The Oxford Deep WFC Survey

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Summary. We wish to continue the Oxford WFC survey to cover our full survey area of 25 deg^2 in $BVRi'Z$ plus a subarea in U, and also to produce a second-epoch survey in $i'Z$ using bright time. The principal scientific aims are to study weak lensing by large-scale structure, the angular clustering of faint galaxies, the clustering of Lyman-break galaxies at high-redshift and to measure the faint QSO luminosity function at $z > 5$. There are a number of subsidiary projects and collaborations with other groups.

RA (2000)	dec (2000)	l	b	$E_{\mathrm{B-V}}$	Filters	obtained no.	obtained /deg^2	required no.	required /deg^2	semester
00 17 30	+34 30 00	115	-27	0.054	$BVRi'Z$	11	3.0	20	5.4	01B
					$i'Z$ 2^{nd} epoch	0	0.0	31	8.4	02B
09 09 45	+40 50 00	181	+42	0.017	$BVRi'Z$	14	3.8	17	4.6	01A
					$i'Z$ 2^{nd} epoch	0	0.0	31	8.4	02A
16 39 30	+45 24 00	70	+41	0.014	$BVRi'Z$	5	1.4	26	7.0	01A
					U	1	0.3	30	8.1	01A
					$i'Z$ 2^{nd} epoch	0	0.0	31	8.4	02A

Table 1. Target fields

Band	U	B	V	R	i'	Z
Limiting magnitude	26.0	26.5	26.0	25.5	24.5	22.0
Integration time /s	6×1200	3×900	3×1000	3×1200	3×1100	1×600

Table 2. Integration times.

Scientific Justification

Introduction We wish to both complete the Oxford WFC survey and extend it with a second epoch (bright-time) survey in i' and Z. Progress on the survey up to September 2000 is presented below. The scientific rationale covers four main topics, discussed here, plus a number of subsidiary programmes which are already making use of the existing data. The survey extends to $R < 25.5$ and as such complements extremely well the wider but less deep Wide Angle Survey.

Large-scale structure from weak lensing. The mass in cosmological large-scale structures causes shear of the images of background galaxies: this "weak lensing" distortion can only be detected by statistical analysis of very large numbers of galaxies. This topic is causing much excitement because of its potential for measuring directly the matter fluctuations in the universe independently of assumptions about the distribution of luminous baryonic matter. Four groups have now reported detections of spatial variation in image shear at about the level expected from cold dark matter models[1−6], but based on data covering only $\sim 1\,\mathrm{deg}^2$. These results show the feasibility of weak lensing detection, but do not yet allow us to make an accurate determination of the cosmological parameters or the shape of the mass power spectrum. In fact, a survey such as ours, covering $25\,\mathrm{deg}^2$ to a depth of $\sim 10^5$ galaxies deg^{-2}, is needed to determine parameters such as Ω_0 to $\sim 10\%$ accuracy[7]: given our current lead in obtaining sufficient high-quality data, it is our aim to be the first consortium to publish such a determination. We also have the immense advantage of obtaining deep data in BVRI, which allows a more sensitive detection of the shear signal, but more importantly allows photometric redshift estimates to be made of the lensed galaxies, leading to greatly improved cosmological parameter estimation[8]. This aim is challenging on two grounds: although these groups have analysed datasets which are factors > 6 smaller than our existing dataset, they are accumulating new data fast (MegaCam aims to survey $100\,\mathrm{deg}^2$ eventually, for example). But also the analysis is very challenging, requiring a thorough understanding of the point-spread function and its spatial variation, as well as other shear sources such as atmospheric refraction and optics distortion, coupled with algorithms which can optimally extract an unbiased estimate of the shear signal[9−12]. We have one staff member, two postdocs and one PhD student working on this at present. Data requirements are to complete the survey of $25\,\mathrm{deg}^2$ in the three widely-separated regions in $BVRi'$: the choice of the three regions is important to minimise the cosmic variance.

$z \sim 3$ and $z \sim 4$ Galaxies. The pioneering work of Steidel et al.[13,14] has shown how galaxies at $z \sim 3$ and $z \sim 4$ can be efficiently selected from broad-band UGR and GRI colours respectively. One of the startling discoveries is that these galaxies have high rates of star formation ($\sim 10 - 100\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$) and are also strongly clustered, leading to an interpretation of these galaxies as being the progenitors of today's spheroidal galaxies in a hierarchical CDM-like universe[13]. The Steidel et al studies cover $< 1\,\mathrm{deg}^2$ to $I_{AB} < 25$ ($I < 24.4$) and our completed survey will yield a unique measurement of the Lyman-break population correlation function for $z \sim 4$ galaxies over areas large enough to minimise the uncertainties caused by cosmic variance. By completing one of the three regions in U we will be able to compare directly the clustering of $z \sim 3$ galaxies with the $z \sim 4$ population. Characterisation of the redshift distribution of the selected galaxies is important, especially at $z \sim 4$, and we aim to do this by Gemini spectroscopic follow-up of a small subset. We have one staff member and one Ph.D. student working on this project.

A photometric and variability search for $z \sim 6$ QSOs. Quasars at redshifts comparable to the highest-known-redshift galaxies are extremely rare, but recent multicolour selection from the SDSS[15] has shown that they do exist. Construction of the luminosity function of quasars at high redshift places good limits not only on models of quasar formation but also on the link to the formation of normal galaxies (e.g. [16]). We have had some success in AAT-LDSS and CTIO spectroscopic follow-up of high-z candidates fainter than those reported from SDSS, and we aim to continue this work both using photometric ($Vi'Z$) selection, and also using the multi-epoch i'-band survey to detect high-z quasars from a combination of variability and colour selection. The long-term variability of QSOs is now well-characterised[17] and we expect to detect 50 percent of QSOs by this method: given the present uncertainty in the high-redshift space density of a factor ten the selection efficiency is not the major issue. The method has the great advantage that a broader range of colours can be included, enabling a bigger range of quasar spectral types to be detected, and also allows us to probe to higher redshifts than the limit of pure photometric selection which requires Ly-α to be in or bluewards of the i'-band. If the second-epoch is successful we hope to extend the survey to further epochs. We have two staff members and one Ph.D. student working on this project.

Angular clustering of faint galaxies. The primary goal of the Oxford WFC survey was to investigate the angular clustering properties of faint galaxies as a function of colour. The critical requirement for this part of the project is that the fields be contiguous to allow substantial overlap areas between adjacent fields. This allows us to restrict the uncertainties in the individual zero points to $\lesssim 0.01$ mag, which corresponds roughly to residual uncertainties in $w(\theta)$ of $\sim 10^{-4}$)[18]. This allows determination of the shape of the angular correlation function out to redshifts $z \sim 1$ (we expect $w(1^{\circ}) = 5 \times 10^{-4}$)[19] at $Bsim26$). To measure $w(\theta)$ on these scales requires a contiguous area of $sim10$ deg^2 to allow fair sampling of 30–40h^{-1}Mpc physical scales over the redshift range of interest. Preliminary investigations using the reduced and matched data that is available to date suggest that after rejecting chips from the mosaic which suffer badly from bright stars or poor seeing, we can currently measure $w(\theta)$ out to ~ 0.2 degree scales for $25 < R < 25.5$. Once the behaviour of the two-point correlation function is understood we plan to measure the evolution of higher order moments which give information on the evolution of galaxy bias and deviations from Gaussian initial conditions. We have one staff member and one PhD student working on this.

Other projects are currently in hand with the existing dataset. These would all benefit from larger datasets, but do not form the main part of the current case. We include here a summary of the progress to date on these programmes. **Extremely Red Galaxies.** We are using infrared K-band follow-up to select extremely red objects, $R-K > 6$. To date, 2.5 deg^2 have been surveyed to $K = 19$ with the ONIS 1024x512 InSb camera on the MDM 1.3m. (PI Wegner): this survey is continuing. It now appears that the extragalactic population of ERO's comprises dusty poststarburst galaxies such as HR10[20] and also old cluster elliptical galaxies at $z > 1$ (e.g. [21]). We have been following up EROs in our existing data with Keck and Subaru (PI Maihara) spectroscopy to search for HR10-like galaxies, and also have identified some candidate high-z clusters. The latter are particularly important as the space density of high-z clusters is one of the main tools for setting low limits ($\Omega < 0.3$) on the matter density (clusters formed relatively recently, $z < 1$, in a high-density universe). **A low-frequency radio survey.** New deep VLA observations at 74, 330 and 8000 MHz have been obtained (PI Blundell) to search for extremely steep-spectrum $z \sim 5$ radiogalaxies, complementing our parallel programmes for optical AGN. **NVSS identification.** NVSS radio sources are clustered on the sky: here our aim is to interpret the large-scale structure by quantifying the redshift distribution of the sources. This is being done with a modest amount of spectroscopy coupled with photometric redshift estimation from the WFC multicolour survey. **SCUBA follow-up.** We are currently proposing a SCUBA survey (PI Rawlings) to search for dusty star-forming galaxies at high-redshift, potentially identifiable from the joint radio-infrared-optical dataset that we have constructed. A separate group (PI Ciardullo) is using our data to interpret an extremely deep **narrow-band search for high-z galaxies** and Tolstoy is using the data in a search for dwarf galaxies. We are encouraging as many groups as possible to make use of our exceptional dataset.

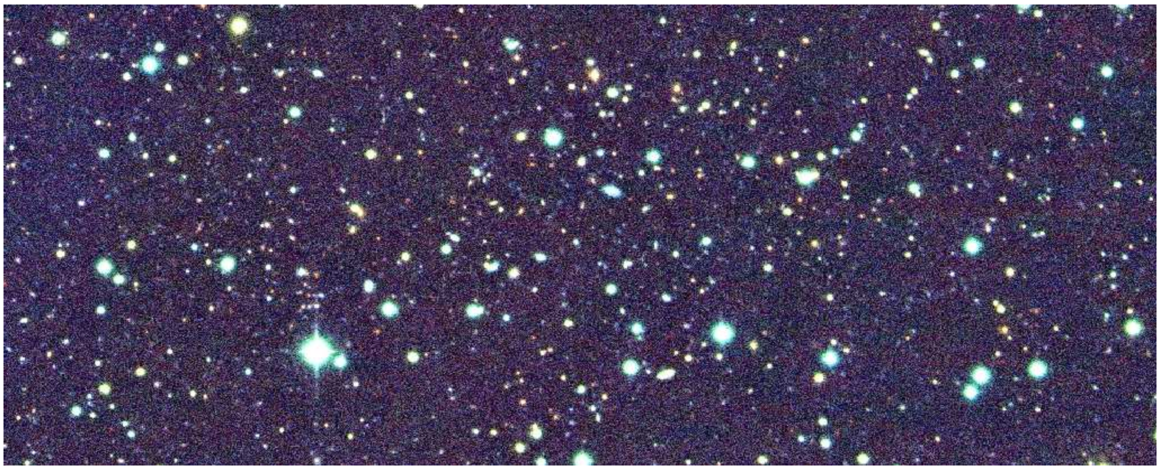

Figure 1: A sub-area of roughly 60 arcmin^2 taken from a pseudo-colour (BVR) image made up of one of the OWFC frames. The faintest objects visible in this image have $B \sim 27$. The bluest galaxies clearly exhibit a stronger clustering signal than complete B-band magnitude-limited sub-samples.

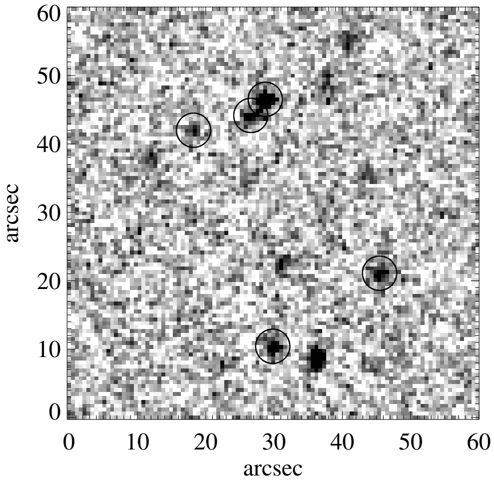

Figure 2: An example of a likely high-redshift cluster as seen in our K-band survey data. The five objects circled are all identified as EROs with $R - K > 6$. Gemini NIRSPEC service observations of this cluster were obtained in May 2000, and reveal featureless continuum spectra in K and blank spectral images in J.

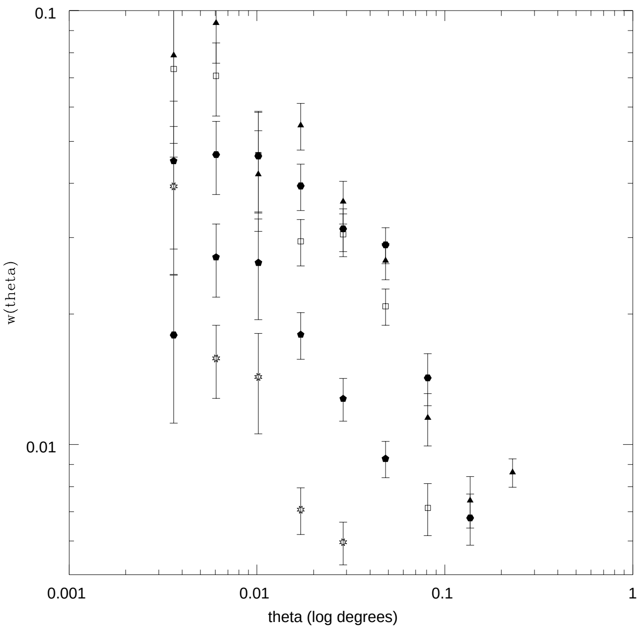

Figure 3: Preliminary results on the the angular correlation function of faint galaxies in the R magnitude ranges 23.5–24 (red triangles), 24–24.5 (blue squares), 24.5-25 (green hexagons), 25-25.5 (black pentagons), 25.5-26 (yellow stars, tentative).

Technical Description

Previous data from the Oxford WFC Survey. By September 2000 we have obtained deep data over $\sim 9\,\mathrm{deg}^2$ which is about one-third of our original goal. Of the 28 nights which have been used to date, 14 have been lost due to weather and instrument problems. A further week of time was allocated in 2000B starting 28/09/00. On the clear nights seeing has been in the range $0.9 - 1.3''$ with the exception of one night of poor seeing in February 1999. Coverage of the 0^h field in December 1999 was restricted by bad weather and by PATT-override M31 microlensing observations, but we hope to redress this in the September 2000 observations.

The requirement for new data. The weak lensing survey requires completion of the full $25\,\mathrm{deg}^2$ in BVRI in order to (a) obtain sufficient signal-to-noise to make accurate estimates of the the mass power-spectrum and the cosmological parameters (b) to reduce the uncertainty caused by cosmic variance (c) to allow photometric redshifts to be esimated over the entire lensing survey area. The larger area will allow accurate galaxy clustering estimates to be made at large angular scales. The high-redshift galaxy survey also requires completion of the same area in these bands, in order to significantly improve on the work of Steidel et al., which covered 10 fields, each of only $40 - 180\,\mathrm{arcmin}^2$.

We also propose a faint I and Z-band variability study which will allow selection of the highest redshift quasars independently of their colours at wavebands longwards of Ly-α even at $z \sim 6$. The space density of such quasars is expect to be so low ($0.05 - 0.5\,\mathrm{deg}^{-2}$ at $m_Z < 21$) that the full $25\,\mathrm{deg}^2$ is required. The same survey will allow photometric and proper-motion selection of the faintest stars in our Galaxy.

Feasibility. The integration times in each band quoted on page one are based directly on our existing observations. The strategy is to take multiple exposures in each band, offset by $5''$. Fields are observed in a diagonal grid pattern with the camera rotated by $180°$ for alternate strips to give complete sky coverage and overlaps between fields.

Filters. We use SDSS i' because of the lack of a red cutoff in RGO I, but Harris R for consistency as r' was not available at the time we began the survey.

Observing time needed. We require a total of 162 dark/grey hours of on-sky integration in BVR, 68 bright hours in $i'Z$ to complete the full survey once, 60 dark hours in U to cover $8.4\,\mathrm{deg}^2$, and a further 100 bright hours for the second epoch in $i'Z$. To date we have obtained 112 hours on-sky in 14 clear nights out of 28 allocated, and hence we estimate that we need a total of 4 (clear) weeks of dark/grey time plus 3 weeks of bright time. We have one further week allocated starting 28 Sept 2000, so we request here 6 weeks over four semesters: two weeks in each of 01A and 01B plus one bright week in each of 02A and 02B.

References

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Strategy

All the image analysis is done at Oxford. We currently have a substantial share of the processing power of 5 fast alpha workstations and PCs with ~ 100 Gb of dedicated disk space. We have processed all the data that has been taken to date. Gavin Dalton coordinates the project, and we have devoted a substantial part of the research effort of the observational cosmology group at Oxford to working on this project, including three current PhD students and three more due to start work on various aspects in October 2000. We also have a policy of encouraging other groups to make use of the data. The following table summarises the effort provided by the core team on this proposal.

Name	Status	Role	time spent
Gavin Dalton	Temporary lecturer	Project Leader Infrared follow-up, EROs, clustering, Highz dropouts & QSOs	30%
Steve Rawlings	Lecturer	SCUBA follow-up survey	30%
Lance Miller	Lecturer	Weak lensing	30%
Jasper Wall	Visiting Professor	radio follow-up & clustering	20%
Gary Wegner	Professor	Infrared follow-up	10%
Katherine Blundell	Royal Society U.R.F.	radio follow-up	30%
Lexi Moustakas	PDRA	EROs, photometric redshifts	50%
Bill Ballinger	PDRA	Weak lensing theory	30%
Jane Booth	PhD 1997-2000	Faint galaxy clustering	-
Ed Olding	PhD 1998-2001	EROs	100%
Chris Blake	PhD 1999-2000	radio follow-up and clustering	50%
Molly Gale	PhD 2000-2003	Galaxy Clusters	100%
Paul Allen	PhD 2000-2003	High-z dropouts and QSOs, clustering	100%
Catherine Heymans	PhD 2000-2003	weak lensing	100%