Abstract. High redshift galaxy clusters have traditionally been a fruitful place to study galaxy evolution. I review various search strategies for finding clusters at \( z > 1 \). Most efforts to date have concentrated on the environments of distant AGN. I illustrate these with data on the cluster around 3C 324 (\( z = 1.2 \)) and other, more distant systems, and discuss possibilities for future surveys with large telescopes.

1 Finding distant clusters

At one time, galaxy clusters served as the most observationally straightforward means of studying galaxy evolution at high redshift. The reason was primarily one of contrast: even without spectroscopy, very rich clusters are recognizable as enhancements in the galaxy surface density out to \( z \sim 1 \), and the properties of the cluster galaxy population can be studied statistically with imaging data alone if a proper “control sample” of field galaxies can be observed in the same manner. In this way, Butcher and Oemler (1978, 1984) provided the first convincing evidence for galaxy evolution, identifying an apparently systematic bluing trend for galaxies in the cores of rich clusters beyond \( z \approx 0.3 \).

At very large redshifts (\( z > 1 \)), however, even quite rich clusters are no longer so clearly visible against the tremendously numerous population of faint field galaxies, and thus become correspondingly more difficult to discover and study. This is illustrated by figure 1, a cartoon representing the peak surface density contrast in the \( I \)-band of identical rich clusters observed at \( z = 0.3 \) and \( z = 1.2 \). Because the angular scale changes only slowly with redshift beyond \( z = 0.3 \), there is very little boost in the galaxy surface density as one moves a cluster further away, while the combination of distance modulus and k-correction dims the cluster galaxies considerably. The result is that a cluster with a contrast 10× over the field galaxy population at \( z = 0.3 \) barely peaks up over the field at all at \( z = 1.2 \). The effects of the k-correction are much more severe for early-type galaxies, rendering a rich, elliptical dominated cluster nearly invisible at optical wavelengths for \( z > 1 \), even assuming reasonable amounts of passive evolution.

On the one hand, thanks to highly efficient multiplexing spectrographs, the tremendous progress which has occurred in the study of high redshift field galaxies has meant that clusters are no longer “needed” to provide large samples of distant galaxies. But at the same time, the higher the redshift, the more interesting a rich cluster becomes from a cosmological viewpoint. Firstly, as the most massive collapsed structures in the universe, their properties and evolution are highly sensitive to the fundamental cosmological parameters, as well as to the power spectrum of mass fluctuations which give rise to large scale structure in
Fig. 1. Schematic plot of surface density contrast for a rich cluster observed at \( z = 0.3 \) and 1.2. The dotted line sketches \( I \)-band field galaxy counts, while the solid curve represents the central galaxy surface density of a rich cluster with a Schecter luminosity function. At \( z = 0.3 \), the cluster core has a peak contrast of \( \sim 10 \times \) the background, while at \( z = 1.2 \) the contrast is \( < 2 \times \). A k–correction for Sb-type galaxies with mild luminosity evolution has been assumed – the contrast is reduced to virtually nothing if the cluster galaxies are all ellipticals (dashed line) due to the stronger k–correction.

the galaxy distribution. The abundance of massive clusters, and their detailed properties, become increasingly important constraints on cosmological models at larger redshift. Secondly, today’s rich clusters are dominated by elliptical galaxies, whose evolutionary history is of particular interest since they may represent the oldest galaxy–sized stellar systems. Tracing their spectrophotometric properties may point back to the earliest epochs of star formation.

The observational challenge in finding and studying distant clusters is one of enhancing their contrast against the field. Simply imaging in a single, broad bandpass is not sufficient. In the absence of extensive spectroscopy, multi–color or narrow band techniques must be used to screen out the multitude of mostly foreground galaxies and to isolate candidate cluster members. Here, I consider a variety of means by which this may be achieved. Many of these are costly in terms of observing time: regardless of the method, one must work to very faint apparent magnitudes in order to see distant clusters, requiring large telescope apertures and long exposure times. Thus far, virtually all attempts to find extremely high–\( z \) clusters have been “targeted” surveys. Rather than blindly search the sky for contrast enhancements in the galaxy density, 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, more normal companions. In particular, various previous surveys (e.g. Yee & Green 1984, Yates et al. 1989, Hill & Lilly 1991) have found that radio-loud AGN at $z \approx 0.5$ are frequently (but not always) situated in rich galaxy clusters. For this reason, my collaborators and I, as well as others, are studying the environments of distant radio galaxies and quasars. Our initial results have been encouraging, and suggest that this may be a fruitful pursuit for future surveys with large telescopes such as the VLT.

2 A case study: 3C 324

One means of enhancing the contrast of distant clusters is to search in the near–infrared, where the field galaxy number counts exhibit a shallower slope, and where the k–correction which dims the light of distant early–type galaxies is significantly reduced. Peter Eisenhardt and I have been carrying out a systematic survey of the environments of radio galaxies at $0.8 < z < 1.4$, using deep infrared and optical imaging to search for enhancements in the galaxy surface density around the AGN. Several promising cluster candidates have been found in this manner. In order to confirm these and to study their properties in more detail, Hy Spinrad, Arjun Dey and I have been following these up with Keck multislit spectroscopy. We have also obtained deep HST images of two of these clusters so far. Here I will use the environment of 3C 324, a powerful radio galaxy at $z = 1.206$, to illustrate the challenges and promise of these methods.

![Fig. 2. Deep $R$ (left) and $K$ (right) images of a $2.5'$ field around the $z = 1.206$ radio galaxy 3C 324, which sits at field center. The cluster is evident in the infrared image, but is nearly invisible in the optical data.](image-url)
is nearly invisible in the optical image. Figure 3 demonstrates this by showing the radial surface density profile of the cluster in the two images. Optically, the cluster contrast peaks at a factor of only $\sim 2 \times$ the background density, whereas in the infrared the contrast reaches a factor of $\sim 6 \times$. This is because there are many very red galaxies in this field, which mostly have the expected elliptical morphologies in our deep HST images (cf. Dickinson 1995a, b). The k–correction for these ellipticals is killing the cluster contrast optically, but leaving it more prominently visible in the near infrared. Figure 4 demonstrates another means by which distant clusters may be recognized: color contrast, wherein a judiciously selected set of broad band filters allows one to distinguish high–z cluster galaxies from the lower redshift field objects by their unusual colors.

![Fig. 3. Radial cluster contrast profile for 3C 324 in the optical and infrared, normalized to the “field” density of foreground/background galaxies. As is evident in figure 2, the cluster contrast is much stronger in the $K$–band.](image)

Figure 5 shows the results of our spectroscopy around 3C 324, primarily carried out using the Keck LRIS, but with additional redshifts provided by Olivier LeFèvre from the NTT. The vast majority of the galaxies we have observed, particularly at larger separations from the radio galaxy, lie in the foreground or background. However, two sharp spikes in the redshift distribution appear at $z \approx 1.15$ and $z \approx 1.21$. These galaxies are strongly clustered around the radio galaxy: considering only galaxies at radii $< 60''$ from the radio galaxy, these high–$z$ spikes dominate the redshift histogram. Evidently, the “cluster” which appears in the $K$–band images is comprised of two distinct clumps or sheets of
Fig. 4. Histogram of $R - K$ colors for galaxies around 3C 324. The prominent spike at $R - K = 5.9$ largely consists of faint galaxies with elliptical morphologies in the HST images.

galaxies separated by $\sim 7500$ km s$^{-1}$ in their rest frame. Whether this is merely a chance projection, or an indication of supercluster–scale structure at $z \sim 1.2$, is not yet clear.

We believe that one of these two redshift “spikes,” probably the one associated with the radio galaxy itself, is genuinely a rich, bound cluster. As part of an x–ray survey of distant radio galaxies, we obtained a Rosat PSPC observation of 3C 324 which detected a faint (6σ) source within 10$''$ of the radio galaxy position. At low signal–to–noise, the PSPC resolution was insufficient to show whether the source is resolved, so the question remained whether or not the x–rays arose in the radio galaxy AGN or from the cluster environment. A subsequent 72.1 ksec Rosat HRI exposure clearly shows that the x–ray emission is resolved over a detectable diameter of $\sim 60''$. The redshift distribution shown in figure 4 exhibits spikes at $z < 1$ such as are seen in all faint field galaxy surveys (cf. Cohen et al. 1996). However, none of the foreground spikes consists of galaxies particularly concentrated toward the radio galaxy position. Given the close positional agreement between the x–ray source and 3C 324, we regard it as unlikely that the x–rays arise from a foreground group or cluster. If the x–rays indeed originate at $z = 1.2$, the 3C 324 cluster has a bolometric x–ray luminosity $L_X = (8.0 \pm 1.6) \times 10^{44}$ erg s$^{-1}$ (for $H_0 = 50, \, q_0 = 0.5$), comparable to that of the Coma cluster. The presence of a large mass is also supported by the detection of weak shear gravitational lensing centered on the radio galaxy in our WFPC2 images (Smail & Dickinson 1995). This demonstrates the promise of
Fig. 5. Redshift histograms of galaxies in the 3C 324 field for samples restricted at several radii from the radio galaxy. The various shadings indicate different redshift “quality classes,” with the filled area indicating fully secure redshifts (multiple spectral features) while the hatched area largely represents redshifts based on single emission lines, generally assumed to be [OII]. The “cluster” separates into two structures at $z = 1.15$ and $z = 1.21$. Within $30''$, where extended x-ray emission is found in our Rosat data, these high-$z$ spikes dominate the redshift distribution, suggesting strongly that the x-rays originate at $z = 1.2$. 
cluster–hunting at high redshift: the properties of such massive, collapsed structures at \( z > 1 \) may provide useful constraints on theories of structure formation and evolution.

3 Search techniques at higher redshift

The preceding section demonstrates two methods of contrast enhancement: searches in the infrared, and searches by color contrast. At higher redshifts, it is unlikely that contrast in a single broad bandpass, even in the infrared, will be sufficient to allow recognition of even rich clusters except perhaps in a statistical fashion. More carefully “tuned” methods must be adopted.

Just as optical–infrared color contrast helped us to discover the 3C 324 cluster, various infrared–infrared color combinations may be effective for isolating galaxies at \( z > 2 \). In particular, combined \( JHK \) imaging may be effective for detecting galaxies with evolved (ages > 1 Gyr) stellar populations at \( z \approx 2.5 \), where the \( J \) band lies shortward of 4000 Å in the rest frame and the \( H \) and \( K \) bands roughly measure the rest–frame \( B – R \) color. Modelling suggests that older galaxies at \( z \approx 2.5 \) should have identifiably unique colors in this bandpass combination, separating out from the locus of lower redshift objects.

At \( z > 3 \), the 912 Å Lyman limit passes through the observed \( U–band \). This fact has been exploited to great effect by Steidel and collaborators (cf. Steidel et al. 1995 and 1996, and the contributions of Giavalisco and Macchetto to this conference), who have identified and spectroscopically confirmed large numbers of \( 3 < z < 3.5 \) field galaxies by selecting them according to their colors in a specially tuned \( UGR \) filter system. This is another means of multicolor selection, using a spectral break in the rest–frame UV rather than the rest–frame optical. Giavalisco (priv. comm.) has used this filter system to identify a density enhancement around the \( z = 3.6 \) radio galaxy 1243+036, and Lacy & Rawlings (1996) have reported similar results for 4C 41.17 at \( z = 3.8 \).

The Lyman–break technique has been especially effective for studying field galaxies because it probes a large redshift interval, and hence a large volume of space. For this reason, however, it may actually be less optimal for cluster surveys, where one would ideally like to restrict as much as possible the redshift range over which one isolates candidate cluster galaxies. Narrow band techniques searching for line emission may therefore also prove useful and effective, although they are limited to the detection of star–forming galaxies and AGN. But this may not be a strong drawback at high redshift, where many or most galaxies may be actively undergoing star formation. Lyman \( \alpha \), while optically convenient for \( z > 2 \), is a fragile line to work with and is easily extinguished by dust. Nevertheless, it has been successfully used by Francis et al. 1996 (and this volume), Pascale et al. 1996, and Møller & Warren (1993) to identify galaxies in candidate groups or clusters at \( 2 < z < 3 \). LeFèvre et al. (see also contribution by J.–M. Deltorn at this meeting) have also detected and confirmed two Ly\( \alpha \) companions to the \( z = 3.14 \) radio galaxy MGO 0316-257.
In the future, narrow band infrared searches may be particularly effective, probing Balmer and forbidden line emission which is less affected by dust than is Ly\(\alpha\) (cf. contributions by Mannucci to this meeting). A particularly “magic” redshift is \(z \sim 2.3\), where [OII], [OIII]/H\(\beta\), and H\(\alpha\) are shifted into the \(J\), \(H\) and \(K\) windows, respectively, and where Ly\(\alpha\) is shifted to \(\lambda_{\text{obs}} > 4000\) Å, facilitating narrow band searches and spectroscopic confirmation. At \(z \sim 2.3\), the multicolor IR broad band techniques suggested above may also be used to look for older, non–star–forming galaxies. Indeed, Paul Francis has taken advantage of all of these methods in studying the \(z = 2.38\) system he described in his contribution to this conference.

4 Future prospects and the VLT

At present, there is very little known about any of these very distant cluster candidates except that a few galaxies are present at similar redshifts. But these are early days yet, and preliminary detections can, with intensive follow–up studies, lead to more far–reaching results. For 3C 324, the detection of x–ray emission and gravitational lensing gives a first hint at cluster masses beyond \(z = 1\). Our redshift survey of the 3C 324 field, particularly the unexpected discovery that the “cluster” divides into two distinct redshift–space structures seen in projection, serves as a reminder that extensive spectroscopy is needed to confirm and interpret any individual cluster candidate. This is where telescopes like the VLT will excell, providing the firepower needed to do this efficiently.

For future cluster surveys, the techniques described above will require wide field imaging to very faint flux levels in bandpasses ranging from \(U\) through \(K\). The wide field imaging aspect must be stressed, especially in this era of increased angular resolution and adaptive optics, which often drives instrument design toward smaller pixels and smaller fields of view. Systems capable of multiplexed imaging (simultaneously observing through several bandpasses, split by dichroics) would be highly desirable. Narrow band capabilities, ideally tunable to any wavelength, are also likely to be particularly useful for cluster work where restricted redshift coverage is desirable, much more so than for field galaxy surveys. Narrow band work is often difficult on very large telescopes because of the large sizes of the optical beams, but should be considered carefully in future instrument designs for the VLT.

For detailed follow–up studies of high–\(z\) clusters, spectroscopy is the key. Proposed future VLT instruments such as VIRMOS will be ideal, permitting simultaneous spectroscopy of hundreds of faint galaxies, and extending into the near–IR where [OII], [OIII] and Balmer emission will be redshifted. And while emission lines are useful and important, the success of Steidel et al. in measuring redshifts from \(UV\) absorption line in young, star forming galaxies at \(z > 3\) should be kept in mind. In the future, infrared continuum and absorption line spectroscopy may be essential for studying the properties of older stellar populations of \(z > 1\) galaxies in clusters and in the field.
5 Acknowledgements

I would like to thank my collaborators, particularly Hy Spinrad, Arjun Dey, Peter Eisenhardt and Richard Mushotzky, for permitting me to show data in advance of publication. I also thank the conference organizers for an invigorating meeting in (admittedly frigid) Garching, and for their financial support.

References

Butcher, H.R., and Oemler, A. 1978, ApJ, 219, 18.
Butcher, H.R., and Oemler, A. 1984, ApJ, 285, 426.
Cohen, J.G., Hogg, D.W., Pahre, M.A., and Blandford, R. 1996, ApJ, 462, L9.
Dickinson, M. 1995a, in Fresh Views on Elliptical Galaxies, eds. A. Buzzoni, A. Renzini, & A. Serrano, (ASP, San Francisco), p. 283.
Dickinson, M. 1995b, in Galaxies in the Young Universe, eds. H. Hippelein, K. Meisenheimer, & H.-J. Röser, (Springer–Verlag), p.144.
Francis, P.J., Woodgate, B.J., Warren, S.J., Møller, P., Mazzolini, M., Bunker, A.J., Lowenthal, J.D., Williams, T.B., Minezaki, T., Kobayashi, Y., and Yoshii, Y., 1996, ApJ, 457, 490.
Hill, G.J., and Lilly, S.J. 1991, ApJ, 367, 1.
Lacy, M., and Rawlings, S., 1996, MNRAS, 280, 888.
LeFèvre, O., Deltorn, J.-M., Crampton, D., and Dickinson, M., 1996, ApJ Letters (in press).
Møller, P., and Warren, S.J., 1993, A&A, 270, 43.
Pascarelle, S.M., Windhorst, R.A., Driver, S.P., Ostrander, E.J., and Keel, W.C., 1996, ApJ, 456, L21.
Smail, I., and Dickinson, M., 1995, ApJ, 455, L99
Steidel, C.C., Pettini, M., and Hamilton, D. 1995, AJ, 110, 2519.
Steidel, C.C., Giavalisco, M., Pettini, M., Dickinson, M., and Adelberger, K. 1996, ApJ, 462, L17.
Yates, M., Miller, L., and Peacock, J. 1989, MNRAS, 240, 129.
Yee, H.K.C., and Green, R.F. 1984, ApJ, 280, 79.