Chapter 25
The UKIRT Infrared Deep Sky Survey (UKIDSS): Origins and Highlights

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Abstract UKIDSS is now roughly half finished, covering several thousand square degrees, and expected to complete by the middle of 2012. So far 13.5 billion rows of data have been downloaded by several hundred users, resulting in 154 publications concerning high-z quasars, the nearest and coolest brown dwarfs, the evolution of galaxies, the sub-stellar mass function, and many other topics. I summarise the origins and status of UKIDSS, and briefly describe some scientific highlights.

The UKIRT Infrared Deep Sky Survey (UKIDSS)

UKIDSS is currently the major activity of UKIRT. It is the successor to the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), but many times deeper, and so is the IR equivalent of the Sloan Digital Sky Survey (SDSS; York et al. 2000). Unlike 2MASS it does not cover the whole sky. In fact it is really a portfolio of five sub-surveys. Three of these are "shallow" surveys – the Large Area Survey (LAS), the Galactic Plane Survey (GPS), and the Galactic Clusters Survey (GCS) – designed to cover almost 7,000 sq.deg. in several bands to a depth of $K \sim 18$ (I will be using Vega magnitudes throughout.) Two of the surveys are smaller and deeper – the Deep Extragalactic Survey (DXS) aiming to cover 35 sq.deg. in four fields to $K \sim 21$, and the Ultra Deep Survey (UDS) covering a single 0.8 sq.deg. field to a target depth of $K \sim 23$. More details can be found in other talks at this meeting, in the UKIDSS core reference (Lawrence et al. 2007), in papers describing the calibration, data access, and processing (Hewett et al. 2006; Hodgkin et al. 2009;

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A. Adamson et al. (eds.), *Thirty Years of Astronomical Discovery with UKIRT*, Astrophysics and Space Science Proceedings 37, DOI 10.1007/978-94-007-7432-2_25,

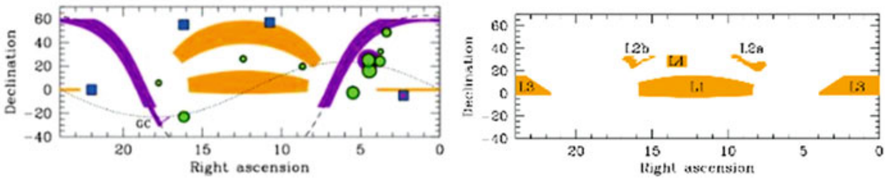

Fig. 25.1 *Left*: original UKIDSS survey design from 2001. *Orange* is the Large Area Survey (*LAS*); *purple* is the Galactic Plane Survey (*GPS*); *green* is the Galactic Clusters Survey (*GCS*); *blue* is the Deep Extragalactic Survey (*DXS*); *pink* is the the Ultra Deep Survey (*UDS*). *Right*: revised footprint for LAS from the September 2009 completion plan approved by the UKIRT Board. Other footprint changes since 2001 are that the DXS XMM-LSS field is now abutting the UDS rather than surrounding it; the GPS is not surveying Taurus-Auriga-Perseus; and the GCS is now not surveying the Hyades

Hambly et al. 2008; Irwin et al. in preparation), and at the UKIDSS web page.[1] The survey is implemented using UKIRT's Wide Field Camera (WFCAM; Casali et al. 2007)

Figure 25.1 shows the UKIDSS survey design, together with the revised footprint for the LAS approved by the UKIRT Board in November 2009, for completion by mid-2012. The survey plan maximises multi-wavelength coverage – in particular the UDS is the same field as the Subaru-XMM Deep Survey, and the LAS has a large commonality with SDSS, making a unique large area, well matched ugrizYJHK data set.

As well as providing a rich legacy database, UKIDSS aims are 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.

The data is public but released in two steps for each release slice – first to registered European astronomers, and then to the world 18 months later. All data are accessible through a flexible query interface at the WFCAM Science Archive (WSA), which also hosts all other WFCAM data.[2]

Origins

UKIDSS is an unusual community based project, mixing elements of the public and the private. It is therefore interesting to see how it developed. The idea of an ambitious survey programme was developed and proposed along with concept of

[1] http://www.ukidss.org

[2] http://surveys.roe.ac.uk/wsa

the camera itself, and was then developed as a "wedding cake" programme and proposed to PPARC by a relatively small number of people (Lawrence et al. 1998, 1999). The reaction of the Board was to make an Announcement of Opportunity to build on this concept and involve more people. The result was the formation of a large consortium with a single purpose, but much improved scientific design. The consortium included almost all astronomers in the UK likely to be actively interested in such a survey. When the UK joined ESO, the consortium expanded again to include astronomers from across Europe. Finally a single proposal was put to the UKIRT Board in March 2001. The Board has approved UKIDSS in a series of provisional stages, each peer reviewed, with significant updates in Nov 2001, Nov 2006, and Sept 2009.

Although UKIDSS has distinct scientific and practical components, it is designed and implemented as a single whole, with frequent discussions between working groups, including many trade-offs and compromises to optimise the whole programme, occasional full consortium meetings, a single web site, and a single method of data access. Most such large coherent projects have in the past been conducted by public bodies (e.g. the UK Schmidt Unit) on behalf of the community. Alternatively, telescopes run as facilities tend to allocate time to many small groups. Increasingly such facilities have offered "key programme" time, and sometimes proposing consortia are obliged to make their data public in due course, but they are still essentially private projects. UKIDSS represents perhaps the first time a community has come together to propose use of the *majority* of a public facility. VISTA is in some ways a second example, but in that case the distinct surveys are run as separate projects. The fact that UKIDSS acts a single community project may perhaps be a lucky accident due to growing organically from a seed, rather than from a facility requesting proposals to fill a space.

Although I am stressing that UKIDSS is a community project, this is an oversimplification. In fact part of the reason for its success is that it operates within a larger UKIRT ecosphere, each component of which is professionally conducted. First and foremost, UKIDSS relies on the existence of UKIRT as a mature and efficient operating observatory. Second, it relies on the existence of WFCAM, built by the UKATC, and expressly designed for UKIDSS-like surveys (as well of course as regular PATT PI time, and other smaller "campaign" proposals). Third, the pipeline processing and science archive development has also been run as a professional funded project by Cambridge, Edinburgh and QMUL, with a transition to VISTA anticipated (the VISTA Data Flow System – VDFS). The community could therefore concentrate on what it does best – scientific design and implementation, and input of requirements to UKIRT, ATC, and VDFS. The relationship between the UKIDSS consortium and the VDFS team was particularly close and detailed.

Along with UKIRT, UKATC, VDFS, and the UKIDSS consortium, the Fifth Estate is the wider community which exploits the data and writes papers. The UKIDSS consortium has no proprietary rights over the data. Its purpose is to design and implement the survey. Of course people in the UKIDSS working groups have been thinking about the survey for many years, and so are typically in a strong

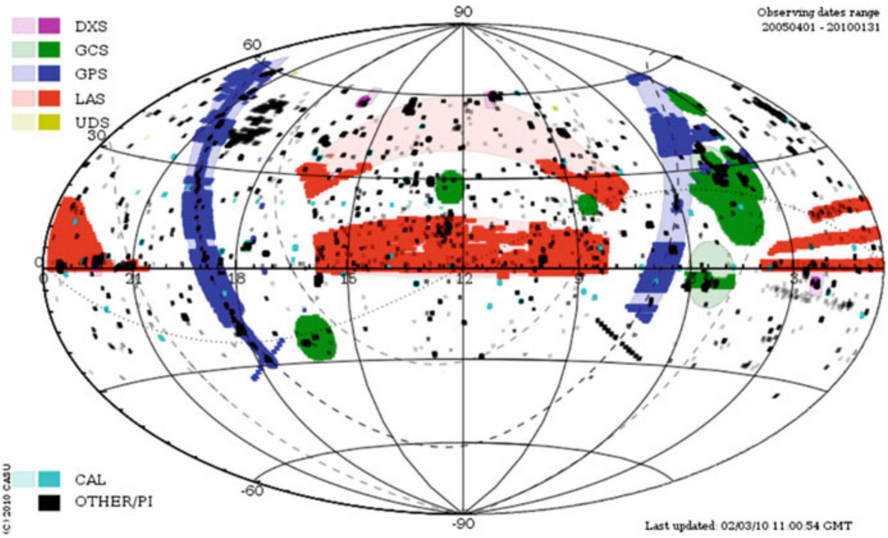

Fig. 25.2 Status of WFCAM observations as of 1-Feb-2010. The *light coloured areas* show the original design footprint. The *darker coloured areas* show areas with observations in at least one filter. *Black squares* show non-UKIDSS WFCAM observations

position to exploit it; but they have no structural privileges. Interestingly, unlike some other large private programmes I am aware of, UKIDSS has had little trouble staffing its observing runs (Fig. 25.2).

Status

At the time of writing (April 2010), each of the UKIDSS surveys is already the largest of its kind and will remain so until VISTA has been operating for a few years. In the latest data release (DR7, February 2010), UKIDSS is approximately 40 % complete compared to the 2001 goals, and 50 % complete compared to the 2009 revised plan. The UDS has so far accumulated a depth $K \sim 22.3$. The LAS currently covers 2,468 sq.deg. in any filter, and 1,818 sq.deg. in the complete YJHK set, out of a planned total of 3,792 sq.deg. The total number of detections in the database is well over 10^8, dominated by the GPS (See the DR7 release page at the WSA for more details).

The rate of completing the survey has been a little slower than hoped, but the quality of the data collected is very close to that planned. For example, the median seeing is $0.82''$; the median stellar ellipticity is 0.07; the astrometric accuracy is 50–100 mas depending on latitude; and the absolute photometric accuracy is 2 %. The 5σ depths reached in the shallow surveys are close to expectation (e.g. for LAS $Y = 20.16$, $J = 19.56$, $H = 18.81$, $K = 18.19$). In the deep (stacked) surveys the rate of improvement of depth with accumulated exposure falls a little short of the naive $t^{1/2}$ expectation, but is coming closer at each data release due to processing improvements (e.g. dealing with structured background). For the GPS, the effective depth reached is very sensitive to source crowding.

The UKIDSS data has been heavily used. As of Sept 2009, there were 890 registered users for the initial Europe-only data releases, and of course an unknown number of anonymous users of the subsequent world wide releases. The number of SQL queries run as of Sept 2009 was 805,000, extracting 13.5 billion rows of data. The publication rate for papers wholly or partly based on UKIDSS data is increasing; 7 in 2006, 24 in 2007, 35 in 2008, 60 in 2009, and 26 in the first 3 months of 2010.

The completion of UKIDSS depends of course on the status of UKIRT itself, but all being well we expect to complete the project by the middle of 2012.

Highlights

Other papers from this meeting present scientific progress from the UKIDSS sub-surveys. Here I present a personal selection of highlights.

The LAS is particularly well suited to finding rare but important objects. Figure 25.3 shows the optical spectra of four new z ∼ 6 quasars (Mortlock et al. 2009 and Patel et al. in preparation). Around z ∼ 6 UKIDSS finds the quasars already seen

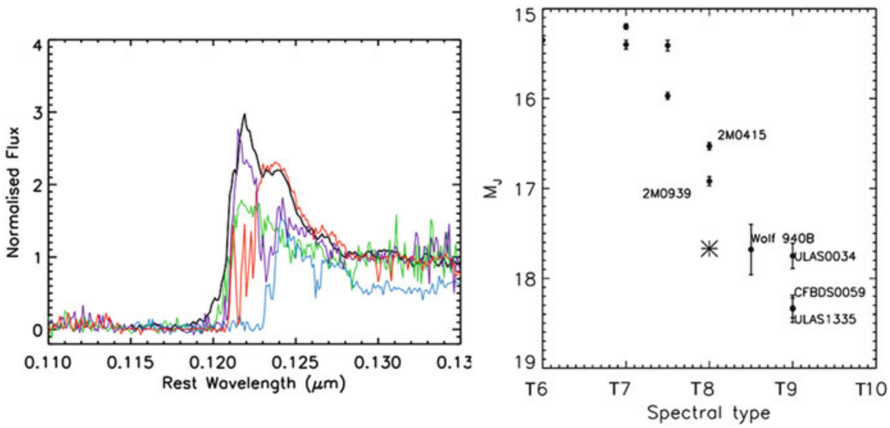

Fig. 25.3 *Left*: four new UKIDSS-LAS-selected z = 6 quasars from Patel et al. (in preparation), compared to the mean spectrum of z = 6 quasars from SDSS (*black curve*, Fan et al. 2004). UKIDSS is finding weaker lined objects missed by SDSS. *Right*: Absolute magnitude M_J for *cool brown* dwarfs as 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

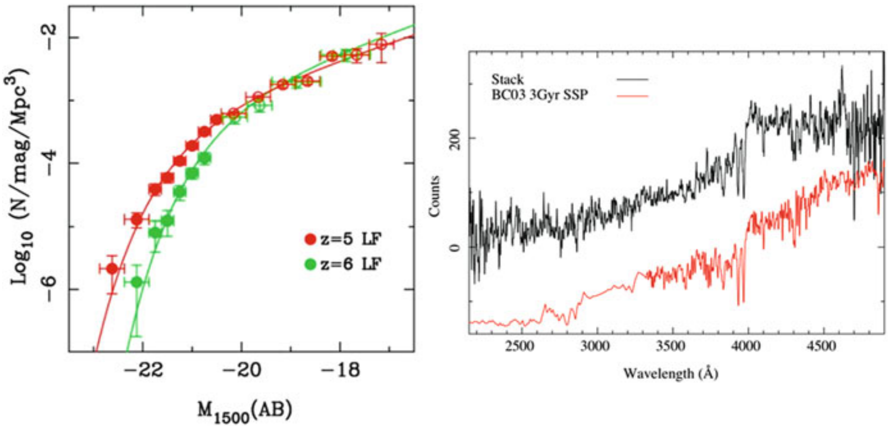

Fig. 25.4 *Left*: evolution of the luminosity function of UKIDSS-UDS UV-selected galaxies at $z > 5$ (From McLure et al. 2009). *Right*: Mean spectrum of 38 distant Luminous Red Galaxies selected from UKIDSS-DXS, showing strong Hδ absorption indicating a significant contribution by young (<2 Gyr) stars

by SDSS, and around the same number again not found by SDSS. However, LAS has not yet found quasars at $z > 6.4$, as predicted from extrapolation of the Fan et al. (2004) luminosity function evolution. This is now becoming highly significant, and indicates a steep rise in quasar numbers at just the time of re-ionisation.

At the opposite end of the distance scale, Fig. 25.3 shows the properties of very cool brown dwarfs. UKIDSS has now found the majority of known T dwarfs, including a succession of "coldest star" record holders (Warren et al. 2007; Burningham et al. 2009; Lucas et al. 2010). Along with new 2MASS and CFHT work, UKIDSS has extended the brown dwarf sequence by nearly 2 magnitudes. We have not yet however definitively identified the expected new class of Y dwarfs, where Ammonia absorption should become apparent.

The deeper surveys (DXS and UDS) are especially effective at statistical studies of the higher redshift universe. An early highlight was the identification of a supercluster structure 30 Mpc across at $z \sim 1$ (Swinbank et al. 2007). Combining UDS with Subaru data to obtain photometric redshifts has led to some impressive results, including the evolution of the K-band luminosity function from $z \sim 4$ to the present day (Cirasuolo et al. 2010), and the detection of evolution of the Lyman Break Galaxy (LBG) population between $z = 5$ and $z = 6$ (McLure et al. 2009). Figure 25.4 shows the LBG result, and also the mean spectrum of 38 luminous Distant Red Galaxies from selected from DXS, showing strong Hδ absorption, indicating a significant contribution from young stars.

The prime aim of the GCS is to measure the substellar luminosity function and its dependence on environmental factors. Figure 25.5 shows the measured mass functions for three large Galactic Clusters (Lodieu et al. 2009). All three are consistent with a log Gaussian form, which therefore shows that the star formation

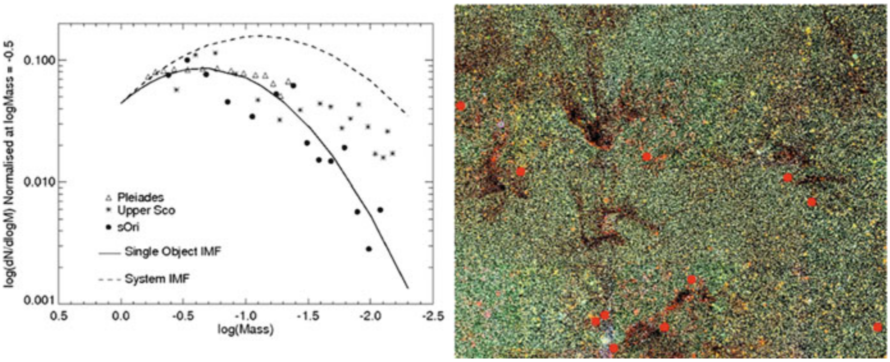

Fig. 25.5 *Left*: Mass functions (number of stars per unit logarithmic mass interval) derived from GCS data. The figure compares Upper Sco, the Pleiades and the sigma-Orionis clusters (*solid circles*, *open triangles* and *asterisks* respectively plotted without error bars for clarity – for details see Lodieu et al. 2009 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. *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 $\Delta K > 1.0$

process has a characteristic mass, which is very close to the nuclear burning threshold. The GPS has located ~400 open clusters in the Galactic Plane, only half of which were previously known, leading to a large variety of follow-on projects. More surprising has been the discovery of a number of new high-amplitude variables within a relatively small area (DK > 1 mag; see Fig. 25.5). The nature of these is currently unknown, but they are likely to be eruptive pre-main sequence stars, or FU Orionis stars (Lucas 2010). The GPS therefore holds the possibility of finding large numbers of such objects.

The Future

UKIDSS is expected to complete in mid-2012, UK politics permitting. The mantle for large near-IR surveys now passes to VISTA, which is an ESO 4 m telescope with an even larger IR array, dedicated to survey programmes. It will take a few years for VISTA to overtake UKIDSS in volume. At longer wavelengths, WISE is as I write surveying the sky in the mid-IR, at a sensitivity well matched to UKIDSS-LAS for a variety of object types. At shorter wavelengths, PanSTARRS-1 is just starting a survey that covers all the Northern sky and some of the Southern sky. Eventually we will have LSST producing a very deep southern sky survey, and possibly PanSTARRS-4 producing a northern sky survey that is almost as deep. Until that time, in the near future, the southern hemisphere will be better served in the IR, and the northern hemisphere better served in visible light. With this prospect in mind, in 2006 the UKIDSS consortium proposed that UKIRT should follow on from UKIDSS by conducting a UKIRT Hemisphere Survey (UHS), which together with the VISTA Hemisphere Survey (VHS) would make an (almost) complete NIR sky survey.

The current default is that the UHS will not now happen, as UKIRT is planned for closure after completion of UKIDSS. However, if new UKIRT funding partners emerge, there is still a possibility that UHS could be part of a continuing UKIRT programme. Alternatively, the idea of a relatively modest space-based NIR sky survey obviously has appeal. Several manifestations of such a mission have come close to happening, but not quite made the cut. The international community should keep trying!

References

Burningham, B., et al.: The discovery of an M4+T8.5 binary system. Mon. Not. R. Astron. Soc. **395**, 1237 (2009)

Casali, M.M., et al.: The UKIRT wide-field camera. Astron. Astrophys. **467**, 777 (2007)

Cirasuolo, M., et al.: A new measurement of the evolving near-infrared galaxy luminosity function out to $z = 4$: a continuing challenge to theoretical models of galaxy formation. Mon. Not. R. Astron. Soc. **401**, 1166 (2010)

Fan, X., et al.: A Survey of $z>5.7$ quasars in the Sloan Digital Sky Survey. III. Discovery of five additional quasars. Astron. J. **128**, 515 (2004)

Hambly, N.C., et al.: The WFCAM science archive. Mon. Not. R. Astron. Soc. **384**, 637 (2008)

Hewett, P.C., Warren, S.J., Leggett, S.K., Hodgkin, S.L.: The UKIRT Infrared Deep Sky Survey ZY JHK photometric system: passbands and synthetic colours. Mon. Not. R. Astron. Soc. **367**, 454–468 (2006)

Hodgkin, S.L., Irwin, M.J., Hewett, P.C., Warren, S.J.: The UKIRT wide field camera ZYJHK photometric system: calibration from 2MASS. Mon. Not. R. Astron. Soc. **394**, 675 (2009b)

Lawrence, A., Adamson, A., Hawarden, T., Peacock, J., Saunders, W., Hambly, N., Casali, M.: Paper to PPARC Ground Based Facilities Committee, 22 Sept 1998

Lawrence, A., Hambly, N., Peacock, J., Saunders, W., Adamson, A., Hawarden, T., McMahon, R., Irwin, M., Casali, M., Warren, S., Ward, M., Eales, S., Sekiguchi, K.: Proposal to UKIRT Board, 1 Nov 1999

Lawrence, A., et al.: The UKIRT Infrared Deep Sky Survey (UKIDSS). Mon. Not. R. Astron. Soc. **379**, 1599 (2007)

Lodieu, N., et al.: A census of very-low-mass stars and brown dwarfs in the σ Orionis cluster. Astron. Astrophys. **505**, 1115 (2009a)

Lucas, P.W., et al.: Thirty Years of Astronomical Discovery with UKIRT. Astrophysics and Space Science Proceedings, vol. 37. Springer, New York/Berlin

Lucas, P.W., et al.: The discovery of a very cool, very nearby brown dwarf in the Galactic plane. Mon. Not. R. Astron. Soc. **408**, 56 (2010). arXiv:1004.0317 (2010)

McLure, R.J., et al.: The luminosity function, halo masses and stellar masses of luminous Lyman-break galaxies at redshifts $5 < z < 6$. Mon. Not. R. Astron. Soc. **395**, 2196 (2009)

Mortlock, D., et al.: Discovery of a redshift 6.13 quasar in the UKIRT infrared deep sky survey. Astron. Astrophys. **505**, 97 (2009)

Skrutskie, M.F., et al.: The Two Micron All Sky Survey (2MASS). Astron. J. **131**, 1163 (2006b)

Swinbank, A.M., et al.: The discovery of a massive supercluster at $z = 0.9$ in the UKIDSS Deep eXtragalactic Survey. Mon. Not. R. Astron. Soc. **379**, 1343 (2007)

Warren, S.J., et al.: A very cool brown dwarf in UKIDSS DR1. Mon. Not. R. Astron. Soc. **381**, 1400 (2007)

York, D.G., et al.: The Sloan Digital Sky Survey: technical summary. Astron. J. **120**, 1579 (2000)