

# The Red-Sequence Cluster Survey

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Galaxy clusters are the largest and most massive discrete structures in the Universe. They represent the endpoint of gravity's influence on the growth and collapse of the Universe's large scale structure. Mass in the Universe, as traced by galaxies, is distributed in sheets surrounding large, nearly empty spherical voids. At the intersection of these sheets, at places referred to as filaments, the density of the universe is even larger. At the intersection of filaments, sitting much like spiders in a 3-D cosmic web, are galaxy clusters. Clusters are extremely dense, with central densities  $\sim 1000$  times that of their surroundings. As the Universe ages, galaxy clusters are thought to become larger and larger, as mass drains along the filaments into the central clusters. Galaxy clusters are extremely important laboratories for the study of a number of questions in astronomy, and will be one of the most important targets for observations by both ground-based and space observatories in the coming years.

The Red-Sequence Cluster Survey is an ambitious project designed to identify a large sample of galaxy clusters over a wide range of redshifts (distances). The resulting sample of galaxy clusters will yield answers about the way in which structures formed and grew in the Universe, and will facilitate a number of other projects. The survey is the largest area survey ever conducted on 4-m class telescopes, and as such will yield

important new insights on hitherto poorly measured or unknown phenomena. Despite the large area of the survey (90 square degrees of sky - roughly 500 times the apparent area of the full Moon) a very efficient observing strategy allowed this unprecedented area to be covered in only 25 nights of observing time. Two telescopes were used to complete the project (the Canada-France-Hawaii 3.6 m telescope for the northern hemisphere, and the Cerro Tololo Inter-American Observatory 4 m telescope for the southern hemisphere). The survey began in mid-1999, and observations were finished by late 2001. We are currently using the powerful ESO VLT telescopes for following up some of the highest redshift clusters in the sample.

## The method

In conjunction with the extensive data from the RCS project, we have devised a new algorithm for finding clusters in two-filter survey data. This algorithm exploits the fact that all clusters so far observed have a central population of old red galaxies. While the properties of the overall cluster galaxy population do evolve with redshift (i.e. the fraction of blue or actively star-forming galaxies is generally higher at higher redshift), in all well-formed significant clusters so far observed there is a red population. In essence, we define a cluster as an overdensity in both position and colour. The distribution of galaxy clusters, even in systems with a large fraction of blue galaxies, represents a colour distribution not generally found in the field (i.e. non-cluster) galaxy population. Additionally, the filters used for the RCS survey provide a particularly deviant (and hence readily identified) colour for clusters at modest to very high redshifts. Thus, simple colour cuts allow us to select 2-D groupings of red galaxies, which are very likely to be real 3-D clusters of galaxies at high redshifts. We have tested this method extensively using both real redshift survey data, and using complex and thorough simulations, and find that it works extremely well (a detailed description of the method can be found in Gladders & Yee 2000).

## Clusters and Cosmology

The number density of galaxy clusters as a function of their mass and red-

shift,  $N(M,z)$ , is strongly dependent on the cosmological parameters  $\Omega_m$  and  $\sigma_8$ .  $\Omega_m$  describes the matter density of the Universe, and  $\sigma_8$  describes the amplitude of the early fluctuations in the Universe, which seed the growth of structures on the physical scale of galaxy clusters. In an expanding low-density universe (small  $\Omega_m$ ), structures like galaxy clusters must form relatively early, when the universe was still compact and relatively dense. Only in this setting does such a universe have sufficient mass density to cause large structures to collapse under the influence of gravity, and even then only if the initial fluctuations which seed the growth of structure are relatively large (high  $\sigma_8$ ). Conversely, in a universe with much greater mass content (large  $\Omega_m$ ) structure continues to form as the universe expands and ages, even when the seed fluctuations are relatively modest (low  $\sigma_8$ ).

We have known for a long time that the local universe contains many galaxy clusters. These clusters could result from either a low matter density, large fluctuation cosmology, or a high matter density, small fluctuation cosmology. However, as described above, the past history of this local cluster population is wildly different in these two cosmologies, and so studies of clusters at great distances (which, due to light travel-time effects also corresponds to the distant past) offer a powerful constraint on cosmological models. The RCS seems to contain many high-redshift, massive clusters, and hence initial results strongly favour a low  $\Omega_m$  and high  $\sigma_8$  universe. However, this conclusion depends critically on correct mass estimates for these systems, and our ongoing spectroscopy with the VLT+FOR2, for which the first data have just been taken, represents a critical step in confirming this initial result. A summary of the first clusters with confirmed redshifts is shown in Figure 1.

## Cluster Galaxy Evolution

Clusters of galaxies also provide us with natural laboratories to study galaxy evolution, since we find a number of galaxies in a relatively small region of the universe that can be traced to high redshift, or equivalently to an epoch when the universe was much younger.

Our studies are focussed on measuring properties such as the galaxy luminosity function (LF), blue fraction, and

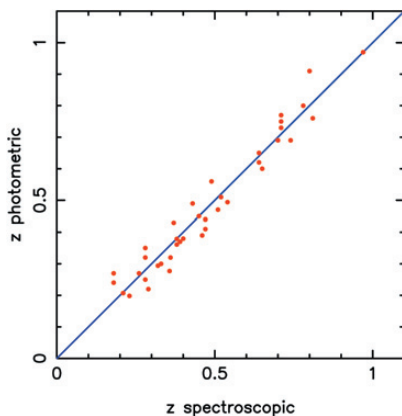


Figure 1: Spectroscopic confirmation of the first clusters found in the RCS. The measured spectroscopic redshift for the clusters in this sample agrees very well with the estimates obtained from the photometric data alone. We are currently working with the VLT and FOR2 to populate this diagram in the region at  $z > 0.9$ .



Figure 2: IJK colour composite image of the field centred on RCS0439.6-2905. North is up and East to the left. This image shows approximately the central  $1.1 \times 1.1$  Mpc.

the CMR (colour-magnitude relation, i.e. red sequence), for clusters over a range of richnesses and redshift (individually for rich clusters, in redshift bins for poor clusters). These data will allow investigations of the evolution of cluster galaxies, and will constrain their formation time and process through a detailed analysis of the evolution of the slope, scatter and colour of the CMR. As the sample will be volume limited for rich clusters over a large portion of the redshift range, we will be able to trace cluster galaxy evolution without strong selection biases.

### RCS0439.6-2905: A Cluster Galaxy Evolution Case Study

As an example of such studies we present in Figure 2 an image of RCS0439.6-2905, one of the most massive distant clusters found in the RCS. Recent spectroscopy confirms that RCS0439.6-2905 is at  $z = 0.97$  making it more distant than all but a handful of known galaxy clusters. The  $I$ ,  $J$  and  $K$ -band colour composite in Figure 2 ( $I$ -band taken at Magellan and  $J$  and  $K$ -bands at the VLT) shows numerous galaxies with similar colours that presumably are cluster members.

Figure 3 shows the colour-magnitude relation for the galaxies in the field of this cluster. The quality of the images taken with the VLT was very good, with a seeing of  $\sim 0.4$  arcsec, and this allows us to perform a morphological study by applying galaxy image fitting tech-

niques. The galaxies selected as elliptical or lenticular galaxies (E/S0s) on the basis of their 2-D light profiles are shown as red circles. Clearly these galaxies define a tight colour sequence in this cluster. The red sequence as it would appear at the distant redshift for the E/S0 galaxies in the Coma cluster, a nearby cluster of galaxies and the canonical example of a rich cluster, is shown as the blue broken line. The galaxies in RCS0439.6-2905 appear intrinsically slightly bluer than those in the Coma cluster, consistent with these galaxies being like those seen in Coma, but at a much younger age.

The excellent image quality of the VLT not only allowed us to segregate the E/S0 galaxies in this cluster at  $z = 0.97$  but also to determine the size of the galaxies. The size of the galaxies, accounting for the seeing profile, is given by the effective radius, the radius that encloses half of the light of the galaxy, and is shown in Figure 4 as a function of their absolute magnitude. The red

symbols are the galaxies in the cluster at  $z = 0.97$  and the blue crosses are their equivalent in local clusters of galaxies. The red solid line and the broken blue line are the best fit for the galaxies at  $z = 0.97$  and for those in local clusters, respectively, keeping the same slope for both sets of galaxies. The offset between the lines is approximately 1.2 magnitudes. This brightness shift can be interpreted as the galaxies at  $z = 0.97$  following a similar size-magnitude relation than those in local clusters but being 1.2 magnitudes brighter than their local counterparts. Much like the colour evolution, this is consistent with models of early formation of the stellar population in these galaxies, with subsequent fading and reddening as they age.

### Strong-Lensing Clusters

The large area and depth covered by the RCS provides large samples of galaxy clusters spanning a wide range of properties. A particularly interesting subsample is the strong-lensing clusters, which due to gravitational effects act as lenses magnifying and distorting the images of distant objects background to the cluster. We have so far found 8 new strong lensing systems in the RCS, some of them with the presence of multiple giant arcs (Gladders et al. 2003). The incidence of such a large number of strong lensing clusters in the surveyed area is discrepant with current theoretical predictions (standard expectations are 0-1 such clusters in a survey the size of the RCS).

The first studied RCS lensing cluster, RCS0224.5-0002, is shown in Figure 5. Spectroscopy of this cluster was acquired using the 8.2 m Kueyen Telescope and FORS-2 in Director's

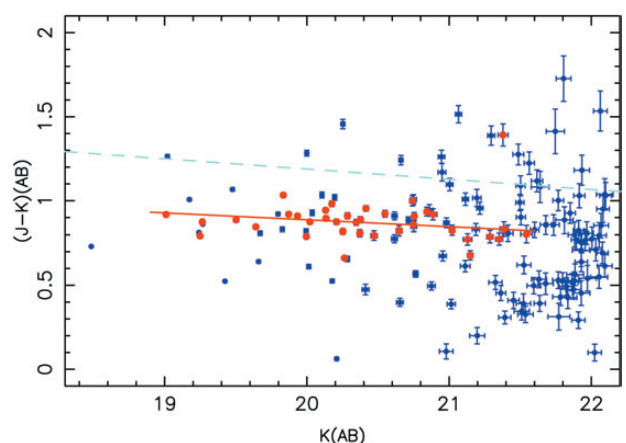


Figure 3: IR colour-magnitude diagram in the field of RCS0439.6-2905. All the objects are included and shown as filled circles. The morphologically selected E/S0 galaxies are shown as open circles. These galaxies define a tight sequence, similar to that found in local clusters. The solid line shows the best fit to the sequence of E/S0 galaxies in the cluster. The broken line corresponds to the colour-magnitude relation for the E/S0 galaxies in Coma cluster redshifted to  $z = 0.97$ .



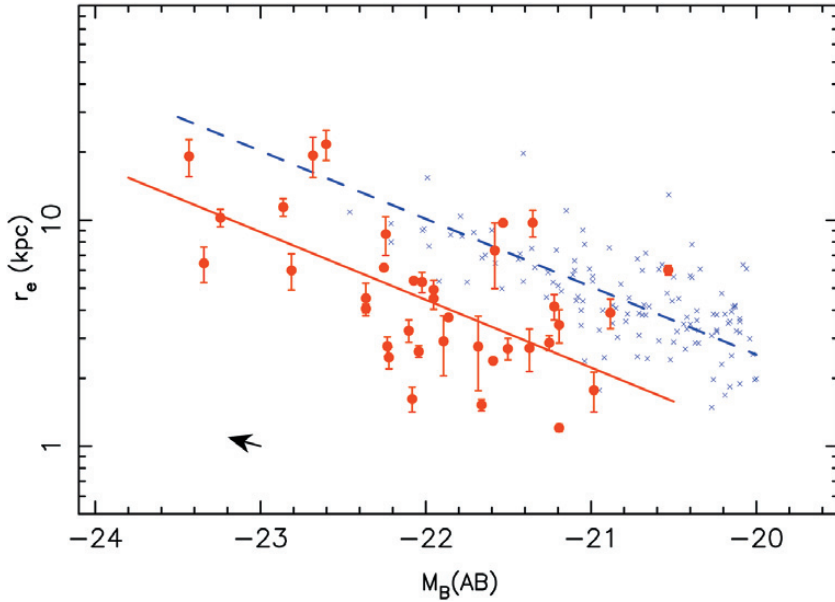


Figure 4: Size-magnitude diagram for the E/S0 galaxies (filled circles) in the field of RCS0439.6-2905. The size has been obtained from the 2-D galaxy light profile fitting algorithm. For comparison the E/S0 galaxies in local clusters are shown as crosses, including the best linear fit to these galaxies (broken line). The solid line corresponds to the fit for the galaxies in RCS0439.6-2905, constrained to have the same slope as that for the local E/S0 galaxies. There is an offset for the fit at  $z = 0.97$  from the local relation that amounts to  $\Delta M_B(AB) = -1.20 \pm 0.09$ .

Discretionary Time, soon after the cluster was discovered. This initial spectroscopy demonstrated that the cluster was at  $z = 0.773$ , and showed that one of the arcs (the arc labelled 'C', visible in Figure 5) was extremely distant, at a redshift of 4.8786 (Gladders et al. 2002). The FORS spectrum of this arc at Ly- $\alpha$  is shown in Figure 6, along with the images of the arc in the  $R$  and  $I$ -bands. The Ly- $\alpha$  emission (shown by both the spectrum and the  $R$ -band light), with an equivalent width of several hundred Angstroms, is spatially extended compared to the UV continuum just to the red of Ly- $\alpha$  (shown by the  $I$ -band light). At the time of discovery, RCS0224.5-0002 was the most distant cluster known with such spectacular strong lensing, and the high redshift arc was one of only two known giant arcs at such great distances, the other being an arc at  $z = 4.92$  formed around the  $z = 0.33$  cluster CL 1358+62 (Franx et al. 1997). Notably, the distant arc in RCS0224.5-0002 appears rather different in detail; it is spatially smooth with an extended Ly- $\alpha$  halo surrounding a compact star-forming core, and shows no velocity structure, whereas the one in CL 1358+62 is knotty in appearance and shows velocity structure of  $\sim 300$  km/s.

Since the discovery of RCS0224.5-0002 we have found several other spectacular multiple-arc strong lens clusters. Of the total of 8 strong-lens systems, 2 more are comparable to RCS0224.5-0002. This high proportion of multiple arc systems argues that there must exist a class of "super-lenses" which, for some yet undetermined reason, act as particularly powerful lenses. Notably, the strong lens clusters in the RCS are all at  $z > 0.64$ , and it thus seems likely that the source of this lensing boost is associated with early times when clusters are still forming, and that whatever is responsible for the lensing boost evolves away as clusters age (Gladders et al. 2003).

### Additional Projects: Clustering and Evolution of Small Galaxy Groups

The wide area, depth and homogeneity of the RCS data allow us to pursue other relevant problems in galaxy evolution, such as the study of the formation and evolution of structure in the Universe, ranging from clusters, groups, pairs of galaxies to individual galaxies.

As is well known, the distribution of galaxies in the universe is believed to be different from the distribution of dark matter; the distribution of galaxies is a biased tracer of the matter. To understand the clustering pattern of galaxies through a good interpretation of observational data and to compare them to current predictions of cosmological models, this bias has to be understood.

In simulations, pairs, triples, small groups, groups and clusters of galaxies

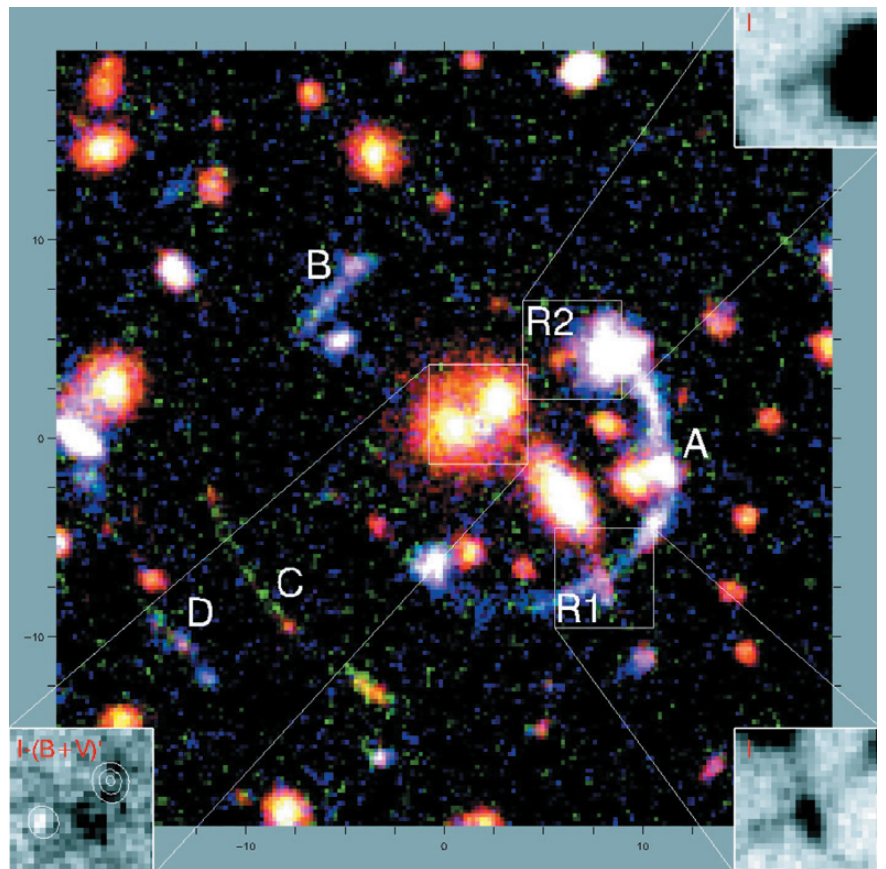


Figure 5: This  $40'' \times 40''$  image is a colour composite of  $zI+R+BV$  images of RCS0224.5-0002. Various features – two candidate radial arcs, and excess blue light in the cluster centre – are highlighted in grey-scale inserts. Arc C is at  $z = 4.8786$ . (Adapted from Gladders et al. 2002)

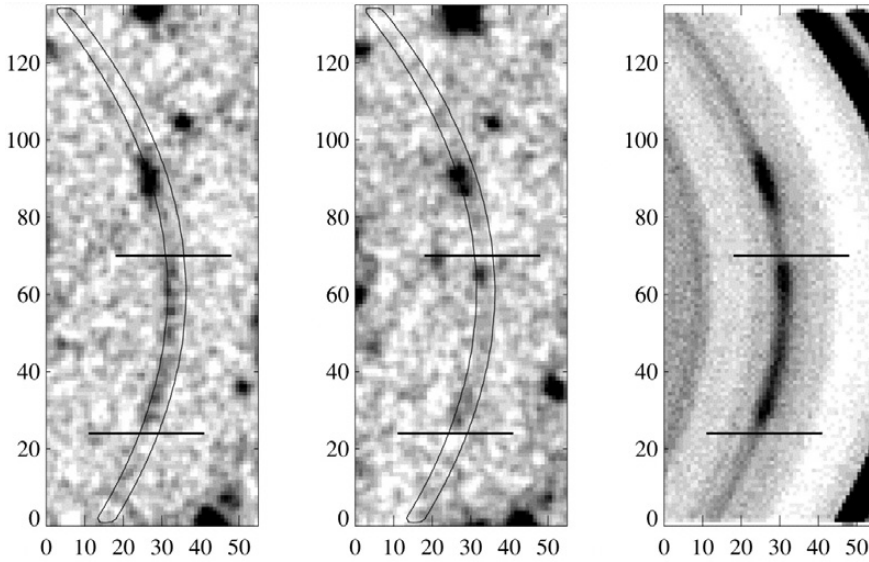


Figure 6: Arc C in R band (left), I band (middle), and in Ly emission (right). The spectral image has not been sky subtracted. The position of the slit as reconstructed after the FORS observations, is also indicated in the broadband images. (Adapted from Gladders et al. 2002)

are fully characterized by their corresponding halo dark matter mass. If so, how can observations be used to measure the “bias”? Theoretically, there is a

strong relation between the dark matter halo mass and the number of members with similar luminosities in clusters, cluster number richness,  $m$ . In the ob-

servational plane, the measured quantities are  $N(z, m)$  and the two-point correlation function,  $\xi(r, m)$ .

No clustering studies of small galaxy groups with  $m > 3$  have been carried out, basically because of small survey area, bad number statistics and lack of deep homogeneous data. To find groups at different redshifts, deep wide field imaging is needed. In this project, SDSS and RCS provide the low and high- $z$  groups, to  $z < 0.7$  respectively. A number of groups have been detected on the RCS data. In order to measure the spatial clustering properties, inversion of 2-dimensional data is required. Currently, redshifts of group members selected from SDSS and RCS are being measured.

## References

- Gladders, M. D., & Yee, H. K. C. 2000, *AJ*, **120**, 2148  
 Gladders, M. D., Yee, H. K. C., & Ellingson E. 2002, *AJ*, **123**, 1  
 Gladders, M. D., Hoekstra, H., Yee, H. K. C., Hall, P. H., & Barrientos, L. F. 2003, *ApJ*, in press  
 Franx, M., Illingworth, G. D., Kelson, D. D., van Dokkum, P. G., & Tran, K.-V. 1997, *ApJ*, **486**, L75

# Long Period Variables in the Giant Elliptical Galaxy NGC 5128: the Mira P–L Relation at 4 Mpc

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In a stellar population older than a few hundred Myr, the near-infrared light is dominated by red giants. Among these, the stars lying on the red giant branch (RGB) are the brightest among the metal poor stars older than 1–2 Gyr. In intermediate-age populations (~ 1–5 Gyr old) numerous bright asymptotic giant branch (AGB) stars are located above the tip of the RGB. However, also among old populations like Galactic globular clusters with  $[\text{Fe}/\text{H}] \geq -1.0$  and in the Galactic bulge, bright stars have been detected above the tip of the RGB implying the presence of bright AGB stars in metal-rich and old populations. All of the bright giants above the RGB tip in globular clusters seem to be long period variables (LPVs; Frogel & Elias 1988). Old populations of lower metallicity are known not to have AGB stars brighter than the RGB tip.

Long period variables are thermally pulsing asymptotic giant branch (TP-AGB) stars with main sequence masses between 1 and 6  $M_{\odot}$ . They have variability with periods of 80 days or longer, and often the longest period variables show variable or multiple periods. Two main classes of LPVs are Mira variables (Miras) and semi-regular variables

(SRs). SRs usually have smaller amplitudes as well as shorter and more irregular or even multiple periods. They are sometimes divided into subclasses (SRa, SRb) depending on the regularity and multiplicity of their periods and shape of their light curves. The separation between Miras and SRs is not always very clear. The classical definition requires that Miras have V-band amplitudes larger than 2.5 mag and regular periods in the range of 80–1000 days. Mean K-band amplitudes of Miras are typically 0.6 mag. SRs show more irregular variability, as their name indicates, and have smaller amplitudes.

So far, LPVs have been studied in the Milky Way, Magellanic Clouds and a few other Local Group galaxies. However, the Local Group lacks the important class of giant elliptical galaxies. At the distance of about 4 Mpc (Harris et al. 1999), NGC 5128 (Centaurus A) is the closest giant elliptical galaxy, the closest active galactic nucleus (AGN), one of the largest and closest radio sources and a classical example of a recent merger. It is the dominant galaxy of the nearby Centaurus Group of galaxies. Rejkuba et al. (2001) presented optical-near-IR colour-magnitude diagrams

(CMDs) of two fields in the halo of this giant elliptical galaxy (Figure 1). These CMDs show broad giant branches indicating a large spread in metallicity. The RGB tip is detected at  $K \sim 21.3$ .

A large number of sources are observed brighter than the tip of the RGB. These can belong to one of the three categories: (i) intermediate-age AGB stars with abundances similar to those found in Magellanic Clouds, (ii) old and metal-rich AGB stars similar to those found in the Galactic Bulge and metal-rich globular clusters, or (iii) blends of two or more old first ascent giant branch stars. While Rejkuba et al. (2001) have shown with simulations that only a small part of these sources can be ascribed to blends, a definite proof that these bright red giants belong to the AGB population in NGC 5128 is through the detection of variability of these sources. Furthermore, the near-IR properties of long period AGB variable stars can be used to investigate the presence or absence of an intermediate-age component in the stellar populations of this giant elliptical galaxy. This has important consequences for the formation and evolution of giant elliptical galaxies.

Using the multi-epoch K-band pho-