The ESO Nearby Abell Cluster Survey: Properties of the Galaxies

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Abstract.
In this paper we summarize the main properties of the ENACS (the ESO Nearby Abell Cluster Survey), which was one of the ESO Keyprogrammes carried out in the first half of the 1990’s, and we discuss some recent work on the properties of the galaxies in the rich clusters in the ENACS sample. We stress the importance of the ENACS sample as a local, volume-limited sample of rich ACO clusters, which in many respects can serve as a local calibration of the properties of optically selected rich clusters. However, by itself the ENACS has also provided several useful insights into the properties of a sample of rich clusters, and of the galaxies in them.

Here, we describe recent results on the properties of the galaxies in the ENACS clusters: in particular their morphological types (inferred from the spectrum) and their projected distribution. Combining the morphological data with CCD photometry and internal velocity dispersions, we will study the Fundamental Plane of early-type galaxies. We discuss some preliminary results about the universality of the Fundamental Planes in a few ENACS clusters. For a summary of the results based on the velocity information obtained within ENACS, we refer the reader to the companion review by Biviano et al. in this volume.
1. Introduction

In the late 1980’s a large amount of observational information had been obtained about rich clusters of galaxies. However, even though the quantity of the available data was quite impressive, the selection of the clusters and the quality of the data in general was not sufficiently homogeneous for statistical studies of the properties of rich clusters as a class. For that reason an ESO Key-programme was carried out in the late 1980’s and the early 1990’s, with the aim to provide homogeneous velocity and magnitude data for a well-defined sample of rich, nearby clusters. The cluster sample was chosen such that, in combination with data in the literature, information would become available for a complete, volume-limited sample of rich clusters.

The observations of this survey, which has become known as the ENACS (the ESO Nearby Abell Cluster Survey) have produced a catalogue of redshifts and magnitudes for 5634 galaxies in the directions to 107 ACO clusters (and cluster candidates). In this review we recapitulate briefly the properties of the ENACS and we summarize the results of the analyses to date, as far as these do not involve the velocities of the individual galaxies. I.e., we describe briefly the observational set-up, the properties of the cluster sample, and some of the properties of the cluster galaxies.

In order to allow a study of the distribution and kinematics of the various types of galaxies, and possible differences between them, we have used the ENACS spectra to derive a classification in terms of early- and late-type galaxies, and we discuss some results of that classification. As we find significant differences between the projected distributions of the various types of galaxy in the ENACS, we also analyze the projected distributions of the total galaxy samples using the COSMOS catalogue.

Finally, we discuss an ongoing project in which we use the ENACS spectra to derive internal velocity dispersions of individual galaxies. Using also photometric data from CCD imaging, we hope to study the Fundamental Planes of the early-type galaxies in 20-25 ENACS clusters. Here, we present some preliminary results from that project.

2. The Survey

The sample of target clusters constituting the ENACS was defined to contain all $R_{ACO} \geq 1$ clusters in a ‘cone’ of 2.55 sr centered more or less on the Southern Galactic Pole, which had a spectroscopic redshift less than 0.1 or, failing that, a value of $m_{10}$ in the ACO catalog (Abell et al. 1989) less than 17.0. The latter condition implies a high probability for the redshift to be less than 0.1. In the ENACS we obtained multi-object spectroscopy for those clusters in this volume (the ‘cone’) for which no extensive redshift data were available in the literature.

In Fig[1] we show the redshift distribution of the combination of ENACS and literature clusters in the ‘cone’. This figure gives the number of clusters in 10 equal-volume shells between redshifts 0.0 and 0.1. So, for constant space density these numbers should be equal to within the statistical noise. From this figure we conclude that the ENACS plus literature clusters constitute a truly volume-limited sample of $R_{ACO} \geq 1$ clusters. We refer to Mazure et al (1996)
Figure 1. The number of clusters in 10 equal-volume shells within a redshift of 0.1, for all 128 clusters in the combined ENACS/literature sample (dashed line), for the 80 clusters with at least 10 ENACS redshifts (solid line), and for the richest 33 clusters (dotted line).

for a more complete discussion of the volume-completeness of the sample, and of the completeness with respect to richness.

The samples of galaxies that were observed spectroscopically were defined from scanning with the Leiden Observatory plate-measuring machine of, mostly, film copies of the SERC IIIa-J plates or glass copies of the red PSS-I survey plates. A comparison with the COSMOS catalogue shows the ENACS galaxy samples to be magnitude-limited, but positionally unbiased subsets of the COSMOS catalogue. The effective completeness limits of the samples of galaxies with redshifts range from 16.5 to 17.5 in R_{25}, but redshifts were obtained for a substantial fraction of the galaxies beyond these limits (see Katgert et al. 1998).

As the name of the survey implies, the observations for the ENACS were done with ESO telescopes at La Silla, viz. with the 3.6-m telescope equipped with the OPTOPUS multi-object fibre-fed spectrograph for the spectroscopy, and with the Danish 1.54-m and 0.92-m Dutch telescopes for the calibration of the photometry through CCD-imaging. The resolution of the multi-object spectroscopy was 130Å/mm, and with the 2.3 arcsec diameter fibres projecting onto ≈ 50µm on the detector, the effective resolution was about 6Å.

The spectroscopic observations consist of 170 CCD exposures each containing about 50 spectra (see Katgert et al. 1996, for an example). Effective integration times ranged from 60-100 minutes, often divided up into two equal-duration exposures. Redshifts were obtained from cross-correlation with template spectra, and much care was taken to establish the linearity of the redshift scale and the correctness of its zero-point. As a result, the advertised accuracies of velocities of between 40 and 120 km/s are thought be realistic total (i.e. not just internal) errors (see Katgert et al. 1996, for a discussion of the reliability and
robustness of velocity estimates in the ENACS). Note that within the ENACS we found no evidence for the systematic difference between redshifts from absorption and emission lines, as reported recently by e.g. Cappi et al. (1998), who also used the OPTOPUS multi-object system.

The spectral range of the observations was from \(\approx 3900\) to \(\approx 5600\) Å which, for redshifts between 0.05 and 0.1 allows detection of the emission lines OII 3727 Å, H\(\beta\) 4860 Å and OIII 4959/5007 Å. About 1 in 5 of the galaxies in the ENACS shows at least one of these emission lines in its spectrum (see Biviano et al. 1997). The fraction of galaxies with at least one of these emission lines (ELG) decreases to about 1 in 8 if one considers only the galaxies in compact velocity systems (i.e. clusters). About 75% of the total of 5634 galaxies in the ENACS is in such a system with at least 4 members. Using morphological information from Dressler, Biviano et al. (1997) concluded that 6 out of 7 of the ELG are spirals, while the ELG represent about 1/3 of the total spiral population.
In Fig. 2, we show a summary of the redshift information provided by the ENACS. This figure illustrates that the large majority of the ACO clusters with $z \lesssim 0.1$ and $R_{ACO} \geq 1$ are real. From a detailed analysis, Katgert et al. (1996) concluded that about 90% of these peaks in the projected galaxy distribution correspond to compact structures in redshift space.

The ENACS redshift catalogue has been made public and can be accessed via [http://cdsweb.u-strabg.fr/abstract.html](http://cdsweb.u-strabg.fr/abstract.html); it is described in Katgert et al. 1998 and Katgert et al. 1996.

3. Galaxy populations in the ENACS clusters

3.1. Classification on the basis of the ENACS spectrum

In addition to using the ENACS spectra for deriving redshifts by cross-correlating with template spectra, we have recently used the spectra also to estimate the type of a large fraction of the galaxies in the ENACS catalogue (de Theije and Katgert, 1998). Note that the selection of the galaxies for the spectroscopic observations was done on survey plates with a scale that did not allow the determination of the morphological type of the galaxy for all except the most extended galaxies. Actually, we did not classify the galaxies at all in the selection process, but fortunately morphological classification by Dressler is available for a few hundred galaxies in the ENACS (Dressler 1980b), and this information was used to calibrate our spectral classification procedure.

In order to estimate the galaxy type from the spectrum we first derived for each spectrum the 15 most significant Principal Components (PCs), $e_1$ to $e_{15}$. In other words: the information in each spectrum, which we first sampled with 371 spectral fluxes, was condensed into 15 numbers. The latter cannot give a full description of the spectrum, but they do very nearly so, as can be seen from the left-hand panel in Fig. 3.

The physical interpretation of the weights $w_{ij}$, which define the PCs $e_i$ as follows

$$e_i = \sum_j w_{ij}(f_j - <f_j>)/\sigma_j$$

in which $f_j$ is the j-th flux value in the normalized spectrum and $\sigma_j$ is the dispersion of that normalized flux value among all spectra, can be gauged from the right-hand panel in Fig. 3 for $e_1$ to $e_3$. Clearly, $e_1$ is very much like a colour, as it measures the slope of the continuum and $e_2$ measures its curvature. The meaning of $e_3$ is somewhat less obvious although the 4000 Å break and the G-band seem to be involved. The meaning of the higher PCs is even less obvious.

By themselves, the PC’s do not provide a very good discrimination between the spectra of galaxies of different morphological types, although the value of $e_1$ increases systematically from early- to late-type galaxies. However, the distributions of $e_1$ for the galaxies with emission lines (which are mostly spirals, and which constitute about one-third of all spirals) and those without emission lines (early-type galaxies and the other two-thirds of the spirals) suggests that a better separation may be possible if one uses the most significant PCs together.

Therefore, the 15 PCs $e_1$ to $e_{15}$ were used as input for an Artificial Neural Network (ANN), with 15 input values, one hidden layer with 5 nodes, and a
single continuous output node. The ANN was trained with morphological types from Dressler (1980b). As the spectra of ellipticals and S0’s are quite similar, the separation between these classes on the basis of the spectrum is not very good. For that reason, a two-class system was used with an early-type (E+S0) class and a late-type (Sp+Irr) class. The fact that most of the ELG are known to be spirals was used to fine-tune the separation between early- and late-type galaxies in the value of the output-node.

Using an independent set of galaxies from Dressler (1980b) to test the performance of the combined PCA/ANN classification, we find that the success rate is about 75%, i.e. on average 1 out of 4 of the announced 'spectroscopic' types does not agree with the morphological type. A large part of these 'errors' must be due to an intrinsically non-perfect spectral separation of early- and late-type galaxies, and these are unavoidable and probably more or less symmetric between the two classes. However, part of the 'errors' may be due to a real inconsistency between spectrum and morphology, especially for spirals which may have an early-type (bulge-) spectrum when observed in the central 2–3 kpc region (corresponding to the diameter of the fibres used for the ENACS spectroscopy). In this respect it is noteworthy that for the separation between early- and late-type galaxies that we adopted, 4 out of 5 of the early-type galaxies are classified correctly from the spectrum, but only 2 out of 3 of the late-type galaxies. This is the asymmetry one would expect for the type of real inconsistency between morphological and spectral classification mentioned above.
3.2. Projected distributions of various types of galaxies

The PCA/ANN analysis yielded ‘spectral types’ for 3798 of the 5634 ENACS galaxies (as the PCA was done on a fixed zero-redshift interval, spectra of galaxies with too high or low redshifts could not be included, and for one of the observing periods, the calibration was not sufficiently good). For the 3798 galaxies with spectral types we also have information on the presence or absence of emission lines. Using that information, we have derived the projected density profiles for the various galaxy types, for a composite clusters of 66 ENACS clusters containing 2594 galaxies, and those profiles are shown in Fig. 4.

This figure confirms the morphology-density relation first quantified by Dressler (1980a). It also confirms the differences between the projected distributions of galaxies with and without detectable emission lines, ELG and non-ELG respectively (see e.g. Biviano et al. 1997). We now find that within the late-type class the galaxies without emission lines are more centrally concentrated than those with emission lines. Therefore, the late-type ELG avoid the central regions of their cluster more strongly than any other type of galaxy. For an interpretation of this result, kinematical data are also required, for which we refer to Biviano et al. (1997, and this volume) and de Theije and Katgert (1998).

4. The overall projected galaxy density in the ENACS clusters

4.1. Cores or central cusps?

In recent years, the mass profile of clusters has received renewed attention, largely as a result of the work by Navarro, Frenk and White (hereafter also
NFW, e.g. 1997) who found that the density distributions of dark matter halos in their simulations all follow a universal profile, when the differences in mass are properly taken into account. This universal profile has a clear cusp for which observational confirmation has been sought in cluster mass profiles based on observations. The experimental determination of mass profiles requires application of the Jeans equation for the solution of which both the number density profile of tracers of the potential (galaxies) and their kinematics must be known.

However, barring a complete solution of the Jeans equation one can investigate the presence or absence of a cusp in the projected number distribution of galaxies. This type of analysis has a long history, and until recently common wisdom held that galaxies (and probably also total mass) in clusters follow distributions that have a core, like the King and Hubble profiles. This view has been challenged, in particular by the modelling of the mass distributions in clusters which act as a gravitational lens (e.g. Kneib et al., 1993) and by the result of NFW.

As the ENACS cluster sample is essentially volume-limited, it presents a good starting point for an analysis of the galaxy distributions in (rich) clusters. However, as the ENACS galaxy samples are subsets of the total galaxy population in these clusters, we decided to use galaxies from the COSMOS catalogue in apertures centered on those ENACS clusters, which from the redshift data are known to be real. The disadvantage of the COSMOS catalogue is that even towards the rich ENACS clusters it contains a substantial contribution of unrelated foreground and background galaxies, but the advantage is that completeness to faint magnitude limits is ensured, so that many more galaxies are included than in the ENACS samples.

We have analyzed the projected galaxy distributions in about 60 individual clusters, and in a composite cluster of 29 ENACS clusters which from the COSMOS galaxy density contours are known to contain little, if any, substructure. For the individual clusters, there is a general tendency for the galaxy distributions to favour profiles with a core rather than a cusp, but the preference is seldom very significant. The evidence from the composite cluster, which contains close to 5000 COSMOS galaxies, is more robust. Note that in the construction of the composite cluster we took every care to avoid destruction of a possible cusp (due to bad centering), as well as creation an artificial cusp due to neglecting the ellipticities of the individual galaxy distributions (see Adami et al. 1998).

From Maximum-Likelihood fits to the galaxy distribution in the composite cluster we obtained likelihood ratios which indicate a clear and significant preference for profiles with a core rather than a cusp (at significance levels of between 95 and 99 percent, depending on the way the projected distances are scaled in the determination of the composite cluster). This result is supported by a visual comparison of the observed projected density distribution in the composite cluster with a King- and a 2-D analogue of the NFW profile, as can be seen in Fig. [FIGURE].

From the likelihood ratios derived for subsets of the galaxies selected on the basis of absolute magnitude, we conclude that the preference for profiles with cores is strongest for the fainter galaxies. The preference for profiles with cores...
Figure 5. The projected galaxy number density profile in a composite cluster of 29 regular ENACS clusters (based on the COSMOS catalogue). The open circles indicate the observed values, and the dashed lines the 1-σ uncertainty range.

is not observed for the brighter one-quarter of the galaxies, but the latter do not show a strong preference for profiles with cusps either.

4.2. The outer slope of the density profile as a cosmological probe

In recent years, several authors have discussed the relation between the outer slope of the density profiles of clusters on the one hand, and the details of the formation process of large-scale structure in the Universe on the other hand (e.g. Crone et al., 1994, and references therein, Jing et al. 1995, to name but a few). Although a description of the formation process includes the shape and the amplitude of the initial fluctuation spectrum, it appears that the value of Ω₀ has a very strong influence on the average value of the outer slope of the cluster density profile. Generally speaking, the lower Ω₀ is the steeper is the density profile, and this global trend can be understood in terms of the dependence on Ω₀ of the amount of material ‘raining’ in on the clusters at the present time.

For the individual clusters as well as for the composite cluster we have made Maximum Likelihood fits to the galaxy distribution in which we solved for position, elongation, characteristic radius, outer slope and background (see Adami et al. 1998). In view of the preference for profiles with cores we have fitted King profiles with a generalized 2-D outer slope, β₂D as follows:

$$\Sigma(r) = \Sigma_0 \left(1 + \left(r/r_c\right)^2\right)^{-\beta_2D}$$

From these fits to the data we find an average value $\beta_{2D} = 1.02 \pm 0.08$. Using the relation $\beta_{2D} = \beta_{3D} - 0.5$ we have been able to compare our observations with
average values of $\beta_{3D}$ from numerical models for various cosmological scenarios. The result is shown in Fig. 1. For a detailed description of the codes used to identify the scenarios, we refer to Adami et al. (1998). Here we only summarize the main conclusion of this comparison, which is that only the models with $\Omega_0$ of at most a few tenths produce values of $\beta_{2D}$ that are within the range allowed by the observations (note that direct estimates of $\Omega_0$ through $M/L$-ratios of clusters give similar values). Although not all possible scenarios have been included in the comparison, this conclusion seems to be rather robust; there even seems to be an indication that in general models with low $\Omega_0$, but with a flat geometry (i.e. with $\Omega_\Lambda \neq 0$) do not do a good job.

5. The Fundamental Plane of Early-type Galaxies in ENACS clusters

As is well-known, the Fundamental Plane (hereafter FP) of early-type galaxies is the relation between the two photometric parameters, $r_e$ and $\mu_e$, which describe the structure and luminosity of a galaxy, and the central velocity dispersion due to the motions of the stars in the galaxy. It was first studied by Dressler et al. (1987) and Djorgovsky and Davis (1987). If light traced mass, and if all early-type galaxies had the same (phase-space) structure, this relation should simply reflect the virial equilibrium of the systems. However, there are indications that the $M/L$-ratio of galaxies increases somewhat with increasing luminosity, while there may be differences in phase-space structure between different galaxies.
Nevertheless, Jörgensen et al. (1996) find that the early-type galaxies in the Coma cluster define a very narrow FP, and that the FP’s of various local clusters are consistent with the assumption of a universal FP, although this conclusion is not very strong in view of the sometimes rather limited statistics. Recently, the FP’s in 4 clusters at different redshifts out to $z = 0.58$ were shown to be consistent with a universal FP, with a redshift dependence that is consistent with passive luminosity evolution of the early-type galaxies (Kelson et al, 1997). Although all evidence thus seems consistent with the assumption of a universal FP, we have embarked on a study of the FP’s in about 20 rich, nearby ENACS clusters.

The photometric parameters that are required for the determination of the FP are obtained through CCD-imaging with the Dutch 0.92-cm telescope at La Silla. At present, close to 1500 images have been obtained, about 850 of which are of early-type galaxies. The velocity dispersions are derived from the ENACS spectra, calibrated with long-slit observations. Preliminary results appear to indicate that, when properly analyzed, the ENACS spectra can yield reliable estimates of the internal velocity dispersions for about half of the galaxies in the ENACS catalogue. In Fig. 7 we show the provisional results for three ENACS clusters and the Coma cluster (lower right). It is clearly too early to reach firm conclusions, but there may be an indication that there are differences between the various FP’s, either in orientation of the FP, its flatness or the dispersion around it.
6. Conclusions

We have summarized the main characteristics of the ESO Nearby Abell Cluster Survey (the ENACS), and described some of the recent results obtained from it. The ENACS defines, in combination with literature data, a volume-limited sample of $R_{500} \geq 1$ clusters, with good redshift and magnitude data. We have used the ENACS spectra to estimate the morphological type of the galaxies. Using these spectral 'morphological' types, we studied the distribution of early- and late-type galaxies in clusters. The late-type galaxies appear to be less centrally concentrated than the early-type galaxies, and in particular the late-type galaxies with emission lines in their spectra appear to avoid the central regions. Using COSMOS data for a subset of regular ENACS clusters we have studied the projected galaxy distribution, and we find no evidence for the cusp that is expected from the Navarro, Frenk and White density profile. The outer slope of the projected galaxy distribution seems to indicate a fairly low value of $\Omega_0$. Finally, we show some preliminary results on the universality of the Fundamental Plane of early-type galaxies in clusters.

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References

Abell, G.O., Corwin, H.G., Olowin, R.P. 1989, ApJS, 70, 1
Adami, C., Mazure, A., Katgert, P., Biviano, A. 1998, A&A, 336, 63
Biviano, A., Katgert, P., Mazure, A., Moles, M. et al. 1997, A&A, 321, 84
Cappi, A., Zamorani, G., Zucca, E., Vettolani, G. et al. 1998, A&A, 336, 445
Crone, M.M., Evrard, A.E., Richstone, D.O. 1994, ApJ, 434, 402
Djorgovsky, S., Davis, M. 1987, ApJ, 313, 59
Dressler, A. 1980a, ApJ, 236, 351
Dressler, A. 1980b, ApJS, 42, 565
Dressler, A., Lynden-Bell, D. Burstein, D. et al. 1987, ApJ, 313, 42
Jing, Y.P., Mo, H.J., Börner, G., Fang, L.Z. 1995, MNRAS, 276, 417
Jörgensen, I., Franx, M., Kjaergaard, P. 1996, MNRAS, 280, 167
Katgert, P., Mazure, A., Perea, J., den Hartog, R. et al. 1996, A&A, 310, 8
Katgert, P., Mazure, A., den Hartog, R. et al. 1998, A&AS, 129, 399
Kelson, D.D., van Dokkum, P.G., Franx, M. et al. 1997, ApJ, 478, L13
Kneib, J.-P., Mellier, Y., Fort, B., Mathez, G. 1993, A&A, 273, 370
Mazure, A., Katgert, P., den Hartog, R., Biviano, A. et al. 1996, A&A, 310, 31
Navarro, J.F., Frenk, C.S., White, S.D.M. 1997, ApJ, 490, 493
de Theije, P.A.M., Katgert, P. 1998, A&A (in press)