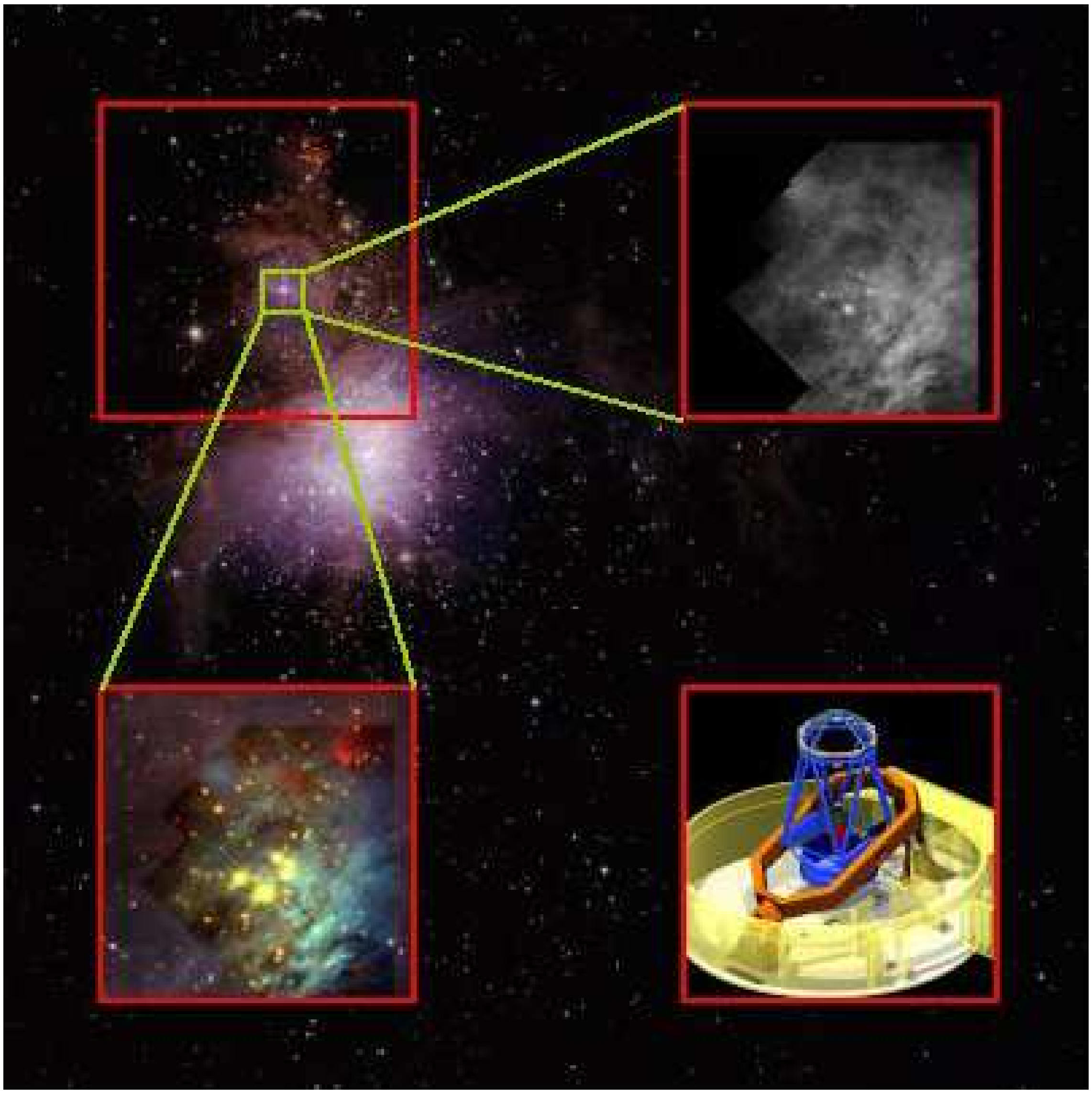
# *UKIDSS*

**The UKIRT Infrared Deep Sky Survey**



**Cover Caption:**

In the background is the 2MASS image of the Orion Nebula covering some 48 x 48 arcminutes. The red squares illustrate the WFCAM footprint (each chip covers 13.6x13.6 arcminutes, with a 90% interchip spacing). For comparison, the UFTI footprint is the small box in green centered on the Trapezium Cluster (about 1.5 x 1.5 arcmins). The zoomed images show the optical (top right) and multi-colour infrared (bottom left) HST data for the Trapezium. They illustrate that the low mass stars and brown dwarfs in the cluster are much more easily detectable in the infrared than the optical. The bottom right inset shows a model of UKIRT with WFCAM.

**Picture Credits:**

1. Background picture taken from the 2MASS image gallery (http://pegasus.phast.umass.edu/). Mosaic image construction by E. Kopan (IPAC).

2. HST images from Glen Schneider's WWW page:
(http://nicmosis.as.arizona.edu:8000/TRAPESIUM/TRAP_COLOR.html). The colour picture is a composite near infrared + visual image using WFPC2 and NICMOS data. The monochrome image is from WFPC2 and combines NII, H-alpha and CIII line imaging.

3. The solid model image comes from:
http://www.jach.hawaii.edu/JACpublic/UKIRT/public/images/telescope/ukirt_solid_assembly.gif

# *UKIDSS*

**The UKIRT Infrared Deep Sky Survey**

A proposal for a large public survey programme
using the UKIRT Wide Field Camera

Submitted by


**The UKIDSS Consortium**

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# Contents

# Chapter 1

# The UKIDSS Proposal

## Summary

We propose to undertake a large area public IR survey programme using the planned UKIRT Wide Field Camera (WFCAM). There are several components to the programme. (i) A high latitude survey covering 4000□° of the SDSS survey region to a depth K=18.4. (ii) An atlas of the Milky Way to a depth K=19. (iii) A survey of large area nearby open clusters and star formation regions to K=18.8, covering a range of ages and metallicities. (iv) A deep extragalactic survey, covering 35□° to a depth of K=21, including coverage of multi-wavelength key areas. (v) An ultra-deep survey covering 0.77□° to a depth of K=23.

The scientific impact of such a programme ranges from the very nearest and faintest objects in the solar neighbourhood, through the structure of the Milky Way, to the most luminous and distant quasars at z=7. We aim to measure the sub-stellar mass function, to detect the era of re-ionisation, to measure cosmological parameters from the abundance of clusters at $z > 1$, and to detect the era of spheroid formation if there was one. As well as achieving these intended goals, the public database resulting from the survey will be a fundamental international resource, and a goldmine of scientific projects for years to come.

## 1.1 The importance of surveys

Much of modern astronomy has sprung from systematic surveys – the 3C, NVSS and FIRST radio catalogues, the Ariel V and Uhuru sky surveys, the *IRAS* far-infrared catalogue and the *COBE* sky-maps. Through much of this time the UK Schmidt photographic sky atlas (and its Palomar counterpart) has been the backbone of UK astronomy. As well as providing identifications of X-ray and radio sources, and saving huge amounts of 4-m telescope time by acting as a fundamental reference atlas, it has been a source of science in its own right (e.g. Abell clusters, Lynds dark clouds, the APM galaxy catalogue).

There are several arguments for the importance of large systematic surveys. (i) The first is the idea of a sky atlas as a fundamental resource, as support to other kinds of astronomy, as a leaping-off point by selecting samples of unnusual objects for detailed study, and as a gold-mine of hidden information whose future uses can only be guessed. (ii) Some science goals simply take large amounts of telescope time, for example because a very large sample is needed for statistical reasons. If a project takes more than say 100 nights, it is unlikely to be undertaken by individuals. Furthermore such ambitious goals will almost certainly be the aim of a whole community. A communal approach to collecting the data therefore makes sense. (iii) Sometimes an intrinsically large sky area is needed, as in studies of large scale structure or the Milky Way. (iv) The same dataset can often be used for many different purposes - for example a large area of sky may be mapped to get a sample of 10 million galaxies, but somewhere in there are perhaps 10 cool halo white dwarfs that may be the solution to the dark matter problem. Once again, a communal approach is far more efficient.

Of course strong arguments can also be made for highly targeted research in small chunks of competitive open time. However with WFCAM there is an exciting opportunity for a truly ground-breaking survey project that will be of world significance. We can expect that the most productive and scientifically exciting results will flow from survey work whenever we move into a new region of parameter space. The growing importance of the IR is well recognised - for the detection of cool objects, for seeing through the extinction caused by dust, and as a shortcut to the high-redshift universe. The first IR sky surveys (DENIS and 2MASS) are just now taking place, but these are relatively shallow - more equivalent to, say, the Shapley Ames catalogue, than the Palomar/UK Schmidt surveys, let alone the SDSS. Our proposed survey programme will be the true match of the SDSS optical survey, but will also go well beyond it, as we probe deeper into smaller regions.

## 1.2 The UKIRT Wide Field Camera (WFCAM)

The opportunity arises from an innovative new instrument being designed for UKIRT - the Wide Field Camera, which is will have an instantaneous field of view of $0.21\square^{\circ}$ (See Henry et al 2000, SPIE Proceedings, Vol 4008, p.1325. Project web pages are at `http://www.roe.ac/uk/atc/projects/wfcam/index.html`) As UKIRT is a 4m class telescope, and is on a site with excellent seeing and low temperature, the effective survey rate (field of view divided by point source detection time) is one or two orders of magnitude faster than just about anything else on offer. There are only two rivals. IRMOS on the VLT is almost as fast at J and H but has no K-band facility, and will spend most of its time in spectroscopic mode. Furthermore it will only be used for a small fraction of the time, whereas with WFCAM we are proposing precisely to dedicate *most* of future UKIRT time to completing an ambitious project of world significance. The other rival is of course VISTA, which will have an even more impressive IR mosaic camera, but will not begin operations until several years after WFCAM, and will operate in a separate hemisphere. We see WFCAM partly as a pathfinder for VISTA, and this is one reason why we have designed a targeted suite of surveys rather than a monolithic atlas.

The key novel feature of WFCAM is the forward-Cassegrain Schmidt-like camera design, which makes possible the wide field of view (40 arcmin) on a telescope not originally designed for this purpose. The mosaic camera has four $2048\times2048$ Rockwell arrays with a pixel size of 0.4 arcsec. This gives an instantaneous field of view of 0.21 □° However the arrays are spaced by 0.9 detector widths (see Fig. 1.1). The pixel size somewhat undersamples the expected median seeing of approximately half an arcsecond. (Note that tests indicate that the tip-tilt system on UKIRT primarily corrects wind-shake, so that the image size across the whole field of view is expected to be that of the free-atmosphere seeing). However the intention is to micro-step by sub-multiples of the pixel size, as the 2MASS project have successfully done, producing a properly sampled (and much larger !) image, with a somewhat broadened PSF compared to the natural seeing. Complete sky coverage can then be achieved by any one of several mosaic patterns. This always involves some overlaps of course, because of the 90% detector spacing. The effect of this is considered fully later.

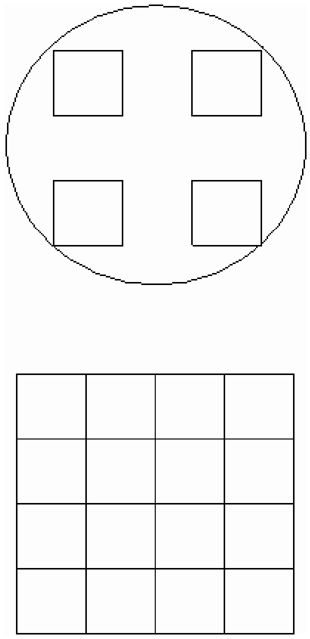

Figure 1.1: **Upper** : *Focal plane arrangement of WFCAM. Each array is 2048×2048 pixels, with each pixel size 0.4 arcsecond. The spacing between arrays is 0.9× the detector width. The instantaneous coverage is 0.207□°* **Lower** : *Filled-in tile after 4×4 macro-steps. Allowing for the overlaps, the tile width is 3.85 detectors, i.e. 0.88 degrees, giving an area of 0.77□°*

The likely speed of the camera on the sky has been estimated using recent experience with the UFTI camera on UKIRT. We do not yet know the DQE of the Rockwell arrays or the final realised throughput of WFCAM, but we have assumed that point source speed is the same as UFTI except that DQE should be somewhat better at J and H - around 45% versus the UFTI 30%. The UFTI measurements were based on a simple software aperture. We have therefore made a further small correction to represent what we should be able to achieve with optimal PSF fitting. The final result, approved by the WFCAM project scientist, is that in half–arcsecond seeing we will achieve S/N=5 in one hour integration for a point source with J=22.1, H=21.2, and K=20.8. [1] For a variety of reasons, and judging by figures quoted by various other IR camera projects, these may be somewhat conservative

[1]These are point source sensitivities - detection of extended sources such as galaxies may be considerably slower. Note also that here and throughout, the magnitudes we quote are on the Vega system. This includes reference to SDSS survey depths, which we have converted to Vega equivalents.

figures. On the other hand of course, half the time the seeing will be worse than the median. UFTI experience suggests that in 1 arcsec seeing the point source sensitivity is 0.3 – 0.4 mag worse. For the moment we believe the sensitivity figures above are the most sensible for preliminary survey design purposes.

Another important characteristic is the minimum sensible exposure time, in order for elapsed time not to be dominated by overheads. (See section 1.7). This is around 40 seconds exposure per sky position. This is discussed in detail later. Here we note simply that this leads to the fact that the shallowest sensible survey already reaches K=18.4

## 1.3 The UKIDSS proposal and consortium

The WFCAM concept has been in development since early 1998. The idea of surveys in a loose sense has always been part of the science case for WFCAM. However the first proposal for a very large survey taking several years and operated as a public project in the manner of the UK Schmidt surveys was made in a paper to the GBFC by Lawrence *et al* in September 1998. A formal proposal was made to the UKIRT Board in November 1999, who requested an open Announcement of Opportunity to allow all interested UK astronomers to participate. This was extremely successful, leading to the establishment of a consortium of 61 astronomers from many different organisations. Several meetings, and two workshops in Japan, led to development and organisation of the science goals, and the invitation to several Japanese astronomers to participate. The proposed survey programme is the "UKIRT Infrared Deep Sky Survey (UKIDSS)", and the consortium refers to itself as the "UKIDSS Consortium". The consortium is the list of individuals, not the list of their employing organisations.

The consortium is not requesting proprietary data rights. The proposal is to collaborate to produce an ambitious survey programme with the intention that it is immediately open to *all* UK astronomers, plus individual Japanese astronomers within the consortium, and open to all astronomers world-wide after some initial UK ownership period. This document concentrates on making the science case for such a survey programme. Some discussion of how it will be implemented in practice is presented in later sections.

## 1.4 The survey programme concept

The "shallow survey" depth of K=18.4 seems a sensible match to POSS II, as typical galaxy colours have $B - K \sim 4$, and the plates reach $B \sim 22.5$. From the latitude of UKIRT one can see roughly 30,000 $\square^{\circ}$, three quarters of the sky. Allowing for likely inefficiencies and weather (see later), such a complete JHK survey would take about 1200 nights, i.e. around 5–10 years depending on what fraction of UKIRT time we use. Such an IR sky atlas would be an incredible resource and in the long term may be a sensible goal. But in the medium term, it is not the best strategy, for several reasons. (i) Much of the exciting science we would like to tackle is much deeper, while still requiring large amounts of data. (ii) Just as Schmidt era surveys fed spectroscopy on 4m class telescopes, we should be looking towards feeding spectroscopy on 8m telescopes. This suggests that we should be looking for exposures of a few hours rather than a few seconds. (iii) Multi-wavelength identifications - from current and imminent X-ray, submm, and radio facilities - are expected to be several magnitudes fainter than the Schmidt limit. (iv) For given science goals, even very ambitious ones, we don't necessarily *need* all that area, or quite so many sources. (v) Any given area should ideally be covered many times - for reliability, for variability, and for proper motions.

All this argues for looking at the *science drivers* and tuning survey design accordingly. Of course these are hard to get right in advance, looking 5–10 years ahead, and different goals may push us in different directions. The net result from debate amongst our consortium is to propose not a single monolithic survey, but a *survey programme*, made up of a suite of distinct component sub-surveys with a variety of areas and depths. The particular areas and depths are driven by specific science goals. However, somewhat inevitably the general result is a kind of logarithmically spaced "wedding cake" plan with wide-shallow, medium, and narrow-deep surveys.

## 1.5 Key science goals

Our primary goal is to produce IR sky atlases as a fundamental resource of lasting significance analogous to the UK Schmidt photographic sky surveys. None of the survey components we propose covers the whole sky, but nonetheless we feel that each component deserves the term "atlas", as the volume surveyed, and the number of objects detected, are comparable to the Schmidt surveys, and each survey maps out some significant part of the universe - the solar neighbourhood, the Milky Way, the local extragalactic universe, the universe at z=1, and the universe at z=3. In addition, the datasets will act as data mines, becoming the source for much future work we can only guess at.

However, as the consortium debated scientific topics that an IR survey programme could make an impact on, we designed the parameters of the programme to meet specific scientific goals. The most important of these specific goals are as follows :

- to find the nearest and faintest sub-stellar objects
- to break the z=7 quasar barrier
- to determine the epoch of re-ionisation
- to determine the substellar mass function
- to discover Pop II brown dwarfs, if they exist
- to measure the abundance of galaxy clusters at $1 < z < 1.5$
- to measure the growth of structure and bias from $z = 3$ to the present day
- to determine the epoch of spheroid formation
- to clarify the relationship between quasars, ULIRGs, and galaxy formation
- to map the Milky Way through the dust, to several kpc

- to increase the number of known Young Stellar Objects by an order of magnitude, including rare types such as FU Orionis stars

## 1.6 Summary of the survey programme components

In this section we present an overview of each component of our proposed survey programme. Detailed science cases for each component are presented in subsequent chapters. Fig. 1.2 shows the K-band depth and area for each component, and compares these to existing or imminent surveys. This figure makes the point that *each* of our proposed survey components is an improvement in the current situation by one or two orders of magnitude.

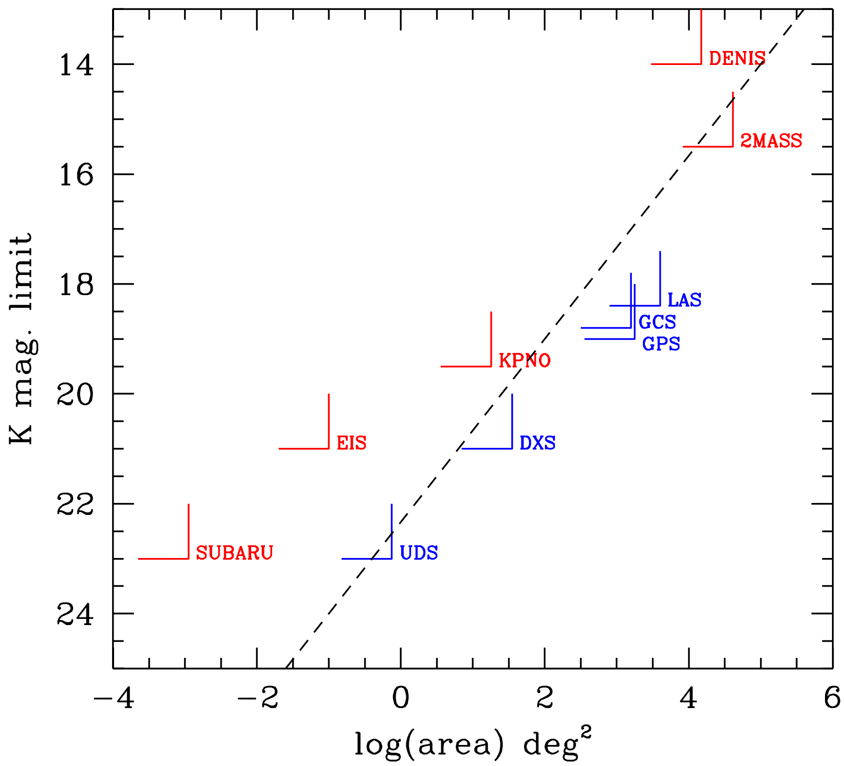


Figure 1.2: *K-band limiting magnitude versus area for various near-IR surveys. In blue : the proposed UKIDSS survey components. In red : various other surveys, either completed or underway. Note that the envelope of blue points lies about 2 orders of magnitude to the right of the envelope of red points. In other words the UKIDSS surveys will cover approximately 100 times the area of current planned surveys at any particular depth. The dashed line shows the Euclidian number counts relation* $N \propto 10^{0.6K}$ *i.e. the position of a survey relative to the line is a relative measure of the volume of space surveyed. This illustrates, for example, that for surveys for brown dwarfs 2MASS will detect many more than the KPNO survey, and the LAS is an order of magnitude bigger than 2MASS.*

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**General considerations : shallow versus deep surveys**

For many of our science goals it is essentially volume that matters, either in order to construct large samples of objects, or to maximise the chance of finding rare objects. In this case, surveying more area increases the volume in proportion to time $t$, whereas going deeper in a fixed area increase volume as $t^{3/4}$. For such projects then a large shallow survey is the best. For some other projects, such as searching for high redshift quasars or clusters, the tradeoff between area and depth is more subtle, depending for example on redshift of interest, assumed cosmology and the shape of the luminosity function, but the net effect is that in these case also large area is preferable. However too short an exposure leads to overheads dominating time. For an exposure of 40 seconds per sky position we expect an efficiency of 65% (see Fig 1.2), and this drops rapidly with shorter exposures. This leads to a natural basic shallow-survey unit, which gives a $5\sigma$ point source limit of K=18.4. Note that this is already $\sim$ 25 times deeper than 2MASS. For shallow surveys then, the depth is effectively fixed, and the main decision comes in the area required to achieve the science goals, in competition with other components of the programme. Our high latitude Large Area Survey comes into this category. The proposed Galactic Cluster Survey is also effectively in this category as the clusters are so large.

In other cases, science goals have intrinsic depth requirements. For our Galactic Plane Survey we wish to map to large distances through the Milky Way, and to be able to detect specific types of object such as the bottom end of the IMF, or X-ray binary counterparts, to kpc distances. In addition, in a reasonable amount of time we can map the majority of the available Galactic Plane and so would like to go a little deeper. Some extragalactic goals have intrinsic depth requirements, for example to be able to detect typical galaxies at a given redshift. There are also intrinsic area requirements, for example to measure clustering on a given scale at a given redshift. In fact the crude depth required ($K = 21$ for $z = 1$ and $K = 23$ for z=3) is reasonably clear, leading to the idea of Deep and Ultra-Deep surveys, but the time spent in depth versus multiple wavebands versus more area needs careful thought.

**The Large Area Survey (UKIDSS – LAS)**

The Large Area Survey (LAS) aims to map as large a fraction of the Northern Sky as feasible (4000 square degrees) within a few hundred nights, which when combined with the SDSS, produces an atlas covering almost an order of magnitude in wavelength. Furthermore a huge number of objects will already have spectroscopic data from the SDSS project, making an unparalleled dataset. The basic shallow survey reaches J=19.6, H=18.8, K=18.4, but we also require a second pass in the J-band to detect proper motions of low mass objects to determine their kinematic distances, so that the final J depth is J=20.0. In addition we propose to use a new filter we have called Y, covering 0.97 to 1.07 microns, specifically designed to detect extremely high redshift (z=7) quasars, and to distinguish them from very low mass stars.

The Large Area Survey will produce a catalogue of a million galaxies with colours and spectra, and 10 million galaxies with photometric redshifts; will detect thousands of rich clusters out to z=1; will find fifty times more brown dwarfs than 2MASS, will probe to much fainter objects, and can get statistical ages and masses from kinematics; and will produce a complete sample of 10,000 bright quasars, including reddened quasars, using the K excess method.

We are particularly driven however by three especially exciting prospects. (i) A search for the nearest and smallest objects in the solar neighbourhood. Our survey is deep enough to detect brown dwarfs and free floating planets with as little as 5 Jupiter masses, and has a volume large enough to find of the order ten such objects at *sub-parsec* distances even for fairly pessimistic mass function extrapolations. (ii) The combination of IR and optical colours, and large expected proper motions, will allow us to find halo brown dwarfs if they exist, testing the universality of star formation processes, and the formation history of the Milky Way. (iii) We hope to find quasars at $z = 7$ and to detect the epoch of re-ionisation. SDSS have found z=5-6 quasars by "$i'$ drop-out". Beyond z=6 quasars become rapidly redder, indistinguishable from brown dwarfs in standard colours, and too faint to be in the SDSS $z'$ survey. We therefore propose a survey in the new Y filter to match our JHK survey. Extrapolating popular evolution functions, we expect to find 10 quasars in the range z=6-7 and 4 in the range z=7-8.

**The Galactic Plane Survey (UKIDSS – GPS)**

The Galactic Plane Survey (GPS) aims to map half of the Milky Way, to within a latitude of 5°. Given the declination constraints of UKIRT, we can survey $l = 15 - 107$ and $l = 142 - 230$. Confusion in the crowded star fields may prevent accurate photometry at $l < 40$ or so (test data is being taken to assess this problem) but for now we assume we can map all the way in to $l = 15$. The scientific goals require as large an area as possible, but in a reasonable time this gives an impressive depth - J=20, H=19.1, K=19.0. This is deep enough to see all the way down the IMF in distant star formation regions, to detect luminous objects such as OB stars and post-AGB stars across the whole Galaxy, and to detect G-M stars to several kpc. The K-band exposure is built up in three separate passes in order to detect variable objects. In addition, we propose to make a narrow-band molecular hydrogen survey in a smaller region (300 square degrees).

Like the high-latitude LAS, the GPS has its prime importance as a fundamental resource for future astronomy. We expect to detect $10^{8-9}$ sources in total. However there are a number of immediately expected achievements. (i) We expect to increase the number of known Young Stellar Objects (YSOs) by an order of magnitude, and to measure the duration of the YSO phase versus mass and environment. (ii) Rare brief-duration YSO variables such as FU Orionis stars will be found in significant numbers for the first time. (iii) Thousands of evolved objects such as post-AGB stars and PN will be found, a huge increase over previous samples. (iv) Star formation regions will be mapped throughout the Milky Way, measuring star formation efficiency versus Galactic radius, and estimating the overall star formation rate of the Galaxy. (v) Many stellar populations will be mapped to large distances through the Milky Way extinction, measuring scale height versus stellar type, and for the first time mapping the arms and warp, so far seen only in gas, in the stellar populations. (vi) Hundreds of X-ray binaries will be identified, and hundreds more such objects located in advance of X-ray measurements.

**The Galactic Clusters Survey (UKIDSS – GCS)**

The Galactic Clusters Survey (GCS) aims to survey eleven large open star clusters and star formation associations, covering a total of $1600\square^\circ$ using the standard single pass depth plus a second pass in K for proper motions, giving a depth of J=19.6, H=18.8, K=18.8. These clusters are all relatively nearby and so are at intermediate latitudes and are several degrees across.

The GCS is the most targeted of our surveys, being aimed at the crucial question of the sub-stellar mass function. The stellar mass functions is well determined down to the brown-dwarf boundary but more or less unknown below, and it is not known whether the IMF as a whole is universal or not. The mass limit reached varies somewhat from cluster to cluster, but is typically around $M_L \sim 30 M_J$. The number of objects expected to be detected in the range $M_L$ to $M_L + 10M_J$ ranges from 100 to 3000 for the range of possible mass function models, showing how well we will constrain the IMF compared to current knowledge.

To find extreme objects - the very nearest examples, the lowest mass objects - the large area survey is better. But to measure the IMF, one wants to target the 30 – 100 $M_J$ region, and to obtain masses one needs both a distance and an age, for which mapping clusters are ideal. This approach has of course already been started. Our survey improves on current studies not by going deeper but by collecting much larger numbers, and examining objects with a range of ages and metallicities, to examine the question of universality.

**The Deep Extragalactic Survey (UKIDSS – DXS)**

The Deep Extragalactic Survey (DXS) aims to map 35□° of sky to depths of K=21, and J=22.5, in three separate large regions. (The sensitivities are for point sources; we expect the target galaxies to be roughly an arcsecond across and so have total magnitude detection sensitivities several tenths of a magnitude slower.) The theme of the DXS is a comparison of the properties of the Universe at $1.0 < z < 1.5$ against the properties of the Universe today. The DXS will survey a similar volume at these redshifts to the 2dF and Sloan Digital Sky Survey (SDSS) volumes, and the near-infrared gives coverage of the same rest-frame wavelengths as SDSS. We will ensure that deep optical imaging will be collected for the same areas, giving photometric redshifts for nearly all the galaxies. As the final fields are selected over the next year or two, at the same time as XMM-Newton, GALEX, CFHLS, VIRMOS, and SIRTF plans are finalised, international multi-wavelength key areas will emerge.

There are four main scientific goals. (i) To measure the abundance of rich galaxy clusters at $1 < z < 1.5$. This is the principal goal and defines the scope of the survey. The purpose is to obtain constraints on cosmological parameters that are complementary to measurements of the cosmic microwave background. Ultimately we hope to make an important contribution to reaching beyond the three-parameter $H_\circ$, $\Omega_m$, $\Omega_\Lambda$ cosmology that describes the geometry and dynamics of the Universe, to obtain useful constraints on the dark energy equation of state parameter $w = P/\rho$, and thereby to explore quintessence models. (ii) To measure galaxy clustering at z>1, and more specifically the evolution of bias, a key test of hierarchical models. The aim is to reach two magnitudes down the luminosity function at z=1, which requires a depth of K=21. To test the models we need to measure the correlation function on a series of scales, ideally out to 200 Mpc comoving, which is 3.5° at z=1 [2]. To overcome cosmic variance, we need three such regions. (iii) To quantify the contribution from star formation to the cosmic energy budget, as a function of wavelength over the ultraviolet to far-infrared region. This will include studying a large sample of the rare but important

[2]Cosmological parameters $\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_\circ = 70$ are assumed throughout this proposal, unless otherwise stated.

Extremely Red Objects (EROs), and the precise measurement of their clustering properties. (iv) To measure the contribution of AGN to the cosmic energy budget, as a function of wavelength, by systematically identifying sources discovered in XMM X-ray and SIRTF mid-infrared surveys.

**The Ultra Deep Survey (UKIDSS – UDS)**

The Ultra Deep Survey (UDS) aims to map $0.77\square^{\circ}$ of sky to a depth of J=25, H=24, and K=23, the first large volume map of the high redshift universe. The depth of K=23 is needed to reach galaxies at z=3 and greater. Many of the galaxies of interest, especially the reddened ones, will be undetectable in visible light until NGST, so that full JHK coverage is very important. The combination of depth and area will make this the most important existing archive of near-ir data for *statistical* studies of the early stages of galaxy formation. The inspiration for the UDS came from observing the success of the HDF as a public legacy database that has been used for all kinds of landmark science that had not been thought of at the time of conception.

There are three prime aims - the abundance of high-redshift ellipticals, the clustering of galaxies at z=3, and the relationship between EROs, ULIRGs, and AGN. We expect to detect 50,000 galaxies in total and 10,000 galaxies at z>2, mapping a region 100 Mpc comoving across and 2 Gpc deep ($2 < z, 4$), giving the first picture of large scale structure at z=3, and together with the DXS and local surveys, measuring the growth of structure with cosmic epoch. However as well as measuring the general field population, the key goal is simply to see whether giant ellipticals exist at z=3. The many successes of hierarchical models strongly suggests that no such large units existed at that time, but the ages of radio galaxies, and the local colour-magnitude relation strongly hint that they did. This then is one of the key questions of modern cosmology. If the density of giant ellipticals is similar to that of today, we should see of the order of 1000, whereas a traditional high density CDM model predicts about 30, and a $\Lambda$CDM model about 100, giving us a sensitive test of galaxy formation theories. It is tempting to identify EROs and/or SCUBA sources as spheroids in formation, in which case a matching post-starburst population of at least similar density should be present.

## 1.7 Modelling the survey programme

Here we look briefly at how observations will be carried out, their efficiency, and the time required to carry out each of the survey programme components.

**Observing efficiency $E_o$.** The camera needs to be moved in both microsteps (to sample the PSF) and in macrosteps (to produce a complete mosaic of the sky). The time spent staring at sky before any movement is $t_{stare}$. (This might be broken into smaller individual exposures $t_{exp}$, for example to avoid saturating on the sky). The number of micro-steps is $S = N \times N$. (This is likely to be $2 \times 2$ or possibly $3 \times 3$.) The interleaved data from a complete set of micro-stepped stares is known as a *pointing*, resulting in four separated images of the sky with a total integration time $t_{int} = S \times t_{stare}$. Multiple pointings at a variety of positions can then be mosaiced and stacked to produce the final map of the sky. In the process a particular *position* on the sky may be visited say $M$ times, so that the

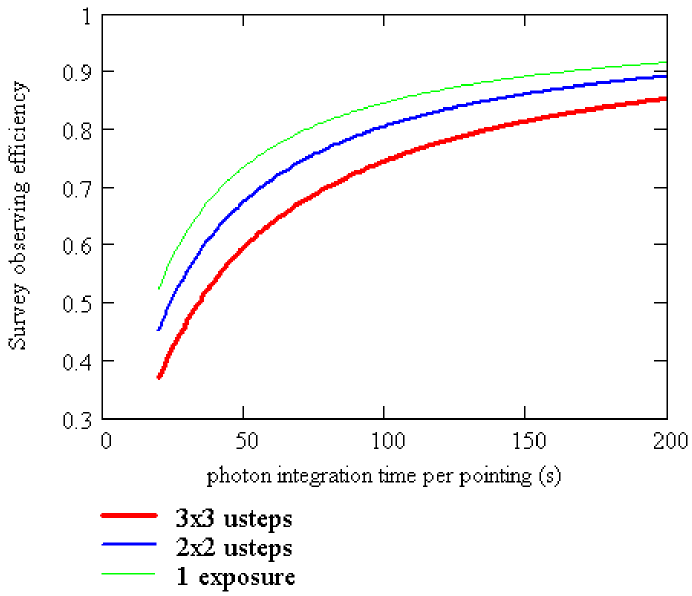


Figure 1.3: *Estimated efficiency curves for WFCAM observing, i.e. the integration time over elapsed time in a single pointing as a function of integration time.*

accumulated exposure on that sky position is $t_{pos} = M \times t_{int}$.

However the actual time taken to produce a pointing is larger than $t_{int}$ because of overheads in initial acquisition, telescope movements, and readout. If the efficiency of observing is $E_o$, then the actual time taken over a pointing is $t_{point} = t_{int}/E_o$. Likewise after multiple visits and an accumulated exposure $t_{pos}$, the total time spent visiting that sky position is $t_{sky} = t_{pos}/E_o$. The WFCAM Project Scientist has estimated $E_o$ as a function of integration time and microstepping mode. This is shown in Fig. 1.2. Clearly very short integration times are not sensible. On the assumption of $2 \times 2$ microstepping, we choose $t_{int} = 40$, i.e. $t_{stare} = 10$ seconds as the minimum integration time, with $E_o \sim 0.65$. For deeper surveys one can achieve higher efficiency by staring longer before microstepping, but not so long that there is danger of significant seeing changes between micro-step positions. This needs more investigation, but for now we take a safe limit to be $t_{stare} = 40$ seconds, $t_{int} = 160$ seconds, leading to $E_o \sim 0.85$.

**Mosaic efficiency** $E_m$. Mosaics of pointings can be made in a number of ways, but there is always some inefficiency because of frame overlaps. The area of sky covered in the four disjoint frames is 0.21 $\square^\circ$ If the area of sky to be covered is $A$ then the number of pointings required is $A/(0.21 \times E_m)$ where $E_m$ is the mosaic efficiency. The simplest mosaic is filling in the gaps in a $2 \times 2$ macrostep pattern to make a filled *tile*. Because the detectors are spaced at 90% of a detector width, one gets three 5% overlap strips in each direction so that the tile is 3.85 rather than 4 detector widths across, and $E_m = 0.93$. For a large area but shallow survey, each tile should be overlapped by a similar amount, so that it is 3.8 detector widths across and $E_m = 0.90$. For deep surveys, we can space the many pointings that are to be stacked on a fine grid to achieve a uniform exposure map, apart from a ramp-down at the edges. For a large area stacked survey, the edge effects will be negligible so that

$E_m \sim 1$. For a small area deep stacked survey, the optimum gridding pattern is not clear because of the tradeoff between exposure uniformity and edge effects. We will investigate this further, but for the moment model our ultra-deep survey as a simple 4×4 tile, with mosaic efficiency $E_m$=0.93.

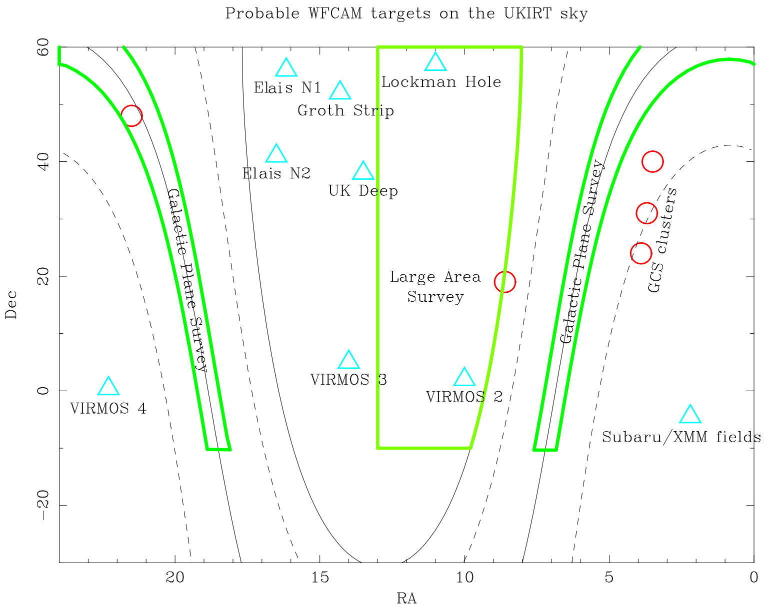


Figure 1.4: *The sky distribution of UKIDSS targets, showing the preliminary choice of fields, as well as alternative targets. The GPS and LAS areas fall within the thick green solid lines. The GCS clusters are marked with circles. The possible DXS and UDS survey areas (as well as single deep X-ray fields) are marked with triangles. The current choice for the UDS is the Subaru/XMM field. This is also one of the chosen DXS fields, together with Elais N1, and the Lockman hole. Other possibilities for the DXS include UK Deep, a field with good X-ray and SIRTF coverage, and VIRMOS 2 and 4 which are currently listed as targets in the CFH Legacy Survey.*

**Useable time.** We assume a fraction of useable time $F_u = 0.7$. This is meant to encapsulate losses due to cloud, telescope down time, instrument problems etc. Assuming that we achieve a good RA balance (see below), we will observe at all times of year, and so assume an average number of 10 hours per night. The *transmission* does not need to be perfect. The deep stacked surveys (DXS and UDS) will be effectively self-calibrating and so able to use nonphotometric but still reasonably clear time. The shallow surveys (GPS, LAS, and GCS) would ideally be made in photometric conditions, but could conceivably be made in poorer conditions and calibrated later with repeat UKIDSS observations (for variability and proper motion) or from 2MASS photometry. For *image quality* we will simply need to take almost all seeing conditions, as we propose to take such a large fraction of UKIRT time. We will probably want to use the best seeing to progress the deepest surveys, but this needs further modelling and scientific debate.

**Calibration.** We believe that the UKIDSS will be largely self-calibrating. Deep fields with many repeat visits only need one photometric visit and self-calibrate thereafter. Shallow surveys with only a single visit will require a set of calibration fields spread around RA, but these can largely be component fields of the various deeper surveys. Finally we will be able to calibrate from 2MASS stars, of which there will be a few per frame. These will often saturate in the stare time, but we intend to routinely perform 1sec non-destructive readouts for calibration purposes.

**Sky distribution.** Plotting the distribution of the target areas (Fig. 1.4) demonstrates there are potential targets at all RAs with most at peak zenith distances $< 30°$. The most direct way to assess demand for observing time spread over the whole survey is to plot the requested time in hours against RA. Figure 1.5 shows the result. This is reasonably uniform over RA, except for a mismatch between the RA ranges $0-5$ and $19-24$ hours. Optimising the RA distribution will be an important consideration in our final field choice. Adjustment of the final observation list will also have to take into account weather and darkness statistics and limitations due to the scheduling of the instrument.

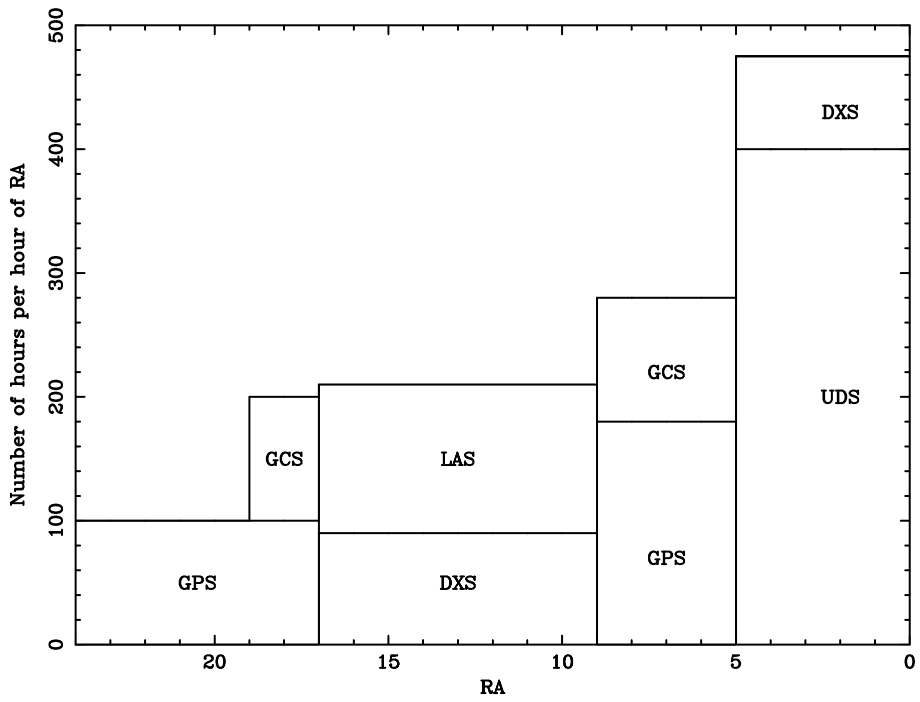


Figure 1.5: *A histogram plot of the total number of hours integration (net) required with RA. The contributions from each survey are marked. The LAS area covers a slightly wider range of RA than in Figure 1.4. The UDS field is assumed to be the Subaru Deep field, and for this plot we have assumed that the DXS fields are XMM-Newton/LSS, the Lockman Hole and ELAIS N1. The plot indicates a mismatch between the required time in the RA range* $1-5$ *hours, and* $19-24$ *hours that will need to be addressed when finalising the fields to be observed.*

**Time required.** Table 1.1 lists the characteristics of each component of the survey programme. The justification for the filters, depths and area of each component is given in the detailed science cases. The mosaic and observing efficiencies appropriate to each survey follow from the discussion above. The number of actual elapsed nights is estimated assuming an average of 10 hours per night, and 70% of night-time hours being useable. The total number of nights required is 946, or three years.

How long will the programme take in elapsed years? We have calculated this as follows.

The number of UKIDSS nights per year would be $365 \times F_{UK} \times F_{WFCAM} \times F_{UKIDSS}$. Here $F_{UK} = 0.8$ accounts for the 15% apportioned to the University of Hawaii, plus some Japanese time and Director's and engineering time. The Board has stated that WFCAM will be on the telescope for $F_{WFCAM} > 0.6$ of the total time. Of the WFCAM time a healthy fraction should be given over to PATT open competitive time, but we propose that the majority $F_{UKIDSS} = 0.8$ be used for the UKIDSS public survey. The future operational programme of UKIRT is still under debate, but the simplified operational mode required in the post-ESO era requires WFCAM to be on the telescope a large fraction of the time. For $F_{WFCAM} = 0.8$, $F_{UKIDSS} = 0.8$, there would be 187 UKIDSS nights per year and the surveys would take 5.1 years. Alternatively for, say, $F_{WFCAM} = 0.6$, $F_{UKIDSS} = 0.75$, there would be 131 UKIDSS nights per year and the surveys would take 7.2 years.

## 1.8 Implementation of the survey programme

The current document is intended to make the science case for the UKIDSS survey, and not to address its practical implementation. There are obviously some non-trivial issues here, which have been partly addressed by earlier papers to the UKIRT Board, and will be the subject of more detailed papers in the near future. For context, however, we add some brief words of explanation here.

The UKIDSS proposal is made in the context of WFCAM being a funded instrument under construction, including operational software and so on. The proposal is also made in the context of WFCAM being operated within a fully operational telescope environment, supplied by the Joint Astronomy Centre (JAC). Thus we can assume that routine maintenance of the instrument is the obligation of JAC, not the UKIDSS consortium.

The implementation of the survey in terms of actual night-time operations carries a mixed obligation. The UKIDSS consortium will design the survey strategy, i.e. tiling algorithm, adaptive scheduling, and so on. Operation at the telescope will be shared between JAC and UKIDSS, being undertaken by a mixture of JAC staff astronomers, TOs, and visiting UKIDSS staff members and PDRAs. We anticipate that UKIDSS PDRAs will visit for extended periods, accommodated in an apartment provided by JAC.

The next step down the chain is pipeline reduction - removing instrumental signatures, photometric and astrometric calibration, stacking and mosaicing, and source extraction. This entails very considerable software development and operational effort but is not primarily the responsibility of UKIDSS. Rather, a collaboration between JAC, the Cambridge Astronomical Survey Unit (CASU) and the Edinburgh Wide Field Astronomy Unit (WFAU) already have an agreement to provide a standard pipeline analysis service for *all* WFCAM data regardless of whether from UKIDSS or PATT open time. This effort is funded within the current PPARC business plan line for wide field astronomy, and a preliminary plan has gone before the Wide Field Astronomy Panel (WFAP). The UKIRT Board will obviously want to view and approve these plans, but it is not appropriate to discuss them in detail here. It is also clear that UKIDSS will need visibility of these plans and will provide extensive advice on the detailed service, and will set functionality and performance goals on the service in order to satisfy UKIDSS requirements. Finally UKIDSS members will be expected to be involved in quality assurance, in refining photometric and astrometric

| **Survey** | **Area** | **Filter** | **mag limit** | $t_{stare}$ | $t_{pos}$ | $E_o$ | **Total** | **Nights** |
|---|---|---|---|---|---|---|---|---|
| LAS | 4000 | J×2 | 20.0 | 10s | 80s | 0.65 | 734h | 262 nts |
| $E_m$=0.9 | 4000 | H | 18.8 | 10s | 40s | 0.65 | 367h | |
| | 4000 | K | 18.4 | 10s | 40s | 0.65 | 367h | |
| | 4000 | Y | 20.5 | 10s | 40s | 0.65 | 367h | |
| GPS | 1800 | J | 20.0 | 20s | 80s | 0.75 | 286h | 186 nts |
| $E_m$=0.9 | 1800 | H | 19.1 | 20s | 80s | 0.75 | 286h | |
| | 1800 | K×3 | 19.0 | 10s | 120s | 0.65 | 495h | |
| | 300 | $H_2$× 3 | — | 37.5s | 450s | 0.85 | 237h | |
| GCS | 1600 | J | 19.7 | 10s | 40s | 0.65 | 147h | 84 nts |
| $E_m$=0.9 | 1600 | H | 18.8 | 10s | 40s | 0.65 | 147h | |
| | 1600 | K×2 | 18.7 | 10s | 80s | 0.65 | 294h | |
| DXS | 35 | J | 22.5 | 40s | 2.1h | 0.85 | 415h | 118 nts |
| $E_m$=1.0 | 5 | H | 22 | 40s | 4.4h | 0.85 | 124h | |
| | 35 | K | 21 | 40s | 1.5h | 0.85 | 287h | |
| UDS | 0.77 | J | 25 | 40s | 209h | 0.85 | 983h | 296 nts |
| $E_m$=0.93 | 0.77 | H | 24 | 40s | 174h | 0.85 | 818h | |
| | 0.77 | K | 23 | 40s | 58h | 0.85 | 271h | |
| **TOTAL** | | | | | | | | 946 nts |

Table 1.1: *Summary of requirements for each survey.* Notes : *(i) Mag limits are for point sources in median seeing. The assumed 5 $\sigma$ sensitivity in one hour is J=22.1, H=21.2, K=20.8. (ii) The necessary accumulated sky exposure in hours at one position is then* $t_{pos} = (10^{(\Delta m/2.5)})^2$ *where* $\Delta m$ = *target mag - 1 hour sensitivity limit. (iii) The Total on-sky exposure required is then* $t_{pos} \times (A/0.207) \times (1/E_m) \times (1/E_o)$ *where A is the area in square degrees, and* $E_m$ *and* $E_o$ *are the mosaic and observing efficiencies respectively. (iv) The number of nights required assumes an average of 10 hours per night, and a fraction of useable hours* $F_u = 0.7$.

calibrations, and source extraction algorithms, as their performance will become clear as scientific results emerge.

The key role of UKIDSS members will of course come downstream of this point, in analysis of the resulting databases. This in turn will rely on datamining hardware and software tools intended to be put in place by the AstroGrid project, recently approved.

# Chapter 2

# The Large Area Survey

## *Finding the smallest stars and the most distant quasars*


### Summary

We aim to survey a large area of sky (4000 $\square^\circ$) in the near-IR to a depth which will match the Sloan Digital Sky Survey (SDSS), making a combined dataset of covering a factor of 6 in wavelength. Its combination of area, depth and multi-filter coverage make it a powerful tool for determining statistics on common objects (stars, galaxies, clusters of galaxies) and isolating extreme objects (low mass dwarves and high redshift quasars). At our standard shallow survey depth, the magnitude limits of the survey are J=20.0, H=18.8, K=18.4 over a total area of $\sim 4000\,\square^\circ$. Observations are also desired in a proposed new "Y" filter covering 0.97 - 1.07 $\mu$m that would reach a depth of Y=20.5.


## 2.1 Motivation

Our starting point is the desire to produce an IR survey which matches the Sloan Digital Sky Survey (SDSS) to produce a combined dataset of lasting importance. A large area shallow survey is the most efficient way (i) to provide large statistical samples, and (ii) to find rare objects. The result will be a greatly improved galaxy catalogue for the local ($z\sim 0.1$) universe, and a more complete and less biased sample of quasars. But the IR perspective also allows us to look for particularly important rare objects - the very nearest and very smallest sub-stellar objects, and the most distant and luminous quasars.

The Sloan Digital Sky Survey (SDSS) aims to cover some 10,000 $\square^\circ$ principally around the north galactic pole. The survey 10-$\sigma$ limits vary from $g'(\sim V)=22.6$ to $i'=21.7$ [1] and

[1] Quoted SDSS survey limits are in AB magnitudes, but we have converted these to equivalent Vega-based magnitudes for consistency with the rest of our case.

the survey is thus a major improvement on existing large area surveys such as those from the UK and Palomar Schmidts The aims and initial results of the SDSS can be found at `www.astro.princeton.edu/PBOOK/strategy/.htm`.

Clearly the power of any survey to extend existing knowledge and produce surprises depends on its wavelength coverage. It seems scientifically desirable therefore to extend the SDSS into the near-IR by observing as large an area as possible to a depth matched to the existing optical dataset. Unfortunately, the 2MASS survey is too shallow (limits J=16, K=15) to provide near-IR photometry for most of the sources detected in SDSS – given a typical galaxy colour of I–K$\sim$3 – a limit of K$\sim$18.5 is required. The UKIRT Wide Field Camera (WFCAM) is capable of mapping large areas of sky at a limit 4–6 magnitudes more sensitive than the 2MASS and DENIS surveys: reaching K$\sim$18.5 over 3000 $\square^\circ$ in a reasonable time. Thus the UKIDSS Large Area Survey (LAS) clearly provide a better match to Sloan than existing near-IR surveys and thus provides an unique opportunity to undertake joint optical/near-IR studies over very large regions of the sky.

Below we examine the likely scientific impact of the LAS, moving from the solar neighbourhood outwards. The three scientifically most exciting issues tackled by this survey are: (1) searching for the nearest, faintest objects; (2) identifying population II brown dwarfs and (3) surveys for QSOs at the highest redshifts possible.

## 2.2 Cool stars and brown dwarfs in the solar neighbourhood

Brown dwarfs were initially discovered in open star clusters and in the case of Gl229b as a companion to a nearby star (Nakajima et al. 1995). See Jameson & Hodgkin (1997) for a recent review. More recently numerous L dwarfs have been discovered by the 2MASS and DENIS surveys. L dwarfs are cooler than M dwarfs (T$\sim$2200K) and may be either very low mass stars or young brown dwarfs. More T dwarfs, objects like Gl229b, with methane in their atmospheres, have also been found by SDSS. T dwarfs have temperatures T<1300K, and must be brown dwarfs.

The LAS will be 4 magnitudes deeper than 2MASS/DENIS and will thus survey a volume 250 times greater, finding a correspondingly larger number of L/T dwarfs. This will greatly improve the statistics of the L/T dwarf luminosity/mass functions. More importantly by probing 40× fainter, the LAS will identify intrinsically much fainter sources than 2MASS/DENIS are capable of. Table 2.1 shows how far away brown dwarfs/planets can be seen in the LAS survey as a function of object mass and age, using J-band absolute magnitude predictions models from the models of Burrows *et al.*

The LAS will also measure proper motions since these give a handle on the kinematics and hence rough ages for the sources. Ages are vital for determining the masses of isolated brown dwarfs (although the best determination of the mass functions, which require reliable ages, will come from the UKIDSS cluster survey).

**The nearest faintest objects.** Due to $H_2$, $H_20$, $CH_4$ and $NH_3$ opacities the BDs, and even free floating planets, have their maximum surface brightness in the J band. This surface brightness does not drop too drastically until $T_{\rm eff}$ < 400 K, and all these objects

| | **m=5M$_J$** | **m=10M$_J$** | **m=40M$_J$** |
|---|---|---|---|
| **t=0.5 Gyr** | 7.6pc | 26pc | 171pc |
| **t=1.0 Gyr** | 2.3pc | 14pc | 101pc |
| **t=5.0 Gyr** | 0.1pc | 1.8pc | 32pc |

Table 2.1: *Distance limit for brown dwarf detections as a function of mass and age, assuming a limit of J=20. Absolute magnitudes taken from the models of Burrows et al.*

have $R \sim 0.1\,R_\odot$. As a result, the LAS, probing a large area to J=20, can detect objects that are much cooler than any T dwarf yet discovered. (See Table 2.1). The LAS is for example capable of finding objects such as: a free floating planet of age 200 Myr and $M=4\,M_{Jup}$; or a Population II brown dwarf of age 13 Gyr and $M=30\,M_{Jup}$.

Such very small objects may well be common but so far undiscovered in the solar neighbourhood. Free floating planets $M \sim 5$–$10M_{Jup}$ have been discovered in the $\sigma$–Ori and $\theta$–Ori clusters. Zapatero–Osorio et al. (2000) find the IMF has a slope of $-0.8$ in the $\sigma$–Ori cluster. Anchoring this to the low mass star MF in the solar neighbourhood (Tinney 1995) suggests 0.03 planets per $pc^3$ in the mass range 5 to $15\,M_{Jup}$. The LAS could therefore find $> 10$ free floating planets. The identification of such systems in our local neighbourhood would generate immense public interest.

**Population II Brown Dwarfs.** An important element of star formation theory is the lowest mass object star or brown dwarf that can form. The answer to this question for Population I stars should come from studying open clusters and field objects (see above). For Population II objects it is difficult to use clusters since the nearest globular cluster has a distance of 2.4 kpc so the only hope of finding Pop II brown dwarfs would be to find nearby halo brown dwarfs. Using the ratio of halo to disc stars and assuming a population II mass function slope of $-1.0$ would predict the LAS survey to find about ten $80\,M_{Jup}$ brown dwarfs and possibly one of mass $30\,M_{Jup}$. These would be recognised by their large proper motions. Such a discovery would be of great importance to the issues of the universality of the IMF, and the formation history of the Milky Way.

**Very cool white dwarfs with He atmospheres.** White dwarfs with pure He atmospheres are known to cool very rapidly since their atmospheres are very transparent. Assuming T=2500K, $R=0.01\,R_\odot$ and a black body spectrum gives $M_{Jup}=17$. Clearly these could be found by the LAS if they exist. He-rich WDs account for about 50% of the coolest known WDs (Bergeron at al. 2000). Unlike H-rich WDs, He-rich WDs are thought to be red in all colours. However their future cooling rates are uncertain so it is difficult to predict the numbers that the LAS might find.

## 2.3 Galactic structure

Above we have concentrated on sub-stellar objects. But ordinary low mass stars, mostly M dwarfs, will be detected in huge numbers. Stars at the very bottom end of the main sequence, with absolute magnitude $M_J = 10$, can be seen to a distance of 1kpc. With the second epoch survey, proper motions will be available for huge numbers of the nearer brighter objects. The star counts and kinematics from this immense database will provide a valuable addition to our knowledge of Galactic structure. In particular, the number of halo subdwarfs identified in the survey will make them become almost as numerous as the number of disc M dwarfs now known.

## 2.4 The local extragalactic universe

The LAS will create a fundamental data base of JHK photometry of galaxies in the local universe. A large fraction of the galaxies detected will have optical spectra from SDSS, and all will photometric redshifts from combined optical and IR colours. Using a K-band selected sample of galaxies for large scale structure and galaxy population studies is superior because it provides a much clearer estimate of the stellar mass of galaxies regardless of the age and metallicity of their stellar population and the dust content of the galaxy (Bell & de Jong 2000).

The galaxy database will have many possible uses. However several principle science drivers stand out.

**Measurement of the galaxy stellar mass function**. Although the galaxy luminosity function can be constructed in any photometric band, theoretical models most readily predict the stellar *mass* of galaxies. The K band data thus test the key ingredients of these models rather with minimum dependence on the modelling of the metal abundance, age or dust content (Cole et al. 2001). The K band luminosity function is key to addressing issues such as the efficiency of galaxy formation in different environments.

**A mass-selected census of galaxy properties**. The K-band data will be used to select a sample of galaxies based on their mass. We can the use this to compare the colours, dust content and star formation rates of galaxies free from the biases generated by selecting the sample in optical bands. For example, most known low surface brightness giant galaxies are blue and gas rich (Malin 1 is a spectacular example). By selecting galaxies in the IR, we will be able to determine whether these galaxies are the prominent tip of a population which includes red, old LSB galaxies, or whether these galaxies represent a mode of star formation which has only become established at low redshift.

The quality of the Sloan spectra will also allow us to obtain velocity dispersions for many galaxies allowing detailed comparison of the stellar and dynamical masses of galaxies as a function of environment.

**Local clusters of galaxies** The LAS will also greatly benefit the study of low redshift clusters of galaxies. For instance, the Virgo cluster which is in the LAS survey region provides a unique opportunity for studies of galaxy properties. Because it is so close, the galaxy population can be studied in unprecedented detail. This, combined with its richness, allows a representative *volume-limited* galaxy catalogue to be readily created. Near-IR photometry covering this region will create a galaxy catalogue that probes to fixed stellar mass (independent of star formation history) providing a unique measurement of the stellar mass, size and surface brightness distribution of galaxies.

The survey of the Virgo cluster region has six specific science goals that will maximise return from the wide-field optical survey currently being undertaken by the INT: (1) we will extend the near-IR luminosity function well into the dwarf regime, testing the up-turn in the luminosity function predicted by CDM theories; (2) By differentiating the luminosity function according to galaxy colour and H$\alpha$ emission line strength we will test the distribution of star formation among different galaxy types (another key test of hierarchical models); (3) we will determine how the luminosity function varies across the cluster (another important constraint for galaxy formation models); (4) the survey will give near-IR morphologies for the cluster galaxies so that their optical appearance can be contrasted with the distribution of the underlying stellar mass; (5) deep HI observations of the cluster will allow us to contrast the stellar mass and gas content (as a function of luminosity and position within the cluster); (6) galaxies in the background of the cluster will be used to determine the intergalactic dust content across the cluster (this is an exciting issue which is currently unexplored).

We therefore wish to prioritize observations of the Virgo cluster within the first year of UKIDSS operations to ensure rapid progress on this topic. Should deeper observations be warranted to study galaxies further down the luminosity function then this will be found from PATT or by diverting time within the LAS and/or DXS.

## 2.5 Distant clusters of galaxies

The number of rich clusters of galaxies beyond a redshift of one is a strong function of the density of the Universe. In high–$\Omega_o$ models very few clusters are expected beyond z=0.8 whereas low–$\Omega_o$ models predict many per square degree. The UKIDSS LAS offers an unique opportunity to select clusters in the crucial z=0.5–1.5 range through detection of galaxy overdensities. For a limit of K=18.4, we predict at least 1,000 rich clusters ($>10^{14}\,M_{\odot}$) between z=0.5–1.0 and 100 with z=1.0–1.5 for an $\Omega_m$=0.3, $\Lambda$=0.7 Universe (Gillbank & Bower, in preparation). With multi-colour photometry it is possible to suppress the z<1 galaxy foreground and detect lower mass clusters, bringing the number of detected cluster up to 6,000 and 1,000 in z=0.5–1.0 and z=1.0–1.5 respectively.

This sample of rich clusters will complement the samples coming from the deeper, but narrower field DXS and UDS surveys. The LAS-based sample will be especially useful to trace the large scale structure on the largest scales at z>1 and reliably measure the cluster–cluster correlation function for the most massive collapsed systems at this epoch. In addition it will provide an unique laboratory for galaxy evolution studies, extending the baseline for tracing the evolution of galaxies in high density environments across 75% of the Hubble time, back to z$\sim$1.5.

## 2.6 KX selected quasars

Over a wide enough wavelength range, quasar spectral energy distributions are very distinctive. The combination of IR and optical colours therefore allows a very clean selection of quasars. The K-excess or "KX" method has been proposed by Warren, Hewett and Foltz (2000) and is illustrated in 2.1. As well as providing a clean selection, the method is very insensitive to reddening, and works over a wide wavelength range. Extremely large numbers of quasars will be found, including large numbers of bright quasars suitable for follow-up work. Such a large complete sample, unbiased against dust, will be suitable for many statistical projects, and will for example remove the reddening bias in the evolution of quasars. The scientific goal we have taken as our key driver is however for searches of special objects - damped Ly$\alpha$ systems, and gravitational lenses.

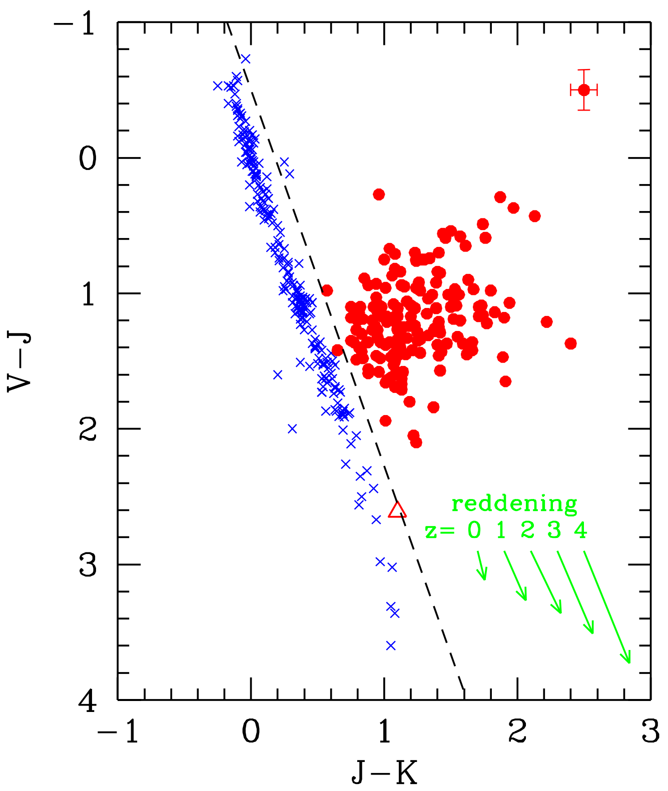


Figure 2.1: *Two colour diagram illustrating the KX method, from Warren et al. (2000). Here the blue crosses mark the colours of main-sequence stars, and the red circles mark the colours of quasars. The arrows show reddening vectors for E(B–V)=0.1 in the restframe of the intervening absorber at the redshift marked, indicating that the KX method is insensitive to reddening.*

**Damped–Ly$\alpha$ galaxies and gravitational lenses free of biases due to dust**

In a recent paper Warren, Hewett & Foltz (2000) explained the motivation for undertaking surveys for bright high-redshift (here z>2) quasars, flux limited in the $K$ band. Optically-selected quasars have been used for two important cosmological studies: (1) the history of gas consumption in star formation, from the analysis of the statistics damped Ly$\alpha$ absorbtion (Pei, Fall & Hauser 1999), and (2) the fraction of quasars that are gravitationally lensed, which provides information on the cosmic geometry (Falco, Kochanek & Munoz 1998). The samples of absorbers and lenses may suffer from a bias, because any absorbers or lenses containing dust could remove quasars from the optical samples, and this would have consequences for the conclusions of these studies. Over 4000 deg$^2$ we estimate there will be 2300 z>2.2 quasars brighter than K=16, and >10,000 over all redshifts. These would produce samples of 500 damped Ly$\alpha$ absorbers z>1.8, and about 100 gravitational lenses.

## 2.7 The redshift seven barrier

The combination of SDSS and 2MASS data has recently created considerable interest by breaking the long-standing z=5 quasar barrier, and indeed reaching z=5.8 (Fan et al 2000). Finding quasars to even higher redshifts is of considerable importance for several reasons :

- To detect the epoch of reionisation, or place a more stringent lower limit to $z_{rei}$.
- In the event of detection of a quasar of redshift $z>z_{rei}$, to probe the neutral IGM before reionisation through measurement of the inverse effect, as well as the detection of the predicted Ly$\alpha$ halo around the quasar (Heep et al. 2000; Loeb & Rybicki 1999).
- To measure the decline of the quasar luminosity function with lookback time. The measurement of the space density of bright quasars at very high redshift provides a sensitive test of theories of structure formation (Haiman & Loeb 2001). The luminosity function also quantifies the contribution of quasars to the ionising background.
- To provide targets for the detection of neighbouring galaxies and structures at the same very high redshifts.

**The epoch of re-ionisation** Perhaps the most exciting reason for searching for very high redshift sources, and much of the motivation for the construction of *NGST*, is due to the hope of detecting and studying the epoch of reionisation. The transition from isolated HII regions around bright sources at early times, through the period of overlap of the ionised regions, to almost complete reionisation of the IGM is predicted to be very rapid, lasting only 10% of the Hubble time (Gnedin 2000). The transformation, then, is of the nature of a phase transition, and marks an era of fundamental significance in the history of the Universe. The reionisation epoch $z_{rei}$ is predicted to occur within the redshift range $7<z_{rei}<12$. Detectable flux in the Ly$\alpha$ forest (i.e. the absence of a Gunn–Peterson trough) in the spectrum of the most distant known quasar at z=5.8 (Fan et al. 2000) places a lower limit on the epoch of reionisation at the emission redshift of this quasar. With the LAS we aim to reach z=7.2 and possibly even higher.

**Need for a new quasar selection technique**. The multicolour technique for finding high-redshift quasars requires three filters, one containing the quasar's Ly$\alpha$ emission line, one blueward (the "dropout" band), and one redward. (See Fig 2.2.) Fan et al. 2000) combined i$'$ and z$'$ from SDSS data with the 2MASS J filter.

| | 4000 deg$^2$ | 4000 deg$^2$ |
|---|---|---|
| | Y<19.0 | J<19.5 |
| | 5.8<z<7.2 | 7.2<z<8.0 |
| Fan et al. | 10 | 3 |
| SSG | 11 | 4 |

Table 2.2: *Estimated numbers of quasars computed using the luminosity functions of Fan et al. (2001a), and Schneider, Schmidt & Gunn (1995).*

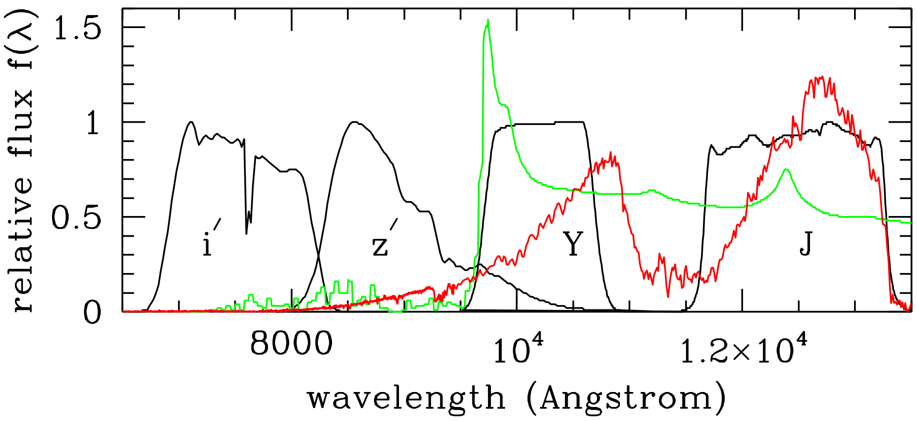


Figure 2.2: *Illustration of drop-out method for finding quasars, and the proposed new Y filter. The green line plots a model spectrum of a typical quasar of redshift z=7. The red line shows the spectrum of the T dwarf SDSS1624 (Leggett et al. 2000b). The filter transmission curves (including atmosphere) are plotted black. For i′, z′, these are based on the latest SDSS measurements in Fan et al. (2001b). The gap between Y and J is a region of strong atmospheric absorption.*

The shallowness of the 2MASS J survey (J=16.7) means that this technique uses only a fraction of the SDSS data, down to z′ ∼18.8, compared to the survey limit of 19.9. With the LAS survey limit of J=20, we will match the SDSS better and will find greatly increased numbers of z=6 quasars, and probe further down the luminosity function.

However even with deep J data, the i′z′J method breaks down beyond z=6, because the quasars become rapidly redder and much fainter in z′, so will have only upper limits in z′, and so will be indistinguishable from T dwarfs. This is illustrated in Fig.2.3 and is also clear from Fig.2.2. We have undertaken a methodical study of filter choice for finding z>6 quasars. This is described in Appendix A, but a brief summary follows.

One might imagine that z′JH or z′JK is the obvious choice. However, using z′ with any combination of of J, H, K is not satisfactory as quasars have very similar colours to cool stars over the redshift range 6<z<7.2, and beyond $z = 7.2$ are extremely faint in z′. At z=7 we predict z′–J=3, so that to match J=20 requires a survey z′ ∼23, much deeper than SDSS. Instead of relying on z′, imagine shifting the central Ly$\alpha$ to a band between z′ and J. We call this proposed new band the Y band, covering 0.97–1.07$\mu$m, as shown in Fig 2.2. Fig. 2.3 shows the i′YJ two-colour diagram, showing that we can distinguish z=6-7 quasars from T-dwarfs clearly, if we survey to a depth Y=20.5. In the longer term our aim would be to envisage a large area very deep z′ survey, perhaps with VISTA, to probe the region z=7-8.

All quasars 5.8<z<7.2, Y<19.0 are selected by the criteria shown in Fig2.3. Beyond z=7.2 quasars redden rapidly in Y–J. The Y magnitude limit is set by the i′–Y>3 colour selection limit, and by the i′=22 limit of the Sloan survey i.e. we are picking the *very brightest* quasars in this redshift range, which are of course the most valuable for absorption-line spectroscopy. We can compute the expected numbers using the latest luminosity function of Fan et al. (2001a), as well as the older luminosity function of Schneider, Schmidt & Gunn (1995), based on lower-redshift data. The results are provided in Table 2.7. By surveying 4000 □° we can expect to find 10 quasars at 5.8<z<7.2. These numbers can easily be increased when deeper i′ data become available. More interestingly, as explained in the appendix, one can envisage extending this work up to redshift z=8 (and beyond) with very deep widefield data in the z′ filter, reaching to z′=22.7. With imaging to this depth over 4000 □°, then a survey to J=19.5 would be expected to find 3 to 4 quasars in the redshift interval 7.2<z<8.

## 2.8 Technical requirements

**Survey depth**. The natural depth of the survey is set by the expected overheads, as discussed in section 1.7, leading to $5\sigma$ point source limits limits Y=20.5, J=20.0, H=18.8, and K=18.4. Each of these results from a single pass at the minimum sensible integration time without becoming too inefficient, except for J that has two passes. Note also that we have defined a standard magnitude scale for the proposed new Y filter assuming zero colours for Vega. The increased J-depth follows from both the need for proper motions, and the need to measure red objects.

**Proper motions**. To determine proper motions a repeat visit in either J or K (see below) is required 2–3 years after the main JHK observation. It was originally envisaged that the repeat observation would be done in the K band. This would improve the overall K limit by a factor $\sqrt{2}$ or 0.4 mag. However, the objects that have proper motion stars, in particular L and T dwarfs, are best measured in the J band. In particular, the best hope of recognising Population II brown dwarfs must be from their large proper motions. This suggests the second epoch survey should be done in the J band. The ultimate decision on this issue will be made when the J–K colours of L, T and brown dwarves are better constrained.

**Choice of filters**. Many of the most interesting objects will be very red, and the fainter ones will not be present in the SDSS. Three IR bands (JHK) are therefore certainly necessary for diagnostic purposes. Furthermore, to measure colours for the reddest objects J needs to be deeper than a single pass. (see Fig. 2.4.) On the other hand, the coolest T dwarfs are expected to be relatively blue, so that searches for these may have to limit the search to J<19.5.

In the previous section we made the case for the use of a new Y filter to look for high-z quasars. More detail is provided in the Appendix. Here we add the inverse point, that the Y filter will help to separate out T dwarfs from quasars, and indeed help in stellar classification in general.

**Survey Area**. The ambition of being a fundamental sky atlas argues for complete Northern Hemisphere coverage but that is not yet feasible. Large scale structure and galaxy and quasar population studies require a few thousand square degrees in order to build up large statistical samples. The key issue is the rare object searches - redshift seven quasars, solar neighbourhood substellar objects, halo brown dwarfs. We set survey size at 4000 sq.deg. to aim at approximately ten of each of these.

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# Appendix A: selection of very high-redshift quasars $5.8 < z < 8$

We have made a detailed study of the opportunities for UKIDSS to extend the explorable redshift range substantially beyond that reachable by Sloan. Fig 2.5 shows how Fan et al. (2000) found the highest-redshift quasar currently known, z=5.8. At redshift z∼6, in i′–z′, quasars are redder than all stellar objects except brown dwarfs, but bluer than brown dwarfs in z′–J. Redshift z∼6 quasars can be found by searching in the selection box shown. In principal this method works up to about z=6.4, but reaching beyond z=6 may be difficult for Sloan because of the limited depth of the near-infrared data provided by 2MASS, and because the quasars rapidly dim in z′ beyond z=6 due to absorption in the Ly$\alpha$ forest. More z=6 quasars will be found by employing the deeper J data from UKIDSS, but the redshift limit can only be extended substantially by searching at longer wavelengths.

Using z′ rather than i′ as the dropout filter is an order of magnitude more difficult. This is because in the red colour, which would now be either J–H or J–K (or indeed H–K), the quasars are no longer bluer than the brown dwarfs. This is illustrated in two plots in Fig 2.5. Using combinations of the z′JHK filters, quasars in the redshift range 6<z<7.2 have very similar colours to cool M stars, and L dwarfs. Either of the two-colour diagrams shown in Fig 2.3 become effective at higher redshift still, beyond z=7.2, but three things act against such a search: (1) the colour limit z′–J>3.2 is very red, requiring very deep $z'$ data, (2) the quasars are fainter, as further away, and (3) the quasars are rarer, because of the decline in space density. Clearly a z′JH survey is too ambitious as the first step beyond Sloan – there may not be any z>7 quasars.

The discussion above explains the motivation for introducing the new Y filter, and surveying the redshift range 5.8<z<7.2, as laid out in the main text.[2] In fact it is difficult to see how this redshift range can be explored in any other way. This approach has the advantage that the optical data already exist, and that the depth is relatively easily achievable, because the filter is sampling the quasar continuum.

WFCAM in any case is not really competitive for surveys in the z′ band, because optical cameras with much wider fields of view are being planned. On a similar timescale to the UKIDSS surveys one can envisage deeper i′ and z′ data becoming available. The J and H data of the UKIDSS LAS will reach deep enough to make a survey for quasars in the redshift interval 7.2<z<8 feasible. If UKIDSS finds quasars at redshifts as high as z=7, this will provide the argument for a wide-field very deep survey in z′, using VISTA for example. As noted in the main report, a survey covering 4000 □° to z′=22.7 would be required.

[2] We also considered a narrow filter $Y_n$ at 1.05–1.07$\mu$m, where the sky is darker. This filter is faster, but because of the longer wavelength does not provide discrimination between T dwarfs and quasars.

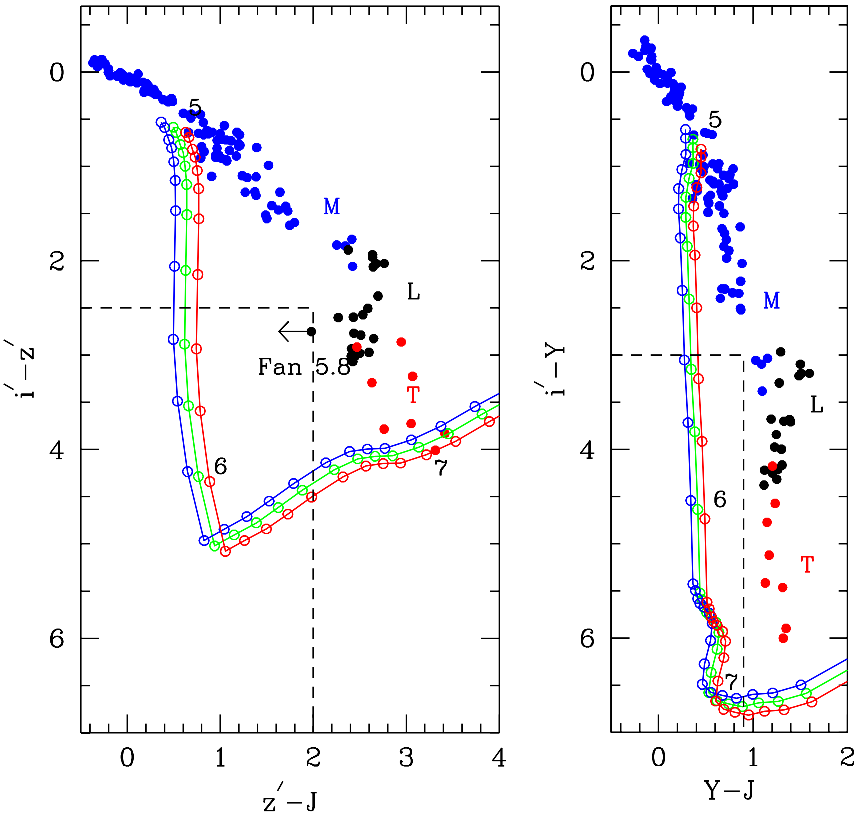


Figure 2.3: *Two-colour diagrams used for finding high-z quasars. The blue circles are main sequence stars in the Gunn-Stryker atlas, as well as cool M dwarfs, down to M9.5, from Leggett et al. (2000a, 2001). The black circles marked L and the red circles marked T are brown dwarfs taken from Leggett et al. (2000b, 2001). The open circles are the modelled colours of quasars in the redshift range $5<z<8$ in steps of $\Delta z$=0.1, and with three different continuum slopes from hard to soft, represented by blue, green, and red lines.*
**LHS :** *$i'z'J$ diagram as used by Sloan for finding quasars in range z=5-6. This illustrates how quasars become hard to distinguish from T-dwarfs by z=7.*
**RHS :** *$i'YJ$ diagram using the proposed new Y filter, and the selection box that could be used to find quasars in the range z=5.8 –7.2.*

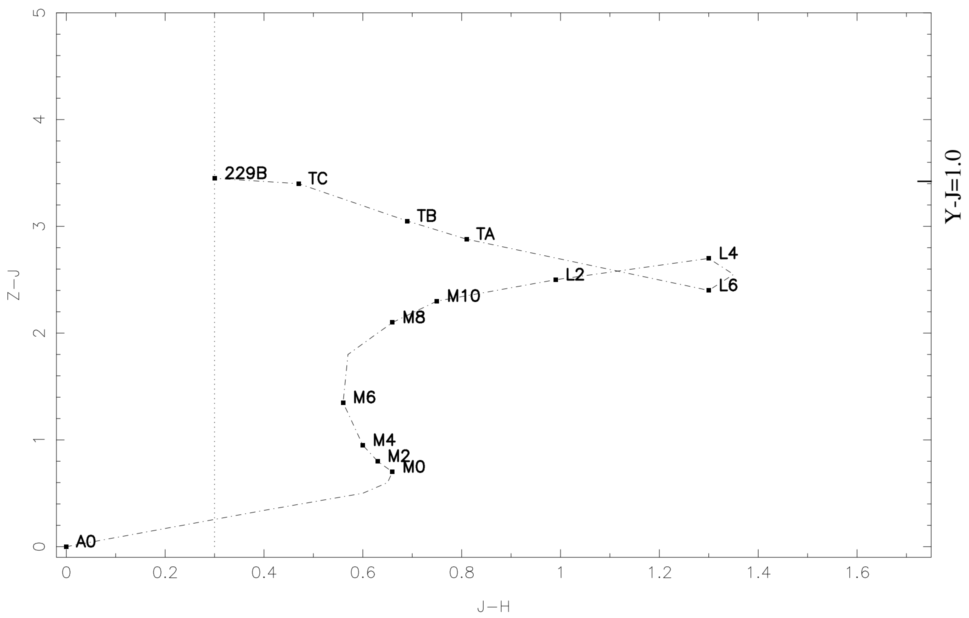


Figure 2.4: *Colour-colour plot for late type stellar like objects.*

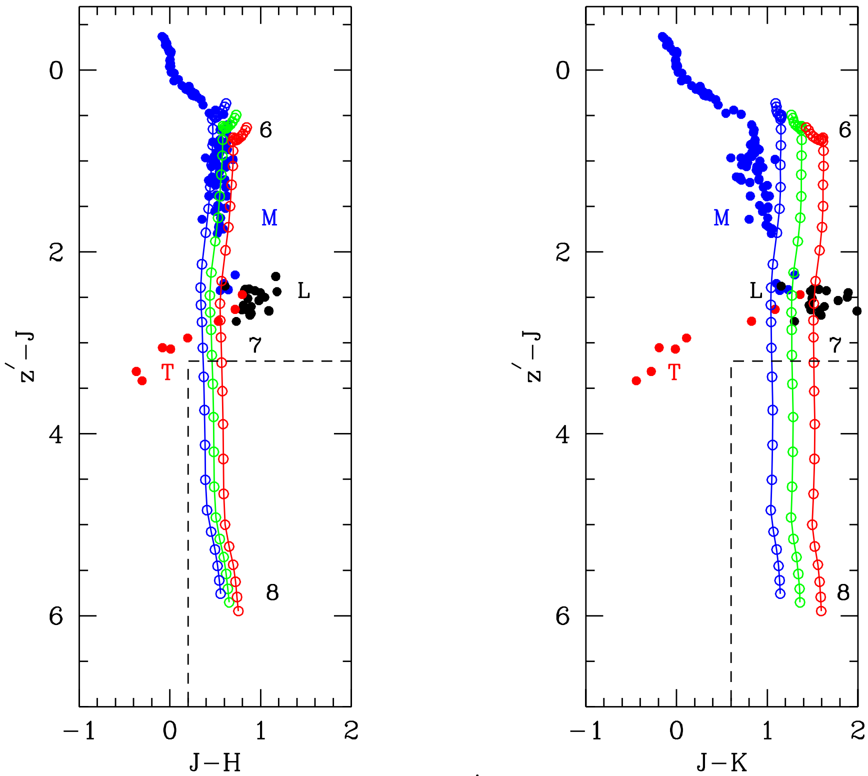


Figure 2.5: *Two-colour diagrams showing how the z′ filter would be used as the dropout band. LHS is the z′JH diagram, and RHS is the z′JK diagram. The symbols and colour coding are as in the main text. Using either J–H or J–K as the red colour, quasars do not stand out clearly from the cool M stars and L dwarfs. Quasars at redshift z>7.2 could be selected by identifying objects lying in the box shown. Note that in J–H and J–K, brown dwarfs become bluer as they cool along the sequence L to T.*

# Chapter 3

# The Galactic Plane Survey
*Lifting the veil on the Milky Way*

## Summary

Optical studies of the galactic plane are hindered by the absorption by material in the disk of the Galaxy. The infrared window offers a much clearer view of the structure of the Milky Way and WFCAM will allow us to study individual objects and the Galaxy itself with unprecedented precision. This survey will map a large fraction of the galactic plane and will form the basis of a complete survey of the Galaxy. The 5-$\sigma$ magnitude limits of this survey are J=20.0, H=19.1, K=19.0 over a total area of $\sim 1800\,\square^\circ$. Additional more specialised observations of $300\,\square^\circ$ in star-formation regions with a narrow band $H_2$ filter are also proposed.

## 3.1 Motivation

A large area near infrared (IR) survey of the galactic plane (GPS) will be beneficial to many areas of stellar astrophysics, e.g. Star Formation, X-ray Binaries, AGB-stars, Protoplanetary Nebulae and Brown Dwarfs. In addition, the proposed GPS is conceived as a Legacy database and Atlas, with the long term goal of complete coverage of the Galactic Plane, which will require the addition of data from VISTA. The Atlas will lead to a major advance in understanding of the structure of the galaxy. The science described below is not intended to be a complete list but merely an indication of the most important science drivers presenlty identified by the UKIDSS consortium. The UKIDSS GPS will cover the entire northern plane in JHK up to 60° Declination, with two repeat scans at K band to provide the data needed to identify variability in the $10^8$–$10^9$ sources detected. The variability data on so many sources will also detect phases of stellar evolution which are rarely or never observed, such as ignition of helium or carbon in the core or envelope of evolved stars. The database will be an invaluable resource for future science in all wavebands both for statistical studies and for baseline infrared photometry of newly discovered sources. The Atlas will locate all bright stellar populations (main sequence types O–F and giant stars) throughout the galaxy by virtue of the low galactic extinction in the K band. The fainter stellar populations (main sequence types G–M) will also be detected at distances of several kiloparsecs. Distances will be determined by dereddening in a two–colour diagram and kinematically via follow up in the radio waveband.

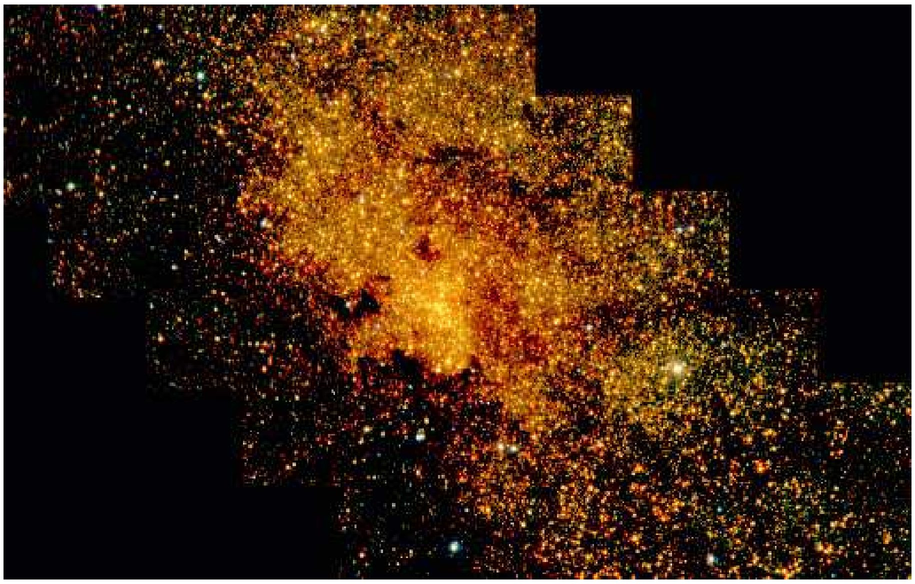

Figure 3.1: *True colour JHK mosaic of the Galactic Centre, taken in July 1999 with UFTI on UKIRT, and covering a region approximately 7.5 × 4.5 arcmin. The exposure was 30 seconds per filter. Image taken from the UKIRT web page. Data obtained and reduced by Ant Chrysostomou.*

## 3.2 Star formation

A wide-field WFCAM survey would advance our understanding of star formation in three main areas: (1) the star formation process; (2) the distribution of star formation regions (SFRs) throughout the galaxy and spatial variation in their properties; (3) the shape of the IMF. Some of this science overlaps with the Galactic Clusters survey, which is targeted toward nearby star clusters outside the galactic plane.

**The star formation process:** A consensus is beginning to develop concerning the main evolutionary stages of low and high mass star formation but the picture becomes very uncertain for the youngest objects. These are initially visible only at far-IR and radio wavelengths, but later become bright near-IR sources as the birth cloud disspiates. High mass YSOs swiftly settle on to the Main Sequence and blow away their circumstellar material. Their presence in a cluster can profoundly influence the evolution of lower mass YSOs by triggering more star formation or by photoionising the envelopes of low mass systems which are still in the process of forming. This is seen in Orion and M16. Hence there are probably many modes of star formation and it is desirable to obtain high quality images of a large number of SFRs to see all the various modes at as many different stages as possible.

The embedded, rapidly accreting phases of star formation are the least understood. We estimate that the GPS will detect 100–500 embedded high mass YSOs (8–100 $M_{\odot}$), at least $10^4$ YSOs of solar mass and perhaps $10^5$ YSOs integrated over all masses (see Technical Justification). This is an order of magnitude increase on the known populations.

UKIDSS can answer the following key questions by surveying several hundred SFRs:

**(Q1)** : What is the duration of the early evolutionary phases as a function of mass, and how much is this altered in different environments ?

**(Q2)** : Jets, macrojets and molecular outflows - are they ubiquitous, when do they begin, how long do they last, do they remove much angular momentum ?

**(Q3)** : Is accretion in the disk steady or unsteady and does this lead to discrete ejection of matter which can be traced by knots in stellar jets?

Questions (1) and (3) can be addressed by JHK imaging. The evolutionary stages will be characterised by luminosity, extinction, K band excesses, circumstellar nebulae and variability. With $10^4$ low mass sources the sample could be divided into e.g. ten mass and ten age bins yielding a statistically reliable sample of 100 sources per bin. The existing mid-IR galactic plane survey of the *Midcourse Space Experiment, MSX* (Egan & Price 1996) will be very useful for detecting and quantifying weak IR excesses, at least in nearer clusters which were spatially resolved. A key bonus of a very large survey will be the detection of 10 to 100 FU Ori systems during the onset of an outburst. FU Ori systems are YSOs in the rare state of very rapid accretion and associated outflow activity, with a duty cycle of $\sim$ 1% of the pre-main sequence period. This unsteady accretion behaviour is believed by some leading researchers (e.g. Hartmann & Kenyon 1996) to be ubiquitous among YSOs at some level, although the level of contrast between high and low accretion states may have some variation. FU Ori stars are young, at least partially embedded systems, which undergo a large increase in brightness (6 magnitudes for FU Ori) with spectral signatures of strong accretion. This bright state persists for years or decades. Only eight such systems are known, none of which have undergone an outburst recently enough for the onset to be observed with modern IR instrumention. The rise in flux would easily be detected with a few epochs of data over a period of $\sim$5 years. The pre- and post-outburst fluxes will quantify the frequency and magnitude of these events. A multipass survey is also essential to identify YSOs via variability in T Tauri stars and Herbig Ae/Be stars. This will tend to identify the older, optically visible YSOs which lack clear IR excesses. Only $\sim$1/3 of YSOs have detectable K band excesses (Kaas 1999) and these cannot be measured if the source is obscured at J band.

A handful of parsec-scale “macrojets” have very recently been discovered in nearby SFRs, subtending significant fractions of a degree on the sky and with dynamical ages implying a very early origin. A 2.12 $\mu$m $H_2$ survey will detect a statistically useful number of macrojets, measure their proper motions and dynamical ages. The assembled statistics will answer Question (2). $H_2-K$ difference maps will distinguish unresolved knots from stars and reflection nebulae from line emission nebulae. Crucially, the maps will detect the youngest, most embedded (Class 0) systems with no apparent source via stellar jets, providing key data for Question (1). Knots and working surfaces in the jets will also trace the ejection/accretion history of YSOs over a period of thousands of years and the interaction between jets and the interstellar medium (ISM). The proper motion information will also illustrate the dynamics of each jet. Do macro-jets accelerate, decelerate, or exhibit periodic velocity variations? Such information is important for jet models and for interpreting the influence the large-scale ISM has on macro-jets, but requires statistically significant sample of measurements. The detection of more FU Or systems will shed light on the relationship between steady/unsteady accretion and stellar jets, i.e. Question (3). An $H_2$ survey would become time consuming and ineffective at large distances (kpc) so we propose a complete JHK+$H_2$ survey of the Taurus-Auriga-Perseus molecular cloud complex, since this is the nearest SFR in the northern hemisphere. The region lies on the galactic plane but extends some way below it. The region has an area of 300 $\square^\circ$ is defined by the presence of molecular gas, e.g. Ungerechts & Thaddeus (1986). It includes all the well known dense Lynds subclouds, the lower density gas between them and the nearby high mass IC348 star forming region. This will provide an unbiased survey of outflows in SFRs, probing Class 0, Class I and Class II systems. Since this region will also be observed at JHK in the Galactic Clusters survey, there is no need for narrow band continuum observations. Radio continuum follow-up with SCUBA/SCUBA-2 and CO observations with HARP at the JCMT are expect to begin in the 2004–2005 time frame as soon as the first scan is complete. We would expect to detect several dozen macrojets in this complex but the number cannot be well quantified. The JHK component is included in the Galactic Clusters–IMF case. The survey would be followed up by observations of the continuum sources which power the jets using SCUBA/SCUBA-2 and by large scale CO(J=2–1) mapping of the molecular outflows with HARP on the JCMT.

**Distribution of star formation and the IMF:**
The distribution of SFRs in the galaxy is at present inferred primarily from low resolution CS and *IRAS* mapping. We wish to learn how the density of SFRs varies with distance from the galactic centre and in different spiral arms and also study spatial variations in the IMF. At present there is evidence that star formation efficiency is higher at the solar circle than in the inner galaxy (Bronfman et al. 2000; Casassus et al. 2000) but this information depends upon the heating of dust and gas by young OB stars for IRAS detection of dense clouds emitting in the CS(J=2-1) line. Since low mass YSOs are brighter than their main sequence counterparts, UKIDSS will have the sensitivity to study the IMF down to brown dwarf masses in the nearer spiral arms and down to a few tenths of a solar mass throughout the galaxy (except along lines of sight which suffer very high extinction). These data will complement the more sensitive UKIDSS Cluster Survey by studying a much larger number of clusters in a wider range of environments, and will therefore measure how much environmental dependence exists in the IMF. The distances to clusters will be determined from the colours of the brightest members (see below), and independently by radio follow up. The *MSX* mid-IR satellite located several hundred SFRs, most of which will be accessible to WFCAM. The coadded IMFs of all the clusters will yield the first near-IR measurement of the galactic star formation rate, which is presently a highly uncertain quantity.

## 3.3 The atlas and galactic structure

By imaging in 3 near-IR bands it will be posible to construct a 3-D Atlas of the galaxy. Distances will be determined by dereddening in a JHK two–colour diagram and kinematically via follow up in the radio waveband. It will not be possible to reliably determine the distance to every star, since many will not have J band detections. However O, B and A type stars all have similar and well known IR colours (Planckian spectra) so it will be possible to deredden these sources to a colour–magnitude main sequence even with just H and K band detections. Uncertainty in derived luminosity may be ~10% due to the width of (or calibration errors in) the main sequence but this leads to only a 5% uncertainty in distance. We emphasise that the near-IR dereddening law is effectively uniform throughout the galaxy (Clayton, Cardelli & Mathis 1989) despite the spatial variation seen in the optical; this is because dust grain radii are much smaller than the wavelength of observation for $\lambda \geq 1$ $\mu$m, except in extremely dense environments such as accretion disks.

By mapping out all the bright stars throughout a large fraction of the Milky Way, the GPS Atlas will provide an unprecedented tool for studying the three-dimensional structure of the Galactic disk. 21cm studies have shown that the outer parts of the Milky Way's gas disk is strongly warped away from the Galactic plane (Burton & te Lintel Hekkert 1986), and it would be very interesting to ascertain whether the stellar distribution is similarly warped. If there turns out to be a difference between the two, then it will be hard to explain the warp as a purely gravitational phenomenon, and gas dynamics must be viewed as an important factor.

Carney & Seitzer (1993) found tentative evidence for a stellar warp using optical data, but were hampered by reddening, and were unable to quantify its morphology. Porcel et al. (1997) analyzed the diffuse K-band emission in the Galactic plane (as recorded by the COBE satellite), and concluded that these data were not consistent with the warp in the gas unless the stellar distribution is truncated at $\sim 15$ kpc, or the light is dominated by local features in the stellar distribution. However, lacking distance information, they were not able to discriminate between these interesting hypotheses.

With the GPS observations providing positions and distances to stars throughout a large part of the Milky Way, it will be possible to see directly where (if at all) the disk is truncated, and whether the stars's locations deviate from the Galactic Plane in the same manner as the gas. The sky coverage of the survey will sample the warp structure very effectively. In the integrated K-band flux, Porcel et al.'s (1997) model for a non-truncated warped disk shows a maximum deviation in the peak surface brightness of $\sim 2°$ above the plane at $l \sim 100°$, while the GPS observing window $150° < l < 230°$ would trace such a warp from approximately the Galactic mid-plane down to the maximum deviation below the plane of $\sim -2°$. By introducing the third dimension of approximate distances, the stellar distribution will be fully mapped out in these regions, finally giving a definitive picture of the stellar warp and its origins.

## 3.4 Counterparts to X-ray and $\gamma$-ray sources

Most X-ray binary systems are strong IR sources. The *XMM-Newton* satellite is studying the hard X-ray radiation from these systems, which also penetrates high galactic extinction, so the UKIDSS GPS offers an excellent opportunity for comparative studies which will identify the infrared counterparts. The *INTEGRAL* satellite will also provide complementary data at hard X-ray and $\gamma$-ray energies.

A clear goal of combining the UKIDSS-GPS/*XMM-Newton* surveys is to resolve the galactic X-ray Galactic Ridge Emission. This ridge emission may be truly diffuse hot gas, or more likely consists of a large number of currently unresolved point sources, such as Cataclysmic Variables (CVs) and Active Stars. In addition *XMM-Newton* will locate many new supernova remnants, star formation regions (SFRs) and X-ray binaries (see Technical Justification), all of which will detected by the GPS in statistically useful numbers. The X-ray emission from SFRs will aid in the identification of very young clusters (5-20 Myr) detected by WFCAM but lacking significant extinction after star formation is completed.

In high-mass X-ray binaries (HMXB), IR emission arises from the circumstellar disk which undergoes major expansions in phases of X-ray activity. The near-IR flux and J–K colour provides valuable information on the temperature and density in the circumstellar environment. This information can then be related to the mass accretion rate on to the compact object. In low mass X-ray binaries (LMXB) the emission arises both from an accretion disc around the black hole or neutron star, and from the companion star. Both are heated by X-rays from near the compact object and reradiate this energy at IR to ultraviolet wavelengths.

Transient LMXBs appear to be predominantly black-hole systems which spend most of their time in X-ray quiescence, leaving their optical/near-IR emission dominated by the cool secondary star and with only a small component from the residual disc. Hence accurate IR colours contain valuable information about the luminosity and spectral type of the companion and allow, by comparison of data taken when sources were in quiescence and activity, the unraveling of the physical properties of the system and the details of the outburst events.

The GPS will provide photometry and colours for several hundred known X-ray binaries. Many more will be identified via variability in a multipass survey, which is especially crucial in cases where X-ray coordinates are accurate to only a few arcsec. Thousands of CVs and active stars will also be detected in the regions of the *XMM-Newton* galactic survey, providing an invaluable database for statistical studies. For X-ray binaries WFCAM will provide the following scientific benefits:

1. X-ray all-sky monitors, such as that on *RXTE*, permit the immediate location of new transient sources. When such new sources appear, access to the UKIDSS survey will provide prompt identification of the quiescent IR counterparts (provided X-ray coordinates are accurate to several arcsec). This is extremely valuable (when combined with new images of the field) in determining the nature of transient (HMXB or LMXB) and deciding on the appropriate rapid follow-up observations that are necessary with ground based telescopes.

2. Many known X-ray binaries in the galactic plane are only visible in the near-IR due to extinction. Thus, the GPS data will often be the only optical/IR information available on the counterpart. These reddened objects are crucial because (i) by accessing a larger population we can draw firmer statistical conclusions and (ii) there may be different X-ray binary populations in different parts of the galaxy, e.g. there appears to be a population of transients in the Galactic bulge exhibiting much shorter outbursts than those in the nearby disk (days instead of months).

3. For known transient sources (both HMXB and LMXB) the survey will provide us with a complete and systematic study of their quiescent counterparts. This will allow a detailed investigation of the properties of the mass-losing star, quiescent disc and circumstellar disc. For the X-ray bright (and "steady") X-ray sources, this survey will provide a valuable reference catalogue of near-IR magnitudes and colours, which is essential for individual follow-up campaigns.

## 3.5 AGB stars/PPN/Pne

AGB stars, protoplanetary nebulae and planetary nebulae are widely distributed throughout the galaxy. These objects are very bright in the IR ($> 10^3 L_\odot$) and often shine right though the Galactic Plane extinction, which makes them useful probes of Galactic dynamics and chemical evolution (e.g. Dejonghe & Caelenberg 1999). Since the post-AGB/PPN phase is brief, only a few hundred of these sources are presently known, most having been detected by the *IRAS* all-sky survey. UKIDSS has the capability to detect and image many thousands of AGB and post-AGB objects thus providing essential information of their Galactic distribution. There has been substantial progress recently in observing the complicated processes at work as a red supergiant star evolves into a planetary nebula, both with *HST* and using ground-based techniques such as imaging polarimetry (Ueta et al. 2000; Gledhill et al. 2001). The UKIDSS survey will have sufficient spatial resolution to detect structure in the dusty envelopes of the more evolved post-AGB sources and provide a unique survey of PPN morphology. The near-IR survey can be combined with mid- and far-IR data to identify PPN via the thermal continuum emission and solid state signatures of the shells of gas and dust which they are ejecting. Mid-IR data will be provided by the *MSX* galactic plane catalogue and we anticipate that far-IR data will be provided by *Astro-F*, a Japanese satellite due to be launched in 2003, which will survey the whole sky at 50–150 $\mu$m with 20 times better sensitivity than *IRAS* at 50–60 $\mu$m. These wavelengths will be most useful for detecting new sources, whose IR counterparts will then be located in the UKIDSS GPS. Finally, since AGB and post-AGB stars are variable both photometrically and in their mass loss rate, a multipass survey such as the GPS will provide greater completeness (by ensuring that fainter objects are not missed because they were at minimum) and information on variabilities and hence evolutionary state. Variability data will also pick up the very rare AGB stars undergoing nuclear pulses in the envelope (e.g. Sakurai's object) and possibly other, so far unobserved periods of rapid stellar evolution.

## 3.6 Brown dwarfs

The study of brown dwarfs has progressed with astonishing rapidity in recent years. This science is described in detail in the Large Area Survey and the Galactic Clusters Survey but we note that similar science can be done with the GPS, detecting L dwarfs, T dwarfs and even cooler objects at very small distances. The strengths and capabilities of the GPS differ slightly however from those achievable by the LAS and GCS. There will be no Sloan i or z band coverage of the GPS, necessary to identify brown dwarfs via the steep rise in flux from 0.7–1.1 $\mu$m. Cool T-dwarfs (such as Gl229b) can be confused with O–F type stars with similar near-IR colours. However, this will not be an issue near the galactic plane because an A0V star with T dwarf colours would have to lie at $\sim$10 kpc distance to appear as faint as a T dwarf at 10 pc at J band. Such interlopers will readily be rejected by their reddening: $A_V > 10$, E(J–K)$>$ 1.7 mag. In addition proper motions detected by a few epochs of observation over several years will clearly identify sources at $\leq$ 100 pc. The only sources which will be hard to identify will be objects at the L/T transition, with similar colours to M and L dwarfs, but the few sources in this narrow temperature range near 1400 K will be adequately studied by the Large Area survey.

The GPS will have the following strengths for brown dwarf work. (1) It will have high sensitivity at J band, to combat extinction toward distant stars, so it will be very sensitive to the coolest, nearest brown dwarfs. (2) The survey will be capable of detecting L dwarfs ($11.8 < M_{\rm Jup} < 14.5$, Kirkpatrick et al. 2000) to distances of several hundred pc. This sample of more distant L-dwarfs will allow us to confirm that the local space density is not unusual. (3) Detection of many brown dwarfs in star formation regions, as noted earlier. (4) Proper motion data which will provide an indication of source age. We expect kinematic differences between young L-type brown dwarfs and old L-type red dwarf stars which have cooled off the M-dwarf sequence after many Gyr.

## 3.7 Technical requirements

**Repeated observations** For much of the proposed GPS science, variability or proper motion is a valuable component. For the outflow work proposed above one would like to survey the same region three times over $\sim$ 5 years. Such a repetition rate would be suitable for X/$\gamma$-ray studies as well, although three passes is the bare minimum for identification of variables. Observing efficiency is reduced if the survey is split into many shallow passes, so we recommend three scans in the K filter spread over $\sim$ 5 years as the best compromise, with more efficient single scans in the J and H filters.

**Choice of filters** The J, H and K filters are essential for all programs since JHK imaging permits extinction correction and luminosity/distance derivation for stars whose intrinsic colours and distance are not precisely known (which will usually be the case) by dereddening in a two colour diagram. At least 2 filters are also needed to measure the temperature of stars and accretion disks.

A multipass survey in the narrow band $H_2$ filter (2.12 $\mu$m) in a single nearby SFR is an important component of the Star Formation science case. The youngest, most embedded protostars will only be identified via detection of their molecular outflows and these outflows will also measure source age and accretion history.

UKIDSS could undertake Y band observations (see Large Area case) at $\sim$1 $\mu$m, sampling the small peak in the spectral energy distribution of brown dwarfs near 1.05 $\mu$m and thereby providing a measurement of effective temperature. However this would not be very useful for any other galactic science outside the solar neighborhood owing to the relatively high extinction at 1 $\mu$m, so such observations should be conducted as a follow up study to determine source temperatures. The extinction of distant high luminosity main sequence stars will permit simple and reliable identification of brown dwarfs in the (J–H) versus (H–K) plane without Y band.

**Numbers of YSOs:** Using a Salpeter IMF with the currently accepted star formation rate of about 1 $M_\odot$/yr, we estimate that the galaxy contains about 2000 high mass YSOs (8–100 $M_\odot$) and 2 million low mass YSOs of solar mass and above, assuming pre-main sequence lifetimes of $10^4$ yr for the high mass sources and $10^7$ yr for the lower mass sources respectively. There are perhaps $10^8$ YSOs of all masses, assuming there are $10^{11}$ stars in the galaxy with ages randomly distributed between zero and $10^{10}$ years. A UKIDSS GPS covering the northern half of the plane will detect 100–500 embedded high mass YSOs (assuming 50–90% are obscured by dust): an order of magnitude increase on the known population. Solar mass and above YSOs will be detected at distances of up to 5 kpc to a limit of $m_K$=18.8, depending on the amount of extinction, so the GPS will detect at least $10^4$ of these and perhaps $10^5$ YSOs in total. These numbers are order of magnitude extimates, which become highly uncertain at the low mass end.

**Survey depth and area coverage** Large area coverage is more important scientifically than pushing right to the confusion limit: a substantial section of the plane is required to enable meaningful cross-correlation with the *Astro-F* and *INTEGRAL* surveys, and to create a useful atlas. However, obtaining the greatest practicable depth consistent with a large survey is important for all of the science cases described in Section 3.1, with the possible exception of AGB stars.

The basic logic behind our choice of area and depth is then as follows. We aim to survey to latitude $\pm 5°$, as this matches many other surveys, for example the recent MSX 4-20$\mu$m survey, and includes most of the galactic disk at more than 2kpc distance. We then aim to survey as much longitude as possible, given a reasonable airmass restriction ($\delta > -15°$) and the UKIRT declination limit ($\delta < 60°$). This leads to two longitude regions defined by $15° < l < 107°$ and $142° < l < 230°$, an area of $1800\square°$. Given this area, in a reasonable fraction of the total UKIDSS programme time we can afford to go approximately a factor of two longer than the standard minimum “shallow” depth.

Depth in K is more important than depth in J, because of reddening. It is the K-band that allows us to reach to the far side of the Galaxy. We also wish to have repeat observations, and choose to do these in K. Our final strategy is therefore to visit each position once at J and H, with twice the standard shallow depth, and three times at K, each of which being equal to the standard depth. This leads to survey limits J=20.0, H=19.1, and K=19.0.

Source confusion is potentially a limiting factor for the GPS. However UKIRT observations made with UFTI by A. Adamson have shown that confusion is not significant at K=19, at least for $l \geq 40°$. By this we mean that accurate photometry of $\geq 90\%$ of point sources can be obtained – occasional confusion among sources at the detection limit is not important. There are complicated latitude and longitude dependent variations in confusion but these cannot be usefully quantified in advance of the survey. It will be important to test the confusion limit at $15 < l < 40°$ during summer 2001, in case it should be much brighter but this is only a small part of the survey area.

The only additional requirement is the proposed $H_2$ survey of the Taurus-Auriga-Pereus (T-A-P) region, with an area of $\sim 300\ \square°$, defined by the presence of molecular gas. The JHK observations of this region are included in the galactic clusters survey. The T-A-P region lies just below the plane, and in fact $18\,\square°$ of it are inside the b= $\pm 5°$ band of the GPS, near l=165° and l=180°.

For the $H_2$ survey an integration time of a 2 to 3 minutes is the minimum to detect typical outflows. The broadband K filter can be used for continuum subtraction. We aim to detect proper motions of the brighter knots, and so build up the survey in three separate passes.

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# Chapter 4

# The Galactic Clusters Survey
## *The substellar mass function : young brown dwarfs and planets*


### Summary

The UKIDSS Galactic Clusters Survey aims to measure the substellar mass function (MF) in a number of Galactic clusters and star formation associations. We will determine, with good statistics, the form of this function down to masses between 10 and 40 Jupiter masses (depending on cluster age/distance) in a variety of Galactic environments. These observations will yield a survey of the MF and the evolution of the fundamental initial MF as a function of environment and age. The required magnitude limits of this survey are J=20.0, H=19.2, K=18.4 over a total area of $\sim 1600\,\square^\circ$. The total on–source integration time is $\sim 370$ hours.


## 4.1 Motivation

Broadly speaking, the process of star formation (SF) is now reasonably well understood in terms of hierarchical fragmentation of collapsing molecular clouds (Levy & Lunine 1983; Mannings, Boss & Russell 2001). In detail, however, there is no complete picture of SF (Shu et al. 1987). In particular, the spectrum of masses resulting from the SF process, commonly known as the initial mass function (IMF), cannot be predicted. This is unfortunate, because the IMF is a fundamental tool in studies of galaxy formation, stellar birthrate (Miller & Scalo 1979), the chemical evolution of galaxies (Cameron 1993) and the contribution of substellar objects to the total mass in stellar systems (Hambly, Knox & Hawkins 1999a). This last point is particularly interesting, since brown dwarfs (BDs; $m < 0.08\mathrm{M}_\odot$) have relatively high mass–to–light ratios at large ages and are not easily observed. It is only recently that small–scale, deep infrared studies have begun to tackle the question of the form of the very low mass IMF.

This proposal aims to *measure* the very low mass end of the stellar MF in a number of clusters and associations to masses $m \sim 0.01\mathrm{M}_{\odot}$ ($\sim 10\mathrm{M}_{\mathrm{Jup}}$, units of Jupiter masses) in order to provide a firm footing for theoretical models and more general galactic studies. By measuring the MF in a number of Galactic environments and at a range of different ages, we aim to study the evolution of the MF over time, its relation to the IMF, and the universality (or otherwise) of this fundamental tool of stellar astrophysics.

## 4.2 Our knowledge of the stellar mass function

Since the pioneering work of Salpeter (1955), there have been many determinations of the MF for various stellar clusters and associations reaching ever lower masses. In restricted mass ranges, MFs have usually been modelled using power law forms, $\xi(m) \propto m^{-\alpha}$. For example, Salpeter (1955) found $\alpha$=2.35 in the solar neighbourhood. However, later work demonstrated a flattening of the MF at low masses $m < 0.3\mathrm{M}_{\odot}$. A better fit to the observed MF over a large mass range is the log–normal function (e.g. Miller & Scalo 1979; Hambly et al. 1999b):

$$\log_e \xi(\log_e m) \propto \frac{-1}{2\sigma^2} \log_e (m/m_{\mathrm{C}})^2, \tag{4.1}$$

i.e. $\xi(\log_e m)$ is normally distributed about characteristic mass $m_{\mathrm{C}}$ with width $\sigma$.

The deepest data available show a flat, slowly rising or slowly decreasing MF in the sub-stellar régime (e.g. Lucas & Roche 2000; Martín, Zapatero–Osorio & Rebolo 1998), and it is now clearly important to firmly establish the form of the MF in as many clusters as possible, with good statistics, to build upon these new results. The possibility that free–floating planetary mass objects exist (Lucas & Roche 2000; Zapatero–Osorio et al. 2000), and if so, their relation to the "exoplanets" being found in increasing numbers (see `http://exoplanets.org`), are related questions that can be tackled given sufficiently deep survey data.

Theoretical predictions of the form of the IMF have advanced considerably over the last decade or so. Simple scaling arguments predict power–law forms of the IMF in a hierarchical fragmentation procedure (Zinecker, McCaughrean & Wilking 1993). However, some more recent work (Adams & Fatuzzo 1996) has concentrated on the following compelling argument: in the limit that many independent physical variables come into play in the SF process, then the central limit theorem dictates that the IMF should approach a log–normal distribution. This clearly has important implications for normal distributions having characteristic masses $m \sim 0.1\mathrm{M}_{\odot}$ (e.g. Hambly et al. 1999b; Adams & Fatuzzo 1996) since the number of BDs predicted at $m \sim 0.01\mathrm{M}_{\odot}$ becomes very low (see later) relative to power–law forms with all except the most negative exponents. There is currently not enough observational data to verify (or refute) such interesting theories.

Our current knowledge of the mass function is summarised in Fig. 4.1, which shows the Pleiades mass function and various feasible extrapolations. It is clear that its is crucial to measure the mass function in the sub-stellar regime. The most extreme objects (a few Jupiter masses) are in principle the most sensitive test, but we may simply not find any. The practical next step is to find and count brown dwarfs in the 20-100 Jupiter mass regime.

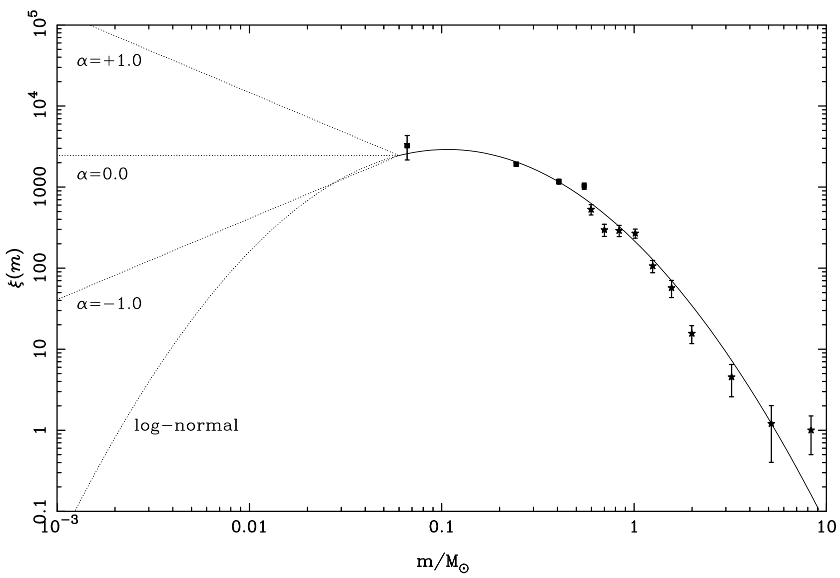


Figure 4.1: *Various extrapolations (dotted lines) of the Pleiades mass function (after Hambly et al. 1999) illustrating the present uncertainties in the behaviour of the MF in the brown dwarf régime.*

## 4.3 Testing substellar MF models

Theoretical predictions (e.g. Burrows et al. 1997; Chabrier et al. 2000) of the temperature and luminosity of very low mass objects as a function of age have become much more secure over the last few years with the incorporation of non–gray atmospheric models and dust. These advances are timely, since we can now predict, with some confidence, the infrared absolute magnitudes and colours of very low mass objects. This is of course pivotal in the derivation of the mass function from observables.

The UKIDSS Large Area Survey (LAS) will find large numbers of brown dwarfs, but to measure the mass function we need to survey clusters. First, all the objects found will be at a known distance so that the luminosity function is easy to derive. Second, to derive the mass function we need to know the age of the brown dwarfs concerned to correct for cooling. To test our assumptions about cooling, and the universality of the mass function, we should look at clusters with a range of ages. We would also like to test the universality of the mass function with respect to metallicity.

In order to provide estimates of the numbers of BDs expected in our proposed surveys, we have used these two model forms along with data from the Pleiades (e.g. Martín et al. 1998; Hambly et al. 1999b). For power–law MFs we assume $\alpha = 2.35$ for $m > 0.5\mathrm{M}_\odot$; $\alpha = 1.5$ for $0.5 > m/\mathrm{M}_\odot > 0.1$; and the plausible values $\alpha = +1, 0, -1$ for $m < 0.1\mathrm{M}_\odot$. For the log–normal, we assume a shape extrapolated from that measured in Hambly et al. (1999b) – see Figure 4.1. In each case, the MFs are normalised to give the total mass estimated for each cluster in Table 1.

## 4.4 Complementary data from other sources

The *Astro-F* satellite mission (*IRIS*, `http://www.ir.isas.ac.jp/ASTRO-F/index-e.html`, launch due in 2003) will comprise a 70-cm IR telescope which will undertake, pointed observations in K, L and M to depths of approximately 22, 21 and 20 respectively over $10 \times 10$ arcminute fields. We expect that observations using *IRIS/Astro-F* will be an important follow–up for confirmation of JHK candidates from this survey. Also, in the youngest star formation associations very young objects may have hot, circumstellar material and could be missed in JHK data alone. *IRIS/Astro-F* data will help to quantify possible missing populations.

## 4.5 Technical requirements

The advantages of using clusters/associations for determining the IMF are many, especially when compared to studies of the general field population (e.g. Liebert et al. 2000). A cluster presents a single coeval population of stars whose global properties (e.g. distance, age, metallicity) are known, in some cases very accurately, via independent means. This is in stark contrast to the field populattion, whose complex dynamical evolution and star formation history makes measurement of the MF very difficult and derivation of the IMF almost impossible.

The requirements for this programme are a selection of clusters/associations with: small distances (to allow investigation of the least luminous and therefore lowest mass objects); a good spread in ages (to allow investigation of temporal evolution of the MF and inference of the IMF); and a variety of Galactic environments (to allow investigation of the universality of the IMF). Such a sample is presented in Table 1, with explanation in the caption. In order to predict the mass limits achievable we have used the DUSTY models of Chabrier et al. (2000), interpolating/extrapolating where required. While some of these numbers are necessarily uncertain, they give an estimate of the mass limits achievable. The numbers of BDs expected given certain assumptions about the form of the mass function are also given. Here, we have assumed for the sake of argument a universal MF based on that measured in the Pleiades (Martín et al. 1998; Hambly et al. 1999b) with various extrapolations to low masses. The normalisation is to the total mass estimate for the cluster/association. In order to be able to disentangle age/metallicity/environment effects and to quantify evolutionary effects as the IMF translates into the present–day MF, we feel that 10 targets is close to a minimum requirement. Assuming that these targets are representative of the birthplace of most Galactic disk stars, this study will yield information applicable to the Galactic disk as a whole. Follow–up observations may include studies of the binary fraction and searches for eclipsing BDs that will confront theoretical models with real data.

Photometric identification of candidates requires JHK measurements: two–colour diagrams are needed to measure reddening and hence extinction before transformation of luminosity to mass; K photometry is useful for detecting very young sources via hot dust emission. Proper motion measurements are highly desirable to refine membership lists selected by photometry alone since some cluster non–members will inevitably contaminate regions of colour–magnitude and colour–colour diagrams where the cluster members are found. All the regions surveyed will be revisited in the K band for proper motion measurement over a 5 year baseline. The second epoch observations will also enable detection of YSOs from K–band variability.

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| Cluster or association (1) | RA (J2000) hh mm (2) | Dec (J2000) sdd am (3) | $\mu$ (mas yr$^{-1}$) (4) | Ang. radius (arcmin) (5) | $A_V$ (mag) (6) | Total mass ($M_\odot$) (7) | Dist. (pc) (8) | Age (Myr) (9) | Depth J (mag) (10) | Depth K (mag) (11) | Mass limit $m_L$ ($M_{JUP}$) (12) | Tot. exp. time (ksec) (13) | No. of BDs in $m_L$ to $m_L$+10$M_{JUP}$ Power–law MF $\propto m^{-\alpha}$ $\alpha = +1$ (14) | $\alpha = 0$ (15) | $\alpha = -1$ (16) | log–norm (17) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Open clusters: | | | | | | | | | | | | | | | | |
| Alpha Per | 03 26 | +40 30 | 34 | 240 | 0.3 | 530 | 190 | 50 | 19.7 | 18.4 | 15 | 42.3 | 399 | 80 | 16 | 7 |
| Pleiades | 03 50 | +24 14 | 50 | 300 | 0.2 | 800 | 118 | 100 | 19.7 | 18.4 | 24 | 66.1 | 422 | 121 | 35 | 17 |
| Hyades | 04 19 | +15 34 | 100 | 600 | 0.0 | 670 | 45 | 600 | 19.7 | 18.4 | 41 | 264.6 | 221 | 101 | 47 | 24 |
| Praesepe | 08 39 | +19 26 | 38 | 180 | 0.0 | 670 | 180 | 400 | 19.7 | 18.4 | 46 | 23.8 | 199 | 101 | 52 | 26 |
| Coma–Ber | 12 25 | +26 08 | 15 | 300 | 0.0 | 270 | 87 | 500 | 19.7 | 18.4 | 43 | 66.1 | 85 | 41 | 20 | 10 |
| M39 | 21 29 | +48 20 | 21 | 60 | 0.2 | 130 | 310 | 100 | 19.7 | 18.4 | 30 | 2.6 | 56 | 20 | 7 | 4 |
| Star formation associations: | | | | | | | | | | | | | | | | |
| Perseus | 03 46 | +31 42 | 0 | 60 | 5.0 | 100 | 350 | 1 | 19.7 | 18.4 | 13 | 2.6 | 86 | 15 | 3 | 1 |
| Taurus | 04 25 | +23 01 | 23 | 600 | 5.0 | 150 | 185 | 1 | 19.7 | 18.4 | 11 | 264.6 | 146 | 23 | 4 | 1 |
| Auriga | 04 58 | +31 33 | 23 | 400 | 5.0 | 100 | 170 | 1 | 19.7 | 18.4 | 11 | 117.6 | 99 | 15 | 2 | 1 |
| Orion | 05 27 | +03 17 | 0 | 600 | 5.0 | 1000 | 440 | 1 | 19.7 | 18.4 | 14 | 264.6 | 816 | 151 | 29 | 11 |
| Sco | 16 19 | −21 41 | 0 | 540 | 5.0 | 200 | 220 | 10 | 19.7 | 18.4 | 12 | 214.3 | 179 | 30 | 5 | 2 |
| | | | | | | | | | | | TOTAL: | ~ 1330 | | | | |

Table 1: **Cluster/star formation association targets.** Notes: *for columns (1) to (9) the primary data source is Allen (1973) with updated information where available; (5) is the angular extent proposed to be surveyed; (6) is the average visual extinction and we have assumed* $A_{J,H,K} \approx 0.27, 0.16, 0.10 A_V$*; total masses (7) have been calculated assuming the clusters to be 'Pleiades–like' and have masses scaled by the number of known higher mass stars; where available in (8)* Hipparcos *distances from Robichon et al. (1999) have been used; the JK depths (10,11) are the proposed depths in each case to survey the cluster to obtain the mass limit (12) calculated using the DUSTY models of Chabrier et al. (2000) – luminosities depend on both distance and age; total exposure times are on source integration times and include H plus repeat K measurements for proper motions; columns (14) to (17) give model predictions of the number of BDs expected in the cluster given power–law or log–normal 'Pleiades–like' MFs normalised to give the total mass in (7) – these give an indication of the sampling errors in the lowest mass bin of the MF derived from these data for the different MF forms.*

# Chapter 5

# The Deep Extragalactic Survey

*Mapping the Universe at z=1*

## Summary

The lookback time to redshifts $z > 1$ is greater than half the age of the Universe. We aim to produce a map of the Universe at these early times, comparable in scope and detail to the maps of the local Universe being produced by 2dF and SDSS. This requires a survey at infrared wavelengths in order to sample the restframe optical. By comparing the properties of the Universe at these widely separated cosmic times we can perform critical tests of the current $\Lambda$CDM paradigm for the origin and growth of structure. For example the evolution of the abundance of galaxy clusters from $z = 0$ to $1 < z < 1.5$ is very sensitive to cosmological parameters. We will examine the evolution of bias for galaxies of different luminosity and type. And we will provide the crucial near-ir imaging for identification of reddened populations such as starburst galaxies and obscured AGN, that will allow a census of the individual contributions of stars and AGN to the global energy budget from X-ray to mm wavelengths. We propose to reach K=21 and J=22.5 over a total of $35\square^\circ$ in three independent fields.

## 5.1 Motivation

The theme of the DXS is a comparison of the properties of the Universe at $1.0 < z < 1.5$ against the properties of the Universe today. By the time the DXS commences, the fundamental goal of quantifying the contents of the nearby Universe, in terms of the spatial distribution of the output of electromagnetic radiation from galaxies, will have been completed by the 2dF, SDSS, and IRAS galaxy redshift surveys (optical and far-ir wavelengths dominate the global energy budget). The DXS in combination with other imaging surveys (using XMM, GALEX, MEGACAM, SIRTF, and SZ surveys), and including near-ir spectroscopy with FMOS (§5.5), aims to produce a comparable map at high redshift. The purpose of the DXS, then, is to quantify the evolution of the properties of the Universe over a timespan greater than half the current age of the Universe. The four main goals of the DXS are the following.

**1. To detect a large sample of high-redshift galaxy clusters $1.0 < z < 1.5$ to measure the evolution of the cluster mass function $N(M, z)$**

This is the principal goal of the DXS. It sets the scope of the survey and the case forms a major part of the DXS proposal. The measurement of the evolution of the cluster mass function $N(M, z)$ can be used to obtain constraints on cosmological parameters (e.g. Viana and Liddle, 1996, Eke et al., 1998). These constraints will be complementary to existing and future cosmic microwave background and supernova measures, and can remove degeneracies. Ultimately we hope to make an important contribution to reaching beyond the three-parameter $H_\circ$, $\Omega_m$, $\Omega_\Lambda$ cosmology that describes the geometry and dynamics of the Universe, to obtain useful constraints on the dark energy equation of state parameter $w = P/\rho$, and thereby to explore quintessence models.

In this proposal we emphasise the statistical study of the evolution of the abundance of clusters. Nevertheless the DXS sample of high–redshift clusters will be useful for a variety of interesting studies which will test the current paradigm for the growth of structure and the formation of galaxies, including measuring the evolution of the properties of the galaxies in clusters, and the variation with cluster mass (e.g. Burke, Collins, and Mann, 2001, Kodama and Bower, 2001), investigating the properties of individual clusters (e.g. gravitational lensing measurements of the dark matter mass profiles, Tyson et al, 1998), and exploiting the use of clusters as gravitational telescopes (e.g. Ellis et al, 2001).

**2. The clustering of galaxies, by type and luminosity, at $z = 1$**

The 2dF and SDSS galaxy redshift surveys (respectively $2 \times 10^5$ redshifts, complete, and $1 \times 10^6$ redshifts, projected), are providing accurate measures of the clustering of galaxies in the nearby Universe out to the largest scales, $> 100$ Mpc. These results provide constraints on cosmological parameters (from the shape of the galaxy power spectrum on large scales) and allow tests of the predictions of theories of galaxy formation, exploring the relation between light and mass through the measurement of clustering as a function of galaxy type, luminosity, and star–formation history. These surveys use catalogues of galaxies selected at optical wavelengths. As a consequence, the measurement of the evolution from a comparable galaxy sample at substantial lookback time, $z > 1$, can only be achieved with deep wide-field imaging at near-ir wavelengths: the SDSS $ugriz$ passbands correspond to the observed wavelength range 0.9 to 2.3$\mu$m at $z = 1.5$. WFCAM is the only instrument that can provide the deep and wide-field near-ir imaging required for this work, for the next few years.

To obtain a representative view of the properties of galaxies at z$\geq$1, near-ir surveys must cover a comparable luminosity range to that probed by current surveys of the local Universe (e.g. L$\sim$L$^*$+2). At $z = 1$ this corresponds to a depth of K=21. For the redshift range $1 < z < 1.5$ a survey over $35\square^\circ$ covers the same volume as the 2dF survey out to $z = 0.2$.

**3. Star formation at $z > 1$ from ultraviolet to far-infrared wavelengths**

The multiwavelength SED of normal galaxies is predominantly thermal, with a hot component at optical wavelengths, from the stellar photospheres seen directly in regions of low extinction, and a cool component at far-infrared wavelengths, from regions of obscured star formation where the dominant ultraviolet radiation from massive stars is absorbed by dust and reradiated at longer wavelengths. In the local universe about one-third of the energy emerges at far-infrared wavelengths, but at higher redshift this proportion probably increases, and may dominate, as indicated by observations of luminous sub-mm galaxies and of the cosmic optical and far-infrared background radiation. The DXS will observe fields with complementary deep observations at wavelengths covering the ultraviolet region (from the GALEX mission, www.srl.caltech.edu/galex), the optical, and the mid to far-infrared (SWIRE fields www.ipac.caltech.edu/SWIRE). These multiwavelength fields will provide the data for a comprehensive study of the contribution from star formation at $z > 1$ to the cosmic energy output over the electromagnetic spectrum. The near-ir data are vital for the measurement of photometric redshifts of galaxies, since these wavelengths sample the restframe optical at $z > 1$. And the near-ir data are crucial for the identification of highly reddened objects, detected at longer wavelengths, in order to establish their redshift distribution.

**4. The contribution of AGN to the cosmic energy budget**

While the cosmic background radiation is dominated by star formation at optical and far-infrared to sub-mm wavelengths, in the mid-infrared AGN make an important contribution, while at X-ray wavelengths they dominate. An important question is what is the contribution, and its evolution, of AGN to the total cosmic energy budget? This is generally believed to be about 10%, but has proved difficult to quantify because the bulk of the hard X-ray background is attributed to AGN that are heavily obscured at optical wavelengths. A multiwavelength study covering X-ray (XMM), near-ir (DXS), and mid-ir (SWIRE) can answer this question. The mid-ir and X-ray data are complementary, as these are the wavelengths at which obscured AGN are most visible. The near-ir data are required for identification, to allow spectroscopic observations, and for quantifying the extinction.

To achieve the four goals listed above requires deep near-ir data over a large area. The DXS survey aims to cover three main areas each covering 10 to 15□°. With a transverse size of 200 Mpc×200 Mpc comoving ($3.5° \times 3.5°$ at z=1) [1] and 1000 Mpc along the line of sight, this is the minimum volume needed to reliably establish the correlation function on large scales at z∼1, and to identify statistically useful samples of galaxy clusters at z>1 (as we quantify below). This requirement for deep, panoramic near-infrared imaging means that these goals cannot be addressed before the advent of WFCAM.

## 5.2 Cosmology from the evolution of the galaxy cluster mass function

The abundance of clusters beyond $z = 1$ will be a field of intense activity over the next 5 years. Much of the emphasis will be on X-ray surveys with XMM (e.g. Romer et al., 2001), and the emerging field of Sunyaev-Zeldovich (SZ) survey astronomy (Holder et al., 2000). These surveys will cover large areas, tens of square degrees, and target redshifts beyond $z = 1$. But the usefulness of these surveys is greatly reduced without near-ir imaging. This is because imaging in the restframe optical is essential to detect the galaxies in the clusters,

[1] $\Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7$

to measure spectroscopic redshifts. Optical imaging provides insufficient contrast because of the large $k-$corrections as the 4000Å break moves beyond the $z$ band. *WFCAM is the only instrument suitable for providing the necessary imaging in an efficient way.* But in addition the combination of WFCAM with the FMOS spectrograph on Subaru provides a powerful tool for undertaking an independent survey for high-redshift clusters based on optical/near-ir imaging alone. Surveys at different wavelengths have different sources of uncertainty, and therefore provide an independent check, which is vital for such an important question. Our goal, then, is to cover a large area with complete coverage by X-ray, SZ, and optical/near-ir imaging. In this proposal we present the case for a near-ir survey for high-redshift clusters, sufficient in itself, without consideration of complementary X-ray and SZ coverage. The area required (justified below) is $35\,\square^\circ$. However the proposed DXS will be of considerable interest to the X-ray and SZ communities and it is natural to expect that they will focus their activities on the selected DXS areas. Already one third of this area has completed or approved XMM coverage to the required depth. Additionally Carlstrom's SZ group are in close contact with the UKIDSS team about field choice and survey strategy. We will liaise closely with the X-ray and SZ communities as their survey plans develop further.

To design a survey for high-redshift clusters in the near-ir, we will build on the success of the Red Cluster Sequence (RCS) technique of Gladders and Yee (2000), improving the effectiveness by using multiple passbands, and extending the redshift completeness limit from $z = 1.1$ to $z = 1.5$. Because of the exponential dependence of the comoving density of clusters on redshift the redshift increment $\Delta z = 0.4$ is a very significant step.

### 5.2.1 Galaxy clusters and precision cosmology *circa* 2005

We live now in the era of precision cosmology, heralded by the announcement of the results of the BOOMERANG and MAXIMA experiments of measurements of the temperature fluctuations in the cosmic microwave background on scales of a degree and less. The goal of establishing the type of universe we live in, through measuring the cosmological parameters ($H_\circ$, $\Omega_m$, $\Omega_\Lambda$, $\Omega_b$, $n_s$) to an accuracy of a few per cent could be achieved on a timescale of as little as ten years. The principal field of study is the CMB, which is the most useful because the physics is the simplest. But the reach of the CMB experiments is limited by intrinsic degeneracies between parameters, set by the relevant geometry and physics, the most fundamental being that between $\Omega_m$ and $\Omega_\Lambda$. These degeneracies can be broken with complementary experiments, which also provide a check that there is not some fundamental flaw in the CMB results. Currently the most important of these complementary tests are the Hubble diagram of type 1a supernovae (Riess et al., 1998, Perlmutter et al., 1999), the shape of the galaxy power spectrum on large scales (Efstathiou et al., 2001), and the evolution of the abundance of galaxy clusters (Borgani et al., 2001). Each of these experiments rests on a number of physical assumptions that are plausible but difficult to confirm, and therefore they are prone to systematic errors. Hence the importance of more than one independent method.

Looking ahead four years, to 2005, the results of the Microwave Anisotropy Probe experiment will have been published, as well as the final results on large-scale structure from the Sloan Digital Sky Survey. A proposed satellite experiment SNAP (snap.lbl.gov), not yet approved, would extend the scope of the supernova experiments both in number and redshift. The evolution of the abundance of clusters is currently a topic of intense study, and we believe will make a fundamental contribution to precision cosmology over the next decade. The abundance of galaxy clusters today depends on $\sigma_8 \Omega_m^{0.5}$, where $\sigma_8$ is the *rms* mass fluctuation amplitude in spheres of size $8h^{-1}$ Mpc, and measures the normalisation of the matter power spectrum. The degeneracy between these two parameters can be broken by measuring the evolution of the abundance of clusters. This is a sensitive measure of $\Omega_m$ even if measurements extend only to moderate redshift, z=0.5. At this redshift the difference between high density $\Omega_m = 1.0$ and low density $\Omega_m = 0.3$ models is a factor of 100 for clusters of mass greater than the mass of Coma, $6 \times 10^{14} h^{-1} \mathrm{M}_\odot$ (Bode et al., 2001). The current best measurements from X-ray surveys yield $\Omega_m = 0.35^{+0.13}_{-0.10}$ (Borgani et al., 2001). The differences between cosmologies is greatest for the most massive clusters, and the highest redshifts. Beyond redshift $z = 0.6$ the test can start to distinguish between cosmologies of the same $\Omega_m$, but different $\Omega_\Lambda$, and beyond $z = 1.0$ the hope is to place constraints on the dark energy equation of state parameter $w = P/\rho$ (Newman et al., 2001, Haiman et al., 2001).

The enthusiasm of cosmologists for this test is explained by the fact that it measures the distribution of mass (rather than of light or baryons). In a CDM universe with $\Omega_m \gg \Omega_b$ the growth of structure in the dominant collisionless matter is now a well understood process. There is excellent agreement between predictions based on Press-Schechter theory (Press and Schechter, 1974) and its extensions (e.g. Sheth et al., 2001), and the results of the latest greatest N-body simulations (e.g. Bode et al., 2001). One can anticipate that within a few years this problem can be considered completely solved.

### 5.2.2 Survey techniques: X rays, SZ, and the need for optical/near-ir

Although the first catalogues, due to Abell, were drawn from optical imaging the emphasis in recent searches for clusters has been on X-ray surveys. This is because the Abell catalogues suffered from contamination due to projection effects, and because the correlation between cluster richness and mass $M$ is rather weak. The X-ray surveys do not suffer from projection effects and the selection parameter, luminosity $L$, is reasonably correlated with $M$. The future may be dominated by SZ surveys. There is considerable enthusiasm for this technique because the detectability of a cluster is independent of redshift, so SZ surveys offer the prospect of reaching the highest redshifts, and thereby obtaining the best constraints on cosmological parameters.

In common with a number of authors (Postman et al., 1996, Gladders and Yee, 2000, Gonzales et al., 2001, Willick et al., 2001) we believe that a powerful case can be made for new more ambitious surveys at optical and near-ir wavelengths. The measurement of the evolution of the abundance of clusters is a difficult test to perform, and surveys at different wavelengths have their individual strengths and weaknesses. The X-ray surveys, seemingly straightforward, in fact involve a number of assumptions given that selection is on $L$ rather than the more fundamental parameter temperature $T$, or even the desired parameter $M$. The scatter in the $L-T$ and $T-M$ relations, and any evolution in these relations, and the problem of contamination of the flux by point sources, are all sources of uncertainty. We would agree that the SZ technique appears extremely promising, but the current enthusiasm for SZ surveys should perhaps be tempered by the recognition that this is a technology that has developed rather slowly, and is still relatively immature, and that there may be sources of uncertainty that only become apparent as the surveys get underway.

There are a number of important advantages of searches at optical and near-ir wavelengths. The first of these arises from the fact that it is an optical survey, the SDSS, which will provide the benchmark for the abundance of clusters at $z = 0$, for the measurement of evolution. So the compatibility of selection techniques between two optical/near-ir surveys will ensure that any measured evolution has minimal contribution due to differences in the detection techniques. As explained below we envisage producing a sample of clusters complete above a specified velocity dispersion threshold. This parameter can more easily be compared with theory than the mass. It has the further advantage that it does not involve the Hubble constant, which would stretch the uncertainties on the parameters due to the uncertainty in the Hubble constant itself (Newman et al., 2001). Nevertheless it is a quantity that is difficult to measure accurately, and this reinforces the importance of surveying the same areas with other techniques that provide independent mass estimates. With the development of, successively, objective searches (Dalton et al., 1992, Lumsden et al., 1992), matched filter techniques (Postman et al., 1996, Kepner et al., 1999), the extension to include a single colour (Gladders and Yee, 2000), and then to incorporate photometric redshifts (White and Kochanek, 2001), it is possible to design multicolour optical/near-ir surveys for clusters with low contamination and high completeness, with sensitivty to lower mass objects (down to the masses of galaxy groups) and there is no longer a problem of projection effects.

### 5.2.3 Galaxy clusters in the DXS

**Required flux limit**. The starting point for designing a survey with WFCAM is the Red Cluster Sequence survey of Gladders and Yee (2000) which uses imaging in the $r$ and $z$ bands to $5\sigma$ point source detection limits of 24.9 and 23.2 respectively, over $100\square^\circ$. All known galaxy clusters contain a population of old ellipticals visible as a red sequence in colour–magnitude diagrams. This includes two clusters at $z = 1.3$ (Stanford et al., 1997, Rosati et al., 1999). Gladders and Yee identify clusters by a matched–filter search in spatial+colour space for this sequence at different redshifts. (Note, of course, that since the sequence is visible in all colours, adding extra colours greatly increases the detectability of clusters showing a red sequence, as demonstrated by Gillbank, 2001, thesis). Gladders (thesis, private communication) has recently completed the calculation of the survey selection function. The detectability depends on depth relative to $L^*(z)$, and the fraction of red galaxies in the cluster. However, regardless of the red fraction, the Gladders and Yee survey is complete for clusters of 1D velocity dispersion $\sigma > 750$ km s$^{-1}$ at all redshifts where the survey depth is greater than $L^*(z) + 1$. Additionally he has established that the $5\sigma$ detection limit for cluster galaxies at $z \sim 1$ is 0.75 mag. brighter than for point sources. Their cluster survey is complete to $z = 1.1$ but the completeness falls off rapidly beyond, as the 4000Å break enters the $z$ band. To summarise: using a single colour, to detect all clusters of $\sigma > 750$ km s$^{-1}$ requires a $5\sigma$ point source detection limit of $L^*(z) + 1.75$.

We assume (and will ensure) that our survey areas will have deep imaging in the optical bands $ugriz$, for example by selecting CFH Legacy Survey fields, or obtaining data with the INT Wide Field Camera, or with Subaru SuprimeCam. With WFCAM we propose to image

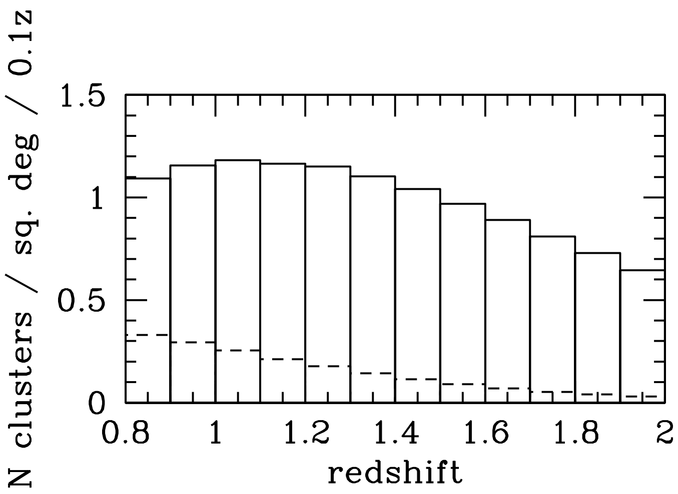


Figure 5.1: *Predicted numbers of galaxy clusters, $\sigma > 700$ km $s^{-1}$, per square degree per $\Delta z = 0.1$, for two different flat cosmologies. The solid line is for $\Omega_m = 0.2$ ($\Omega_\Lambda = 0.8$), and the dashed line is for $\Omega_m = 0.4$ ($\Omega_\Lambda = 0.6$). Further details are provided in the text.*

in the J and K bands. It is impossible to detect clusters efficiently beyond $z = 1.1$ without near-ir data. This is because the dominant spectral feature, the 4000Å break, moves beyond the $z$ band, diminishing the discriminatory power in the photo-z technique of the optical bands, and because the galaxies become faint at these wavelengths. Indeed to a large extent this explains why so few clusters beyond this redshift have been discovered in X-ray surveys (Ebeling et al., 2001). The J band is essential to optimise the contrast at the 4000Å break. The K band maximises the wavelength lever arm. However, additional H band imaging provides only limited extra photo-z constraints (based on Bolzonella et al., 2000) and the extra observing time required cannot be justified. Clusters will be detected by searching in 3D using photometric redshifts (White and Kochanek, 2001). We would argue that a multicolour, as opposed to single colour, approach is essential for $z > 1$ since there is no guarantee that the red cluster sequence exists in most clusters at these early times. (Indeed we would make the general point that the properties of clusters beyond $z = 1$ are not yet well studied and the basic assumptions behind any survey technique may not pertain, further emphasising the requirement for multiwavelength coverage.) The multicolour data will significantly increase our sensitivity to all clusters, especially those with a small red fraction. On the basis of comparisons in Gillbank's thesis, we feel we can safely relax the depth requirement quoted above, by 0.5 mag. To estimate $L^*(z)$ we calculate the apparent magnitude of a passively evolving z=0 $L^*$ elliptical formed at $z = 5$, using the models of Jimenez et al. (1999). At $z = 1.5$ we find $L^*(J) = 20.9$ and $L^*(K) = 19.5$, to which we now need to add 1.25 mag. On this basis we set the survey detection limits to be $J = 22.5$ and $K = 21.0$.

**Required area.** Here we present a simple calculation that uses the unmodified Press–Schechter theory. The purpose of the calculation is merely to illustrate the sensitivity of the survey to cosmological parameters. To account for observational uncertainties in e.g. measuring cluster velocity dispersions we have naively doubled the Poisson errors. The more detailed calculations of Newman et al. (2001) for the DEEP survey, which make a realistic assessment of errors, are useful for comparison purposes. We consider two different flat cosmologies, with $\Omega_m = 0.2$ ($\Omega_\Lambda = 0.8$) and $\Omega_m = 0.4$ ($\Omega_\Lambda = 0.6$), with $\sigma_8$ chosen to match the present–day cluster abundance, i.e. we assume this quantity will be fixed precisely by SDSS and 2dF. In figure 5.1 we plot the expected number of clusters $\sigma > 700$ km s$^{-1}$ per square degree per $\Delta z = 0.1$, for the redshift range $0.8 < z < 2.0$. Note the much smaller predicted numbers for the higher density model, and the much steeper decline towards high redshift. Taking the interval $1.0 < z < 1.5$ the predicted integrated numbers per square degree are respectively $5.6/\square^\circ$ and $0.9/\square^\circ$ for the lower and higher density universes. We can then compute the area required to improve on the result of Borgani et al. (2001), $\Omega_m = 0.35^{+0.13}_{-0.10}$, by a factor 4, on the basis of these simplifying assumptions. In $35\square^\circ$ we would expect to find 197 clusters for the lower density case, but only 32 for the higher density case. Doubling the Poisson errors this is a difference of $6\sigma$, or a $1\sigma$ uncertainty $\Delta\Omega_m = 0.03$, as required. This illustrates the power of surveys for high-redshift clusters, and the complementarity with CMB experiments, and is the basis for choosing a survey area of $35\square^\circ$.

The small uncertainties on $\Omega_m$ from this survey indicated by this calculation illustrate the opportunity for an analysis establishing joint constraints on $\Omega_m$ and $w$ (assuming a flat universe), which we intend to pursue. Newman et al. (2001) have presented a detailed calculation for the DEEP Survey. The characteristics of the DEEP survey are rather different to ours. Clusters will be identified from a spectroscopic survey of 60000 galaxies $z > 0.7$, which will be selected from BRI data reaching $I = 23.5$. They expect to be complete for velocity dispersions $\sigma > 400$ km s$^{-1}$. Under certain assumptions they hope to be able to measure $w$ to an accuracy of 0.1. The larger number of clusters in their survey, due to the low cut in $\sigma$, is offset by the higher redshift distribution of the DXS clusters, and the fact that, for the same number of clusters, surveys with a higher $\sigma$ cut provide greater sensitivity to the cosmology. On this basis we are optimistic that the DXS survey can achieve comparable constraints on $w$.

## 5.3 The galaxy correlation function at $z > 1$

### 5.3.1 Theoretical context

By the time that WFCAM comes on line, the basic geometry and mass power spectrum of the universe will have been established through observations of the microwave background and local galaxy redshift surveys on scales of $\gg 100$ Mpc.

The key issue will then be to understand how galaxies form and how they evolve. *The DXS survey is designed to create a data set for galaxies at $1 < z < 1.5$ that is directly comparable to the 2DF and Sloan surveys at $z = 0$.* We already know that the universe at $z = 1$ is very different form the local universe. In particular, the average star formation declines by almost an order of magnitude over this redshift range. We can determine the driving force behind this decline by quantifying the evolution of the clustering of galaxies, through measurement of the correlation function or the power spectrum and its dependence on colour and galaxy magnitude. driving force behind this decline. One possibility, that is suggested by hierarchical models for galaxy formation (e.g. Cole et al., 2000), is that it is the changing environment of galaxies. On the other hand, classical galaxy formation models suggest that the decline results from galaxies consuming the internal reservoir of gas. By probing colours of galaxies as a function of their environment we can identify which of these scenarios is correct. By using the correlation function, we can probe the full range of galaxy environments from isolated galaxies to galaxy groups; not just galaxies in rare clusters.

The challenge, however, is to invert the correlation function of galaxies to extract the information about the numbers of galaxies found in a halo of a certain mass $M$; and to map the function's dependence on galaxy colours and magnitudes. This function is commonly referred to as the "halo occupation number" ($N_h(M)$) and is easily calculated in any flavour of galaxy formation model. The inversion problem is extensively discussed in Benson (2001). It clearly requires good knowledge of the mass power spectrum. But substantial progress has already been made from the 2dF survey (e.g. Peacock et al. 2001) and from cosmic microwave background experiments. Particularly in the field of microwave background studies substantial progress will be made with the MAP satellite so that in 2005, the mass fluctuation power spectrum will have been measured. The ratio of the galaxy correlation function to the mass correlation function defines the bias, $b_g^2(r) = \xi_g/\xi_{dm}$.

Benson (2001) shows that the correlation function depends not only on the mean $N_h(M)$, but also on its variance. There are two strategies for relating $N_h(M)$ and $b_g(r)$: (1) adopt a trial galaxy formation model to compute $N_h(M)$, and then predict $b_g(r)$; (2) invert $b_g(r)$ under a minimal set of assumptions. Method (1) has received most attention (e.g. Benson et al., 2001), but has only been tested for a limited set of models so far: it is an extremely powerful test, but the models which have failed do not get published! It is vital that we take a long term view: by 2005 a much greater variety of galaxy formation models will be available (e.g. Benson, Bower et al., are developing models in which gas cooling is regulated by heating the X-ray haloes — see Bower et al. 2001 for an introduction; Ostriker et al., and Pearce et al., have numerical models that assume physics that is different again). In any case, by 2005, it is reasonable to expect a formalism for direct inversion of $b_g(r)$ to exist. Although these theoretical techniques are in their infancy, the observational programme to match these developments should be set in motion now.

To demonstrate the observational requirements we turn to the predictions of the latest semi-analytic models which incorporate the results from N-body simulations. (See figure 5.2.) These suggest that to address the question of bias we need to adequately sample scales of order 100 Mpc, or a few degrees across at z>1. Figure 5.2 shows the predicted change in mass correlation against that determined from semi-analytic models for the galaxy correlation at z=0.5 and 1. In order to limit the effects of cosmic variance we need to observe three separate fields.

What area do we need to survey to match the volume of the 2dF galaxy redshift survey? To a depth $z = 0.2$ the volume of the 2dF survey is $1.7 \times 10^8$ Mpc$^3$. For DXS the volume element for the redshift interval $1 < z < 1.5$ is $4.8 \times 10^6$ Mpc$^3$ for $1\Box^\circ$. So a survey over $35\Box^\circ$ matches 2dF. Coincidentally this is the same as the area requirement for the clusters survey. Initially we would rely on photometric redshifts to slice the volume into thin redshift slices $\Delta z \sim 0.2$, inverting angular quantities to obtain the real-space clustering. However preliminary planning for a sparse-sampled redshift survey of $10^5$ $z > 1$ galaxies with FMOS has begun, which will allow a much wider range of clustering analyses.

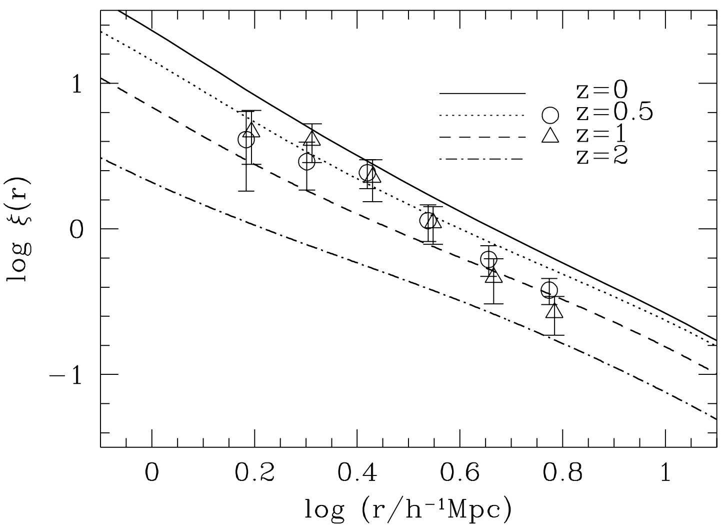


Figure 5.2: *Comparison of dark matter clustering (lines) with galaxy clustering (symbols), extracted from a semi-analytic model (Cole et al. 2000). Note that the dark matter curves are at four different epochs, whereas the galaxies are plotted only for z=0.5 and z=1. The simulation represents a volume of only 1–2% of the proposed DXS survey, and therefore results in relatively poor statistics on both large and small scales. Note the scale-dependent bias, and the fact that the bias seems to change with epoch.*

### 5.3.2 Clustering of Extremely Red Objects

The class of Extremely Red Objects (EROs) is defined as the class of galaxies with $I-K > 4$, or with $R-K > 6$. We estimate that about $10^5$ EROs will be detected in the DXS (1 arcmin$^{-2}$, interpolating between surface densities from Olding et al., 2001, and Moustakas et al., 1997), but the surface density of EROs at K=21 is as yet very poorly determined. In this field two things have become clear recently. First, that while EROs are rare at bright magnitudes, they become very common at faint magnitudes, increasing from a few per $\square^\circ$ to $\sim 1$ per arcmin$^2$ from K=17 to K=21. Secondly, the definition undoubtedly encompasses a mixture of very important populations, including distant quiescent galaxies, dusty starbursts and faint radio and X-ray sources. A wide-field near-ir survey will allow us to trace the evolution of the various sub-populations over the magnitude range in which the total population rises rapidly, if we can adequately separate them.

The predominance of EROs as counterparts to sub-mm selected galaxies confirms the importance of EROs for this field. However, the current modest ERO surveys imply that high redshift ellipticals (a small fraction of which are associated with radio and X-ray sources) may dominate the population at K$\sim$19. Pozzetti & Mannucci (2000) show that quiescent ellipticals and dusty starbursts/AGN can be clearly separated in a I-K vs J-K diagram, figure 5.3, with a reasonably accurate dividing line at J-K=2. This then provides a relatively simple differentiation of the different sub-components of the ERO class, based on near-ir photometry – allowing us to disentangle the different populations and hence study the properties of the individual sub-classes in much more detail. In particular, by undertaking a panoramic survey in J and K we will be able to study the clustering behaviour of both the quiescent, high-redshift galaxies and the equally distant, dusty starbursts and active populations. By focusing on the *correlation function* of these galaxies we can test whether the various classes of EROs are genuinely distinct populations, determining the relationship between them and investigating the origin of the triggered starbursts.

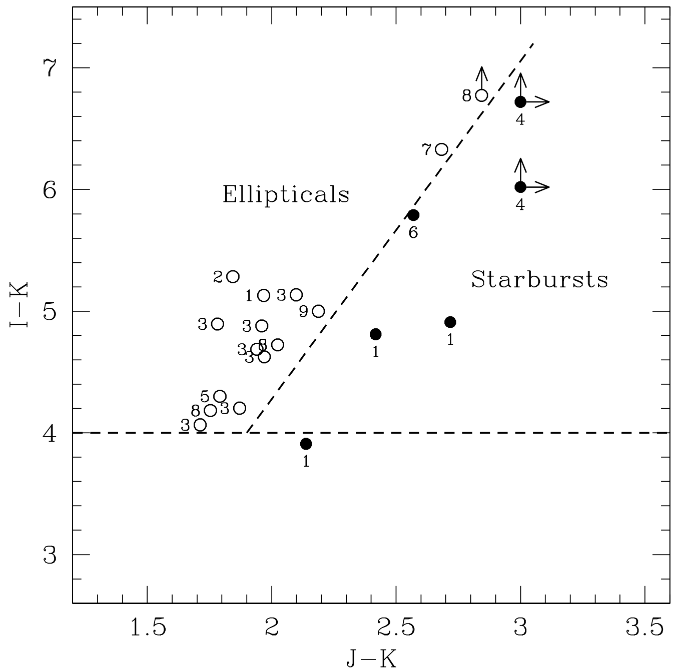


Figure 5.3: *IJK diagram for high-z ellipticals (open circles) and dusty starbursts (solid circles), taken from Pozzetti and Mannucci (2000). The dotted line is a dividing line based on the expected colours of an old elliptical, calculated by redshifting a model SED from z=1 at bottom left to z=2 at top right. (See Fig. 2 of Pozzetti and Manucci 2000).*

It is already known that at $K \approx 19$ EROs are strongly clustered on the sky (e.g. Daddi et al. 2000). From redshift distributions determined by photometric redshifts for this (bright-end) colour-selected population, the median redshift is around $z \approx 1.2$. The spatial correlation function can then be calculated by the relativistic Limber inversion, and the clustering scale lengths have been found to be very large — $r_0 \approx 8 - 10\,\mathrm{h}_{100}^{-1}\,\mathrm{Mpc}$ (e.g. Daddi et al., 2001, Firth et al., 2001, McCarthy et al., 2001), which is comparable to that of present-day ellipticals. This suggests that EROs may in general live in very dense environments. Using an extended Press Schechter formalism, with basic assumptions for the nature of the occupation function $N_h(M)$ of EROs, Moustakas & Somerville (2001) demonstrate that their clustering strength requires them to be in dark matter halos with masses in excess of $10^{13}\,\mathrm{M}_\odot$. When it is possible to clearly separate out the dust starburst population from the "old" population in ERO samples, it will be very interesting to find the relative correlation properties. Indeed, at the limits we are proposing to reach, $K = 21$, we will be able to see large numbers of objects some two magnitudes below $L_*$ at the redshift range of interest, and will probe a huge range of mass scales, and therefore clustering properties.

The argument for the area of the DXS must come from other science (§§5.2, 5.3) because the surface density of EROs at K=21 is not known to within a factor of two. Instead we can indicate the improvements that will result from an area of 35□°. With current wide-field infrared surveys (e.g. the ones described above, as well as the ir-extension of the Oxford-Dartmouth Thirty Degree Survey), the ERO sample sizes are limited to at most $\sim 10^3$ objects. From these surveys, taking a best estimate of the redshift distribution, we have calculated that $r_0$ can be determined to $\sim 20\%$. The expected sample size of $\sim 10^5$ EROs will determine the detailed form of the correlation function, for different subsets, for comparison with galaxy clustering evolution models, in the manner discussed above. It will be particularly interesting to be able to divide the ir-selected galaxies by different physical characteristics (as traced by their colours), and to intercompare their clustering properties at very similar redshifts, further allowing the environment-dependent bias to be explored.

## 5.4 Multi-wavelength key areas

The next decade will see the completion and exploitation of a number of new facilities capable of mapping the distant Universe in a wide range of wavebands spanning the X-ray to radio. *XMM-Newton*, *GALEX*, *SIRTF*, *Astro-F*, *Herschel*, *ALMA*, *SCUBA-2* and *eVLA/eMERLIN* all offer the capability to survey tens of square degrees and detect populations of sources at median redshifts in excess of one. The first three of these missions are undertaking or planning surveys of 10–100 □° in complementary regions. To exploit fully these multi-wavelength surveys deep near-ir imaging data are required to maximise the identification of objects that are heavily obscured at optical wavelengths. These include EROs (i.e. a population defined by their optical to near-ir colours) as well as other objects identified at sub-mm/far-ir wavelengths or in hard X-ray surveys. Near-ir imaging is also essential for normal galaxies, as it defines the rest-frame optical SEDs at $z > 1$. We have an opportunity to take the lead in the definition of the next generation of "Selected Areas" (or "standard survey areas") by knitting together the XMM, GALEX, and SIRTF missions with deep near-ir imaging over tens of square degrees.

These multiwavelength observations will provide the possibility of a comprehensive analysis over all wavelengths of the relative contributions to the cosmic energy budget of stars and AGN at $z > 1$, for comparison against similar measurements in the local Universe. These two populations are considered individually below.

### 5.4.1 Obscured starbursts observed by SIRTF in the far-ir: the wavelength dependence of the cosmic energy budget due to star formation

The three target fields listed in Table 5.1 will all be covered in the SIRTF passbands, from 3.6 to 160 $\mu$m, by the SWIRE consortium, and will also be observed in the ultraviolet (1350 to 3000Å) by GALEX. The DXS J and K imaging will be particularly useful for identifying highly reddened dusty starbursts which will be undetectable at optical wavelengths. In figure 5.4 we present calculations by Xu (2001) showing the expect K magnitude distributions for populations selected in the different SIRTF passbands, for a range of redshift slices. The depth required to detect nearly all the SIRTF sources is established by this calculation to be K=21.

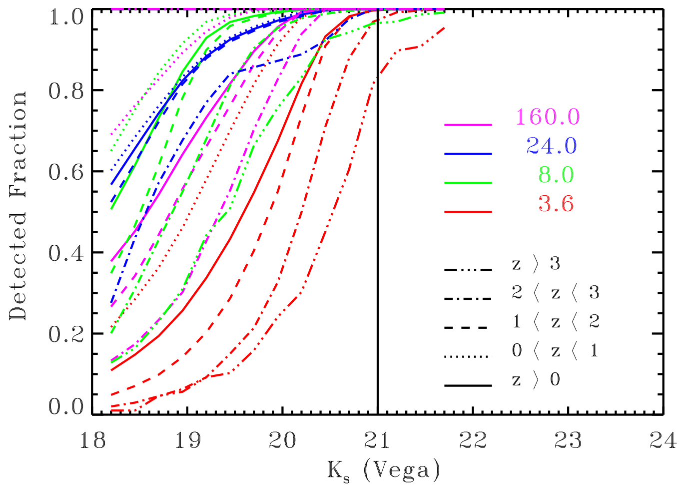


Figure 5.4: *This plot shows a calculation of the expected K-band magnitude distribution of sources detected in the SWIRE survey, using SIRTF, based on the models of Xu et al. (2001). SIRTF has 7 bands in the mid to far-ir, from 3.6 to 160 μm. For clarity the calculations for only 4 bands are shown. For each band the plot shows the predicted cumulative K-band magnitude distributions for the sources detected in each of several redshift slices. This indicates that essentially all sources are detectable in a survey reaching K=21.*

The multiwavelength coverage provided by GALEX, SIRTF, the DXS, and suitable optical data (Table 5.1) will allow a comprehensive study at $z > 1$ of the contribution from star formation to the cosmic energy output over the electromagnetic spectrum. The wide area coverage allows the calculation of the correlation function of galaxies of different star formation histories. Taken together the goal can be thought of as mapping the star formation of galaxies in the Universe in $4D$ i.e. spatial and temporal.

Over the planned $35\square^\circ$ the anticipated numbers of sources detected by SWIRE are $5 \times 10^4$ starbursts, $5{\times}10^5$ ellipticals, 15000 classical AGN, and 100000 obscured AGN, with fractions $\sim 25\%$ at $z > 2$. The near-ir data will be particularly useful for identifying reddened sources not detected at optical wavelengths. These will be predominantly starbursts. In addition the near-ir data anchors the SED of sources at these wavelengths, to establish photometric redshifts. Finally, for sources that are not strongly reddened, the K-band light provides a measure of the stellar mass. This is the integral of the star formation up to that redshift, and therefore provides an additional constraint in determining the history of star formation of the different populations.

### 5.4.2 Obscured AGN observed by XMM and by SIRTF in the mid-ir: the contribution of AGN to the cosmic energy budget

Recent results (eg Mushotzky et al. 2000) suggest that the majority of the X-ray Background (XRB) arises from active galaxies (AGN), obscured by various amounts of dust. Dust reddens the spectrum leading to detections only in the infrared, with no optical counterparts to faint limits (eg Newsam et al. 1997; Lehmann et al. 1999). To confirm this model, to quantify the amount of obscuring dust, and to determine the possible evolution of dust content with redshift (eg Bechtold et al. 1994), we require near IR observations of very deep XMM and Chandra X-ray fields.

The far-ir background is dominated by emission from dusty galaxies. Many such galaxies show signs of strong star formation, which may heat the dust, but the dust may be alternatively be heated by an obscured AGN (eg Genzel et al. 1998). Obscured AGN models for the XRB (eg Gunn and Shanks 2001; Almaini et al. 1999) predict (conservatively) that $5 - 25\%$ of the far-ir background may be produced by obscured AGN. To distinguish the relative contributions of starbursts and obscured AGN we require, together with far-ir observations, deep X-ray and near-ir observations to define the spectral energy distributions (SEDs) and so reveal the presence of an AGN, quantify the amount of dust obscuration and measure dust temperatures.

**Proposed Observations** Our observations must target the deepest available X-ray fields in order to find the most absorbed AGN and so put the tightest constraints on the obscured AGN model of the XRB. However even the very deepest X-ray observations, from XMM ($\sim$ 200ksec), will only contain $\sim$ 200 X-ray sources. Thus one field does not contain sufficient AGN to study evolutionary changes, for which $\sim$ 1000 AGN are required. The XMM-LSS field (Table 5.1) is the primary target for this work. However as described in §5.2 our eventual goal is complete coverage of all three fields.

X-ray background models based on obscured AGN and their evolution indicates that to detect 80% of the AGN in a 50ksec XMM observation requires K=21, and K=22 for a 200ksec observation. Going to K=23 detects only 1% more. Our strategy therefore is to observe selected key fields to K=21 as early as possible within the DXS programme, and to make the case for deeper observations later as required. The highest priority fields are those where 3.6-160$\mu$ are scheduled with *SIRTF* , to complete the SEDs from X-ray to far-ir wavelengths. The *SIRTF* GTOs reach to L$\sim$21 and M$\sim$ 19.5, providing equivalent depth to WFCAM at K=22. The SIRTF Legacy observations will typically be about 2 magnitudes less deep.

## 5.5 Technical requirements

**Survey depth and filter choice**. The depth required is discussed in several sections above. Most importantly, to detect galaxy clusters to $z = 1.5$ (§5.2) requires $K = 21$. The depth $K = 21$ will also ensure virtually complete identification of all SWIRE sources (§5.4.1). In the redshift range of interest the reddest galaxies besides EROs are passively evolving ellipticals which are no redder than $J - K = 1.5$. Therefore a J limit 1.5 mag deeper than the K limit can identify unusually red objects by J-K colour (or colour upper limits). The photo-z study of Bolzonella et al. (2000) demonstrates that where optical data exist, the J and K bands provide most of the SED information in the near-ir, unsurprising since K lies at the long wavelength end, and J lies midway between K and the z band.

To provide colour discrimination within the ERO population it is desirable to reach even

| Field | RA, Dec | DXS J,K $\square^\circ$ | XMM $\square^\circ/t_{exp}$ | GALEX | SIRTF | optical |
|---|---|---|---|---|---|---|
| | | < – – – –**multiwavelength coverage**– – – – > | | | | |
| XMM-LSS | 02 21, -05 00 | 10 | 10/10+ ks | Y | Y | CFHLS |
| Lockman Hole | 10 45, +58 00 | 15 | 0.2/200 ks | Y | Y | |
| Elais N1 | 16 13, +55 16 | 10 | 1.1/30 ks | Y | Y | INT |

Table 5.1: *Summary of provisionally selected target fields. The columns list: 1. field name, 2. the field coordinates, 3. the DXS area to be imaged in J and K, 4. the current completed or scheduled XMM areal coverage and the XMM integration time in kilosec, 5. whether or not GALEX (uv) and 6. SIRTF (mid to far ir) observations are planned, and 7. the existing optical coverage of the field (CFHLS=Canada France Hawaii Legacy Survey, INT=Wide Angle Survey with the INT Wide Field Camera).*

deeper. For this sub-population alone this is most efficiently achieved in the H band, since the short wavelength difference to K provides the maximum contrast. For this reason we propose to cover a small part of the DXS, $5\square^\circ$, to a depth $H = 22$.

**Survey Area**. The chosen survey area $35\square^\circ$ is set by the goals of determining $\Omega_m$ to an accuracy of 0.03 (§5.2), and the requirement of §5.3 to survey a volume as large as the volume of the 2dF galaxy redshift survey.

**Choice of fields**. We have made a preliminary choice of the XMM-LSS, Lockman Hole, and Elais N1 fields as our targets. Table 5.1 summarises the coordinates of the fields and the XMM coverage, as well as coverage at other wavelengths. The XMM-LSS field is chosen because of the wide-field deep XMM pointings, while the two northern fields are well placed for SZ coverage, given the northern latitudes of the SZ observatories. These two fields also already have some XMM coverage.

**Optical coverage**. Deep *ugriz* optical data is required for most of the scientific goals set out in this proposal. This would be feasible with the INT wide-field camera. Alternatively it may be attractive to target VIRMOS fields, or fields from the CFH Legacy Survey. One can anticipate substantial convergence of target fields between groups surveying at the several different wavelengths. Although coverage of $35\square^\circ$ to the required depths to match the proposed J and K limits is a large undertaking, compared to the DXS itself this would require a relatively modest allocation of telescope time with contemporary optical wide-field cameras such as SuprimeCam on Subaru, and MegaCam on CFHT, and we do not foresee this as a limiting factor.

**Follow-up spectroscopy with FMOS**. FMOS is a 400 fibre $R = 600$ multiobject spectrograph being built for Subaru, with expected completion in 2005. FMOS has two characteristic features which make it an excellent counterpart to the DXS. Firstly the wavelength coverage is Z through H, which therefore includes $H\alpha$ (the strongest useful galaxy emission line) in the target redshift range $1 < z < 1.5$. The second advantage is the wide field of view $0.5^\circ$. With OH suppression FMOS will provide the fastest survey speed of any spectrograph for the measurement of redshifts of early-type galaxies at $1 < z < 1.5$, for scales of order

1°. At J=22, for an early-type galaxy, FMOS achieves S/N=15 per resolution element in 4 hours, over the full wavelength range. The speed for measuring redshifts for emission line galaxies will be much faster.

FMOS provides the capability for measuring velocity dispersions of detected galaxy clusters (§5.2). As mentioned in §5.3 preliminary planning for a sparse-sampled redshift survey of $10^5$ $z > 1$ galaxies, covering the entire DXS region, has begun. The scope of this survey is similar to the 2dF galaxy redshift survey. This will provide the opportunity for a statistical analysis of the galaxy spectra, which can be compared against the recent results at low redshift of Baldry et al. (2001).

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# Chapter 6

# The Ultra-Deep Survey
## *Determining the epoch of spheroid formation*


### Summary

We propose an ultradeep survey covering 0.77 $\square^\circ$ to $5\sigma$ point-source limits of K=23, H=24 and J=25. This will give a thousand-fold increase in area compared to any previous survey to this depth, which we anticipate will leave a lasting scientific legacy comparable to the impact made by the Hubble Deep Field. A major motivation is to determine the comoving number density of massive elliptical galaxies at high redshift ($z > 2$) and hence discriminate between competing theories for their formation. Previous IR surveys to this depth, covering only several square arcminutes, have been unable to address this question. With the unique capabilities of WFCAM we can unambiguously test whether the most massive galaxies are already in place at z=3, or whether they form at lower redshifts through the mergers of less massive Lyman-break objects.


## 6.1 Motivation

Elliptical galaxies are the oldest galactic systems in the local Universe. How and when were they formed? How do these massive galaxies relate to quasars and sub-mm sources? These fundamental issues are still controversial and unresolved, but theories of galaxy formation have now matured to the point where they are beginning to make clear, testable predictions.

The primary aim of this proposal is to determine the comoving number density of passively evolved ellipticals at high redshift. Answering this very basic question will test the fundamental principles of hierarchical structure formation. At the conclusion of the recent 'New Era in Cosmology' conference in Durham (September 2001), the final discussion panel (including Peebles, White, Frenk & Madau) agreed on a definitive observational test of the

CDM paradigm. Specifically, it was agreed that if $> 1/3$ of $L^*$ ellipticals were in place by $z = 3$, all current CDM-based models would be rendered untenable.

## 6.2 The formation epoch of massive ellipticals

It can certainly be argued that we already have incontrovertible evidence for some form of biased hierarchical galaxy formation, particularly after the discovery of strongly clustered Lyman-break objects at z∼3 (Steidel et al. 1998). The prediction of these models is, after all, that we expect stronger galaxy clustering in the most massive haloes (Baugh et al. 1998). These massive systems would then represent the progenitors of cluster galaxies in the local Universe.

However this population cannot directly represent the formation of the most massive present-day galaxies (e.g. ellipticals). Even correcting for the possible effects of dust, the inferred star-formation rates in typical Lyman-break objects are too modest (typically $< 50M_\odot yr^{-1}$, falling an order of magnitude short of the $\sim 1000M_\odot yr^{-1}$ required to form the stars in the most massive ellipticals on a timescale of <1Gyr). This leaves a major unanswered question. When were the bulk of the stars in elliptical galaxies formed, and how does this fit in with current theories of biased hierarchical galaxy formation? This is a fundamental issue, since ellipticals represent the most massive galaxies in the local Universe. They also appear to be intimately related to the quasar phenomenon (Kormendy & Richstone 1995, Magorrian et al. 1998, Gebhardt et al. 2000).

For many years the view was held that these galaxies formed the bulk of their stars in a single, explosive burst of star formation at high redshift, after which their stellar populations evolved passively (e.g. Tinsley & Gunn 1976). The discovery of a number of very old elliptical galaxies at high redshift lends weight to this hypothesis (e.g. Dunlop et al. 1996). Furthermore, Ellis et al. (1997) found that the scatter in the colour-magnitude relation of early-type galaxies is very small in clusters at z∼0.5, suggesting that the bulk of the star formation occurred at z>3. In the field, however, the situation is more uncertain. Abraham et al. (1999) argue that many early-type field galaxies have experienced a major phase of star formation since z=1. In short, the formation redshift for massive ellipticals is still a major unanswered question.

If most elliptical galaxies formed at very high redshift (z>3), this would be in agreement with the monolithic collapse scenario expected in both the isocurvature CDM (Peebles 1998) or warm dark matter models (Columbi, Dodelson & Widrow 1995; Moore et al. 1999). Both models predict the assembly of elliptical galaxies at z>3 in single collapse events. This is in stark contrast with the hierarchical CDM models of galaxy formation, in which typical elliptical galaxies form from the merging of intermediate-mass disks at lower redshifts (e.g. Kauffmann, Charlot & White 1996; Baugh, Cole & Frenk 1996). In rich clusters the distinction between these models becomes somewhat blurred, since hierarchical galaxy formation predicts a much earlier epoch of star formation and merging activity (Kauffmann & Charlot 1998). For more typical ellipticals, however, we can form a clear and unambiguous test by determining the abundance of passively evolved ellipticals at z>2. The galaxy colours, clustering and links with the SCUBA and X-ray population provide further constraints on formation scenarios (see below) but the basic goal of this proposal is to determine the comoving number density of passively evolved ellipticals from a representative volume in the crucial era at z>2.

### 6.2.1 Predictions of monolithic and hierarchical models

As we will see below, to detect at $z = 3$ an elliptical galaxy that has an L* luminosity today and which formed at $z > 5$ requires surveying to a point source equivalent depth of K∼23. (The galaxy itself may be brighter, but ellipticals are rather large and low average surface brightness). Over a wide parameter range we should then expect to find all the most massive elliptical galaxies (those more luminous than $4L_*$) in the redshift range $z = 2 - 4$. In the local universe, such objects have a space density of $1.5 \times 10^{-5}$ Mpc$^{-3}$ (Im, Griffith and Ratnatunga 1996, Kochanek et al. 2001).

**Monolithic models** In a pure monolithic scenario, with no merging history at all, the co-moving space density of massive galaxies is the same as today. Assuming a standard cosmology with $\Omega_m$=0.3 and $\Omega_\Lambda$=0.7, we would expect to find $\sim 100$ $4L_*$ ellipticals in the range $z = 2 - 4$ over our survey area of 0.77□°. Down to $2L_*$ we would find $\sim 1000$, with $\sim 5000$ at $L_*$.

**Hierarchical models** In hierarchical models, the abundance of massive ellipticals drops sharply with redshift. For a high density CDM model, the abundance at z=2 drops by a factor $\sim 13$ compared to local abundance, and by a factor $\sim 30$ by z=3. For a low density lamda-CDM model, the drop is by a factor $\sim 3$ at z=2 and a factor $\sim 11$ at z=3. (Kauffmann and Charlot 1998). Clearly a definitive test needs to probe to z=3, and to collect a reasonably large sample. With $\sim 1000$ $2L_*$ objects predicted for the monolithic scenario, Λ-CDM predicts $\sim 100$, and high density CDM predicts $\sim 30$. As well as testing the monolithic idea, one can then also discriminate between the variety of hierarchical models. In addition to pure counts, *colours* will be crucial, both for distinguishing different types of galaxy, and for constraining the formation epoch (see Section 5).

### 6.2.2 Comparison with previous deep surveys

Recent pioneering work by Daddi et al. (2000) has shown the power of wide area K-band surveys, but by reaching $K \simeq 19.5$ they were only able to probe bright elliptical galaxies to $z \sim 1.5$.

Surveys reaching K∼ 23 do, of course, already exist (c.f. the deep surveys with the Keck NIRC camera, Djorgovski et al. 1995), but previous ultradeep imaging has been restricted to very small fields of view (∼1–2 arcmin$^2$). With typically $\sim 30$ sources per field, the samples are clearly insufficient to conduct meaningful statistics, particularly for rare, very red objects.

Results on the abundance of high-z ($z > 2$) passive ellipticals have therefore been totally inconclusive. Cowie et al. (1994) found little evidence for such an old population to a limit of K=22, but this may be due to aperture correction affects (Dunlop & Gloag, in preparation). Djorgovski et al. (1995) and Bershady, Lowenthal & Koo (1998) find a few faint EROs, but from very small samples of $\sim$ 30 sources they cannot draw firm conclusions. Even in a monolithic scenario one would only expect $\sim$ 1 elliptical galaxy of $2\times L_*$ in such small fields. With a thousand-fold increase in area coverage, the proposed WFCAM survey will allow the UK community to make a significant leap forward in this area.

## 6.3 Additional scientific goals and the scientific legacy

Our ambitious proposal is to obtain ultradeep $J, H, K$ observations in a well-studied equatorial field. The unique wide-field capabilties of WFCAM will give a thousand-fold increase in area compared to any previous surveys to this depth, leaving a lasting scientific legacy which will be exploited for many years to come. By choosing a well-studied equatorial region, with existing (and planned) observations across the electromagnetic spectrum, we are aiming to maximise the scientific returns.

Whenever a radically new area of parameter space is explored the scientific benefits often come from unexpected quarters. We believe that determining the abundance and evolution of elliptical galaxies is of fundamental scientific importance, so we have highlighted this particular objective in some detail. A number of additional important scientific goals, mostly related to the high-z Universe, are listed below.

### 6.3.1 The clustering of high-z galaxies

Unlike optical studies of distant galaxies, which sample the restframe UV, the K band provides a more direct link with the mass of the stellar population in these systems, at least up to z=3 where the 4000 Å break lies in the H-band. Therefore the UDS survey will provide the first opportunity to reliably study galaxy clustering at z=2–3 without the very strong star-formation rate bias present in existing surveys. This will provide a very direct and powerful test of biased hierarchical galaxy formation, which predicts that the most massive galaxies form in strongly clustered environments (Baugh et al. 1998).

The $0.86^\circ\times0.86^\circ$ geometry of our proposed survey enables us to study clustering on a scale of 100×100 (comoving) Mpc at $z = 3$, and over a depth of 2 Gpc ($2 < z < 4$. We stress that detailed correlation functions are not required, but with ~10,000 galaxies at z>2 we expect to derive the basic form of the clustering amplitude as a function of galaxy size. Combined with the proposed K=21 DXS (which probes z<1.5) and Sloan/2dF, this will give us an accurate picture of the growth of structure with mass and cosmic epoch.

Significant progress can be made with comparing 2D correlation amplitudes versus magnitude, but of course the survey will be much more powerful with redshift information. Spectroscopic data for more than a minority of objects seems unlikely, but we should be able to get statistically reliable information using the photo-z technique (Benitez 2000). In addition to JHK from UKIDSS, high S/N optical multi-band photometry will be provided by the Subaru SuprimeCam, providing an accurate baseline for redshift determination.

### 6.3.2 The high redshift Kormendy relation

Our proposed depth is designed to detect an L* elliptical at z=3 to 5-$\sigma$ within a representative aperture (see technical section). In good seeing, this will allow an accurate determination of the half-light radius, particularly for larger elliptical galaxies where $r_{1/2} \sim 1$ arcsec. In turn we can then construct the surface-brightness versus radius plot for ellipticals out to z=3 (the Kormendy relation – a projection of the Fundamental Plane). The evolution of these properties with redshift will provide a strong test of any galaxy formation scenarios.

### 6.3.3 The link with sub-mm and X-ray sources

Studying the link between SCUBA galaxies, EROs, quasars and elliptical galaxies is another aim of this survey. Do these apparently disparate types of object represent a formation sequence (Archibald et al. 2001, Smail et al. 2001)? The tight relationship between the black hole mass and the spheroidal velocity dispersion in local galaxies suggests an intimate link between an early epoch of quasar activity and the formation of the spheroid (Gebhardt et al. 2000, Ferrarese & Merritt 2000). One attractive possibility is that the peak AGN activity corresponds to a termination of the major burst of star-formation activity producing the host spheroid, as predicted by Silk & Rees (1998) and Fabian (1999).

The discovery of the sub-mm population with SCUBA was heralded by many as evidence for a major epoch of dust enshrouded spheroid formation (Hughes et al. 1998; Lilly et al. 1999; Blain et al. 1999). Interestingly, with reasonable assumptions about the redshift distribution of this population, the comoving density of bright sub-mm galaxies ($\sim$1–2$\times10^{-5}$ Mpc$^{-3}$) is strikingly similar to the present day density of the most massive ellipticals, i.e. those with $L \sim 4 \times L^*$ (Lilly et al. 1999; Dunlop 2000). Do these SCUBA galaxies eventually become quasars, and thereafter quiescent spheroids (Archibald et al. 2001, Smail et al. 2001)? In principle we can test for this evolutionary sequence by studying the clustering and relative abundance of these populations as a function of redshift. Preliminary studies have already revealed tentative evidence for such a link. While the Chandra/SCUBA populations are only rarely coincident on a source-by-source basis, they appear to be strongly clustered together (Almaini et al. 2001). The implication is that (for a given galaxy) the major episode of star-formation appears to be essentially distinct from the period of (observable) quasar activity.

Pointed observations (e.g. with VLT, Gemini or Keck) are likely to identify dozens of individual SCUBA sources before UKIDSS becomes available, but a detailed clustering analysis including tests of the relationships between sub-mm galaxies, X-ray sources and EROs requires a large, contiguous field including a large sample of EROs. The UKIDSS UDS region is therefore ideally suited for these purposes.

### 6.3.4 Galactic structure

Although the primary aims of the UDS are clearly extragalactic, we also expect to find several hundred L and T dwarfs. The numbers predicted as a function of magnitude are highly uncertain, depending very strongly on the assumed IMF (Chabrier 2001). A very deep number-magnitude relation will therefore place tight constraints on these models. These will be found to much greater distances than in the LAS survey and may therefore be used to complement/extend measurements of the disc scale height for these very low mass dwarfs.

## 6.4 The ideal match with SCUBA-2

Our understanding of the high-redshift Universe changed dramatically with the advent of the SCUBA array at the James Clerk Maxwell Telescope. The next major advance in sub-mm astronomy will be SCUBA-2, the next generation bolometer camera for the JCMT. This will allow wide-field sub-mm mapping $\sim 100$ times faster than before. This will permit the first sub-mm maps covering scales of $\sim 1$ sq degree, and it therefore ideally suited to the UDS.

On a shorter timescale, an ambitious JCMT proposal has been submitted (PI Dunlop) to conduct a shallow survey with SCUBA (8mJy at 850$\mu$m) covering 0.5 sq degree. The list of Co-Is includes everyone in the UK community involved in sub-mm surveys. If approved, this survey would be complete by mid-2004. The proposed field is the same field that we propose for the UDS.

## 6.5 The choice of field - the Subaru Deep Field

A number of factors dictate the choice of field for this survey, ideally including: availability of the deepest data across the entire electromagnetic spectrum, accessibility to major ground-based facilities (e.g. ESO, ALMA, VLA) and an RA which does not clash with the other public UKIDSS surveys (e.g. the Large Area Survey and the Galactic Plane Survey).

One particular field emerges as the clear favourite. The Subaru Deep Field ($02^{\rm h}, -05^\circ$) is already the focus of a major multiwavelength programme, driven by continually accumulating very deep optical imaging (B,V,R,I) with the Subaru SuprimeCam. This is a unique wide-field instrument, housed on an 8m telescope, which consists of a 8k$\times$10k array giving a $24' \times 30'$ field of view. A further 38 nights on Subaru are anticipated over the next two years to complete this programme (A Subaru Key Project). This will readily provide the depth of optical data required to complement the UDS.

This is also the deepest X-ray field covering a $\sim$1 sq degree region, with 7 overlapping XMM-Newton observations consisting of one deep 100 ksec in the central (30 arcmin diameter) field and 50 ksec flanking fields. The Subaru field is also a target for SIRTF legacy observations, the proposed SCUBA survey (see above) and the *BLAST* project (Balloon-borne Large-Aperture Sub-mm Telescope), due for launch in the winter of 2003 (Devlin 2001).

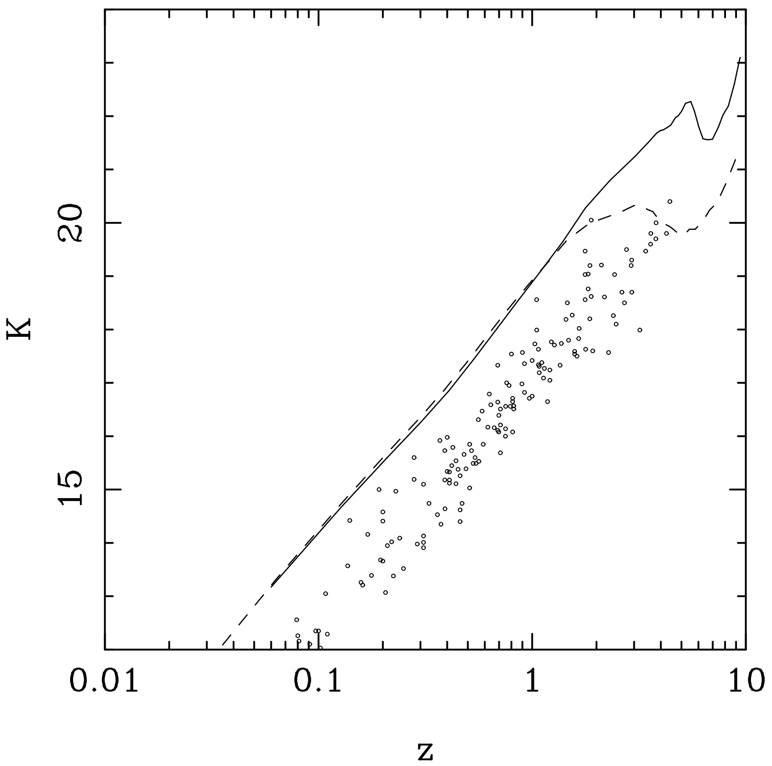


Figure 6.1: *Predicted K-z Hubble diagrams for passively evolving $L^*$ ellipticals, produced by J.S. Dunlop (based on the models of Jimenez et al. 1999). Both models assume a formation redshift $z_f = 10$. The model shown by the dashed line shows residual star formation to $z = 3$, with a more rapid burst of star formation for the solid line (terminating at $z = 5$). We assume a Cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_o = 70$. For comparison, the data points illustrate the observed K-z relation for the hosts of powerful radio galaxies (corresponding to $4\times L^*$ ellipticals). Note that these data track the faint model predictions with very little dispersion.*

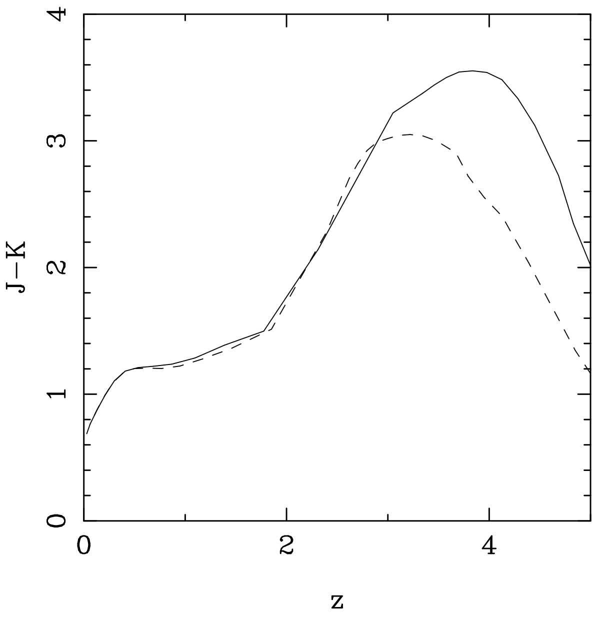


Figure 6.2: *$J - K$ colours as a function of redshift for the 2 evolution models illustrated in figure 6.1.*

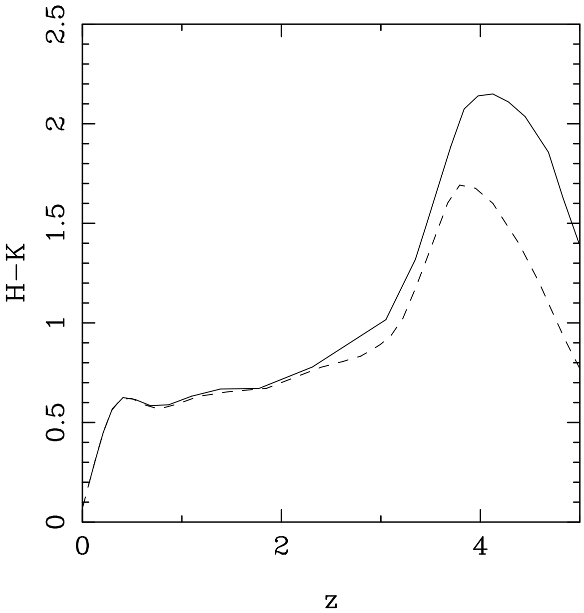


Figure 6.3: *$H - K$ colours as a function of redshift for the 2 evolution models illustrated in figure 6.1.*

## 6.6 Technical requirements

**Survey depth**

Using the models of J.S. Dunlop (private communication) we have estimated the K-band magnitude of a passively evolving L* elliptical galaxy as a function of redshift, assuming a formation redshift z=10 (figure 6.1) and a period of star formation extending to $z = 3$ or terminating at $z = 5$. We find that an L* elliptical galaxy at z=3 in a Λ-dominated cosmology would have a total magnitude in the range $K = 20 - 22$, depending on the duration of the star-forming phase. Alternatively one can extrapolate the observed K-z diagram for brighter (4×L*) elliptical galaxies, as traced by the hosts of luminous radio galaxies (shown as data points on figure 6.1). To convert to an L* elliptical (assuming, of course, that these follow a similar evolutionary track) one would predict a total magnitude $K \simeq 21.5$ at $z = 3$ (using $\Delta K = 2.5 \log 4 = 1.5$ mag)

However, we need to survey to a considerably fainter point source magnitude depth. Elliptical galaxies are large extended sources and hence aperture correction issues must be taken into account. These effects may have led to a systematic underestimate of the prevalence of large elliptical galaxies at high redshift in previous deep surveys (Dunlop & Gloag, in preparation). A large elliptical galaxy will have a half-light radius of $r_{1/2} \sim$ 10kpc, corresponding to $\sim$ 1 arcsec in a Λ-dominated cosmology (1<z<4). An aperture of radius $3 \times r_{1/2}$, i.e. a 6 arcsec diameter, is required to capture $> 90\%$ of the light and so provide an accurate total magnitude. Of course the galaxies may transpire not to be this large, but we stress that to prove this we still need to be able to make a meaningful large aperture measurement. The key point is that to establish both the half-light radius and total magnitude of a high-redshift galaxy with confidence requires that meaningful measurements can still be achieved as the aperture is expanded out to a diameter $\simeq$ 6 arcsec.

For median seeing, the point-source depths used throughout this proposal correspond approximately to using a 1 arcsec aperture, as this optimises the S/N. If we detect K=21.5 in a 6 arcsec aperture, then the through-aperture magnitude detected to the same S/N in a 1 arcsec aperture is K=21.5 + 2.5log 6 = 23.4. However the equivalent point source giving such a through aperture magnitude is K∼22.7. Overall, we see that a survey with a depth corresponding to a point-source limit of $K = 23$ will be able to detect L* passively evolved ellipticals to z=3 (5-$\sigma$) through the necessary range of apertures.

**Filter choice** Colour information is also vital for discriminating between objects, and for the determination of photometric redshifts, particularly using the 4000Å break as it moves through the I, J & H bands over the range 1<z<4 (see figures 6.2, 6.3). Photometric redshifts need two points longward of the 4000Å break and so should work up to roughly z=3. To effectively separate passive ellipticals from starbursts, we need to be able to detect colours of J-K∼ 2 and H-K∼ 1, otherwise the majority of our sample objects may be K-band detections only. By the same reasoning, its is also highly desirable to obtain very deep I-band data to complement the UDS. For an ERO detection, depths of I∼27–28 will be required to match the above. SuprimeCam on Subaru would be ideal for such imaging.

**Survey area** Our prime goal is to measure the abundance of high redshift passive ellipticals. A survey of approximately one square degree size is needed for confident statistics. The simplest strategy would be to stack repeated exposures at an identical pointing, resulting in four separated surveys totaling 0.21 □°. However as well as compromising the statistics, this would damage our secondary aim at measuring the clustering amplitude of various populations, which really needs a contiguous area probing $\sim$ 100Mpc. A contiguous field is also highly desirable for obtaining complementary multiwavelength data in an efficient manner. It may well be best to make such a deep stacked survey on a finely gridded pattern, but the optimum pattern needs further research. For the purposes of modelling, we assume for now that the UDS is a straightforward tile made with four macro-steps, making a filled-in area of area 0.77 sq deg, and mosaic efficiency $E_m$=0.93"

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