Early Science Results from the UKIDSS ESO Public Survey

Steve Warren[1]
Andy Lawrence[2]
Omar Almaini[3]
Michele Cirasuolo[2]
Sebastien Foucaud[3]
Nigel Hambly[2]
Paul Hewett[4]
Richard Jameson[5]
Sandy Leggett[6]
Nicolas Lodieu[7]
Phil Lucas[8]
Ross McLure[2]
Richard McMahon[4]
Daniel Mortlock[1]
David Pinfield[8]
Bram Venemans[4]

[1] Imperial College, London, United Kingdom
[2] University of Edinburgh, United Kingdom
[3] University of Nottingham, United Kingdom
[4] Institute of Astronomy, Cambridge, United Kingdom
[5] University of Leicester, United Kingdom
[6] Gemini North, Hawaii, USA
[7] Instituto de Astrofísica de Canarias, Tenerife, Spain
[8] University of Hertfordshire, Hatfield, United Kingdom

The first large release of data from the UKIDSS ESO public survey took place in July 2006. The size of the data set is about 7 % of the size of the final survey data set. Early science results are presented here, ranging from the nearest coolest brown dwarfs, to the most luminous, rarest, galaxies at $5 < z < 6$. Progress on the headline science goals of UKIDSS, such as the determination of the faint end of the stellar IMF, and the discovery of quasars beyond $z = 6$, is in line with expectation at this stage of the surveys.

The UKIDSS First Data Release (DR1) took place on 21 July 2006 (as announced on the ESO web pages), following on from the small Early Data Release (EDR), in February (The Messenger 123, 67). DR1 is a much larger data set than the EDR, and marks completion of 7 % of the survey programme. The programme and the goals of UKIDSS are set out in Lawrence et al. (2006). This first release is an important milestone on the route to completion of UKIDSS, as it marks the point where the survey surpassed 2MASS as the largest near-infrared survey, quantified by the product $P = A\Omega t$. Here A is the telescope collecting area, Ω is the solid angle of the camera field, and t is the summed integration time. The symbol P stands for photons, since, for the same field, and other things being equal (such as camera throughput), the quantity P is proportional to the number of source photons collected.

UKIDSS is an ESO public survey (see The Messenger 108, 31), with equal data access rights to all astronomers at institutions in ESO member states. The data are available from the WFCAM Science Archive at *http://surveys.roe.ac.uk/wsa/index.html*. The procedure for archive registration is described in a previous article (see The Messenger 119, 56), as well as on the UKIDSS web site (at *http://www.ukidss.org*). The UKIDSS programme comprises five surveys covering complementary combinations of area, depth, Galactic latitude, and filter coverage, from the full *ZYJHK* set of the camera. Table 1 summarises the contents of DR1 for each of the five surveys, in terms of area and depth over regions with coverage by the full filter set for that survey. DR1 contains substantial additional data in fields where the filter coverage is so far incomplete. The contents of DR1, including maps of the areas surveyed, are detailed in a submitted paper (Warren et al. 2006). The median seeing across the data set is 0.82 arcsec.

Although DR1 only appeared at the end of July, some interesting science is already emerging. In this article we publicise some of the early results of which we are aware. The authors of this article are members of the UKIDSS Consortium, which designed and is implementing the surveys. This explains the UK bias, but we emphasise that we have no priority access to the data. The science described here is some of the work with which we have been involved. We look forward to hearing about work being undertaken by other ESO astronomers who have not been involved in the implementation of the surveys.

Survey	Area deg^2	Filters	K 5σ depth (Vega)
Large Area Survey	190	*YJHK*	18.2
Galactic Clusters Survey	52	*ZYJHK*	18.2
Galactic Plane Survey	77	*JHK* (+ H_2)	18.1
Deep ExtraGalactic Survey	3.1	*JK*	20.7
Ultra Deep Survey	0.8	*JK*	21.6

Table 1: Depth and coverage in fields with the filter complement in UKIDSS DR1.

High-redshift galaxies in the Ultra Deep Survey

The deepest, and narrowest, element of UKIDSS is the Ultra Deep Survey (UDS). The final goal of the UDS is to cover 0.8 deg^2 to 5σ depths of $K = 23.0$, $H = 23.8$, $J = 24.6$. The aim of the UDS is to produce a deep, large-scale map of a representative volume of the distant Universe, $1 < z < 6$, providing large samples with which to directly test models for galaxy formation and evolution. The depths reached in DR1 are $K \simeq 21.6$ and $J \simeq 22.7$, over the full field, based on 86 hours of observations (the results reported here in fact use the shallower EDR data set). The area also benefits from public deep optical data obtained with the Subaru instrument SuprimeCam.

Although the UDS campaign is in its infancy, the DR1 data set is already the largest existing near-infrared survey to these depths. This enables surveys for rare objects. For example, McLure et al. (2006) have reported the discovery of nine of the most luminous candidate Lyman-break galaxies at redshifts $5 < z < 6$. These appear to be relatively massive stellar systems ($M_{stars} > 5 \times 10^{10} M_{\odot}$) already in place < 1.2 Gyr after the Big Bang. Because they are so rare, these luminous objects are particularly useful for testing theories of galaxy formation. Another galaxy population of current interest are the Distant Red Galaxies (DRGs), objects selected with $(J - K)_{AB} > 1.3$, which are believed to be the most massive galaxies at $z \sim 2$. Foucaud et al. (2006) used the UDS EDR to produce a sample of 239 bright DRGs. This sample is an order of magnitude larger than existing samples of bright DRGs, allowing a first look at their clustering properties. The computed 2-point angular correlation function is reproduced in Figure 1. Full circles represent DRGs, while open circles mark the correlation function for the parent sample of *K*-selected field galaxies, from which the DRG sample is drawn. The inferred correlation length of r_0 ~ 12 h^{-1} Mpc, confirms that DRGs are hosted by massive dark matter halos.

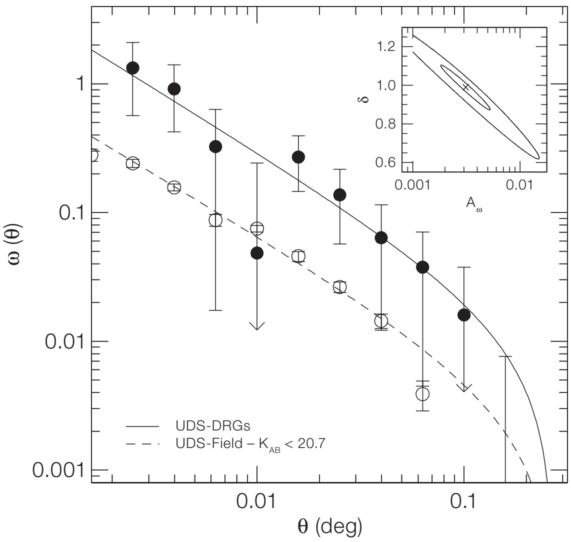

Figure 1: The 2-point angular correlation function determined for a sample of bright Distant Red Galaxies (DRGs), measured by Foucaud et al. (2006) from the UDS EDR.

At somewhat lower redshifts, Cirasuolo et al. (2006) have used the UDS EDR to chart the evolution of the *K*-band luminosity function (LF) over the redshift range $0.25 < z < 2.25$; the first time this has been achieved to such high statistical accuracy. Galaxy colours were also used to separate systems with blue/red rest-frame optical colours. The results are illustrated in Figure 2. It was found that red galaxies dominate the bright end of the LF at $z < 1$, with bright blue galaxies dominating at $z > 1$.

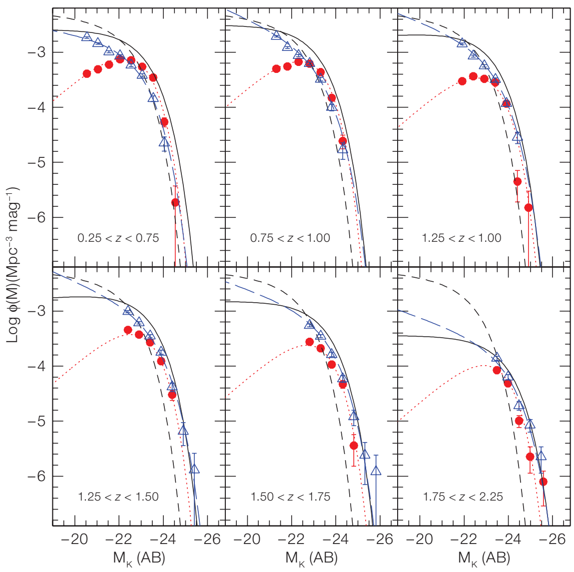

Figure 2: Rest-frame *K*-band luminosity function from Cirasuolo et al. (2006), based on the UDS EDR. The red and blue symbols and lines plot the LF for galaxies with red/blue rest-frame optical colours. The solid line is the LF fitted to the combined sample. For reference the dashed line shows the local *K*-band LF from Kochanek et al. (2001).

Rare objects in the Large Area Survey I: High-redshift quasars

One of the main factors that influenced the design of the LAS was the opportunity to search for rare objects, extending the work of 2MASS in finding very cool brown dwarfs, and of SDSS in finding quasars of very high redshifts, as well as cool brown dwarfs. These goals are described in Lawrence et al. (2006), and Hewett et al. (2006). UKIDSS DR1 provides the first opportunity for teams to exploit a data set sufficiently large to be of interest.

SDSS has been highly successful in discovering quasars beyond $z = 6$. The most distant quasar at $z = 6.4$, found by SDSS, lies near the observable limit of the survey. Due to absorption by intervening neutral hydrogen, at higher redshifts a quasar would be extremely faint in *z*, the longest-wavelength SDSS band. Yet analysis of the very strong absorption in the Lyα forest of the highest redshift quasars has yielded tantalising evidence that at $z = 6$ we have reached the tail-end of the epoch when the Universe was reionised. Therefore there is strong motivation for extending the redshift limit of quasar surveys.

The search for high-redshift quasars exploits the UKIDSS *Y*-band (0.97–1.07 μm). Quasars at $z > 6.4$ will be very red in *i-Y* or *z-Y*, but bluer in *Y-J* than the more common L and T brown dwarfs, and therefore distinguishable from them. So far we have searched some 140 deg^2, and have found a single high-redshift quasar, at $z = 5.86$. The spectrum is shown in Figure 3, and shows the characteristic very strong break in the continuum across Lyα. To a limit $Y = 19.5$ we expect to find about one quasar $z > 6.0$ in 150 deg^2, so our results so far are consistent with this expectation. The discovery of this high-redshift quasar is extremely encouraging for the future of the search, as the LAS database expands.

Rare objects in the Large Area Survey II: Cool brown dwarfs

The coolest brown dwarfs are the T dwarfs, of which 99 are known, all discovered since 1995. The main samples have come from SDSS and 2MASS. The classification scheme of Burgasser et al. (2006) defines nine spectral classes from T0 to T8. The primary spectral standard for the coolest class, T8, is the object 2MASS 0415-09. There are only six T8 dwarfs known. These are the coolest brown dwarfs and have temperatures ~ 700 K. Jupiter has a temperature ~ 150 K. What lies in between? One of the goals of UKIDSS is to explore this temperature range. Ultracool dwarfs are expected to be extremely red in *z-J*, and so difficult to detect in *z*. Therefore the *Y*-filter is again expected to play an important role. At some point a new spectral feature is expected to emerge, possibly NH_3 absorption, defining a new spectral class, for which (coincidentally) the letter Y has been suggested.

One brown dwarf discovered in DR1, ULAS J0034, is extremely cool, and has proven particularly interesting. The spectrum is plotted in Figure 4, where it is compared against the T8 standard 2MASS 0415-09. There are some minor differences, for example, the suggestion of excess absorption in the blue wing of the 1.5–1.6 μm emission peak – a wavelength region where NH_3 may appear – as well as the enhanced flux in the *Y*-band. These hint that ULAS J0034 may be even cooler than 2MASS 0415-09, and they warrant deeper spectroscopy. Nevertheless, because the principal molecular absorption bands, due to water and methane, are practically saturated at these cool temperatures, it may be that it will become necessary to obtain photometry and spectroscopy at mid-infrared wavelengths of candidates such as this, in order to delineate the development of the spectral sequence beyond T8.

The substellar initial mass function below 30 Jupiter masses, from the Galactic Clusters Survey

The aim of the Galactic Clusters Survey (GCS) is to investigate the substellar initial mass function (IMF) in a number of open clusters and star-forming regions, to shed light on the formation of brown dwarfs. The survey will cover 1000 deg^2 in *ZYJHK*, in 10 clusters, to uncover low-mass brown dwarfs. A second epoch coverage will be conducted in a few years time to derive proper motions over a large mass range. One of the regions covered in DR1 is the young (age = 5 Myr) and nearby (d = 145 pc) OB association Upper Scorpius. Over 6 deg^2 have been covered in the central part of the association. The *Z-J versus J* colour-magnitude diagram for stellar sources is striking (Figure 5). The cluster sequence stands out clearly from the field stars over the 0.3–0.01 $M_\odot$ mass range, i.e. right down to 10 Jupiter masses (M_J), and the selection of cluster members is straightforward. We have increased significantly the number of known substellar members in Upper Scorpius, and uncovered over a dozen new brown dwarfs below 20 M_J, the limit of previous studies in the region. Furthermore, we have confirmed all candidates more massive than 15 M_J as proper motion members using the 2MASS database as first epoch. Preliminary optical spectroscopy of the bright members reveals signs of chromospheric activity and weak gravity features, characteristics of young stars. The inferred cluster IMF keeps rising across the hydrogen-burning limit and is best fit by a single power law index $\alpha = 0.6 \pm 0.1$ down to 10 M_J. This result is in agreement with previous IMF estimates

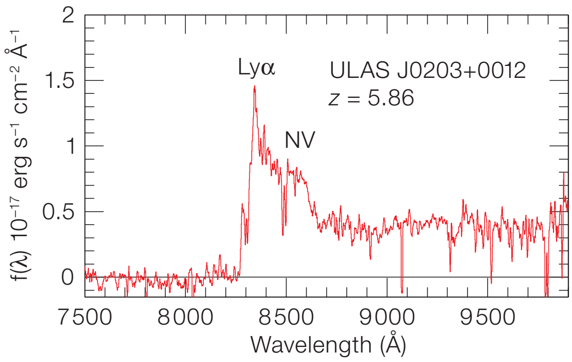

Figure 3: The discovery spectrum of the first very high redshift quasar from UKIDSS (from Venemans et al., in prep.). This 1200 sec spectrum was taken on the night of 1 September 2006, with FORS2 on the VLT.

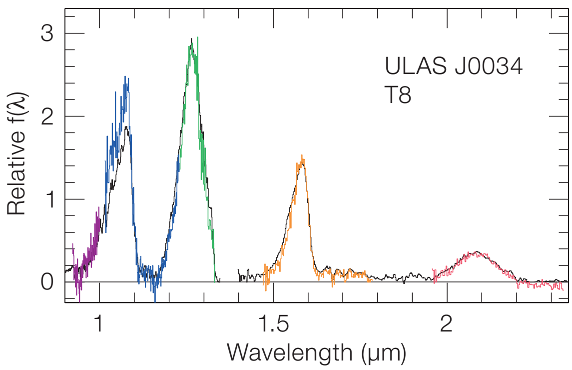

Figure 4: Spectrum of the cool T dwarf ULAS J0034, the coolest brown dwarf found so far in DR1. The colours correspond to different orders of this cross-dispersed spectrum which was a 60 min exposuretaken with GNIRS on Gemini South. The black line plots the spectrum of the T8 standard 2MASS 0415-09, the coolest T dwarf known, for comparison.

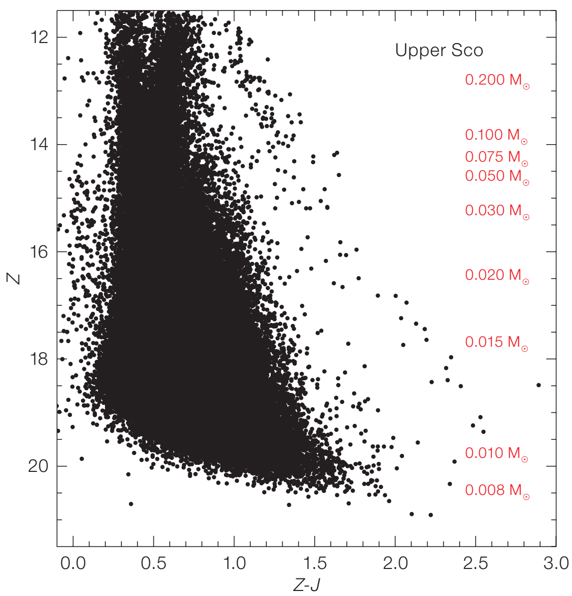

Figure 5: *Z-J versus Z* colour-magnitude diagram for 6 deg^2 in the Upper Scorpius assocation. The cluster sequence stands out clearly from field stars all the way down to 10 M_J, according to theoretical models.

in open clusters but extends our knowledge to lower masses.

Stellar clusters in the Galactic Plane Survey

The Galactic Plane Survey is a legacy survey designed to be useful for all areas of Galactic astronomy. It consists of a first epoch of *JHK* photometry at longitudes $l = -2^{\circ}$ to 107° and $l = 142^{\circ}$ to 230°, and latitudes $|b| < 5$ degrees, followed by two additional epochs of *K*-band photometry to provide proper motion data and to detect rare, high amplitude variable stars.

One of the principal science goals is to search for any variation of the IMF over different star-forming environments, by studying a larger sample of young clusters than any previous survey. To detect Young Stellar Objects (YSOs), the combination of Spitzer-GLIMPSE mid-IR data with UKIRT *JHK* is much more effective than the use of the mid-IR or near-IR data alone. This is illustrated in Figure 6. The image at the top shows a UKIDSS *K*-band image covering $3' \times 3'$, of a star-formation region in the mid plane. The GLIMPSE data on its own in this region can be used to identify YSOs – but there are only 128 four-band IRAC detections, and nine YSOs identified in a (3.6–4.5) *versus* (5.8–8.0) µm two-colour diagram for the field. Alternatively the UKIDSS data alone may be used to select YSOs. The lower-left diagram plots *J-H versus H-K* for 2326 sources, with uncertainties < 0.1 mag on each axis, in the field. We see a well-defined reddening sequence from lower left to upper right. Candidate YSOs are objects with infrared excess to the right of this sequence.

Combining the UKIDSS and GLIMPSE data gives a much cleaner separation. The lower left-hand diagram may be used to estimate *A(V)*. In the lower right-hand diagram the *K*-4.5 µm colour is plotted against *A(V)* for the 1084 sources with GLIMPSE 4.5 µm detections. Candidate YSOs are identified by their *K*-4.5 µm colour excess. These are plotted as red open squares in the upper figure, and show a concentration towards the cluster centre.

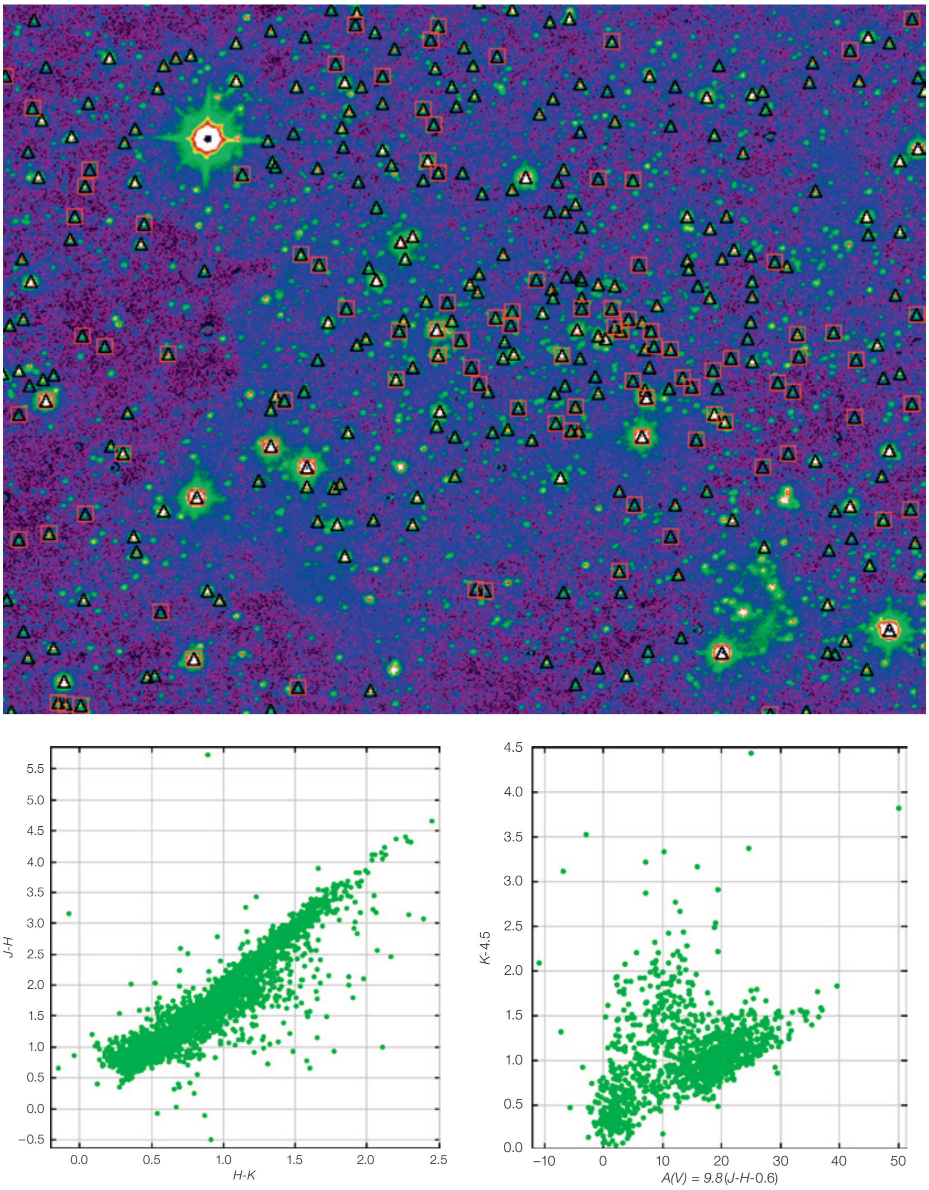

Figure 6: The synergy of UKIDSS-GPS and Spitzer-GLIMPSE data. Upper: *K*-band image of the central parts of a star-formation region in the mid-plane: G28.983-0.603 from Bica et al. (2003). Lower left: The *J-H versus H-K* two-colour diagram, used to establish *A(V)*. Lower right: The *K*-4.5 µm *versus A(V)* diagram, combining UKIDSS and Spitzer data, for sources with GLIMPSE 4.5 µm detections. Candidate YSOs are sources with K-4.5 µm excess, and are cleanly separated in this diagram. In the *K*-band image, black triangles mark GLIMPSE mid-IR detections, and red squares mark candidate YSOs.

Timetable for future releases

The next release, DR2, is planned for the end of February 2007, and will include new data obtained in the period May to July 2006. Note that the UDS was not observable in this block. A new very large WFCAM block began at the end of October 2006, and runs through to mid-May 2007. By the end of this block UKIDSS will be about 20 % complete. These data will be released in DR3, intended to take place late in 2007.

References

Bica E. et al. 2003, A&A 404, 223
Burgasser A. et al. 2006, ApJ 637, 1067
Cirasuolo M. et al. 2006, MNRAS, submitted, astro-ph/0609287
Foucaud S. et al. 2006, MNRAS, submitted, astro-ph/0606386
Hewett P. et al. 2006, MNRAS 367, 454
Kochanek C. et al. 2001, ApJ 560, 566
Lawrence A. et al. 2006, MNRAS, submitted, astro-ph/0604426
Lodieu N. et al. 2006, MNRAS, in press, astro-ph/0610140
McLure R. et al. 2006, MNRAS 372, 357
Warren S. et al. 2006, MNRAS, submitted, astro-ph/0610191