A Deep UBVRI Imaging Survey with the WFC

Gavin Dalton

Katherine Blundell, Enrique Gaztañaga[1], Julia Kennefick, Mark Lacy, Lance Miller, Steve Rawlings, Prasenjit Saha, Will Sutherland, Helen Tadros

University of Oxford
Nuclear and Astrophysics Laboratory
Keble Road, Oxford, OX1 3RH
Tel: +44 1865 273310(GD)
Fax: +44 1865 273390

Summary

We propose to survey four contiguous regions of 10 deg^2 each in broad band BVRI filters to a limiting depth of $B = 26$, $I = 24.5(5\sigma)$. The primary scientific goals of the survey are the evolution of galaxy clustering as a function of colour at faint magnitudes, a well-defined catalogue of rich galaxy clusters at intermediate redshifts, and the detection of a significant number of quasars with $z > 5$. We propose to make use of the small fraction of the required survey time which is likely to have very good seeing conditions to observe two sub-areas of 5 deg^2 each to $U = 26(3\sigma)$ to investigate the large-scale clustering of the Lyman-break galaxies at $z \gtrsim 3$ and investigate the hypothesis that these objects trace the formation sites of present day rich clusters of galaxies. The survey will provide an invaluable resource for the new generation of 8m class telescopes.

Target Fields

$\alpha(2000)$	$\delta(2000)$	l	b	N(H) (10^{20}/cm^2)	Area	Notes
02^h11	$-04°00$	165	-60	2.5	10 deg^2	SGH
08^h45	$+44°00$	177	38	1.5	10 deg^2	ASCA Deep/6C**
21^h42	$-04°00$	51	39	3.2	10 deg^2	SGH, SA113
13^h35	$+37°50$	85	76	1.0	10 deg^2	UK Deep ROSAT/FIRST/6C**
14^h30	$+00°00$	348	53	2.4	10 deg^2	2dF Deep Survey/WIRE
15^h36	$+34°00$	54	54	2.3	10 deg^2	FIRST/6C**

We wish to observe fields covering 10 deg^2 in any four of the above regions (the final choice will depend on scheduling) to 5σ limits of $B = 26, V = 25.5, R = 25.25, I = 24.5$. The total exposure time per pointing will be 3.5 hours, and so the total time requirement for the BVRI survey is 28 nights, which we propose to spread over a two year observing period. In the periods which experience the best seeing conditions at the telescope we will survey sub-regions of two of these fields to give a total of 10 deg^2 to a 3σ limit of $U = 26$ for exposure times of 6500s per pointing, requiring an additional 4 nights. The total time requested is therefore **32** dark nights, or 4.5 weeks, which we would aim to spread over the next four semesters.

The above list of fields has been selected for a combination of accessibility, low extinction, and overlaps with existing data as shown in the final column. All fields overlap with the NVSS radio survey. The 2dF Survey field and the SGP fields are accessible to LDSS++ on the AAT, and to Gemini South. Other target fields meeting the same criteria could also be considered.

[1]Also, IEE de Catalunya, CSIC, Barcelona

Scientific Justification

Background: We propose a wide field multicolour survey to address four main topics in cosmology. Each of these topics requires a deep survey with a large areal coverage, the overall strategy is dictated by the need to investigate the large scale clustering of the different populations of faint galaxies, as this project alone requires that the survey be composed of a small number of large contiguous fields. The minimum size of the survey is dictated by the predicted statistics of high redshift QSOs at our proposed detection limits.

Angular Clustering of Galaxies: Most faint CCD surveys to date have concentrated on small areas of sky ($\lesssim 0.1$ deg^2 at $B \sim 24$)[1], or have been restricted to a single colour. Fainter surveys (e.g. ref [2]) have been limited to correspondingly smaller angles. The observation that the bluest galaxies detected in the photographic survey of ref. [3] are strongly clustered has been supported by our own analysis of a pilot study using the Tek chip at the INT[4](Fig 1), but these data do not cover a large enough area to yield information on the break scale in $w(\theta)$ at these magnitudes. By allowing for large overlaps between individual pointings in our survey we aim to restrict uncertainties in the individual zero points of the CCD frames to $\lesssim 0.01$ mag (corresponding to uncertainties in $w(\theta)$ of $\sim 10^{-4}$)[5], which should allow us to determine the shape of $w(\theta)$ out to $z \lesssim 1$. (At $B = 26$ we expect $w(30'') = 0.05$, and hence $w(1^\circ) = 5\times10^{-4}$)[1]. In terms of angular scales this implies that we should require contiguous regions of our survey to be ~ 10 deg^2 which will allow fair sampling of 30–40h^{-1}Mpc physical scales. We will also use our survey data to investigate the evolution of the 3-point function which will allow us to constrain the evolution of galaxy bias and deviations from Gaussian initial conditions[6].

$z > 5$ **Quasars:** Extrapolating the QSO luminosity function to $5 < z < 6$ predicts between 1 and 20 QSOs to $I < 22$ over 40 deg^2 of sky[7,8], indicating that this is the *minimum* required size of a survey that will be able to distinguish at the 5σ level between model luminosity functions that agree well at $z = 4$. As well as placing restrictions on models for the formation of massive galaxies at high redshifts, the detection of these objects will constrain the ionizing UV background at high redshifts. The hierarchical nature of galaxy clustering also implies that these objects will provide locations of candidates for less massive objects at similar redshifts[9]. Simulations indicate that a colour selection of $V - I > 3.5$ rejects all stars earlier than type M5V while including 80% of simulated $5 < z < 6$ QSOs (Fig 2). Contaminant elliptical galaxies with $0.9 < z < 1.3$ are expected to have $V - I \lesssim 3.9$, but are expected to be resolved.

Galaxy Clusters at $z \lesssim 1$**:** The APM Cluster Survey[10] covers an area of 4200 sq. deg. and contains ~ 1000 clusters with $z < 0.2$. The largest well-defined sample of rich clusters at higher redshifts is the Palomar Deep Cluster Survey[11], which contains ~ 20 rich clusters with $z \gtrsim 0.6$ which have been detected using an extension of the analysis used in our own survey[12]. By extending our analysis to the proposed survey we expect to detect ~ 1000 clusters with $z \lesssim 1$. Clusters of galaxies provide a tracer of large-scale structure independent of the complex physics of galaxy formation[13], and hence this sample will allow us to differentiate between the evolution of the large-scale structure and the evolution of the galaxy biasing mechanism.

Clusters at $z \sim 3$**:** The clustering properties of high-z galaxies are an important diagnostic of biassed galaxy formation models. We intend to investigate the clustering of the Lyman-limit galaxy population discovered by Steidel & co-workers[14]. With a survey of 5 deg^2 to $U \sim 26$ we expect that we will detect $\gtrsim 500$, $z \approx 3$–4 galaxies which we will use to measure the two-point correlation function. Studies of these objects in small fields[14] have indicated that these objects are highly clustered, and therefore associated with a high value of the bias parameter, but with a wide-field survey we will be able to determine the correlation function on much larger angular scales. Comparison of these data with the clustering properties of our $z \lesssim 1$ cluster survey will allow us to make a direct observational test of the prediction that the Lyman-break galaxies occur only in the most massive dark halos at high redshifts which have evolved into galaxy clusters by the present.

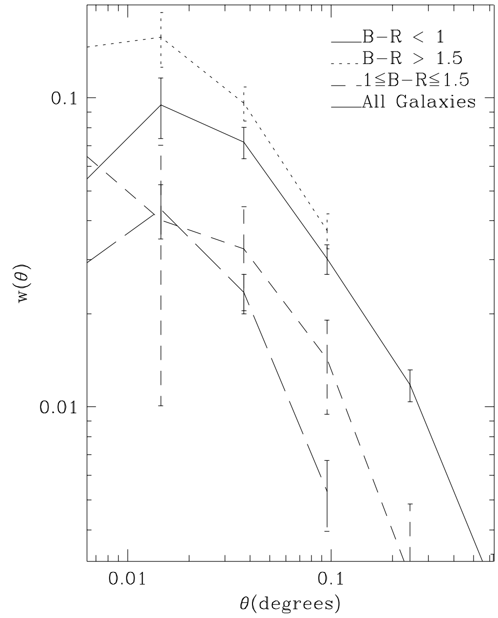

Figure 1: The angular correlation functions for colour selected subsamples of galaxies at $B \sim 24$ from a mosaic of 100 INT Tek pointings. The solid line confirms the result of ref[3] that the bluest galaxies (which correspond to the excess number counts) show clustering comparable to the old population of cluster galaxies (dotted line).

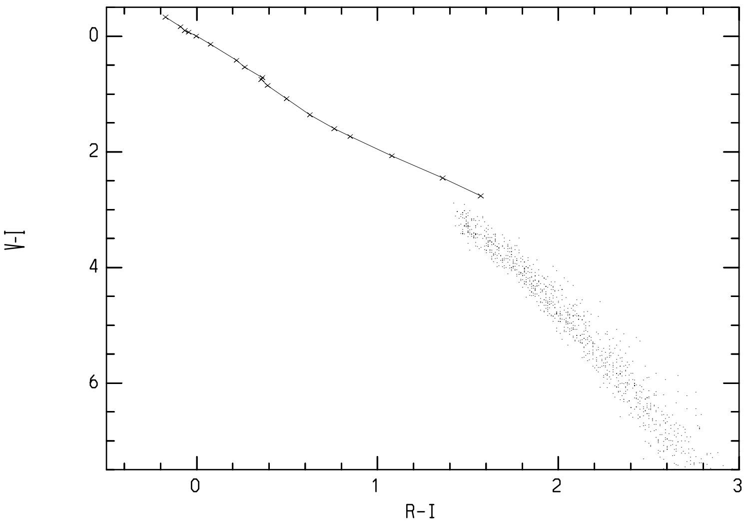

Figure 2: $V-I/R-I$ diagram showing the location of the expected main sequence, $O5V-M5V$ (crossed line). The points show the location of 1000 simulated quasars with $5.05 < z < 6.15$, (100 in each $\Delta z = 0.1$). A cut of $V-I > 3.5$ selects 100% of quasars with $z > 5.3$

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Technical Feasibility and Time Budget

Required limiting magnitudes: By $B \sim 25.5$ the median colour of galaxies has shifted[2] to $B-R \sim 1.5$. Measurements of galaxy clustering over four 10 deg^2 regions will give four independent survey volumes each containing $\gtrsim 10^6$ galaxies, i.e. each will be comparable to the APM Galaxy Survey, but sampling the Universe out to $z \sim 1$.

Exposure Times: Using the ING `signal` program, we obtain the following exposure times for stellar objects or faint galaxies, assuming the median INT seeing of $1''$, and a detection threshold of $5(10)\sigma$:$B = 26(25.25), 2600s$, $V = 25.5(24.75), 3000s$, $R = 25.25(24.5), 3600s$, and $I = 24.5(23.75), 3300s$. For $1.5''$ seeing the 5σ exposure times effectively become 3σ exposure times. For grey moon the R and I thresholds drop to 3σ and 4σ, respectively, with time penalties of an additional $3600s(R)$ or $1700s(I)$ to recover the original 5σ thresholds at these faint limits. In better seeing conditions we would reach these detection thresholds in less time, but we prefer to calculate exposure times for the most likely case. Our U-band override program should make optimal use of the best conditions (see below). Allowing for readout time, these numbers imply a total of 3.5 hours per pointing, or a sky coverage rate of ~ 1.5 deg^2 per typical La Palma night. The total time required to complete the survey is therefore expected to be four dark weeks, with a maximum tolerable grey incursion of $\lesssim 1$ week, which we would aim to spread over a two year period.

Override Program: For a small fraction of the observing time we expect the seeing to be significantly better than the median expected INT seeing of $1''$. For typical galaxy sizes at low redshifts the image sizes are unlikely to fall below $1''$, whereas the typical sizes of the Lyman-break galaxies are known from deep HST images $\sim 0.2''$, and so in seeing of $0.7''$ we expect to obtain 3σ detections to a limiting U magnitude of $U = 26$ in $6500s$, implying that we can achieve a coverage rate of 2.5 deg^2 for the best seeing. We therefore propose to cover the central regions of two of our survey fields to $U = 26$ to give two regions of 5 deg^2 which we will use to identify U-dropout galaxies for a study of the evolution of clustering pattern at $z \sim 3$. By adopting this program as a good seeing override we can achieve this additional goal by extending our survey by an additional 4 nights, or by trading 4 nights ($= 6$ deg^2) of or primary survey. To realise this fraction of high quality seeing we would prefer to restrict our total allocation to dark time only. For comparison purposes only we note that to obtain these detections in more typical seeing would require a doubling of the exposure times, or 8 nights of additional time for this part of the project.

Sampling Geometry: Given the camera geometry of $4096 \times 2048 \times 4$, each pointing covers 0.27 deg^2 (assuming $0.33''$ pixels). By allowing each pointing within a contiguous area to overlap with its neighbour by $1'$ we reduce the effective area of each pointing to 0.26 deg^2, but this strategy gives ~ 300 galaxies in each of the short overlaps and ~ 600 galaxies in each of the long overlaps which translates to an uncertainty in the zero-point of each CCD frame of ~ 0.005 mag. In addition to twilight sky flats we will obtain deep sky flatfield images by dithering individual exposures within a pointing by several arcseconds which will also ensure good sampling of each object by different pixels. The camera geometry implies that we will be left with small holes in our contiguous regions, but these should be unimportant as they will be uncorrelated with the structures we are trying to measure.

Calibration Frames: One of the advantages of surveying contiguous fields is that we are able to use the field overlaps to cross-calibrate those frames which are obtained in non-photometric conditions. On photometric nights we will observe Landolt calibration stars in each of the bands we are observing on that night, although we will aim to window the chips to include as many standard stars as possible while minimising the readout overheads. One of our SGH fields overlaps with Landolt's stars in SA113, so will provide a useful cross-check on our calibrations, as will extinction data from the CAMC telescope.

Analysis and Division of Science Topics

Observers: We aim to send one observer with survey experience for each observing run together with students as appropriate for their training.

Reduction and Analysis: Preliminary reductions will be performed at the telescope, so that flat-fielded data can be released to the community via the La Palma data archive. The level of flat-fielding required to investigate the angular clustering of faint galaxy populations is expected to require a more detailed treatment than is likely to be possible at the telescope, and so more detailed reductions will be performed in Oxford where considerably more computing power is available to us. Utilities for the management of large-scale survey databases are already in place given our experience with other large-survey projects (APM Galaxy Survey(GD,WS,HT), APM Cluster Survey(GD,WS,HT), IRAS-PSCZ(WS,HT), 2dF Galaxy and Quasar Surveys(GD,WS,HT,LM), 6C/7C follow-up surveys(KB,ML,SR), NVSS Survey(KB), UK Deep Rosat Surveys(GD), CTIO-BTC Survey(JK), and the MACHO Project(WS)). Object photometry will be performed using Bertin & Arnout's `Sextractor` package and the STARLINK `PISA` software. In the course of data reduction we will monitor the brighter images over individual readouts to search for variability and transients which will also form part of the final database.

Quality Control, Progress Reporting & Distribution: Image Frames which exhibit poor seeing ($\lesssim 1.4''$) will be flagged for re-observation where possible. Seeing measurements from each frame will be made public via the WWW at the same time as the raw data, and we will aim to provide a continuous update of the survey status.

Calibrated final image catalogues with astrometric solutions and star-galaxy classifiers will be made available to the ING archive. The full set of reduced data will comprise $\sim$ 120Gb as images, or $\sim$ 3Gb when reduced to parameterised images. The latter is a convenient size to make available via CDROM or an SQL-based WWW interface. The former will be require storage on DLT tape, but can be made available through the archive, or as subsets of image data in response to individual requests.

Follow Up: The division of the applicants interests among the specific projects is as follows:

1. **Galaxy Clustering to $z \sim 1$:** Dalton, Sutherland, Gaztañaga, Tadros
2. **High-z QSOs:** Kennefick, Miller, Rawlings, Blundell
3. **Galaxy Clusters:** Dalton, Tadros, Gaztañaga, Sutherland, Saha
4. **Lyman limit systems:** Lacy, Rawlings, Kennefick, Blundell

The addition of a 5th colour to the fields in the good-seeing override will allow the estimation of coarse photometric redshifts using the techniques of Connolly *et al.* which we will use as a constraint in our analysis of the galaxy clustering evolution.

Spectroscopic follow-up for these projects will be particularly suited to GMOS multislit system on Gemini and the optical/NIR fibre system (FMOS) planned for Subaru (GD is the UK project scientist), as well as through collaborative access to the Keck telescopes. Brighter objects will be followed up wth a combination of WYFFOS, 2dF, and LDSS++. Our experience from the combined 2dF galaxy/quasar survey indicates that merging the science projects at the imaging stage will lead to significant gains in terms of the telescope time required for spectroscopic follow up.