High-z Clusters
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From
Encyclopedia of Astronomy & Astrophysics
P. Murdin

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ISBN: 0333750888
High-$z$ Clusters

Clusters of galaxies are the largest and most massive structures in the universe, held together by gravity. Their density is more than a thousand times the average density of the universe, and they are filled with galaxies, hot gas and dark matter.

It is very interesting to study clusters of galaxies out to the largest distances and highest redshifts. The most distant clusters are so far away that the light has traveled for a large fraction of the age of the universe, and we are therefore looking back in time when we study these clusters.

It is very hard to find the high redshift clusters. The oldest method relies on deep optical images taken of the sky. The clusters can be recognized as small concentrations of very faint galaxies. The Palomar Sky Survey was used to find clusters, but it is very hard to find clusters beyond a redshift of 0.4. Other techniques have been more efficient at finding higher redshift clusters. Powerful radio galaxies can reside in clusters, although most of the clusters found in this way are not very rich.

One of the most efficient ways of finding high redshift clusters is based on their x-ray emission. The hot gas that fills clusters emits strongly in x-rays. This x-ray emission is so bright that it can be seen out to redshifts of 1 and higher. An example of such an x-ray cluster is shown in figure 1. This cluster, MS1054–03, was discovered with the Einstein satellite in a deep survey on part of the sky. All x-ray sources in the survey were carefully identified in the optical by Isabella Gioia and collaborators. Finally, optical spectroscopy with the 10 m W M Keck telescope showed that this was the most distant cluster discovered with the Einstein satellite. It has a redshift of 0.83, and the universe was less than half its present age when the cluster emitted the light we observe.

The most distant cluster found in this way is RXJ0848.9+4452, which was first detected by the Rosat satellite, and identified as a cluster at a redshift of 1.26 by Rosati and collaborators. The image is shown in figure 2. The cluster is as massive as nearby Abell clusters. The optical emission is quite faint because the light of the galaxies has been shifted to the infrared by the high redshift. Images in the infrared are necessary to find such high redshift clusters. Surprisingly, this cluster has been found to have a very close neighbor, at the same redshift. The second cluster had been found serendipitously by an infrared survey of the sky. This pair of clusters forms a ‘supercluster’.

Now that large samples of clusters at high redshifts have been found, we can determine whether the clusters change with time, and whether the galaxies inside clusters change with time. The first question to answer is whether the number of clusters is different at high redshift. Many theoretical models predict that clusters...
form 'hierarchically', which means that large clusters grow by the accumulation of smaller clusters. Some of these theories predict that the most massive clusters should not exist, or be very rare at redshifts of 1. Interestingly enough, the cluster MS1054–03 is so massive that its existence at a redshift of 0.83 poses problems for some theories. In general, there is no strong evidence that the number of clusters changes with redshift. The newest results indicate, however, that the most massive clusters are somewhat rarer at high redshift.

The high redshift clusters are also very suitable for studying the evolution of the galaxies inside the clusters. In the nearby universe, rich clusters are dominated by S0 galaxies and elliptical galaxies, and have only a small fraction of spiral galaxies at their center. Only recently has it become possible to obtain images of high redshift clusters with a quality good enough to undertake such studies. The very sharp images taken with the Hubble Space Telescope are of comparable quality to the earlier images taken of low redshift clusters.

Studies by Dressler and co-workers have demonstrated that the fraction of spiral galaxies is significantly higher in clusters at a redshift of 0.5. Figure 3 shows the center of the cluster CL0939+4713 at a redshift of 0.41. The high fraction of spiral galaxies in the center of this cluster is obvious. Generally, high redshift clusters have far fewer S0 galaxies than low redshift clusters. These galaxies are the most common type of galaxy in low redshift clusters. They have probably been added to the low redshift clusters from the outside. Before they fall into the clusters, they look like spiral galaxies. When they fall in, they lose their gas, and appear as S0 galaxies soon after.

At even higher redshifts, the evidence for merging between galaxies becomes stronger. It has been speculated for a long time that elliptical galaxies form by collisions of less massive galaxies. After two galaxies collide, they quickly merge together and form a new galaxy. If the two galaxies contain no or little gas, they will form a regular elliptical after the mergers.

It has always been difficult to find such mergers in clusters. However, a recent study of the rich cluster MS1054–03 shows that 18% of the member galaxies are mergers. These colliding galaxies are shown in figure 4. It is likely that the mergers evolve into elliptical galaxies or S0 galaxies. This is direct evidence that galaxies evolve through merging. (See also galaxies: interactions and mergers.)

The mergers and the conversion of spiral galaxies into S0’s may very well explain why galaxies in clusters are very different from galaxies outside clusters. Understanding the origin of this effect is one of the goals of studies of distant cluster galaxies. By observing these clusters, astronomers can directly see what happened to the galaxies in the distant past.

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Figure 3. The central part of the distant cluster CL 0939+4713, imaged with the Hubble Space Telescope (courtesy A Dressler and NASA). The center contains many spiral galaxies, unlike clusters nearby. Many of these spiral galaxies look disturbed.

Figure 4. Mergers in the distant cluster MS1054–03 (courtesy van Dokkum, Franx, ESA and NASA). These galaxies have been confirmed to be cluster members. They are classified as mergers. Some show tidal arms, others double nuclei, or faint extensions due to the collisions of galaxies. Such mergers may have been much more prevalent in the past. This figure is reproduced as Color Plate 8.