxy clusters. Figure 1 shows a *HST* WFPC2 image of a radio galaxy at $z = 0.62$, 3C 220.1, which is situated in a cluster of modest richness. The depth of the cluster potential well is graphically demonstrated by the presence of a giant lens arc (Dickinson[18]) for which we have measured a probable redshift $z = 1.49$. X–ray emission from hot gas in this cluster has also been confirmed by Hardcastle, Lawrence & Worrall[34] and Ota et al.[46]

This method of cluster hunting has several virtues. It restricts the search area to a manageable solid angle, whereas "blind" surveys must cover rather large area to find rare clusters. It has a moderately high success rate at identifying clusters, and provides an *a priori* redshift (that of the radio galaxy or QSO) for any cluster candidate found. Its disadvantage is that it is difficult to use clusters found in this way for statistical studies, e.g., of the cluster luminosity or richness functions. It is primarily a good way to find individual examples of clusters whose properties (e.g., velocity dispersion, X–ray emission, etc.) or galaxy populations can then be studied in more detail.

[a]Nevertheless, it is telling that many of the galaxy clusters that have been convincingly identified at $z > 1$ have come from infrared surveys.

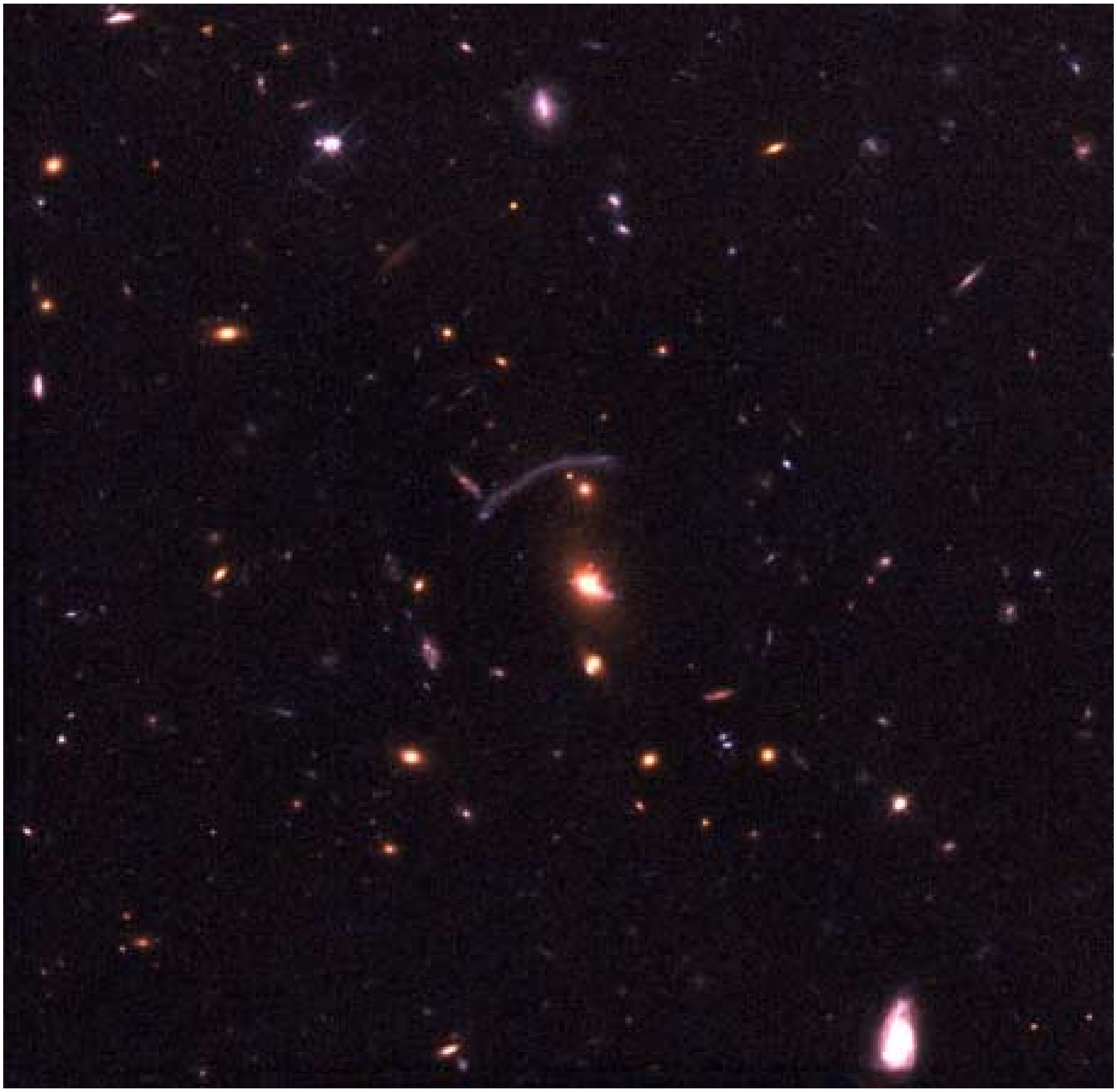

Figure 1: *HST* WFPC2 color composite image (V and I) of the $z = 0.62$ radio galaxy 3C 220.1 and environs. The radio galaxy is situated in a cluster of modest richness – several red E/S0 galaxies are seen in the image. The giant arc gravitational lens has a probable spectroscopic redshift $z = 1.49$.

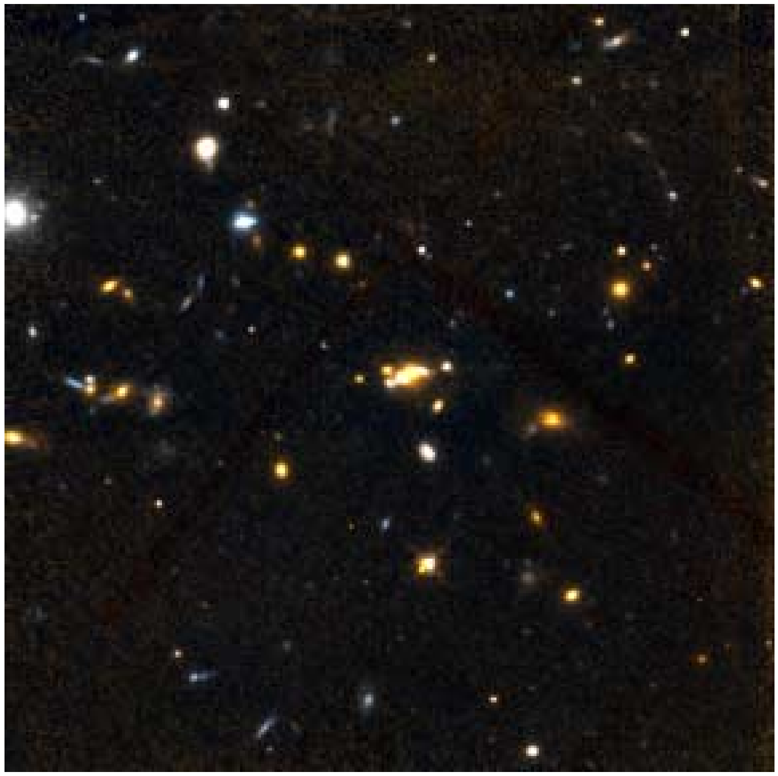

Figure 2: *HST* WFPC2 + NICMOS (R and H) color composite image of the $z = 1.206$ radio galaxy 3C 324 and its environment. At $z > 1$, infrared imaging is essential to study the very red, early–type cluster galaxies. Spectroscopy in this field has confirmed 14 galaxies are at the radio galaxy redshift, although others are in a foreground cluster or "sheet" at $z = 1.15$. The NICMOS image was obtained by Spinrad, Bunker & Dickinson.

2.1 Cluster candidates at $1 < z < 2$

As discussed in the introduction, infrared imaging is extremely valuable and even essential for identifying clusters at $z > 1$, even with targeted surveys. Figure 2 shows a composite infrared+optical image from the *HST* NICMOS and WFPC2 cameras of the cluster around the radio galaxy 3C 324 ($z = 1.206$), one of the first clusters at $z > 1$ identified in this way (Dickinson;[19,20] Smail & Dickinson[59]). Many red, early–type galaxies are visible around the central radio galaxy, and spectroscopy (see Dickinson[21,22,23]) has shown that many share the redshift of the radio galaxy, although an additional foreground cluster or sheet of galaxies is also present at $z = 1.15$. Kajisawa et al.[40,41] have recently studied the 3C 324 cluster using deep near–infrared images from commissioning observations on the Subaru telescope.

By now, many other examples of likely clusters have been found associated with radio galaxies and QSOs at $0.8 < z < 1.4$. Some of the best candidates (albeit most still without spectroscopic confirmation) have been studied by Hutchings et al.;[37,38] Yamada et al.;[70] Tanaka et al.;[67] Chapman et al.;[9] Best,[5] and Haines et al.[32] Few convincing (and no spectroscopically confirmed) examples of AGN–associated clusters have yet been found at $1.5 < z < 2$; the best candidates are probably two examples at $z \approx 1.5$ from Hall & Green.[33] In most of the cases cited above, the cluster candidates were found using infrared imaging, identified either as overdensities around the radio source or, especially, by the presence of a substantial excess of galaxies with atypically red optical–infrared colors, characteristic of early type galaxies at $z > 1$. Other than 3C 324, only a few other 3C radio galaxies at $z \approx 1$ have spectroscopic confirmation of associated clusters, such as those studied by Deltorn.[16,17] Liu et al.[45] measured redshifts for four red galaxies at $z = 1.31$ associated with a MgII absorption system along the line of sight to a background QSO. It is possible, but not yet certain, that these are part of a virialized cluster.

2.2 Cluster candidates at $z > 2$

At $z > 2$, there is an increasing number of examples of galaxy overdensities associated with radio galaxies and QSOs, but in few (if any) cases is there clear evidence for bound or virialized clusters *per se*. Perhaps the three best studied cases of spectroscopically confirmed associations are all found at $2.1 < z < 2.4$, a redshift range where Lyα imaging, infrared spectroscopy, and infrared multi–color selection can all be used effectively.

Francis et al.[26,27,28,29] have made extensive observations of a system of galaxies and gas at $z = 2.38$ originally noted by the presence of several high column density Lyα absorption systems in the spectra of background QSOs. They have confirmed redshifts for several objects via Lyα emission and/or infrared spectroscopy, and argue that there is a very large reservoir of neutral gas out of which a rich cluster may form.

Pascarelle et al.[47,48,49] have studied a group of galaxies and AGN associated with the radio galaxy 53W002 at $z = 2.390$, using narrow– and intermediate–band Lyα imaging to identify a large number of candidates and spectroscopy to confirm redshifts for several. Pascarelle et al. emphasize the compact sizes of many of these galaxies in *HST* images, and suggest that they are sub–galactic "fragments" that will eventually merge to form more massive galaxies. Keel et al.[42] surveyed a wider field around 53W002, identifying still more candidates, and studied their spatial distribution, suggesting that there was no clear evidence for a relaxed, virialized cluster, although it is clear that 53W002 is situated in a locally overdense region of space.

Finally, Pentericci et al.[50,51] and Kurk et al.[43] have been exploring the environment of the $z = 2.156$ radio galaxy PKS 1138-262, an object whose highly distorted radio morphology and extremely high radio rotation measure suggest the presence of a dense, gaseous environment. Using VLT narrow–band Lyα imaging, they have identified ~ 50 candidate emission line companion objects (as well as a giant Lyα emission halo around the radio galaxy itself), of which 15 have been spectroscopically confirmed. Although there is a substantial overdensity of objects at this redshift, their spatial distribution gives no strong indication that there is yet a truly relaxed, virialized cluster present.

There are many other suggestive examples in the literature of galaxy associations and cluster candidates at $z > 2$. Dickinson[22] presented a compendium of examples known up to 1997, and others have been found since that time. Clements[11] has identified an excess of galaxies with red optical–infrared colors around a quasar at $z = 2.15$. Le Fèvre et al.[44] spectroscopically confirmed several Lyα emitters around a radio galaxy at $z = 3.14$, and Deltorn et al. (in preparation) have used the Lyman break imaging technique to find a centrally concentrated group of galaxies around the same radio galaxy. Ivison et al.[39] have noted an excess of sub–mm sources around the $z = 3.8$ radio galaxy 4C 41.17, suggesting that this may be a proto–cluster with massive starbursts in the process of forming cluster ellipticals. Djorgovski[24] and collaborators have identified and confirmed galaxies associated with several QSOs at $z > 4$, and suggest that these are proto–cluster sites.

2.3 X–ray emission around high redshift radio galaxies

One way to firmly establish that an association of galaxies is indeed a relaxed, bound cluster is to detect X–ray emission that would demonstrate the presence of a deep gravitational potential well and a hot intracluster medium. At low redshift ($z < 0.5$), there are two prototypical examples of FR II radio galaxies with radio power comparable to that of the radio galaxies we study at high redshift: Cygnus A and 3C 295. Both are situated in X–ray clusters, probably with central cooling flows. With X–ray observations, we may hope to "elevate" the study of AGN–associated clusters to the level where we may gain physical insight into the early evolution of massive galaxy clusters. This is often complicated, however, by the common presence of X–ray emission from the active nucleus in powerful radio sources.

3C 294

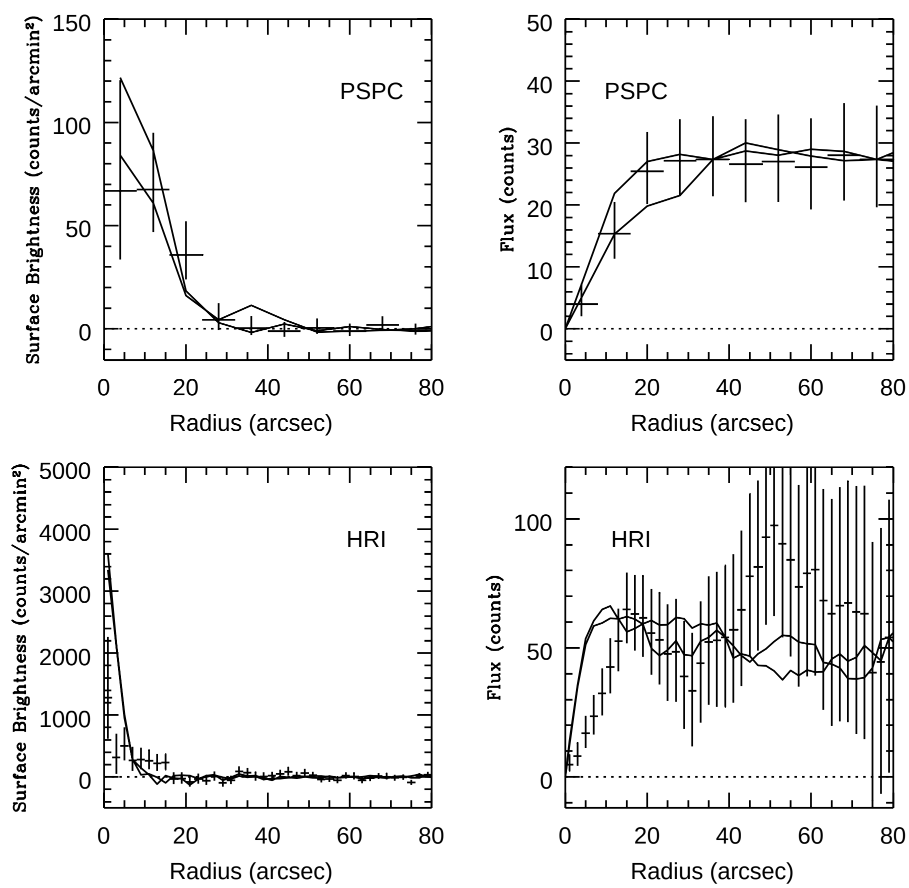

Figure 3: Radial profiles of the X–ray emission from 3C 294 at $z = 1.786$, observed with the ROSAT PSPC (top) and HRI (bottom). Differential profiles are shown at left, and integrated flux curves of growth at right. The points mark the radio galaxy measurements with Poisson errors. The solid lines show profiles for two unrelated point sources in the same data set which have been rescaled to have the same integrated flux as does radio galaxy within a radius of 40 arcseconds. The X–ray emission is probably unresolved by the PSPC, but appears to be extended in the HRI.

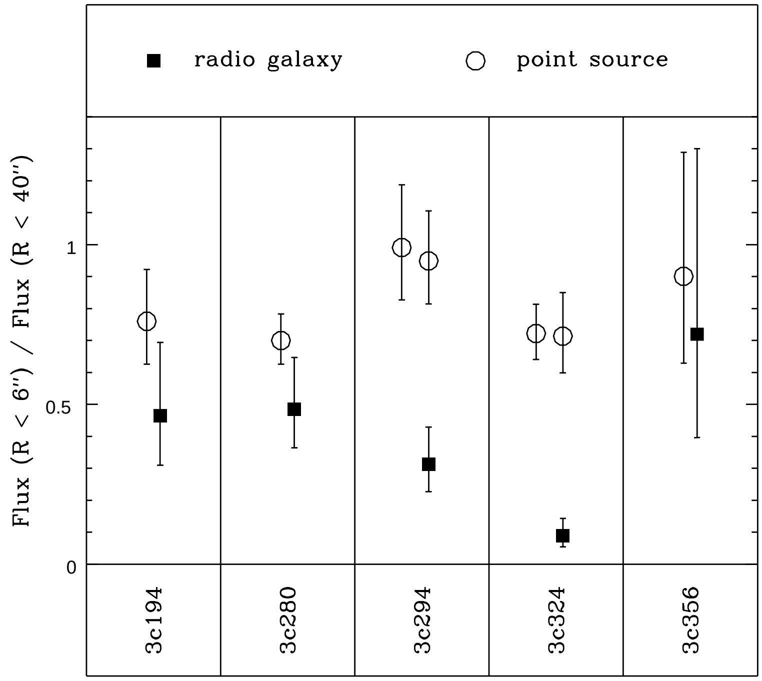

Figure 4: Ratios of fluxes from small ($6''$) and large ($40''$) apertures in the HRI images of five radio galaxies at $0.998 \leq z \leq 1.786$. This provides a rough measure of the spatial extent of the X–ray emission. One or more measurements for serendipitous point sources from the same images are also shown for each radio galaxy. 3C 294 and 3C 324 are both clearly resolved compared to the point sources.

Deep, targeted ROSAT observations have shown that some 3CR radio galaxies at $z > 1$ do indeed have associated X–ray emission (Crawford & Fabian;[12,13,14,15] Hardcastle & Worrall[35]), although only in a few cases (Worrall et al.[69] and Crawford & Fabian[14]) were the X–ray data adequate to provide plausible evidence for spatial extent, an important criterion for distinguishing between cluster and nuclear X–ray emission. In our own ROSAT observing program we observed several $z > 1$ radio galaxies with the PSPC, detecting most of them, and then followed up the four brightest sources with ROSAT HRI observations to establish whether the emission was indeed spatially extended. Given the limited sensitivity and higher background of the ROSAT HRI, it is extremely difficult to detect resolved emission at $z > 1$ directly, but it is straightforward to *exclude* the possibility that the flux detected in the PSPC images arises from a central, nuclear point source. Results for 3C 324 (Dickinson,[22]) suggested that the X–ray emission is indeed extended and thus associated with the spectroscopically confirmed galaxy cluster. Figure 3 shows the X–ray profile data for 3C 294, another radio galaxy at $z = 1.786$. While a large–aperture measurement from the HRI data does indeed recover the X–ray flux expected based on the PSPC count rate, this emission is clearly not point–like. This seems to suggest that 3C 294 is also situated in an extended, cluster–like X–ray atmosphere with bolometric $L_X \approx 9 \times 10^{44}$ erg s^{-1} (for $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega = 1$, $\Lambda = 0$). Figure 4 plots the ratio of HRI count rates in small and large diameter apertures for the $z \gtrsim 1$ 3CR radio galaxies with deep HRI observations. 3C 324 and 3C 294 are clearly more extended than nearby point sources within the same ROSAT HRI images; 3C 280 probably includes both point source and extended components (see Worrall et al.[69]); 3C 194 appears to be nearly point–like, and 3C 356 has too low S/N in the HRI data for this test, but the analysis of Crawford & Fabian[14] suggests that it is extended.

At $z = 1.786$, 3C 294 is a therefore a good candidate for an extremely distant X–ray cluster. At still higher redshift, Carilli et al.[7] used the ROSAT HRI to detect X–ray emission, possibly extended, from PKS 1138-262, the $z = 2.156$ radio galaxy discussed above. All of these observations provide encouragement that X–ray data may help us to establish the true dynamical state (e.g., via X–ray profile fitting and eventually with temperature measurements) of extremely distant clusters identified by AGN–selection.

Unfortunately, life is not always so rosy. Recently, Carilli et al.[8] have present a preliminary analysis of *Chandra* data for 1138-262 which shows that the bulk of the X–ray emission is point–like from the AGN, with only a small extended component which appears to be very closely associated with the radio source structure, and may thus be due to inverse Compton emission or perhaps thermal gas shocked by the radio jets. Since the time of the IAP conference, Mushotzky and I have also obtained *Chandra* data for 3C 324, and find that much (but not all) of the apparently extended X–ray emission seen with ROSAT is in fact due to confusion with several nearby point sources, unrelated to the radio galaxy, which were blended at PSPC resolution but too faint to detect individually with the HRI. The actual luminosity of X–ray emission directly associated with the radio galaxy is thus smaller than we previously believed.

Clearly, AGN–marked cluster searches are an effective means of identifying galaxy associations at high redshift. At present, however, there are very few cases where we have enough supporting information to judge the evolutionary state of these (proto–)cluster candidates, especially at $z > 2$. It seems clear that even with the new generation of more powerful X–ray satellites, it will be long, hard work detecting, confirming, and deriving physically valuable information about the IGM for galaxy clusters at $z > 1$. Nevertheless, we will continue trying, and using X–rays as a search technique. During XMM–Newton AO1, my colleagues and I will observe a number of radio galaxies at $1 < z < 2.5$ in order to search for extended thermal emission.

3 Galaxy clustering at $z > 2$

Although at $z > 2$ there is as yet little evidence for systems that most observers would agree are genuinely relaxed, virialized, massive clusters, the information on galaxy *clustering* at those redshifts is accumulating at an impressive rate. The first suggestions of clustering at such large redshifts came from studies of QSO absorption line systems, which found that the higher column density absorbers (e.g., CIV systems at $z \gtrsim 2$) were strongly clustered along the line of sight (cf. Sargent, Boksenberg & Steidel;[55] Quashnock, Vanden Berk & York[52]), with additional evidence for transverse clustering when multiple sightlines are available: e.g., the multiple absorption systems studied by Francis et al.[26,27] as discussed above. QSOs themselves also exhibit clustering on large spatial scales (cf. Shaver;[58] Shanks et al.;[57] Shanks & Boyle;[56] Stephens et al.;[66] Roukema & Mamon[54]).

The most extensive evidence for galaxy clustering at very large redshift comes from the large survey of color–selected, star forming "Lyman break galaxies" (LBGs) at $z \approx 3$ by Steidel et al.[62,64] Giavalisco et al.[30] detected angular correlation in the LBG population, and Steidel et al.[63] identified a pronounced and highly significant "spike" at $z = 3.09$ in their spectroscopic survey of one field (SSA22). In fact, spikes and voids in the LBG redshift distribution are nearly ubiquitous in our survey, found along every sightline. Figure 5 shows one example, with an interesting twist related to the discussion of AGN clustering in §2. In this field, we found 8 galaxies associated with a QSO at $z = 3.6$, despite the fact that our Lyman break color selection criteria should, in principle, be quite *ineffective* for identifying galaxies at $z > 3.5$. This suggests that this particular QSO may be in a remarkably rich galaxy environment.[b] These structures are large, with transverse dimensions that equal or exceed the scales of our imaging data ($\gtrsim 10$ Mpc).

[b]It should never, however, be thought that *all* high redshift AGN are surrounded by a multitude of companion galaxies. We have also surveyed the field around the $z = 3.395$ radio galaxy 0902+34, but found only two objects (out of 42) with redshifts matching that of the radio galaxy.

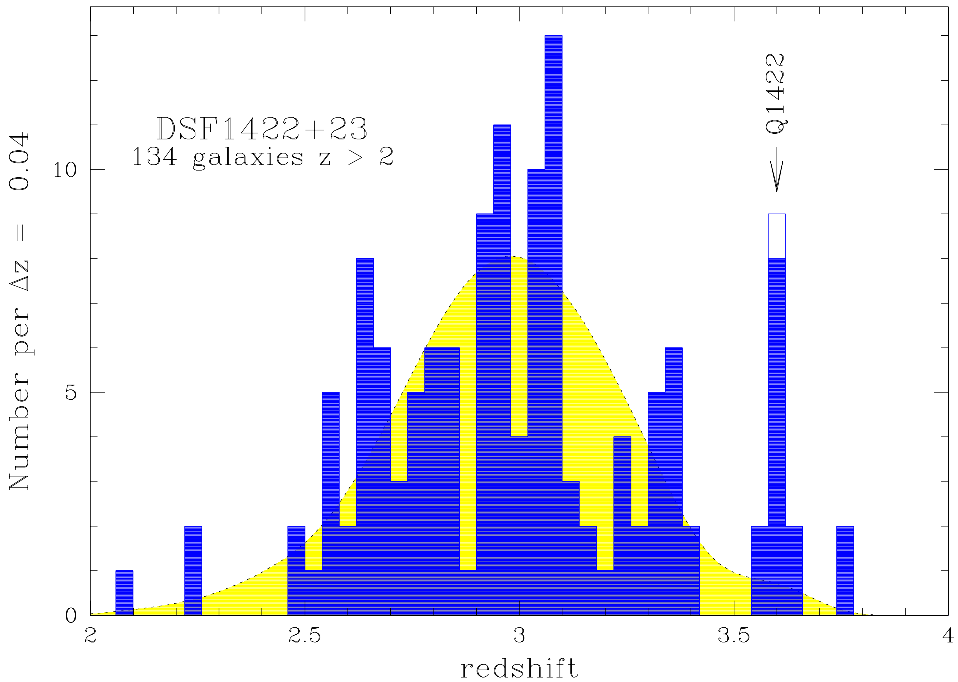

Figure 5: Redshift histogram for Lyman break galaxies in the Steidel et al. survey field DSF1422+23. The smooth shaded curve shows the redshift selection function of the Lyman break technique, derived from the average of many independent fields. The redshift distribution for individual sightlines, however, shows considerable structure, with strong over– and under–densities. This particular field has a "background" QSO at $z = 3.6$, and we have identified 8 other galaxies at similar redshift, despite the fact that the color selection is rather inefficient at that redshift.

Adelberger et al.[1] have carried out a redshift–space counts–in–cells analysis of data from several fields to quantify the degree of clustering. Overall, the results demonstrate that bright LBGs cluster roughly as strongly as do present–day, massive ($\sim L^*$) galaxies, despite the fact that the overall clustering of *mass* in the universe must have been considerably smaller at these large redshifts. We interpret this as direct evidence for early galaxy biasing, in which young galaxies form preferentially in massive dark matter halos, which are expected to be more strongly clustered than the overall dark matter distribution (Bardeen et al.[4]).

We have obtained deep, narrow–band Lyα images of the $z = 3.09$ structure in SSA22 in order to identify additional member objects and to study their angular distribution within the spike (Steidel et al.[65]). Altogether we find ~ 160 objects that are likely members of the structure. Most remarkably, we have found two enormous Lyα "blobs," each with physical dimensions $\gtrsim 100h^{-1}$ kpc and Lyα luminosities $\approx 10^{44}$ erg s^{-1}. These blobs are strikingly similar to the giant Lyα halos sometimes found around powerful radio galaxies (e.g., around the $z = 2.156$ galaxy PKS 1138+262, studied by Kurk et al.[43] and discussed above). However, the SSA22 blobs have no radio sources, and indeed are only loosely associated with UV–bright Lyman break galaxies found near their peripheries. One blob encompasses a red galaxy detected in deep K–band images. This blob is also situated within a larger–scale local overdensity in the distribution of objects within the spike. At this point, the nature of these blobs is unclear. We do not know what powers the Lyα emission, since there is no obvious source of UV radiation for photo–ionization. We may speculate that they trace gas condensing in a massive cooling flow from the surrounding overdense region, perhaps building galaxies in the central regions of a proto–cluster environment, although it is difficult to understand how the tremendous Lyα luminosity could be sustained through cooling alone without some mechanism to keep reionizing the recombining atoms. Most recently, Chapman et al.[10] have detected sub–mm emission from both blobs, including a very powerful 20 mJy source associated with "blob 1" (the one with the central K–band object). This is one of the brightest high–z sub–mm sources known, and highlights the remarkable nature of these objects, although it is still unclear whether this source is an AGN that may be somehow photo–ionizing its environment (although that ionizing emission is invisible from our vantage point), or a site of tremendous star formation, perhaps induced by the cooling and inflow of the surrounding gaseous medium.

In general, the large transverse extent of the LBG spikes would suggest that they are more similar to the sheets and walls seen in local galaxy redshift surveys, rather than indicative of virialized clusters of galaxies. Given current estimates for the LBG bias relative to the mass distribution, the overdensity of these "spikes" relative to the background matter appears to be of order $\delta\rho/\rho \sim 2$ on ~ 10 Mpc scales, suggesting that they are close to turn–around. At low redshift we know that massive clusters tend to inhabit such sheets and walls, occurring particularly at their intersections. It is not unlikely that the structures we find at $z \approx 3$ are thus truly *proto–cluster* cites: the most overdense regions of the universe at that redshift, where galaxy formation is accelerated, and where large–scale motions and infall will eventually lead to the collapse and growth of Abell–type clusters. Simulations of the formation and evolution of galaxies and large scale structure also find that "mock LBGs" formed at $z \sim 3$ preferentially end up in overdense environments such as rich clusters at $z = 0$ (e.g., Governato[31]). The Lyα blobs and the associated, powerful sub–mm emission may indicate the beginnings of the process of rich cluster formation: the early formation stages of massive, central cluster galaxies. Because many high redshift radio galaxies also have similar Lyα emission halos, and are also often detected at sub–mm wavelengths (Archibald et al.[3]), it is tempting to imagine that similar processes are at work in their vicinity, and that they also trace the sites of early cluster formation, much as radio–loud AGN frequently mark the locations of more mature galaxy clusters at $z \approx 1$ and below.

4 Conclusions

The $z = 1$ "barrier" for cluster surveys has now been surpassed on several fronts, using "blind" X–ray and infrared cluster surveys and targeted studies of the environments of AGN and other markers of local galaxy overdensities. The blind searches offer a more direct route to collecting statistically "clean" samples of distant clusters. The AGN–selected searches offer a quicker path to identifying clusters which can then be studied in other ways. The clusters found around AGN, however, tend to be rather "ordinary," and not the most massive and X–ray luminous clusters that are perhaps most interesting from the point of view of constraining cosmology and structure formation. It is also difficult to use AGN–selected clusters for statistical studies because it is hard to know how to relate such a subsample to the cluster population as a whole. Nevertheless, they may offer the fastest route to finding clusters at the highest redshifts, and as such will continue to be the subjects of active study.

The general field of large scale structure and galaxy clustering at very high redshifts has seen rapid gain thanks to the development of highly efficient color selection techniques for identifying ordinary galaxies at $z \approx 3$ and the capabilities of 8–10m telescopes for measuring their redshifts *en masse*. It is now clear that galaxies at those redshifts cluster very strongly, a fact that appears to confirm models of biased galaxy formation in a hierarchically clustered universe. Although truly massive, virialized clusters may be extremely rare or entirely absent at those large redshifts (and certainly there is no compelling evidence for such a system among the candidates that have been identified thus far), it is also entirely likely that the sheets and walls identified at $z \sim 3$ are proto–clusters sites, out of which the clusters that we know and love and study extensively at $0 < z < 1$ will eventually grow.

Now we must bridge the gap between optical, infrared and X–ray cluster surveys at $0 < z < 1$ and the large–scale structure studies at $z = 3$. The new generation of large X–ray observatories, wide–field infrared imagers, and massively multiplexed spectrographs at 8–10m ground–based telescopes (including infrared instruments capable of mining the redshift range $1 < z < 2$) will provide the tools for this effort, although patience and hard work will still be required. Sunyaev–Zel'dovich survey techniques (see Carlstrom's talk at this symposium) offer one of the most promising methods for tying everything together, providing direct physical information about the state of the cluster gas in a way that is independent of cluster redshift. In the next ten years, we may hope to paint a truly cohesive picture of cluster formation and evolution from $z = 3$ to the present.

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