Proposal to UKIRT Board

Completion of UKIDSS

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on behalf of UKIDSS Consortium

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Abstract

We provide a report on the progress of UKIDSS to date, and set out a revised survey design for completion by May 2012. At September 2009, UKIDSS has completed approximately one third of its original 2001 design. Data quality and survey depth are largely achieving design goals. Rigorous quality control means that the survey completion rate is somewhat slower than estimated in the 2001 proposal, but somewhat better than at the 2006 renewal proposal. With the support of high quality UKIRT and VDFS operations efforts, UKIDSS has made public data releases on a regular schedule, and hundreds of astronomers across Europe, and increasingly the rest of the world, are using the database and producing science. To date, UKIDSS has produced 109 refereed papers which have 1542 citations between them, and the rate of production is accelerating. Science highlights include the measurement of the sub-stellar mass function, the discovery of $z \sim 6$ quasars at three times the rate of SDSS, measurement of the evolution of galaxies at $z = 5 - 6$, discovery of the coldest known stars, discovery of many new pre-main sequence eruptive variables, and the measurement of large scale structure at $z \sim 1$.

The original science goals of UKIDSS - for example discovery of the most distant quasars, measurement of the stellar mass function and its dependence on environment, and quantitative study of the epoch of galaxy formation - have not been superseded, and have been only partially completed by the survey to date. The UKIDSS surveys therefore do not need radical re-design. However, given the time remaining, scheduling issues, and results to date, we have carefully considered the balance between survey components, the balance between areal coverage and second epoch coverage, and the balance between different bandpasses, to produce a revised design to completion. Within our expected allocation from semester 09B to 12A, we should complete approximately 80% of the original 2001 design goals. For the Galactic Plane Survey (GPS), the Galactic Clusters Survey (GCS), and the Deep Extragalactic Survey (DXS), the revised plan largely involves reducing areal coverage. For the Large Area Survey (LAS), the footprint is substantially changed compared to the 2001 design, and only ∼half of the surveyed area will have second epoch coverage. (These changes have been largely driven by scheduling efficiency concerns.) The Ultra Deep Survey (UDS) has for various reasons received much less than its expected allocation so far, and so is only ~ 10% complete. We plan an intensive “UDS catch-up” campaign, following which it will reach 43% of its original goal. However this also includes a re-balancing between bandpasses, such that the UDS will achieve its original target of a depth of K=22.8.

1 Introduction

This proposal is a submission to the UKIRT Board as part of the process of optimising the scientific programme of UKIRT up to May 2012. Sections 2-4 report on the technical and scientific progress of UKIDSS to date. Given the guidance on the amount of time available to UKIDSS from here until May 2012, we estimate that we will be able to achieve approximately 80% of the original 2001 design goals. In Sections 5-6 we present an updated science case and revised design which meets this target. In Section 7 we make a proposal for the possible use of extra nights up to May 2012, and in Section 8 we present arguments in favour of a continuation past May 2012, should this be politically possible.

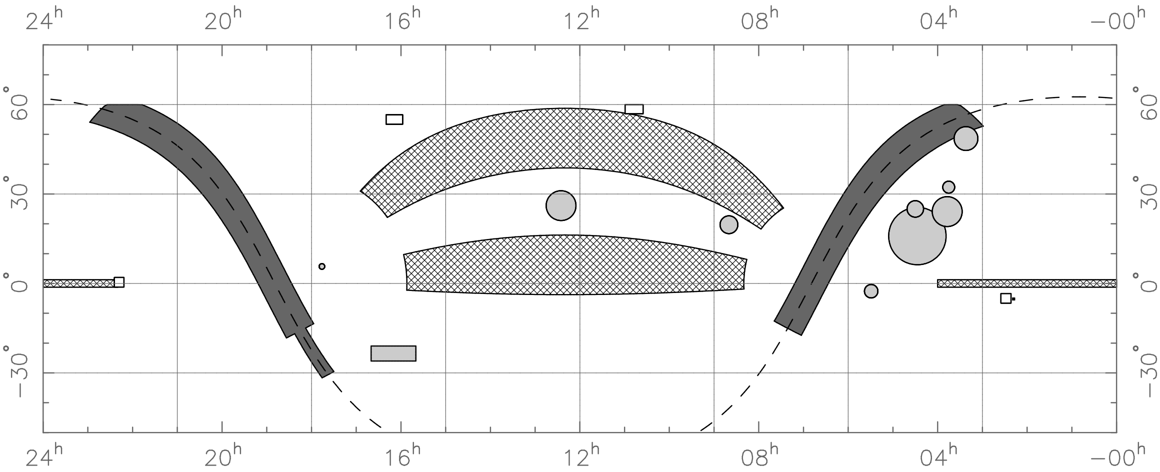

Figure 1: *Footprint of UKIDSS survey as originally designed in 2001, from Lawrence et al. 2007. Cross-hatch: LAS. Dark grey: GPS. Light grey: GCS. Open rectangles: DXS.*

2 Evolution of UKIDSS

2.1 Original goals and design

UKIDSS was formally proposed to the UKIRT Board in March 2001, and the programme resulting from this review was also agreed with ESO as part of the accession process. The design is summarised in Lawrence *et al.* (2007). The original design footprint is shown in Fig.1. The detailed design areas/depths are described in Table 3 of Lawrence *et al.* 2007. In summary, the original design included approximately 7000 sq.deg. to K=18.2 in the three "shallow" surveys - the Large Area Survey (LAS), the Galactic Plane Survey (GPS), and the Galactic Clusters Survey (GCS); 35 sq.deg. to K=20.8 in the Deep Extragalactic Survey (DXS); and 0.77 sq.deg. to K=22.8 in the Ultra Deep Survey (UDS).

The headline science goals were : to provide a long-term astronomical legacy database; to find the nearest and faintest substellar objects; to discover Population II brown dwarfs, if they exist; to determine the substellar mass function; to break the z = 7 quasar barrier; to determine the epoch of re-ionization; to measure the growth of structure from z = 3 to the present day; to determine the epoch of spheroid formation; and to map the Milky Way through the dust, to several kpc.

2.2 Early progress and changes after Nov 2006 review

UKIDSS began observations in May 2005, and together with the VDFS team, has since made six data releases on a regular schedule. The number of nights per semester allocated to UKIDSS has gradually increased, from 67 nights/semester in 05-06 to the current rate of 105 nights/semester, including nights donated by UH and Korea. The rate of deposition of releaseable data into the archive has however been 80-90% of proposal estimates, due to a mixture of observing overheads and and data quality issues, leading to a higher than originally expected QC rejection rate. During 2006-2008 a number of improvements have been made which mean that survey completion rate is significantly improved, but still lower than the original expectation.

In 2006 the UKIRT Board invited further "campaign" proposals, and asked UKIDSS to submit a "renewal" proposal as part of the same process. The result was an overall endorsement of the UKIDSS project, but together with some re-prioritisation. We summarise those changes next, along with subsequent developments:

Release	Europe	World	Summed area all filters	UDS depth
DR1	Jul 2006	Jan 2008	2365 sq.deg.	K=21.5
DR2	Mar 2007	Sep 2008	3673 sq.deg.	K=21.5
DR3	Dec 2007	Jun 2009	7502 sq.deg.	K=21.7
DR4	Jul 2008	(Jan 2010)	8847 sq.deg.	K=21.7
DR5	Apr 2009	(Oct 2010)	10541 sq.deg.	K=22.0
DR6	TBD	TBD	(11461)	K=22.1
DR7	TBD	TBD	(13686)	K=22.1
Design	Nov 2001		35730	K=22.8

Table 1: *Statistics on data releases*

(i) LAS was to be accelerated, with an intention of completing by the end of semester 2009B. In fact this was almost impossible for scheduling reasons. During 2007 the consortium agreed on a significant footprint change for the LAS, adding an autumn equatorial block, and essentially stopping work on the northern block, apart from priority coverage for Herschel. (ii) GCS was to concentrate on the younger clusters. This was interpreted as ceasing further work on the Hyades. (iii) GPS was to concentrate on the main JHK survey. The narrow-band observations in Taurus-Auriga-Perseus were ceased (although they were partly completed in PATT time), and the second epoch K observations were left for a later decision. (iv) The UDS was recommended for a reduced allocation, with the implication of a shallower final depth. In fact for various reasons to do with weather, engineering, and operational algorithms, the UDS has received very little time, and so is a long way behind even the reduced allocation. Over recent months, operational matters have improved yet further, and in particular the rate of observation of UDS has improved dramatically. (v) DXS concentrated solely on J and K band leaving the originally proposed 5 sq.deg. H-band observations to be considered only if any DXS field reaches completion.

3 Technical progress as of September 2009

3.1 Data Releases

Data releases are primarily the responsibility of the VDFS team, but with UKIDSS members playing a key role in the Quality Control process. However, UDS WG members in Nottingham also run additional pipeline processing for the Ultra Deep Survey, in close collaboration with CASU and WFAU, and are responsible for delivering a final stacked product to the archive. VDFS and UKIDSS have kept to an impressive schedule of public releases. An *Early Data Release* was made only seven months after the first observations, and further data releases have been made regularly since. Table 1 summarises the progress of data releases. The area listed is the summed area over all filters for the shallow surveys (LAS, GPS, and GCS), as this can be directly compared with the original survey design in order to calculate fractional completeness of the shallow surveys. The DR6 and DR7 releases (including data up to semesters 08B and 09A respectively) have of course not been made yet, but the forecasts should be reasonably accurate as the observations are complete.

3.2 Coverage so far

Fig 2 shows the sky coverage achieved by all WFCAM observations as of July 2009. This represents all dataframes received and processed by the CASU pipeline, which is somewhat larger than the frames passing QC and being ingested into the archive. (UDS is particularly stringent on data quality, typically accepting 80% of the frames sent from UKIRT). For calculation of the completed fraction of surveys, we consider two baselines - the contents of the database for DR5 (to semester 08A), and the forecast contents of the database for DR7 (to semester 09A). We compare the contents to a slightly adjusted version of the original 2001 design.

For GPS, this excludes the narrow-band H_2 observations, and for DXS it excludes the H-band observations, which have never been attempted. We also use an adjusted average exposed time per frame for DXS - 3.91h versus the 3.6h quoted in Lawrence *et al.* 2007. This is because DXS has been using poorer seeing time, which otherwise would not have been used at all. This is a more efficient use of UKIRT time, but means that DXS on average needs longer to achieve the target depths, which we have not changed.

A breakdown of completeness by survey, together with the required time for proposed completion plan, is given in section 6. Here we provide a textual description of the progress of each survey so far.

For the shallow surveys, because exposure time is fixed, we can quantify coverage by comparing the summed total of area$\times$filters, as in Table 1, with the adjusted 2001 design goal. This shows that DR5 represents 32% completeness averaged over the three shallow surveys, and by the release of DR7 the shallow surveys should be roughly 38% complete. For LAS, compared to the 2001 design target of 4028 sq.deg. at YJHK and second epoch ("J_2") , we expect that DR7 will include 2300 sq.deg at YJ_1, 2650 sq.deg. at HK, and only 265 sq.deg. at J_2. As explained above, the footprint changed following the 2006 review, adding an autumn equatorial block, and leaving most of the original northern block unchanged since 2006. For GCS, no second epoch measurements have yet been made; otherwise two clusters are more or less completely done (IC 4665 and Perseus OB2); three are mostly done, i.e. 40-80% (Pleiades, α Per, Upper Sco); four have a small amount done, i.e 5-20% (Praesepe, Taurus, Orion, and Coma); and the Hyades has a negligible amount, as work was ceased after the 2006 review. For the GPS, about 40% of the plane has been covered, mostly with all three of JH and K, with 580 sq.deg. at K only. A very small area (31 sq.deg.) has been observed in second epoch K.

For DXS, degree of completeness can be estimated two ways. First, one can compare area achieved to target depth against the design area. On this basis, DR5 is 34% complete and extrapolation to DR7 forecasts 41% completeness. On the other hand, one can compare on-sky integration to that originally quoted in Lawrence *et al.* (2007); on this basis the DR7 forecast is 52% completeness. These two estimates are different because DXS has spent longer than expected on each field; this is partly because it has accepted slightly worse seeing conditions that otherwise might not have been used at all. We have therefore used an adjusted exposed hours total based on 3.91h per sky position rather than the original 3.6h abd believe this to be the most reasonable estimate of DXS completness. On this basis the forecast DR7 completeness is 48%. DXS has built up each of its four fields from roughly 12 sub-areas (single tiles) at each of J and K, trying to complete depth in a given filter for each sub-area before moving on. The areal coverage achieved has been somewhat different in the four fields. At September 2009, the sum of sub-areas$\times$filters was approximately : SA22=16; Elais-N1=13; Lockman Hole=6; XMM-LSS=5.

For UDS, because it is a single repeatedly observed tile, the appropriate way to calculate degree of completeness is to measure accumulated on-sky integration time making it past QC into the database, and compare with the design goal. On this basis, UDS is a long way behind the other surveys. In the DR5 database, completeness is only 9%, and the forecast for DR7 is still only 12% completeness. This requires a little more explanation.

Why is UDS so far behind?

The slow progress in the UDS has been caused by a combination of factors. Unfortunate telescope scheduling has certainly been a major contributor, combined with bad luck and poor weather. In 2006 WFCAM was not installed until November, which missed the best two months for UDS observing. In 2007 poor weather was a major culprit, with a further 18 nights lost due to breakdowns and cold-head work. In 2008 the telescope was closed for 26 days in August/September for telescope aluminising, and WFCAM was removed to begin Cassegrain observing at the end of November.

To compound these problems, the UDS has rarely been observed at high airmass. We suspect this is due to an overly-pessimistic seeing model in the query tool (this is being investigated) combined with difficulties in measuring the best zenith seeing given the large WFCAM pixels (the 'seeing floor' problem). Difficulties measuring the *delivered* seeing (given the lack of bright stars in the UDS) have also contributed, and observers may have incorrectly abandoned the field in the past.

Thankfully, most of these issues have now been addressed. The clash with Cassegrain observing is no longer a problem. A new mirror cooling system has dramatically improved the seeing at the start of the night. A new system has been introduced to measure the seeing at the airmass of the UDS directly rather than rely on the

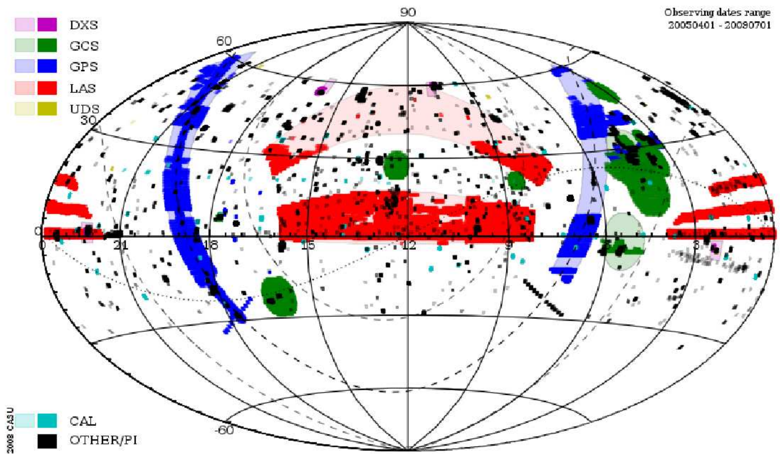

Figure 2: *WFCAM coverage as of July 2009, including UKIDSS, PATT observations, and calibration fields. Taken from the CASU progress page.*

query tool. The UDS constraints have also been slightly relaxed. As a result of these changes, 09B is on course to be the most productive observing season by at least a factor of two. We therefore believe that substantial gains can be made in the remaining two semesters available to UDS.

3.3 Data Quality

The basic data quality characteristics of UKIDSS were reported in Lawrence *et al.* (2007), and have not essentially changed. Median seeing is ∼0.82 arcsec, and median stellar ellipticity is 0.07. The absolute astrometric accuracy ranges from 50 to 100 mas depending on latitude. The absolute photometric accuracy is 2%, limited by the accuracy of 2MASS, to which our calibration is tied (see Hodgkin *et al.* 2009). All these figures are easily within the design goals. Fig 3 shows that the internal accuracy of the photometry is extremely good. It compares multiple measurements of the same point sources in many independent frames in the DXS stacks, showing that at bright magnitudes repeatability is 5 milli-mag.

Characterising achieved survey depth is a little more subtle. The most well defined measure is the magnitude of a point source that can be detected at a specified position using a standard aperture, as this is determined by the local background noise. This varies somewhat from field to field of course, but for the UKIDSS shallow surveys the typical 5σ detection limit in a 2 arcsec aperture, compared to the design goals, is Z=20.36 (20.4), Y=20.16 (20.3), J=19.56 (19.5), H=18.81 (18.6), and K=18.19 (18.2). Detection limit is therefore close to design goals for all except the Y-band, which falls somewhat short. For extended sources such as galaxies, the detection limit is of course brighter, and not uniquely determined, depending on size and profile.

A different question is to ask to what depth the UKIDSS catalogues can be considered complete. Fig 3 demonstrates the point source depth achieved for the shallow surveys. This shows point source number counts for the K-band, taken from all GCS K-band detections. The clear peak indicates 100% completeness to K=17.7. At the 5σ detection limit (K=18.2) counts are roughly 50% complete, very much as expected from simple statistics, thus indicating no major systematic effects in the data or pipeline. Fig 4 shows number counts from two different latitudes in the GPS. At $l = 98.4$, the counts peak is in the same place as in the GCS and LAS, indicating little effect from crowding. Closer to the Galactic Centre this is no longer true - Fig 4 shows that at $l = 30$, the completeness limit is around a magnitude brighter. Fig 5 shows the point source completeness in the much deeper stacked DXS survey. This shows the fraction of simulated point sources recovered versus magnitude, indicating that the DXS is 90% complete for point sources to K=20.8. (This figure also shows how some sub-fields are less deep, mostly due to inclusion of some poorer quality data in the DXS.)

The deeper, stacked surveys are of course dominated by resolved galaxies, for which the completeness limit is somewhat brighter. The deeper surveys are also much more sensitive to problems with background subtraction and background structure, so that catalogue completeness may not achieve what one expects from photon

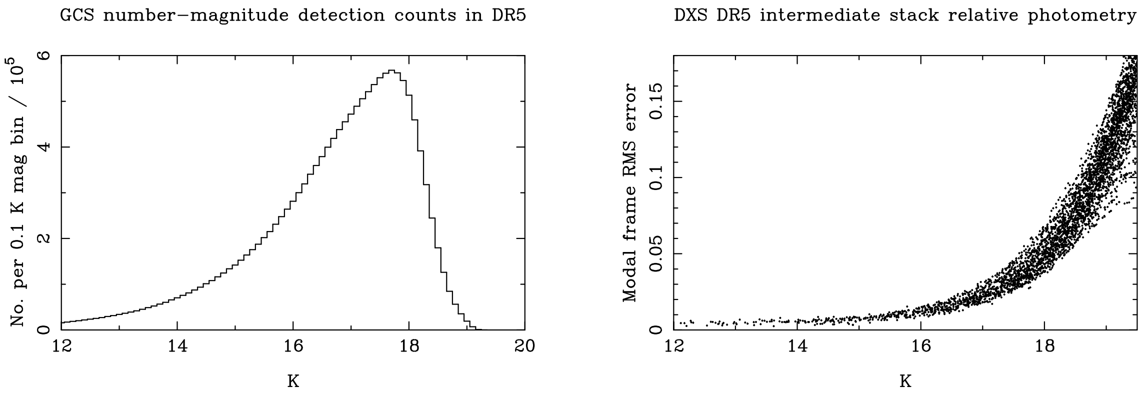

Figure 3: **Left :** *Stellar number counts in the GCS versus K-magnitude. The clear peak indicates that stellar counts are 100% complete to K=17.7, compared to the 5σ detection limit of K=18.2, where completeness is approximately 50%.* **Right :** *Internal photometric repeatability. This shows the RMS scatter in measurements of the same point sources in many different frames within DXS stacks, each of which is processed independently. At bright magnitudes the repeatability is 5 milli-mag, with the rise to fainter magnitudes very much as expected from simple statistics.*

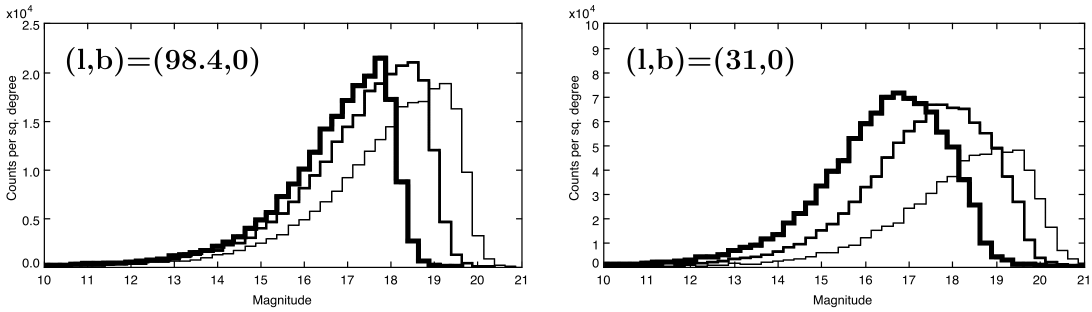

Figure 4: *Stellar number counts in the GPS at two different locations. From left to right the curves are respectively in K, H, and J. At a longitude of 98.4 degrees the counts are 100% complete to K=17.7, just as in the GCS and LAS. (Note that the K-band exposure is the same, but in J and H it is twice as long as LAS). Closer to the Galactic Centre (RH panel), the effects of crowding are apparent, with the K-band completeness roughly a magnitude brighter.*

noise. In these circumstances there is also a tradeoff in completeness versus reliability; one can easily push the completeness limit deeper, at the cost of introducing many more spurious sources. Over the last year UKIDSS WG members and the VDFS team have been working closely together to develop improved algorithms to minimise the structured background issues, and have also been experimenting with different pipeline parameter settings. Fig 5 compares galaxy number counts in UDS DR5 to several very deep (but much smaller area) surveys. The standard “5σ noise depth” in these data is K=22.04. Using the new algorithms in the CASU pipeline, and settings for subsequent deep stack extraction that restrict the spurious fraction at this depth to $<$2%, the UDS is 90% complete for galaxies to K=21.8, close to the expected value, and several tenths of a magnitude better than the depth achieved in earlier data releases. We have also experimented with use of the new algorithms on DXS frames, but here the difference made is smaller, indicating that the background is still largely photon noise limited.

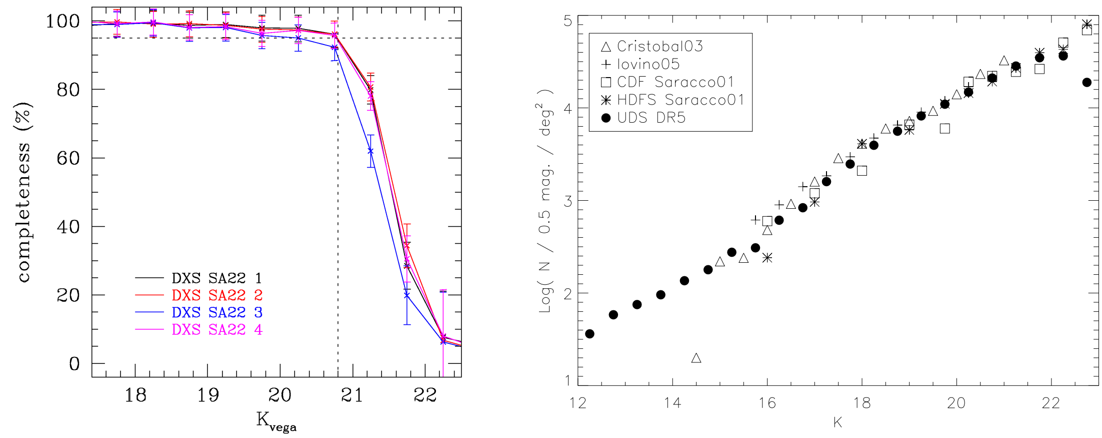

Figure 5: **Left :** *Effective depth in four different K-band tiles within the DXS SA22 region, estimated using simulated point sources. Where full depth and quality have been reached, DXS is 90% complete for point sources to K=20.8. (Equivalent depth for faint galaxies would be approximately K$\sim$20.5.) Occasional tiles, such as sub-region 4 of SA22, have been observed in non-ideal conditions, producing somewhat lower depth.* **Right :** *Depth of UDS at DR5, shown by comparison of galaxy number counts with those in deeper (smaller area) surveys. The 5σ point source detection limit is K=22.04; 90% completeness for galaxies is K=21.8. This figure also demonstrates the impressive dynamic range of UDS data.*

4 Scientific progress

4.1 Use of data

Nearly all scientific use of UKIDSS has been through the WFCAM Science Archive (WSA). There are currently 890 registered users, of whom 427 have actually run queries and extracted data. Note that registration is only required for access to data within the ESO community restricted period. There is extensive and growing additional anonymous access to the world-public data. As of September 2009, the total number of queries run was 805,000, extracting a total of 13.5 billion rows of catalog data, as well as pixel cutouts and flat files.

4.2 UKIDSS publications

A list of publications resulting from UKIDSS is maintained at www.ukidss.org/science/science.html. The papers we count are as follows. (i) Core papers describing the survey (e.g. calibration, archive, data releases). (ii) Papers including science results that are derived in whole or in part from UKIDSS data directly accessed from the archive (analysis of data published in another paper does not count). (iii) Papers containing science results from primary follow-up observations in a programme that is identifiable as a UKIDSS programme (e.g. *The physical properties of four 600K T dwarfs*, presenting Spitzer spectra of cool brown dwarfs discovered with UKIDSS). (iv) Papers which include a feasibility study of science that could be achieved using UKIDSS data (e.g. *The possibility of detection of ultracool dwarfs with the UKIRT Infrared Deep Sky Survey* by Deacon and Hambly). Using this method, as of September 30th 2009 there were 109 published papers. (We count only published papers, not astroph preprints.) The numbers of citations to the core UKIDSS reference, Lawrence *et al.* (2007), is currently 194. Combined citations to all the 109 published papers is 1542, indicating that the UKIDSS papers are on average of considerably higher impact that the typical astronomy paper.

The publication rate is accelerating : 7 papers in 2006, 24 in 2007, 35 in 2008, and 43 in the first nine months of 2009. This compares well with 2MASS and SDSS at a similar early stage, as shown in Table 2. The source used is information on the 2MASS and SDSS web pages. For SDSS, this is probably a significant underestimate, as the listings are for papers including consortium members. Nonetheless, it is clear that at this early stage, UKIDSS productivity is not dissimilar to 2MASS and SDSS. The UKIDSS publications cover a

Survey	Start Date	N(+34m)	N(+52m)
2MASS	Jun 1997	30	100
SDSS	Sep 1998	42	101
UKIDSS	May 2005	39	109

Table 2: *Survey publication statistics*

wide range of science - cool brown dwarfs, local galaxies, high redshift galaxies and quasars, star formation regions, gravitational lenses, and so on. Some publications are specifically planned around UKIDSS, and others are using the legacy value of UKIDSS, adding IR value to other projects. The authors are spread all around Europe, and increasingly in the US and Japan as well. In the next section, we summarise some specific science highlights.

4.3 Science Highlights

LAS Highlights

The main science goals of the LAS are to find the coolest brown dwarfs, with $T_{\rm eff} < 750$K, to find the highest-redshift quasars, with $z > 6.4$, and to provide the near-infrared complement to the SDSS galaxy survey. Some sample science highlights are provided below. Of the 28 published journal papers, nearly half are on cool stars, but other topics include gravitational lenses (Jackson *et al.* 2009), post-starburst galaxies (Wild *et al.* 2008), and red quasars (Maddox *et al.* 2008). The LAS data are also a crucial element in defining the galaxy catalogue for the GAMA survey (Driver *et al.* 2009).

The coolest brown dwarfs. The LAS will survey an order of magnitude more volume than 2MASS, and even though only one-third complete has already discovered more T brown dwarfs, 85 compared to 53 (Lodieu *et al.* 2007, Pinfield *et al.* 2008, Burningham *et al.* 2009, and in prep.). At the start of the surveys the coolest known star was the T8 brown dwarf 2MASS J0415$-$09, with $T_{\rm eff} = 750$K, and one of the main goals was to narrow the remaining gap in our knowledge of the spectral sequence, from 750K to 150K (the temperature of the giant planets in the solar system). So far 7 brown dwarfs have been discovered in the LAS with spectral type later than T8, including the T9 dwarf ULAS J1335 with $T_{\rm eff} = 550$K, the coolest known star (Burningham *et al.* 2009). Parallaxes have been measured for 4 of these targets (including CFBDS 0059, first published by the CFHLS). Fig 6 shows that the T dwarf sequence has been extended to lower luminosities by nearly 2 mag. There are hints that we are on the threshold of a new spectral class, the Y dwarfs, as the $Y - J$ colour turns bluer in moving from T8 to T9.

The highest-redshift quasars. Combining the UKIDSS LAS with SDSS data allows the possibility of searching for quasars in the redshift interval $5.8 < z < 7.2$. The principal goal is to find quasars beyond $z = 6.4$, the current limit achieved by optical searches, and thereby to explore the epoch of reionisation. Reionisation is believed to be a rapid process, akin to a phase transition, and is a milestone in the evolution of the Universe. Today, with the LAS just over one-third complete, four new $z \sim 6$ quasars have been discovered, with redshifts $z = 5.72$ (a BAL), 5.94, 6.04, and 6.13 (Venemans *et al.* 2007, Mortlock *et al.* 2009, Warren *et al.* in prep., Venemans *et al.* in prep). At the same time the two known SDSS $z \sim 6$ quasars in this area, with $z = 5.82$, and 5.93, are recovered. So in this area UKIDSS has discovered three times as many $z \sim 6$ quasars as SDSS. The numbers found in the range $5.7 < z < 6.4$ are in line with expectation, but it is somewhat surprising that none have been found at $z > 6.4$. Over the 1300 sq degs of DR5 we predict 3.2 ± 1.9 (accounting for the selection function), so the detection of none may indicate that the rate of decline in space density is accelerating beyond $z = 6$ – although the discrepancy is not yet very significant. As shown in Fig. 7 the Lyα emission lines of the UKIDSS quasars are weaker than the lines of the SDSS quasars. This is not unexpected: relative to UKIDSS, SDSS is biased to quasars with strong emission lines, as at $z \sim 6$ Lyα lies in the z band, the band used to define the survey flux limit.

The local K-band galaxy luminosity function. Smith et al. (2009) have presented a detailed analysis of the K-band galaxy bivariate brightness distribution in absolute magnitude and effective surface brightness (SB), using $40\,111$ galaxies selected from DR3. This shows a correlation between luminosity and SB, with a broadening

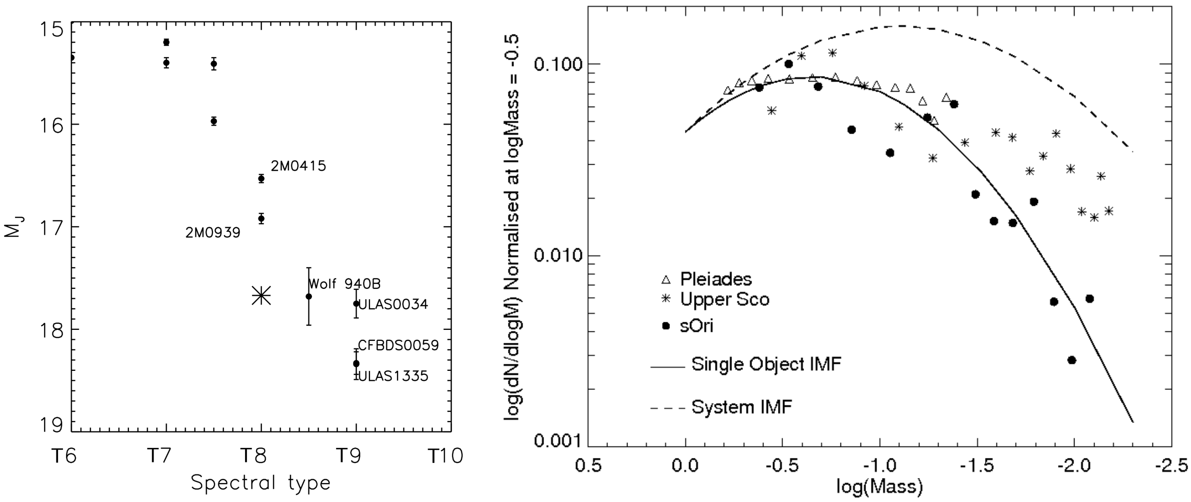

Figure 6: **Left :** *Absolute magnitude M_J for cool brown dwarfs as a function of spectral type. The four LAS brown dwarfs with parallaxes are the T8.5 dwarf Wolf 940B, and the three T9 dwarfs ULAS0034, CFBDS0059, and ULAS1335 (Burningham et al. 2009, Warren et al. 2007). They are all substantially less luminous than 2MASS J0415−09, the lowest luminosity brown dwarf known at the start of the survey. The T8 dwarf 2M0939 is also shown. It is thought that this may be a binary brown dwarf, in which case the asterisk marks the luminosity for the case of equal masses.* **Right :** *Mass functions (number of stars per unit logarithmic mass interval) derived from GCS data. The figure compares Upper Sco, the Pleiades and the sigma-Orionis clusters (solid circles, open triangles and asterisks respectively plotted without error bars for clarity - for details see Lodieu et al. 2009a and references therein). Also plotted is the log-normal parameterised field IMF assuming 50% binarity; the dashed line is the corresponding underlying single-star IMF in the simulation of the system function (see Chabrier 2003 for further details).*

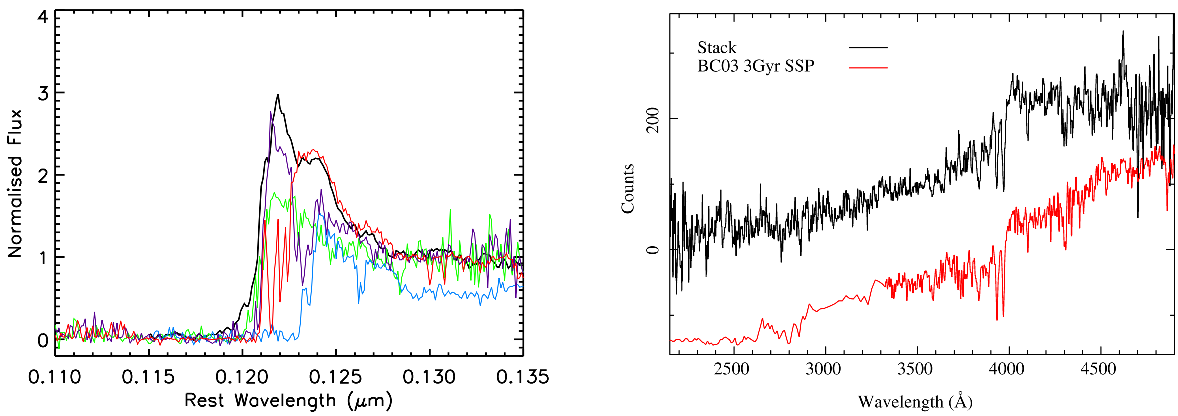

Figure 7: *Comparison of the line strengths of the four new UKIDSS $z \sim 6$ quasars against the average quasar spectrum from SDSS (black), from Fan et al. (2004). Blue: ULAS J0203+0012 (z=5.72, BAL), red: ULAS J0148+0600 (z=5.94), purple: ULAS J1206+0630 (z=6.04), green: ULAS J1319+0950 (z=6.13). The spectra are normalised to the same continuum level, and plotted in the rest frame. The SDSS sample is biased to strong-lined quasars, and UKIDSS is picking up the weaker-lined objects. The spectrum of ULAS J0203+0012 is absorbed over much of the range shown, by the SiIV BAL.* **Right :** *Mean spectrum of 38 distant Luminous Red Galaxies selected from DXS, showing strong Hδ absorption indicating a significant contribution by young (< 2Gyr) stars.*

of the SB distribution at low luminosity and a flattening of the luminosity-SB relation at high luminosity. The K-band luminosity function presented represents the current state of the art, and is an important benchmark for galaxy evolution studies.

GPS Highlights

The main aims of the GPS are: (1) to provide a Legacy Database of 1-2 billion stars for all aspects of Galactic astronomy; and (2) to advance our knowledge of star formation and Galactic structure by detecting pre-main sequence clusters and mapping structure right across the Milky Way. There is a very strong synergy with other Legacy surveys, e.g. Spitzer-GLIMPSE and IPHAS, which is now being extended by recently approved surveys with larger area coverage such as GLIMPSE-360. Some example science highlights are listed below.

FU Orionis stars and the stellar birth line. An exciting recent result from DR5 has been the detection of 16 new high amplitude variable stars ($\Delta K>1$ mag) in the 2 epochs of GPS K band data (see Lucas 2009, UKIRT@30 presentation). Their colours, magnitudes and locations indicate that most of them are likely to be eruptive pre-main sequence (PMS) variable stars, either FU Orionis stars (FUORs) or their even younger equivalents. Eleven of the variables are located in a 1 deg^2 area centred on the Serpens OB2 association (Forbes 2000), a massive 5 Myr old association in which star formation is still ongoing. These 11 are mostly located at the outskirts of molecular clouds in the complex (see Figure 8). All have red colours and evidence for K band excess emission due to hot circumstellar dust, based on their location in the (J-H) vs. (H-K) diagram. Detection of FUORs was one of the original GPS science goals. Only 10-15 FUORs are known but it is thought that they may well represent a ubiquitous phase of PMS evolution, in which the accretion rate increases by up to 3 orders of magnitude (e.g. Hartmann & Kenyon 1996). Baraffe *et al.* (2009) have recently proposed that this can explain much of the scatter that is generally observed in HR diagrams of PMS clusters, as well as the well known luminosity problem (Kenyon *et al.* 1990). The unfortunate consequence is that ages and masses of PMS stars and brown dwarfs derived from existing theoretical isochrones are often likely to be wrong! Future GPS 2-epoch data (aided by spectroscopic confirmation of their distinctive near IR absorption features) will permit the FUOR phenomenon to be quantified for the first time by counting the number of FUORs in a sample of several hundred PMS clusters and associations. Half of these clusters are new discoveries in themselves : see http://star.herts.ac.uk/∼pwl/Lucas/clusters/.

The variables were found in a search for stars that had changed by $\Delta K>1$ magnitude and were brighter than K=16 in at least 1 epoch. Seventeen stars were found out of 5 million with $K<16$ in the 31 deg^2 of sky with 2 epoch coverage. Only 1 is previously known in the literature (Nova Sct 2003, now a faint blue object). Eight have 2MASS K band fluxes that provide a third epoch at low S/N, apparently confirming the variability. Fourteen of the 16 new discoveries are red objects, 8 of them much redder than giant stars in the same field. These stars are all much too faint to be R Cor Bor stars or Asymptotic Giant Branch variables such as Miras. PMS stars are usually variable for a variety of reasons but a large study by Carpenter *et al.* (2001) indicated that r.m.s. variations are always <0.5 mag at K, in the absence of eruptions.

New clusters in the Galactic Plane. A major result from the GPS has been the detection of ∼200 new star clusters at distances of up to 12 kpc in the plane (Samuel & Lucas, in prep). These were found by a Bayesian search of the DR4 source catalogue, supplemented by visual scrutiny of every GPS jpeg image during quality control. The search has revealed ∼400 clusters, of which half are previously known in the literature. Prior to the advent of panoramic IR surveys, the known Galactic clusters were restricted to a distance of 2-3 kpc (excluding globulars), see e.g. Bonatto & Bica (2007). The Spitzer-GLIMPSE began to probe to larger distances, finding 92 new clusters (Mercer *et al.* 2005) but it lacks the sensitivity and spatial resolution of the GPS, which enables it to detect and to resolve distant clusters in far greater numbers. The 2MASS survey has yielded several hundred rather less secure cluster candidates (e.g. Bica *et al.* 2003; Froebrich *et al.* 2007) but for the same reasons the majority of these are located at $d<3$ kpc. About half of the new UKIDSS GPS clusters are pre-main sequence (PMS) and these will be used for a large scale statistical investigation of many aspects of star formation, e.g. the Cluster Luminosity Function, the IMF, and the cluster locations relative to the Infrared Dark Clouds (which clusters are now believed to descend from). The older clusters will be searched for old, metal poor clusters (very few of which are known) in order to investigate the age-metallicity relation and the formation of the Galactic disc.

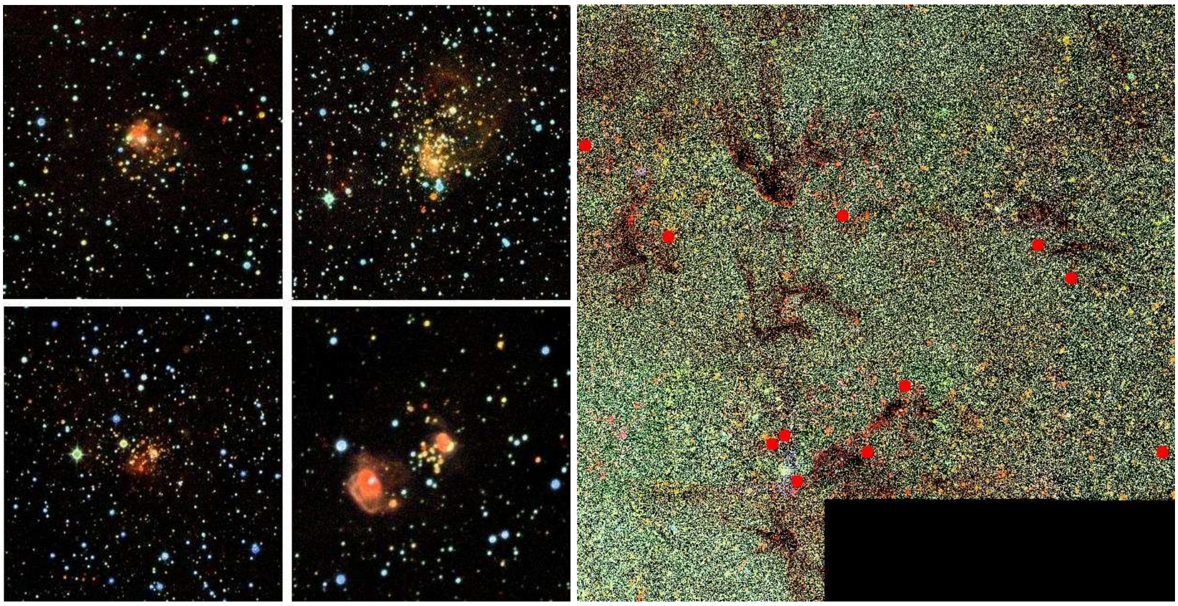

Figure 8: **Left :** *Four new pre-main sequence (PMS) clusters discovered in the GPS by Bayesian search. These JHK colour images are 2 to 3 armcinutes on a side. So far* $\sim$*100 new PMS clusters and* $\sim$*100 older clusters have been discovered in the GPS.* **Right :** *Location of high amplitude variables found in the Serpens OB2 complex. These were found in an automated search of 31 sq.deg. with two epoch K-band data, locating objects where* ΔK *>1.0*

GCS Highlights

Generally, scientific productivity of the GCS is indicated by 12 refereed papers published at the time of writing (along with at least three further papers in press or in preparation). The major science highlight of the GCS is an initial determination of the form of the substellar mass function in a few of the target regions; see Lodieu *et al.* 2009a and references therein. For example, in Figure 10 of that paper, it is clearly demonstrated that the mass spectrum (i.e. the number of stars per unit mass) is flat or rising only modestly down to 0.01 $M_\odot$ in the substellar regime. This has not been seen before over such a large substellar mass range, nor with such good statistics, in such diverse targets using homogeneous survey data. In fact, if we plot the *mass function* i.e. the number of stars per unit logarithmic mass interval (see Chabrier 2003) we see a form that is close to log-normal: a Gaussian as a function of log(m) - see Figure 6. As has been pointed out by several theorists in the past (see Chabrier 2003 for references) this is interesting because it points to a star formation process that is not dominated by a few (or one) physical processes; rather it points to the result of many equally important but independent processes over a wide dynamic range of mass that combine statistically to yield a log-Gaussian form via the central limit theorem. Regardless of the exact functional form, the fact that the mass function has a characteristic mass (coincidentally very close to the minimum mass for stable hydrogen burning in Population I stars) surely provides clues as to the underlying star formation process(es).

Other science highlights of the GCS include the demonstration that the Hyades does indeed contain brown dwarfs (Hogan *et al.* 2008; previous surveys limited in depth and areal coverage simply missed them!) and a colour-age calibration for intermediate age field L-dwarfs (Jameson *et al.* 2008).

DXS Highlights

The full potential of the DXS is locked closely to the large multi-wavelength surveys that are just about to begin (e.g. Herschel, SCUBA-2, AMI, FMOS) but the impact of the DXS has been significant for a wide range of topics.

Large scale structure at $z > 1$. The ability of the DXS to efficiently select galaxies at $z > 1$ over unprecedentedly wide areas allows the large scale clustering of the most massive, distant galaxies to be constrained for the first time. Glen Parish and Matt Jarvis (Herts) have determined the clustering of Distant Red Galaxies (DRGs) which have J-K>2.3 in each DXS field and find that they cluster very significantly (Fig 9).

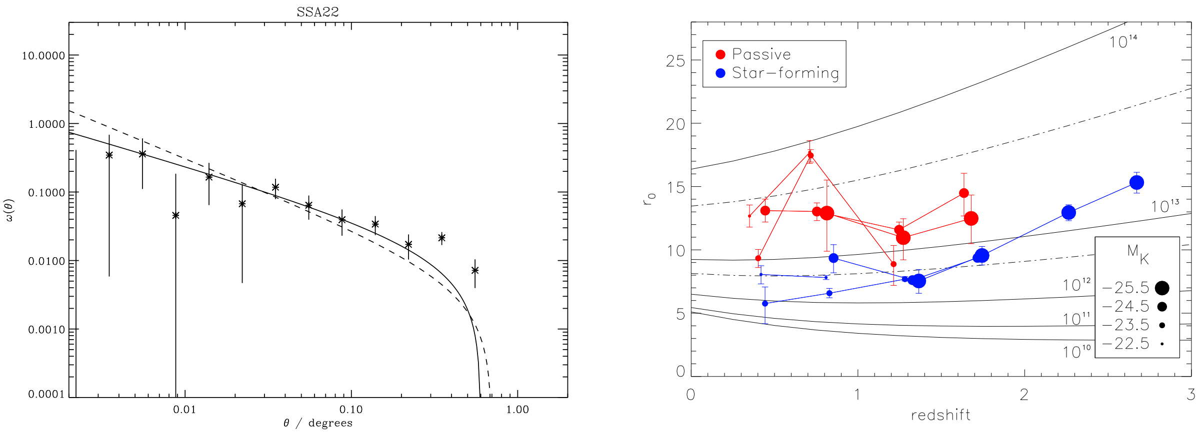

Figure 9: **Left :** *Angular correlation function of Distant Red Galaxies (DRGs) in the DXS field SA22.* **Right :** *The evolution of galaxy clustering in the UDS, divided into galaxies which are passive and actively star-forming (from Hartley et al. 2009). The strength of clustering on linear scales (r_o) can be used to infer the mass of the corresponding dark matter halos (model curves). Passive galaxies can be isolated in substantial numbers to $z \simeq 1.5 - 2$ and show significantly stronger clustering than actively starforming systems. The weak dependence on K-band luminosity suggests that the dark matter halo, rather than the stellar mass, is the key parameter that determines the early truncation of star formation.*

Distant clusters of galaxies. One of the four key DXS science areas is the selection of clusters of galaxies beyond the limits of optical surveys. This was clearly demonstrated by Swinbank *et al.* (2007) where a supercluster of five $z = 0.9$ clusters was identified in the first DXS field, Elais-N1 using Gemini-N GMOS. This initial study has subsequently been built on with Gemini spectroscopy of clusters in the SA22 field (PI Stott) and XMM-LSS (PI Bremer).

Distant elliptical galaxies. The combination of depth and area in the DXS allows the same photometric techniques used to select clusters of galaxies to identify the most luminous elliptical galaxies at $z > 1$. The surface density of these galaxies makes the follow-up of these galaxies very time consuming on even the most efficient 8-10m multi-object spectrographs. However, the completion of four DXS fields in the SA22 field means that the AAT AAOmega spectrograph can be used to target all the likely candidate $z > 1$ "luminous red galaxies" (LRGs) using the nod-and-shuffle technique and very long exposures ($>$ 8hrs). David Wake and Alastair Edge (Durham) obtained AAOmega time in October 2008 in collaboration with Michael Brown (Monash) and, despite obtaining less than half the requested exposure in poorer than median conditions, identified 38 distant LRGs (0.95$< z < 1.15$). The coadded spectrum of these 38 galaxies (Fig 7) shows the expected, passive elliptical spectrum but with a relatively strong Hδ absorption indicating the presence of a contribution of young ($<$ 2Gyr) stars which is consistent with the expected formation redshift of these galaxies ($z \sim$2-3).

Low mass stars. While not one of the primary science goals of the DXS, the combination of its depth and area mean that a meaningful number of low mass stars can be found. Importantly these fainter stars are most distant than the ones selected from the shallower UKIDSS surveys and can be used to estimate the scale length of these stars in the Galaxy. This was demonstrated by Lodieu *et al.* (2009b) who found 2 T dwarfs (a T6 and a T7) that are between 50 and 120pc from Earth from DR2. Expanding this search to the full DXS and including the 3.6 and 4.5μm data from SERVS, will increase this number significantly.

UDS Highlights

The UDS is already the deepest near-infrared survey ever conducted over such a large area. It has produced 27 publications to date, with many more in preparation. The UDS can detect thousands of typical L^* galaxies to $z \sim 3$, which has allowed accurate studies of the galaxy luminosity function (Cirasuolo *et al.* 2009), large-scale structure (Hartley et al. 2008; Quadri et al. 2008) and the build-up of the red sequence (Cirasuolo *et al.* 2007; Williams *et al.* 2009). Below we highlight three major achievements:

Detection of galaxies in the first 1 Gyr: The UDS has produced the largest sample of luminous $z > 5$ galaxies

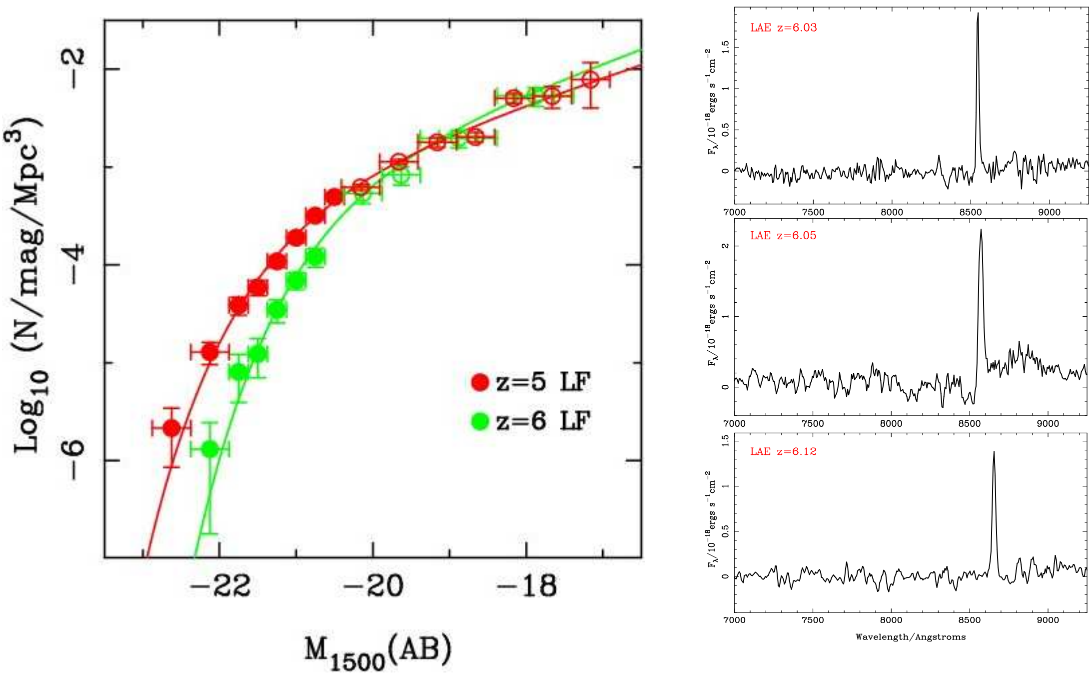

Figure 10: **Left :** *The evolution of the UV-selected galaxy luminosity function at* $z > 5$ *(McLure et al. 2009). The UDS has yielded by far the largest sample of luminous* $z > 5$ *galaxies to date and the most accurate determination of the bright-end of the luminosity function (solid symbols). The data show good agreement with faint-end measurements from ultra-deep HST imaging (from Bouwens et al. 2007).* **Right :** *Spectroscopic follow-up has confirmed a number of* $z > 6$ *galaxies in the UDS. The examples shown were obtained using 5.5 hours integration using FORS2 on the VLT, taken from the ongoing UDSz ESO Large Programme (PI: Almaini).*

to date, providing the first determination of the bright-end of the luminosity function at this very early epoch (McLure *et al.* 2009; Figure 10). Candidates were isolated using the Lyman-break technique, by combining ultra-deep i, z' imaging from Subaru with J, H, K data from the UDS. The luminosity function shows strong evolution, corresponding to the rapid accumulation of stellar mass within the first ~ 1 Gyr of the Universe. The unique combination of depth and area in the UDS has been vital for this high-profile project. Ongoing spectroscopic follow-up at the VLT has now confirmed 5 galaxies at $z > 6$ (see Fig 10).

Downsizing and the formation of the galaxy red sequence: The enormous volume probed by the UDS has yielded the most accurate determination of the near-infrared galaxy luminosity function to $z \sim 4$ (Cirasuolo *et al.* 2009). These data (based on over $50,000$ galaxies) show clear evidence for 'cosmic downsizing', in which the most massive galaxies form first with the low-mass population building up comparatively late in the Universe. The UDS has also had a major impact on understanding the formation of the passive red sequence, which is found to be already established by $z \sim 1.5 - 2$ (Cirasuolo *et al.* 2007; Williams *et al.* 2009; Hartley *et al.* 2009). Combined, these results point to a very early epoch of formation ($z > 4$) for the progenitors of massive elliptical galaxies, followed by rapid termination of their star-formation.

Galaxy clustering and large-scale structure: The UDS has made major contributions towards understanding the growth of structure in the Universe (e.g. Foucaud *et al.* 2007; Hartley *et al.* 2008; Quadri et al. 2008; Williams *et al.* 2009; Hartley *et al.* 2009). Unlike previous pencil-beam surveys, the unique combination of depth and area allows structure on linear scales (dominated by gravity) to be separated from the complex physics within dark matter halos. Such studies allow the mass of the dark matter halos to be estimated, to explore the build-up of structure in the Universe. Recent work by Hartley *et al.* (2009) charts the evolution of clustering over the last 10 Gyr, with the startling conclusion that passive ('red and dead') galaxies occupy the most massive halos to $z \simeq 2$ (Figure 9). Remarkably, however, there is no strong link between K-band luminosity and halo mass. It therefore appears that the age of the host halo, rather than the stellar mass, is the key parameter determining the switch-off of star formation.

5 Scientific case for completion

5.1 Overview

We have reviewed the science goals behind the 2001 proposal and they largely still hold; they have not been superseded by events. This is because we concentrated on science goals to which a large and deep IR survey could uniquely contribute, and since that time no similar competitive survey has emerged, except of course VISTA, which has not yet started. Of course within the broader areas to which those goals relate much has happened (for example detection of high-z galaxies by HST) but generally what UKIDSS can offer remains complementary to those advances - for example HST studies can reach to less luminous galaxies at high-z, but unlike UKIDSS UDS, does not have the volume to construct the luminosity function over its whole range.

We therefore do not repeat here the general UKIDSS science case, but concentrate on specific examples where we foresee significant advances. The actual proposed completion programme is set out in section 6. For UDS, the expected improvement in completeness between DR7 and the proposed completion programme is almost a factor of four, so most of the science gains are yet to come. For the other surveys, we are typically talking about a factor of two improvement overall, but including a major new component in each case - second epoch coverage. There are also several science examples where we are on the brink of something qualitatively new - for example discovery of Y-dwarfs, or the possible absence of z>6.4 quasars - so that the factor of two is particularly crucial.

5.2 Large Area Survey

The coolest brown dwarfs. With one third of the LAS analysed we have found 7 dwarfs later than T8, and extended the temperature lower limit of the main sequence from 750K down to 550K. Therefore by adding twice as much area again, we can reasonably expect to find even cooler brown dwarfs. As noted earlier, the $Y - J$ colour turns bluer in moving from T8 to T9, suggesting that we are on the threshold of a new spectral type. The discovery of the first Y dwarf is possible, and would be a major coup for UKIDSS.

The field sub–stellar IMF. Study of GCS clusters remains the key method for determining the sub–stellar IMF. However the LAS sample of very cool brown dwarfs offers the opportunity to constrain the functional form of the sub–stellar mass in the field and check its consistency with cluster determinations. The reason is that the number of T dwarfs with $500 < T_{\rm eff} < 1000$K is very sensitive to the form of the IMF, while being relatively insensitive to the formation history (see Burgasser 2004; Deacon & Hambly 2006). Using the simulations of Burgasser (2004) as a guide, we project that a sample of 100 T6$-$T9 dwarfs, with $16-20$ objects in the coolest $500-700$K bin, will be sufficient to distinguish, at the $\sim 5\sigma$ level, between flat, lognormal and $\alpha = -0.5$ (for an IMF of the form $dn/dm \propto m^{-\alpha}$). There are 7 such objects in the first third of the survey, so completion of the survey should provide the required numbers.

Second epoch J-band survey. The coolest brown dwarfs are detected at highest S/N in the J band, with a limit of $J = 19.6$. Currently the volume of the survey is set by the requirement to be detected also in the H band, limit $H = 18.8$. We can explore substantially greater volumes by executing a second epoch J survey, and identifying candidates by large proper motion. This is because very cool T dwarfs are bluer than $J-H = 0.0$, so J is seeing > 0.8 magnitudes deeper for such sources. By executing a second epoch in J over 2000 sq degs, roughly half the area of the multi-band coverage, the volume searched for brown dwarfs will be expanded by $> 100\%$, at small cost.

High-z quasars. We predict a total of 9 $z > 6.4$ quasars over the complete LAS. We have found none in the first third, and this non-detection is in disagreement with prediction at the 96% confidence level, i.e. is marginally significant. The detection of none over the whole survey would become highly significant. Alternatively we will discover a handful of $z > 6.4$ quasars, and thereby obtain important new information on the epoch of reionisation, from deep follow-up spectroscopy.

Herschel-ATLAS. The H-ATLAS survey is just starting and is the widest Herschel survey, covering 500 sq degs, over six fields. We have already imaged the three equatorial fields, and the two southern fields will be imaged by VISTA. The remaining, northern, field covers 150 sq degs, and is an appropriate target for UKIDSS, but not VISTA. It is contained within the SDSS footprint, and will be observed by GALEX. H-ATLAS has the best multiwavelength coverage of any survey of a few hundred sq degs or more, so we consider it vital to survey the northern field as part of UKIDSS. The main science goal is a census of star formation at intermediate redshift, and the UKIDSS data will be vital for providing accurate positions, and photometry that will assist in the measurement of photometric redshifts and stellar masses.

5.3 Galactic Plane Survey science case

The GPS aim is to complete the main JHK survey of the Galactic plane, and to undertake the 2nd epoch of K band imaging. The science drivers for completion are as follows:

(i) *Legacy value.* The GPS is one of many Galactic Legacy Surveys that are aiming for complete coverage of the Milky Way, mostly with the same 10 deg wide latitude coverage as the GPS. These include : UVEX (u,g), IPHAS (r,i,Hα) and VPHAS (u,g,r,i,Hα), Spitzer GLIMPSE-360 (3.6,4.5 μm) and Cygnus-X (3.6-8.0 μm). The GPS provides *the largest source catalogue* thereby giving it a central role in this suite of datasets. At longer wavelengths more GPS data is required to complement: the MSX survey (4-20 μm), *Spitzer* Cygnus X (MIPS far IR data); the JCMT/SCUBA-2 SASSy (submm) and BOLOCAM (mm).

(ii) *Galactic structure and formation.* GPS coverage in the 2nd and 3rd Galactic quadrants is presently very limited. Much more data is needed to map the northern warp and to have a chance of detecting old, metal poor clusters at large Galactocentric radii. Very few such clusters are known. More are needed to determine the age-metallicity relation, which will provide clues to the formation of the Galactic disc. The warp will be mapped with old red clump giant stars, providing a different view to existing maps in gas and dust, which tend to trace the younger stellar population.

(iii) *Star formation.* The present JHK coverage is dominated by the mid-plane ($|b| <$1.3) in the 1st quadrant. Further area coverage in areas with lower stellar density would help by (i) making cluster membership easier to determine, (ii) increasing survey depth due to less source confusion, (iii) ease of comparison with far IR and radio data, which are often hard to interpret in the mid-plane. Further coverage of the 2nd and 3rd quadrants would allow us to search for differences in star formation and the PMS cluster population at large Galactocentric radii, where the ionisation fraction in molecular clouds is higher and metallicity is lower.

(iv) *Two epoch coverage.* The first tranche of 2 epoch data (31 deg^2) is looking very promising. Completion of the main JHK survey alone would provide $\sim$500 deg^2 of two epoch data in fields already observed at K in 2005-2007 (often in thin cirrus conditions). However, completion of the full 1851 deg^2 in a 2nd epoch at K would add the highly populated mid-plane region and at least quadruple the number of very rare objects detected, sampling very brief phases of stellar evolution. Examples include: (1) FUORs (10-15 known); (2) highly variable stars undergoing nuclear pulsations in their envelopes in the final stages of their post-AGB evolution (3 known, e.g. Sakurai's object); (3) V838 Mon (unique in the Milky Way). Further 2 epoch data are also useful to more readily identify IR counterparts to X-ray transients.

(v) *Galaxies in the Zone of Avoidance.* These are very hard to detect in the existing 1st quadrant data in the midplane but easy to find in less crowded fields with lower extinction (Lucas *et al.* 2008). Completion of the GPS would make it possible to trace large extragalactic structures such as filaments and walls out to 100 Mpc, which cannot be seen with the present very patchy coverage.

5.4 Galactic Clusters Survey science case

The discovery and characterisation of the coolest T/Y brown dwarfs is a key science goal of UKIDSS, and the LAS has been successfully exploited for this purpose. But the fundamental parameter of interest for a BD is it's mass, and without accurate ages and distances we do not know the masses of field BDs with any useful degree of certainty since all BDs, regardless of their mass, can have the same luminosity at some point as they progress down the degenerate cooling curve. Why is mass such a fundamental quantity? Firstly we want to know how many substellar objects resulting from the star formation process have a given mass, i.e. a histogram of number versus mass or the mass spectrum, in order to ascertain the contribution by number and by integrated mass to the total in stellar systems. Secondly we want to know if there is a minimum mass, or fragmentation limit, to the star formation process. Hence the prime science case for the GCS is to measure the form of the substellar mass function. Note that while LAS T dwarfs may be amongst the coolest BDs currently known, they are unlikely to be the lowest mass, and as stated previously the available mass estimates are very uncertain. It is objects from the GCS that are amongst the lowest mass BDs currently known; furthermore they are members of well-defined cluster samples that enable an accurate determination of the mass spectrum.

The doubling of GCS data will do much more than improve the errors on the mass function shown in Fig 6. Firstly, only three clusters have such good coverage. One of the scientific goals is to test whether the IMF is universal, and to examine the dependence of the mass function on age and metallicity. This requires the other clusters to be completed. Secondly, no second epoch coverage has been attempted so far. Member discrimination will require both second epoch K band coverage for proper motions and substantial additional multi-colour photometry coverage. The gain from continuation to completion will be in the full analysis for all the targets, the elimination of non-member contamination at the lowest masses (and hence the elimination of systematic errors in the MFs), and the ability to compare between all. Firstly, we note that in Lodieu *et al.* (2009a) Figure 10 where we compare MFs for the Pleiades, Upper Sco and sigma-Orionis, at the lowest masses there appear to be differences. In the Pleiades the sudden increase in the lowest mass bins could be real or due to increased contamination; in Upper Sco we also appear to have more BDs than in Orion, but again this could be background non-member contamination since proper motion selection is not possible currently. Secondly, Hogan *et al.* (2008) have shown that the Hyades does indeed contain BDs. Previous searches of limited areal coverage concentrated on the central parts of the cluster but failed to find them; clearly it is important to fully sample the older clusters to their tidal radii in order to get an unbiased census of their lowest mass members. Finally, the level of unresolved binarity must be measured in order to infer the underlying single-object mass function (e.g. Figure 6 above). Full areal coverage, multi-colour photometry and 2nd epoch K for proper motions will enable all these since they optimise sample size, minimise contamination and provide clean membership selections. The accurate and unbiased determination of the mass function as illustrated previously requires uniform, homogenous, multi-colour photometry and proper motions in order to be able to determine accurate formal membership probabilities, the degree of unresolved binarity, and allow for the effects of mass segregation. Too often in the past, small-scale incremental studies that are limited in filter and areal coverage have led to biased and/or incorrect results.

Finally, we note that the GCS adds an extra 20% to the LAS YJHK survey so all the legacy survey arguments for the latter also count for the former.

5.5 Deep Extragalactic Survey science case

(i) *Clusters of Galaxies.* The most important goal of the selection of clusters from the DXS is to identify a statistically meaningful sample to determine the evolution of the cluster mass function out to $z = 1.5$. Doubling DXS coverage in completed J and K fields will make this plausible. To obtain the minimum number of $z > 1$ clusters originally proposed (30) we require as close to the full DXS area of 35 sq.deg. as possible. Also the two northern DXS fields (Lockman Hole and Elais-N1) are now being observed with AMI in a blind Sunyaev-Zel'dovich (S-Z) Effect survey that will cover at least 8 sq.deg. in each field by the end of 2012. To ensure efficient identification of the distant clusters selected by this technique (which is independent of cluster redshift), DXS-depth J and K imaging is vital to obtain a meaningful photometric redshift.

(ii) *Large-scale structure at $z > 1$.* The effect of cosmic variance strongly limits the conclusions that can be drawn from results for clustering of galaxies from single fields. It requires results from at least three fields covering 60–100Mpc on a side to establish unambiguous clustering statistics. In the case of the $1 < z < 2$ regime that is best sampled by the DXS this requires fields of 2–3° on a side. This will be achieved with the DXS if it reaches its full area in at least 3 fields.

(iii) *Multi-wavelength coverage.* The DXS field selection was made at the start of this decade to ensure the maximum overlap with existing and planned multi-wavelength data. Now at the end of this decade we are in a position to reap the rewards of this overlap with the start of surveys with Herschel, SCUBA-2 and

LOFAR. These long wavelength surveys will allow us to address the twin goals of assessing the evolution of star formation at $z > 1$ and the contribution of AGN to the cosmic energy budget. Importantly, all of these surveys will deliver angular resolution of 3–10$''$ at best. To determine the actual counterpart of these sources to the accuracy required for spectroscopy on 8-10m telescopes using instruments such as FMOS on Subaru (being commissioned now) and KMOS on VLT (due for comissioning in 2011) necessitates positions on 0.1-0.3$''$ scales. Due to the very distant and/or obscured nature of these sources then this is best done in the near-infrared. The DXS data are therefore an essential component to the indentification strategy of all of these surveys and any shortfall in coverage will restrict their potential. Also the optical imaging in all four DXS fields will improve dramatically in the next 3 years with the start of the PanSTARRS Medium Deep Survey that will return deep grizY imaging over 7 sq.deg.. Ensuring that the DXS effectively covers these PanSTARRS fields will maximise the potential of both.

5.6 Ultra Deep Survey science case

The UDS has already produced a comprehensive census of the Universe to $z \sim 2 - 3$. Quadrupling the integration time on UDS will enable us to push significantly deeper, with the primary aim of exploring the more distant Universe ($z > 4$) to the same level of detail. We stress that the full area, as well as increased depth, is necessary. A large volume is critical for studies of large-scale structure, to sample a wide range of environments (from voids to clusters) and to complement the wide range of multi-wavelength data in this field. A full UDS mosaic will map 120×120 Mpc (co-moving) at $z \simeq 5$, which is essential for probing structure on linear scales and to sample a sufficient range in environments. The only comparable survey is the Ultra-VISTA project, which is due to commence in 2010. Ultra-VISTA is unlikely to match the depth of the UDS until at least 2013, however, so the UDS will remain a unique resource for several years. Two such deep fields are also important to combat cosmic variance, to provide entirely independent datasets, and to produce targets for future study over a wider range in RA (e.g. for NGST, ALMA).

We therefore aim to push ~ 1 magnitude deeper, with three headline aims:

(i) To extend the reach of the survey to the earliest possible epochs (L^* to $z \simeq 4 - 5$). This epoch is when massive galaxies are in the process of assembly. Using photometric redshifts, fine-tuned by our ongoing redshift survey, we aim to measure the evolution of the luminosity function to unprecedented precision in addition to extending our knowledge of the build-up of large-scale structure, halo occupation and star-formation history. The aim is to produce the most comprehensive map of the Universe ever obtained at these epochs.

(ii) To probe the faint-end of the galaxy luminosity function at lower redshifts. At present a number of galaxy formation models can explain the bright end of the galaxy luminosity function to $z \sim 3$ by finely balancing the effects of rapid star-formation and AGN feedback (e.g. Bower *et al.* 2006). These models differ most strongly in their predictions for the formation of newly forming sub-L^* galaxies (see discussion in Cirasuolo *et al.* 2009). We aim to measure the space density, evolution and environments of these galaxies to distinguish between competing models.

(iii) To study the rest-frame optical properties of ~ 500 luminous galaxies at $z > 6$. These will be identified from Lyman-break techniques (McLure *et al.* 2009). This will enable us to study the build up of the early galaxy mass function and to estimate dark-matter halo masses from their large-scale structure. Combined with recent optical imaging at Subaru (reaching $z'_{AB} \simeq 26.5$) we expect to discover > 2000 galaxies at $z > 5$ and ~ 500 galaxies at $z > 6$.

(iv) To provide long term legacy value. The legacy value of the UDS is significantly enhanced by the rich array of multiwavelength data in this field. The key datasets are outlined below:

- An ESO Large Programme (*UDSz*) began in 2007 to conduct a spectroscopic survey of 3000 high-redshift galaxies using VLT (235 hours; PI: Almaini).
- A Spitzer Legacy programme (*SpUDS*) was awarded to image the UDS using IRAC+MIPS (292 hours; PI: Dunlop). The depths of the IRAC data ($\sim 24\ AB$) are ideally matched to the UDS for the study of L^* galaxies at $z = 3 - 4$ and are the deepest available over such a large area.

- The field has been imaged with Subaru to typical 5σ depths of B=27.5, V=26.7, R=27.0, i'=26.8, z'=26.5 (AB). Complementary U-band imaging has recently been obtained using CFHT Megacam to a depth of $U \simeq 27.5$.
- X-ray observations have been obtained for this field with XMM-Newton, comprising 400ks spread over 7 contiguous fields.
- The UDS has been observed with the VLA to a depth of 20μJy per beam at 1.4Ghz (PIs: Ivison, Simpson). Higher resolution radio data at both the VLA and GMRT have also been obtained (PI: Ivison) to depths of $\sim 8\mu$Jy/beam rms.
- The UDS field is one of the key ultra-deep fields to be imaged at 850 and 450 microns with SCUBA2 as part of the SCUBA2 Cosmology Legacy Survey (to begin in 2010). The UDS J, H, K data will be key for identifying counterparts to these galaxies.

6 Revised Design Goals

6.1 Overview

We have designed a revised programme that is achievable within our expected allocation, and that will achieve roughly 80% of our original design goals. (We are comparing the ”adjusted 2001” design as explained in section 3.2.) This is not quite a simple re-scaling of the original areas; we have reconsidered the balance between bandpasses, and the relative area of the second epoch coverages. For UDS it is now impossible to achieve even 80% of the original design; we will accelerate work on UDS and get it as far along as possible.

The time required, and expected level of completeness for each survey, are shown in Table 3. The time needed is in terms of exposed hours in semesters 09B (i.e starting August 1st 2009) to 12A inclusive. Here exposed hours means exposure time for all data taken at the telescope, whether it passes the QC filter or not. If subsequent QC losses are at the same rate as found to occur in the DR4 and DR5 releases, then the exposed hours shown in Table 3 are sufficient to achieve the required exposure time actually making it to the released database.

We have been actively working with JAC staff to model this programme in terms of real UKIRT nights and their distribution over time. We emphasise that this process is ongoing. If required we can provide the Board with an updated technical report in the coming weeks or months. There are two key issues currently under discussion. (i) Our proposed programme requires a somewhat different balance of allocation between semesters than has been the case in the past, especially to make the “UDS catch-up” feasible - we need substantially more time in semester B than semester A. JAC staff have indicated that this is workable. (ii) The current JAC model indicates that the nights required may be somewhat larger than our expected allocation of 105 nights per semester, requiring 120 nights per semester over six semesters. We in fact believe that further efficiencies can be gained and that the required time will be roughly correct. We will work with JAC over the coming weeks to refine these estimates.

If however the requirement of 120 nights/semester is correct, then the additional 90 nights will become our bid to the extra 100 nights. If this is not possible, then we would discuss descopes as follows, reducing each survey by approximately 12%. For LAS we would remove of the order 250 sq.deg. YJHK in LAS, and 1000 sq.deg. of J_2. For GPS we would remove approximately half of the second epoch area. For GCS we would remove most of the Orion coverage. For DXS we would reduce to a total of 37 tiles selected using the field priority order discussed below. For UDS we would reduce exposure in each band, but disproportionately in H-band.

Survey	DR5 completness	DR7 completenes	final completeness	exposed time needed
LAS	32%	44%	85%	650h
GCS	27%	31%	77%	226h
GPS	27%	35%	85%	480h
DXS	34%	48%	87%	359h
UDS	9%	12%	43%	689h

Table 3: *Completion statistics for current and proposed programme compared to the adjusted 2001 design goals. GPS completeness compares to the main Galactic Plane area, i.e. not including the Taurus-Auriga-Perseus narrow-band observations originally proposed in 2001. DXS completeness is calculated on the basis of exposed hours, using the adjusted design time explained in section3.2.*

6.2 Large Area Survey revised design

For LAS, we decided that the first priority is to complete uniform coverage of the two equatorial blocks. To the north, we will prioritise support of Herschel ATLAS / GAMA, rather than adding to the two odd shaped regions that had already been completed. Finally we will cover as much second epoch J as possible, with separations of two or more years. (Note that for operational reasons, some J_2 observations could take place before the J_1 observations. The revised footprint is shown in Fig. 11, and comprises five blocks :

(i) Block L1. This is the original LAS spring equatorial block, covering 1908 sq.deg.

(ii) Blocks L2a and L2b. The original L2 block was also 1908 sq.deg. Blocks L2a and L2b are areas within that block that were partially completed (in J_2) before the 2006 change of plan. They cover 265 sq.deg.

(iii) Block L3. The original block L3 was coincident with SDSS Stripe 82 covering just 213 sq.deg. To respond to the Board's 2006 request to accelerate LAS, it was necessary to re-balance the RA distribution. As a result, we have defined an expanded L3 covering 1258 sq.deg.

(iv) Block L4. This is a new block intended for Herschel-ATLAS support, defined by $12^h40^m < RA < 14^h00^m$ and $+23° < dec < +34°$. It covers 193 sq.deg.

All the above will be observed at YJHK. The survey definition tool somewhat overfills the outlines above resulting in an increase in area by 5%. The final area planned therefore becomes 3792 sq degs.

The J_2 imaging will comprise L2a+L2b (265 sq degs), plus 1735 sq degs from within L1, making 2000 sq.deg. in total.

6.3 Galactic Plane Survey revised design

The GPS plan is to complete the main JHK survey of the Galactic plane at latitudes $-5 < b < 5$ and also to undertake a second epoch of K band imaging (prioritising the mid-plane). The GPS design presently includes a narrow southern strip down to the Galactic Centre from $l = 358$ to $l = 15$. We have decided not to complete a part of this strip at longitudes $l = 358$ to $l = 10$, latitudes $|b| = 1.3$ to 2 (only a 17 deg^2 area) since this region will be covered by VISTA VVV from 2010. (The midplane part of this strip at $|b| < 1.3$ has been done already).

The total requested area is 1851 deg^2. The survey areas are therefore:

(i) $l = 358$ to $l = 10$ at $|b| < 1.3$

(ii) $l = 10$ to 15 at $|b| < 2$

(iii) $l = 15$ to 107 at $|b| < 5$ and

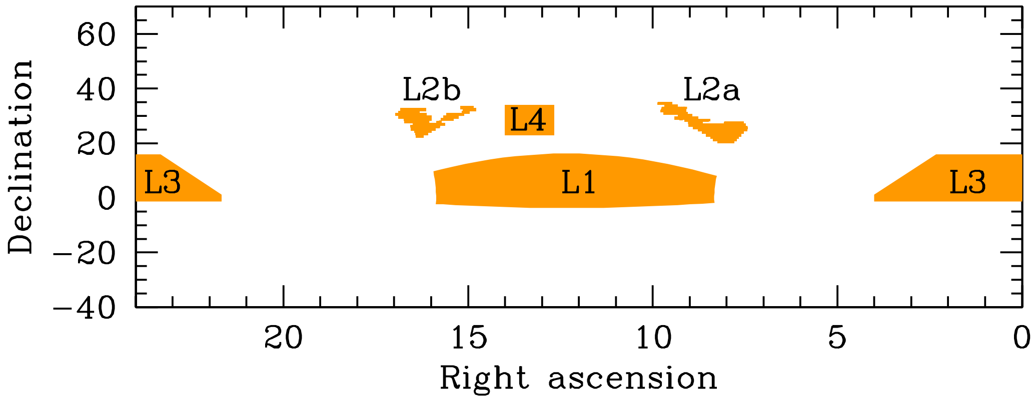

Figure 11: *Revised LAS footprint. The definition of the five blocks is given in the text.*

(iv) $l = 142$ to 230 at $|b| < 5$.

The northern limit of UKIRT is Dec=+60, which puts the $l = 107 - 142$ region off limits. The southern limit of the survey remains at Dec=-15 except for the narrow southern strip.

N.B. VISTA VVV has no significant advantage over GPS in detecting high amplitude long timescale variables: each field is observed in only 3 separate years; the depth is shallower; the area is smaller (520 deg^2); and all the fields are very crowded.

6.4 Galactic Clusters Survey revised design

The original GCS plan involved ten clusters and a total of 1069 square degrees coverage in 6 filter-passes, except for Orion, where we do not require second epoch K. The summed total of filters$\times$area is then 6260 sq.deg.

Following the 2006 review, we ceased work on the Hyades. Our revised plan is then very simple - to continue with the rest as planned. We will complete the necessary multi-colour coverage, and carry out the second epoch K-band measurements. This produces a revised total of 4835 sq.deg, which will comprise 77% of the original 2001 design.

6.5 Deep Extragalactic Survey revised design

For DXS we will maintain the target J and K depths, using the somewhat increased exposure time of 3.91h per key position, and will cover 42 tiles, representing 87% of the original design area. We will not attempt a third band. The choice of tiles is determined both by field priority and by maximising the multi-wavelength coverage from other surveys. Below we discuss the progress and plans for each field, in priority order :

(i) Lockman Hole. This field has extensive radio and X-ray coverage as well as GALEX, SWIRE, S2CLS, AMI and SERVS. Our aim is to cover the SWIRE, SERVS and S2CLS area and the likely area of the AMI S-Z blind survey, which requires 10 WFCAM fields in total. So far 2 tiles are complete and another 2 have partial coverage.

(ii) Elais-N1. This field has a similar level of UV, MIR and FIR coverage as Lockman but has less competition for time from the other UKIDSS surveys so has progressed well in the past 2 years. Our plan is to cover the SWIRE and S2CLS area which requires 12 tiles. So far 4 are complete and another 5 have partial coverage.

(iii) SA22. While this field has the least multi-frequency data it has the highest UKIDSS completion due to the relatively light demand for time from the other surveys. Our aim is to complete 12 tiles in this area. So far 8 tiles are complete in both J and K.

(iv) XMM-LSS. The VISTA VIDEO survey will cover part of this field in due course, so we remove the relevant area from our plan. Our plan is therefore to cover that part of the area covered by GALEX, SWIRE, S2CLS and SERVS that is not going to be covered by VIDEO. This requires 8 WFCAM tiles. So far 2 are complete and a further 2 partially covered.

6.6 Ultra Deep Survey revised design

Achieving the original goal of the UDS (K=23, H=24, J=25 at 5σ) is now impossible by 2012, requiring a total of 1764 hours on source. Furthermore, there is only a limited season during which the UDS field can be observed. Our overall aim is to use the maximum possible such time in order to push the UDS ~ 1 magnitude deeper, and potentially deeper still if additional time becomes available.

Based on the UKIRT scheduling model of Luca Rizzi, the UDS can expect 350 hours observing each year within the current UKIDSS allocation. This corresponds to roughly half the UKIDSS time in the B semester and would yield ~ 530 hours on-source during the remaining semesters (2010B and 2011B). We aim to divide the remaining time in the ratio 2:1:1 for J, H and K. This would yield a final survey reaching noise depths of **K=22.8, H=23.2, J=24.3** (5σ, 2-arcsec diameter aperture).

These depths are designed to detect L^* galaxies to $z \simeq 4-5$ (c.f. Cirasuolo *et al.* 2009) and for measuring the elusive faint end of the luminosity function at lower redshifts. For evolved, red systems we predict $J-K > 2.2$ at $z > 2$, while deep H-band provides a vital redshift indicator (e.g. $H - K > 1.3$ at $z > 3$). The depths above are therefore suitable for measuring photo-zs for evolved galaxies to a precision depth of $K \simeq 22$ (L^* at $z \simeq 4$) and well matched to the Spitzer IRAC depths ($\sim$ 24 AB) for the purposes of stellar-mass estimation.

7 Case for use of extra nights

It is possible that our plan will take more than our expected allocation during the six semesters 09B-12A inclusive, by approximately 90 nights. If so, our proposal for the use of extra nights is simply to be allowed to use those nights to complete the plan described in this document. If allocation of those nights is not approved, then we may need to descope slightly, as described in section 6.1.

If in fact our completion plan can be accomplished within our expected allocation, then use of an extra hundred nights requires an “upscope” of the plan. Because such extra nights are likely to come about in order to optimise scheduling, we believe that it would not make sense to fix a precise plan, but rather to provide a prioritised set of expandable projects, which can be selected from flexibly as time proceeds. This would be :

(i) When UDS is up, add more time. Being so far behind, the UDS benefits proportionately most from extra time.

(ii) Increase the LAS second epoch J area. As explained earlier, second epoch observations add effective volume for cool stars very rapidly. This could be tiles selected from anywhere in block L1 (an additional 173 sq.deg.) or in block L3. There is no need to construct a contiguous area.

(iii) Add back multi-colour coverage of the Hyades; as we now know that there are brown dwarfs in the Hyades, measuring the MF in the oldest cluster in our list could be of great value.

(iv) Revisit DXS fields with poorer depth; uniformity of DXS could be important for many science cases.

8 Case for UKIRT continuation

The primary proposal of the UKIDSS consortium for UKIRT after the completion of UKIDSS is to carry out the UKIDSS Hemisphere Survey (UHS), which was proposed to the UKIRT Board in November 2006. The plan proposed was to cover an additional 12500 sq.deg. in two sweeps - JK and then HK - to the same depth as LAS. The idea was that when added to LAS, GCS, and GPS coverage this would complete a survey above the equator, apart from the region at $\delta > 60^\circ$ that UKIRT cannot reach. Together with the planned VISTA Hemisphere Survey, this would make an all-sky IR survey. The UHS would take approximately 800 nights of elapsed time. If time were shared with the UKIRT Planet Finder (UPF), there would be a competitive lifetime of UKIRT for of the order five years.

The main development since that time has been the potential interest of the PanSTARRs consortium in such a survey. However, their priority is for a single J-band survey to be carried out as rapidly as possible. More generally, the UKIDSS consortium would be happy to revisit the optimum scientific plan for any such post-UKIDSS surveying.

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Head of Galactic Clusters Survey (GCS)	Nigel Hambly	Edinburgh
Head of Deep Extragalactic Survey (DXS)	Alastair Edge	Durham
Head of Ultra Deep Survey (UDS)	Omar Almaini	Nottingham
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The full working group and consortium lists are available at http://www.ukidss.org/consortium

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