Section B

Building clusters

https://doi.org/10.1017/S1743921304000377 Published online by Cambridge University Press

Outskirts of Galaxy Clusters: Intense Life in the Suburbs
Proceedings IAU Colloquium No. 195, 2004
A. Diaferio, ed.

DOI: 10.1017/S1743921304000377

The state of wide-field surveys and their contributions to the study of cluster peripheries

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Abstract. The last decade has seen an explosion in the number and scope of wide-field surveys. The data provided by these surveys will greatly increase our understanding of the relationships between the outskirts and the cluster centers and the field. I summarize the status of current deep-wide optical surveys and describe the plans for the next generations of surveys, with particular emphasis on the applications of these surveys to weak gravitational lensing. As a concrete example of such a survey, I will present results from the Deep Lens Survey (DLS).

1. Introduction

The last ten years have seen an explosion in the depth and breadth of imaging, comparable in terms of the increase in number of objects detected to the effect of the introduction of photographic film at the beginning of the last century. This huge advance has been driven largely by the availabilty of large format CCDs, and, most importantly, of CCD Mosaics (Wittman *et al.* 1998, Starr *et al.* 2000; Wolfe *et al.* 1998). The effect of this explosion has been to change our perception of what a deep imaging survey is. Just as the 2400 redshifts of the original Cfa Survey (Davis *et al.* 1982) now represent a night's work for the large multi-object spectrographs, so too the scope of the surveys today has changed. Up to now, we have surveyed nearly 1/2 of the sky to $R \sim 23$, about 250 square degrees to $R \sim 24.5$, and about 80 square degrees to $R > 26$. The next generation of surveys underway, and especially the dedicated survey missions proposed for the next decade will image the entire sky $R \sim 28$.

With the explosion of available data the types of problems that can be addressed has also expanded. For example, we can now map the distribution of galaxies and of mass (via gravitational lensing) out to angular distances of almost $30'$ from the cluster center. This corresponds to about 3.5 Mpc for a $z = 0.1$ cluster in the currently favored cosmological models (Spergel *et al.* 2003). (Throughout the paper I will assume a cosmological model with $h = 0.71$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$.)

2. Wide-field surveys – current status

The primary distinguishing characteristics of wide field imaging surveys are sky coverage, depth, and spectral coverage (or number of filters). Sky coverage is critical both for obtaining large enough samples of objects (for example clusters), and for overcoming cosmic variance. For large and/or nearby objects, sky coverage also ensures that objects are fully sampled. Depth is essential for source density and the detection of high redshift (and thus primarily faint) objects. Surveys seeking to study properties over a wide range of redshifts obviously require depth, and this is also critical for gravitational lensing (§ 4). Spectral coverage is essential for determining properties of the objects detected,

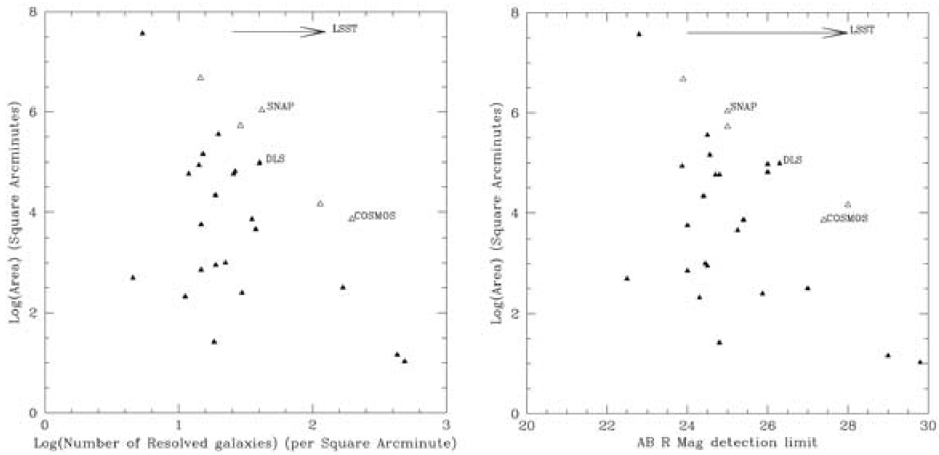

Figure 1. Left: the area coverage versus surface density of resolved objects, the relevant statistic for weak gravitational lensing studies. Right: the area coverage versus photometric depth for a selection of completed, ongoing and future survey projects (adapted from Jannuzi 1999).

and as a way of estimating redshifts for objects too faint or too numerous to pursue spectroscopically.

Because the available telescope time is (still!) not infinite, different survey projects have chosen to emphasize different aspects of this. This can be summarized by Figure 1, right panel, (adapted and expanded from Jannuzi 1999), which plots area coverage versus limiting magnitude in some photometric band for a large selection of current and future surveys, thus probing two of the three dimensions of (size, depth, spectral coverage) parameter space. Note the empty region on the top right–this corresponds to the part of parameter space that is currently inaccessible due to the finite amount of photon-collecting power available. Despite the fact that this is the standard way to describe these surveys, plotting area versus magnitude can be misleading. A better way to plot the choices made by the surveys is to plot area coverage versus surface density of objects (galaxies, resolved galaxies, QSO, etc.), where the nature of the object depends on the goal of the survey. For example, if the aim of a hypothetical survey were to study angular clustering on a variety of scales, the relevant quantities would be number density of galaxies and area. For the detection of weak lensing shear the relevant quantities are the area and the number density of resolved galaxies, which depends on the depth *and* the image quality (and on the filter). A survey studying 3-d clustering would add some measure of redshift-space resolution. In Figure 1, left panel, an estimate of the source density for weak gravitational lensing is given in place of the limiting magnitude. This folds in information about the depth, resolution and filter choice of the survey. As might be expected, space-based surveys such as SNAP (Rhodes *et al.* 2003) or COSMOS (Scoville 2004) fare comparatively better by this metric.

In general, surveys have either aimed to be wide but shallow (e.g. SDSS York *et al.* 2000), or ultra-deep (HDF N+S Williams *et al.* 1996, 1998, UDF Beckwith 2004). Another popular strategy, adopted by the CFHTLS (CFHT, 2004), attempts to combine strategies by having a nested scheme in which large areas are covered to a more shallow depth, with a smaller internal region covered to great depth. The strategy is largely driven by the scientific results desired. For example, the HDF images tell us (almost) nothing about the distribution of matter at $z < 0.1$. Similarly, the source density of

https://doi.org/10.1017/S1743921304000377 Published online by Cambridge University Press

resolved galaxies at $z > 2$ in the SDSS is too low to yield any interesting results. Future missions such as LSST (Tyson *et al.* 2002) and perhaps the VST will image all the visible sky multiple times, building up depth (and thus source density) incrementally.

3. Clusters science from surveys

Wide-field surveys (almost without exception) do not target areas of the sky because of the presence of clusters of galaxies. Indeed, at the lowest redshifts, most of the deeper wide-field surveys are biased against large structures– nobody wants Virgo Cluster galaxies blocking the view of more distant objects! Instead, the power of the wide-field imaging surveys comes about because the clusters extracted from the survey are a truly representative sample down close to the selection limits (whether they be in redshift, photometry or even source density) of the survey. In this situation, one of the most fundamental result from a survey is simply the number density per comoving volume of clusters. However, the problem remains of detecting the clusters in a complete and unbiased way.

3.1. *Photometric methods*

In the absence of spectroscopic redshift information, surveys have moved to photometric techniques such as the red sequence (Yee *et al.* 1999) or photometric redshifts to obtain three dimensional information about the distribution of matter. These methods have been very successful in isolating clusters of galaxies. Other surveys, such as the Las Campanas Distant Galaxy Cluster Survey (LCDGCC) (Gonzalez *et al.* 2000) have used surface brightness fluctuations to detect clusters of galaxies efficiently using less observing time than would have been required to detect the individual galaxies (Dalcanton 1996).

3.2. *Weak lensing*

Today, several surveys are underway that seek to use gravitational lensing shear to detect clusters of galaxies (for example DLS Wittman *et al.* 2002, the CFHTLS surveys, and Suprime33 Miyazaka *et al.* 2003). In addition, several other surveys (RCS Yee *et al.* 1999, NDWFS Jannuzi 1999), although not specifically designed with gravitational lensing in mind, are using gravitational lensing measurements to supplement or complement photometric searches.

Weak gravitational lensing relies on measuring the small induced ellipticities in the shapes of background galaxies due to foreground masses. The basic result (Kaiser & Squires 1993) is that the surface density Σ at any point divided by the critical surface density Σ_{crit} (denoted by κ) is derived by the weighted average of the tangential ellipticity e_t (corrected for PSF smearing) of the background galaxies, where the weight function is approximately $1/r^2$ (but deviates for small r to avoid noise divergences). Therefore, by measuring the shapes and sizes of background galaxies (and hence e_t), we can obtain an estimate of κ.

Compared to photometric techniques, weak lensing has the great advantage of not being baryon-biased. In particular, the detectability of a mass clump via weak lensing does not depend on the number of luminosity function of galaxies in the clump. This opens up the possibility of testing whether the photometric techniques are biased. Indeed, if "dark clusters" exist, as is periodically proposed (e.g. Erben *et al.* 2000), weak lensing might well be the only technique that will reveal them.

Another advantage of weak gravitational lensing is that the current generation of surveys can routinely measure shear values of about 0.005. For realistic clusters, this means detecting the mass out to 2.5-3 h^{-1} Mpc, far beyond the radius where the X-ray emission has fallen below background and the galaxy overdensity has become

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undetectable. Thus, weak lensing is one of the best techniques for measuring how the mass in the outskirts of clusters merges into the large-scale structure distribution.

However, for all the advantages, weak shear lensing does suffer from some serious limitations. One of the most fundamental is that because the measurement depends on shape measurements for galaxies far behind the cluster, the photometric depth (and thus the exposure time) required to detect a typical cluster is significantly greater than for photometric methods. Furthermore, because the information content of each background galaxy is small, weak gravitational lensing necessarily produces a smoothed estimate of the mass distribution. This makes small-scale substructure very hard to map out. In fact, the problem is compounded for the study of the outskirts of clusters, because the effective resolution that can be supported depends on the strength of the lensing signal. Because the shear decreases by a factor of almost 100 from the inner regions of the cluster to the outskirts, the resolution of mass mapping will suffer consequently.

Finally, as pointed out by White *et al.* (2002), weak gravitational lensing suffers significantly from superpositions. Because the window function $D_{LS}/D_L D_S$ for gravitational lensing is not a steep function of the cluster redshift for a given source redshift, galaxies of a given redshift z_s "feel" the effects of a broad range of lens redshifts z_l. This means that unrelated clusters aligned along the line of sight will be detected as if they were one cluster with $M \lesssim M_1 + M_2$. Furthermore, because the large scale structure is filamentary, there will be a contribution to the mass of clusters from filaments aligned along the line of sight, a contribution that cannot be separated from the mass of the cluster itself. Because the contrast between the filament contribution and the cluster contribution scales as the cluster mass, this is expected to be an ever-increasing problem as we work our way down the cluster mass function.

4. Mass clustering in the Deep Lens Survey

4.1. *Survey description*

The Deep Lens Survey (Wittman *et al.* 2002, see also http://dls.het.brown.edu) is a 5 year project (now in its fifth year) that is using the NOAO Mosaic I and II cameras on the 4m telescopes on Kitt Peak and Cerro Tololo to image 24 square degrees of the sky in B, V, R, z′. Total exposure times are 18000 s in R, and 12000s each in each of the three other bands. However, because of the gaps in the CCD Mosaics, and the fact that the regions we seek to image (subfields) are $40'$ by $40'$ compared to a single exposure footprint of $36'$ by $36'$, the effective depth of any part of the survey is only about 14500s in R, and about 10000s in the other bands. This results in a 1σ surface brightness limit in R of 28.7 magnitudes per square arcsecond. In terms of source density, this implies roughly 45 resolved sources per square arcminute.

The individual exposures are kept to 600 seconds (900 in R) in order to avoid too high a sky background and to provide temporal coverage (for the transient object part of the DLS survey Becker *et al.* 2003, 2004). Exposures are typically taken in a sequence of 5 dithered pointings, offset to provide complete coverage through the gaps and also some ovelap with neighboring subfields. Image-to-image differences yield fast-time transients (asteroids, NEOs, bursters and flare stars). Night-to-night, month-to-month, or year-to-year differences yield catalogs of Supernovae, variable stars and AGN. We have made strong efforts to produce subfields of even image quality–when the seeing is better than $0.9''$ we observe in R, with the result that the entire R-band dataset is nearly uniform in image quality. This is very important for weak lensing because the number density of usable sources (as opposed to detected sources) depends quite strongly on the seeing in

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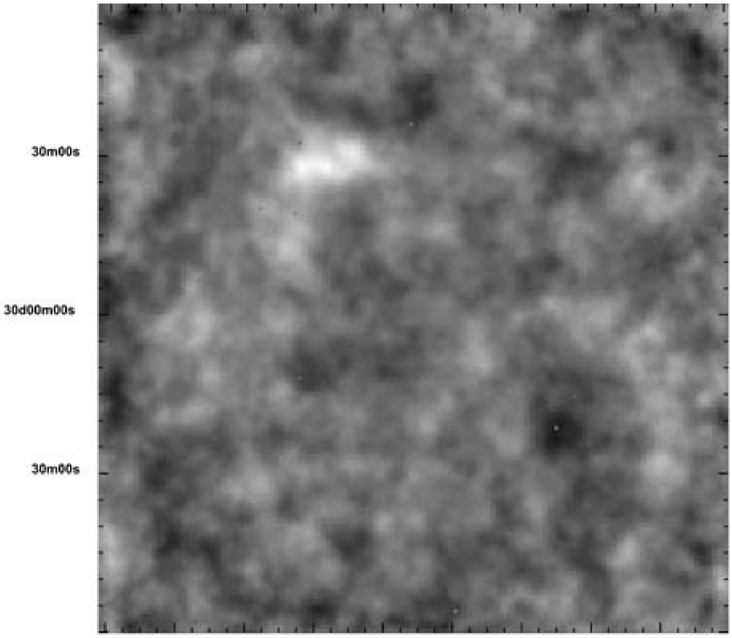

Figure 2. A map of the surface mass density κ for a 4-square degree region of the sky. Light regions represent regions of high surface mass density, dark regions are regions of low surface mass density.

this seeing/depth range. Therefore, non-uniformities in both the photometric depth and image quality result in non-uniformities in the mass sensitivity.

The shape and photometric properties of each individual exposure are calculated based on the properties of the unsaturated stars in the images. The typical density of stars in the images is 100/pointing, or roughly 300 per square degree. After the usual processing, all the images of a given subfield/filter combination are stacked, with each image being simultaneously convolved with a spatially varying circularizing kernel which makes the images of stars round.

4.2. *Lensing results*

Figure 2 shows the mass distribution in the first 2x2 degree field completed by the DLS. About 7×10^5 galaxies were used for this image, which has an effective resolution of about $2'$ by $2'$. The higest-mass concentrations in this region are being followed up spectroscopically with Gemini and through X-ray measurements. To date, we have had Chandra/XMM followup of 10 clusters.

The most obvious set of mass clumps in the image correspond to a known object, Abell 781 ($z = 0.29$). The cluster is morphologically very complex, with two other large mass subclumps in addition to the previously identified A781 core (these subclumps are also traced, albeit less strongly, by the galaxy density). Chandra imaging of the cluster (Hughes *et al.* 2004) shows the same three clumps in the X-rays. However, the M/L_x ratio differs considerably in each clump. The azimuthally averaged ellipticity induced by A781 can be traced out to $r \sim 20'$ from the cluster center, corresponding to a distance of 5 Mpc for our assumed cosmology. In addition to detailed studies of previously known clusters, the DLS has been uncovering new clusters. For example we (Wittman *et al.* 2003) recently discovered a cluster (CL1055-0348) (Figure 3) and estimated its redshift

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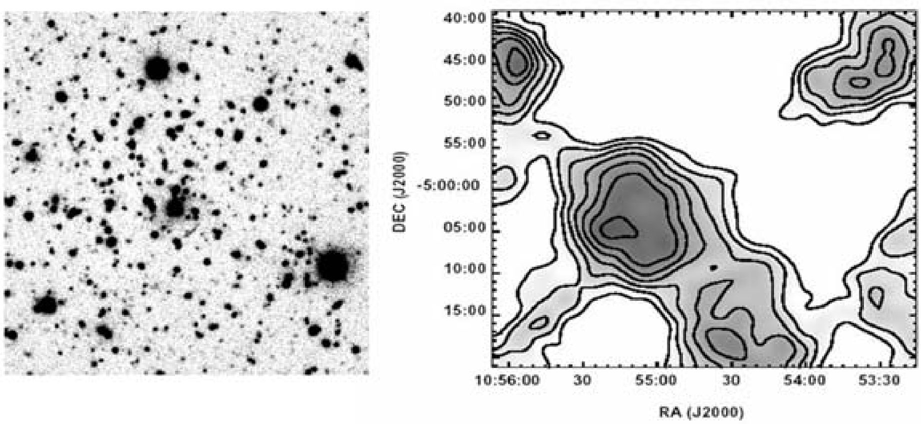

Figure 3. Left: the central region of CL1055-0503. A candidate arc can be seen below and to the right of the central galaxy. Right: The weak lensing map of that portion of the field–the higest peak corresponds to the CL1055-0503.

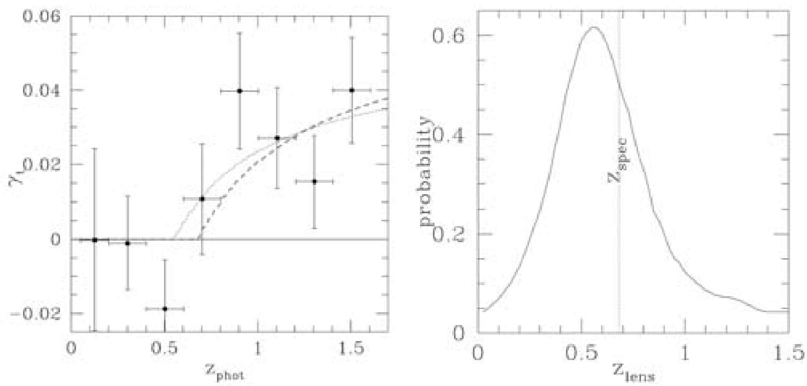

Figure 4. Left: the mean tangential shear for background galaxies as a function of their photometric redshift. Right: the probability distribution for the lens redshift as determined from the data from the left-hand plot (From Wittman *et al.* 2003).

solely from the weak lensing data combined with the photometric redshift estimates of the background galaxies (Figure 4). Spectroscopic follow-up with Keck confirmed the predicted redshift $z = 0.68$, demonstrating the power of weak lensing and photometric redshifts combined to reveal the three-dimensional distribution of mass in the Universe.

5. Conclusions and future developments

Wide-field surveys are providing unique data for the study of clusters of galaxies and their environment. As the depth to which these surveys reach has increased, the redshift range over which clusters can be detected has grown, allowing the study of the mass function of clusters and its evolution to be probed. In particular, the growth of weak gravitational shear as a way of detecting and measuring clusters is providing a clear look at the mass distribution of clusters and its evolution, one that is unbiased with respect to baryons (and, at least for the upper end of the mass-function), relatively insensitive to the large-scale structure distribution. Surveys such as the DLS and others have mapped around 0.1 percent of the sky. The next generation of instruments will provide all-sky maps at comparable (or greater) depth.

A whole host of wide-field surveys are in the different stages of development. Over the next five years we will see the large CFHTLS survey programs and the VST on Cerro Paranal, as well as VISTA in the NIR. On longer timescales, LSST, PanSTARRS and SNAP promise to provide deep information over the whole sky.

Acknowledgements

I would like to acknowledge my collaborators on the DLS– my co-PIs Tony Tyson and Dave Wittman, and also Vera Margoniner, Andy Becker, Dinesh Loomba, Gillian Wilson, Dara Norman, Jack Hughes, Jeff Kubo and Hossein Khiabanian. This work has been partially supported by NSF grant AST-0134753.

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