THE UKIRT INFRARED DEEP SKY SURVEY AND THE SEARCH FOR THE MOST DISTANT QUASARS

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The UKIRT Infrared Deep Sky Survey (UKIDSS) Large Area Survey (LAS) has the necessary combination of filters (Y, J, H and K), depth ($Y \lesssim 20.2$) and area coverage ($\sim 4000\,\mathrm{deg}^2$) to detect several redshift $z \gtrsim 6.4$ quasars. The Third Data Release (DR3) included $\sim 1000\,\mathrm{deg}^2$ of LAS observations which have so far yielded two previously known $z \simeq 6$ quasars and two new discoveries: ULAS J0203+0012, with $z = 5.86$; and ULAS J1319−0950, with $z = 6.13$.

High-redshift quasars are unique probes of the early Universe because they are the only non-transient sources which are sufficiently luminous that high signal–to–noise ratio spectra can routinely be obtained (*e.g.*, Schneider 1999). Such observations not only reveal their intrinsic properties (*e.g.*, Walter *et al.* 2004) but, more interestingly, probe the intervening matter via absorption. The most striking demonstration of this has come from studies of redshift $z \simeq 6$ quasars (Fan *et al.* 2001; Willott *et al.* 2007), which have revealed a sharp increase in the Ly α optical depth beyond $z \simeq 5.7$ (*e.g.*, Becker *et al.* 2001). Combined with the results from the *Wilkinson Microwave Anisotropy Probe* (*WMAP*; Bennett *et al.* 2003) cosmic microwave background (CMB) measurements (*e.g.*, Dunkley *et al.* 2008), these quasar observations contradict most simple ionization histories (*e.g.*, Gnedin 2000), leaving such intriguing possibilities as double reionization (*e.g.*, Furlanetto & Loeb 2005).

Further progress in understanding the ionization history of the Universe will require the discovery of the first quasars with $z \simeq 7$. The most distant quasars known to date (*e.g.*, CFHQS J2329−0301, with $z = 6.43$, Willott *et al.* 2007; SDSS 1148+5251, with $z = 6.42$, Fan *et al.* 2003) have been found by looking for point–sources with very red optical colours in wide-field surveys like the Sloan Digital Sky Survey (SDSS; York *et al.* 2000) and the Canada France High-z Quasar Survey (CFHQS; Willott *et al.* 2007), but optical searches are unlikely to probe beyond the current redshift limits due to an unfortunate combination of astrophysics and detector technology. On the one hand, almost all $z \simeq 6$ photons with wavelengths shorter

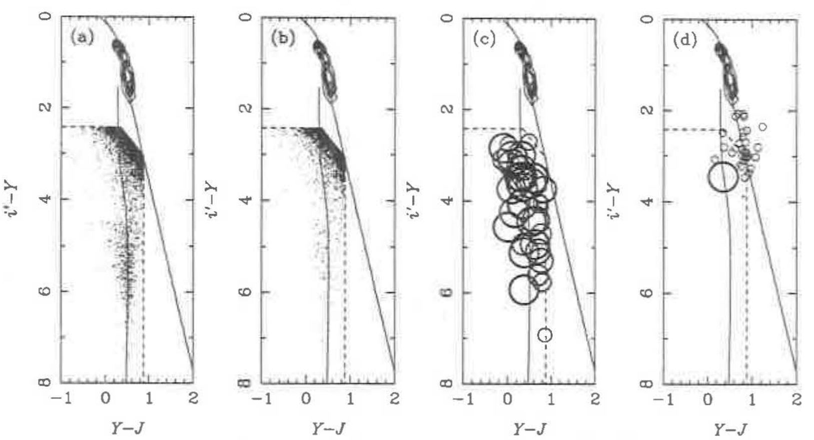

Figure 1: Colour–colour diagrams of a subset of UKIDSS quasar candidates, before filtering (a), after filtering (b), selected according to quasar probability, P_q (c), and after follow-up photometry (d). A sample of bright Main Sequence stars (contours) is also shown, along with fiducial star and quasar loci (solid lines) and the initial colour cut (dashed lines). In (c) and (d) the symbol size scales with P_q. The large symbol in (d) (i.e., the only candidate with $P_q \sim 1$ after follow-up) is the $z = 6.13$ quasar ULAS J1319+0950 (Mortlock *et al.* 2008b).

than the Ly α transition at $\lambda = 0.1215\,\mu$m are absorbed by intervening hydrogen, and so sources are effectively dark below $\lambda \simeq [0.85 + 0.12(z - 6)]\,\mu$m. Conversely, most optical charge-coupled device (CCD) detectors have a poor response beyond wavelengths of $\lambda \simeq 0.9\,\mu$m (*i.e.*, redward of the z'- or Z-bands), so quasars with $z \gtrsim 6.4$ are destined to remain invisible to CCD-based surveys. Combined with the low numbers of $z \gtrsim 6$ quasars (*e.g.*, only ~ 300 over the whole sky to $z' = 21$; Wyithe *et al.* 2008), progress can only be made with wide-field surveys at longer wavelengths, most obviously in the near-infrared (NIR). The largest completed NIR survey, the 2 Micron All Sky Survey (2MASS; Skrutskie *et al.* 2006), only reaches $J \simeq 15.8$, and does not have sufficient depth to find any plausible high-redshift quasars; hence there has been a great need for deeper wide-field NIR surveys. The Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson *et al.* 2004) should cover $\sim 2 \times 10^4\,\mathrm{deg}^2$ to $J \simeq 20$ during the next decade, but the most immediate progress in the search for $z \simeq 7$ quasars will come from the UKIRT Infrared Deep Sky Survey (UKIDSS).

UKIDSS (Lawrence *et al.* 2007) is a suite of five NIR surveys being undertaken using the Wide Field Camera (WFCAM: Casali *et al.* 2007) on the United Kingdom Infrared Telescope (UKIRT). One of these, the Large Area Survey (LAS), was designed to have sufficient area coverage ($\sim 4000\,\mathrm{deg}^2$) and depth (detection of point-sources with a signal-to-noise ratio of 5 at $Y \simeq 20.2$) to find several $z \gtrsim 6.4$ quasars. Its footprint is matched to that of SDSS, and so in the UKIDSS LAS area there will exist complementary imaging covering the wavelength range from $\sim 0.35\,\mu$m (the SDSS u'-band) to $\sim 2.4\,\mu$m (the UKIDSS K-band).

Another important aspect in the design of UKIDSS is the use of the newly developed Y-band filter, which lies between the z'- (or Z-) and J-bands and has significant response in the wavelength range $0.97\,\mu\mathrm{m} \lesssim \lambda \lesssim 1.07\,\mu$m (Warren & Hewett 2002; Hillenbrand *et al.* 2002; Hewett *et al.* 2006). Not only will all quasars with $z \lesssim 7.2$ have significant emission over the whole of the Y-band, but they are expected to be bluer in $Y-J$ than the L and T dwarfs with which they would otherwise be confused (*e.g.*, Warren & Hewett 2002).

UKIDSS observations began in 2005, and there have been a total of $\sim 10^6$ science exposures

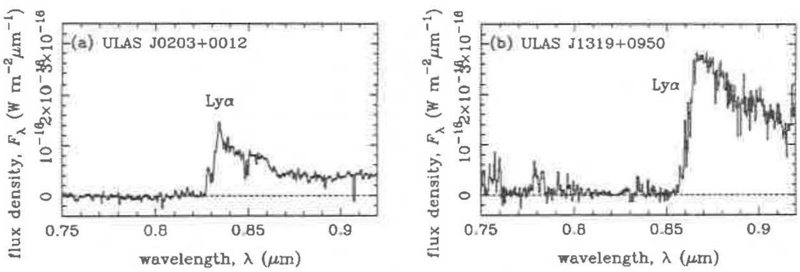

Figure 2: Spectra of the two new high-redshift quasars discovered so far in UKIDSS: (a) ULAS J0203+0012, with $z = 5.86$ (Venemans *et al.* 2007), and (b) ULAS J1319+0950, with $z = 6.13$ (Mortlock *et al.* 2008b).

as of December 2007. The data are made available in incremental releases, first to European Southern Observatory (ESO) countries and then, 18 months later, to the world, via the WFCAM Science Archive[a] (WSA; Hambly *et al.* 2008). The most recent of these is the Third Data Release (DR3) in December 2007, which includes $\sim 1000\,\mathrm{deg}^2$ of LAS imaging in (at least) the Y- and J-bands.

There should be several $z \simeq 6$ quasars amongst the $\sim 5 \times 10^7$ sources catalogued in the DR3 LAS. Applying the obvious astronomical criteria (that high-redshift quasars are expected to be seen as point–sources which are very red in $i'-Y$ or $z'-Y$ and blue in $Y-J$) immediately removes ~ 99 per cent of sources from consideration but, in DR3, still leaves $\sim 10^5$ "pre-candidates", as shown in Fig. 1 (a). Most of these are "glitches" of either the data acquistition or subsequent processing, but in many cases the underlying cause can be identified and accounted for, finally leaving the sample of real sources seen in Fig. 1 (b).

Critically, this sample generated by a fairly well understood statistical process: aside from any actual high-z quasars present, these sources are M, L and T dwarfs randomly scattered to have quasar-like colours. The observational noise can be modelled, as can the star and quasar populations, which means that it is possible to calculate the relative likelihoods that a member of each of these two populations would be measured to have the colours of any given candidate (Mortlock *et al.* 2008a). Folding in the relative numbers of quasars and stars (*i.e.*, that there are far more of the latter) then gives the probability, P_q, that each candidate is a quasar, and in Fig. 1 (c) the small number of sources with $P_q \geq 0.01$ are shown. Importantly, the calculation of P_q is based on fluxes, rather than flux ratios, so two sources with identical colours can actually have quite different values of P_q, which is particularly relevant close to the survey limit. Because all the available information is included in the calculation of P_q, all the candidates can be compared objectively, with the only significant limitation being the degree to which it is possible to model the extremes of the observational error distributions.

Having calculated P_q for each candidate, they can be ranked and the most promising sources selected for follow-up photometry, with i'-band observations especially effective because most candidates are so close to the SDSS i' limit that any deeper measurement provides significant extra information (Mortlock *et al.* 2008a). The utility of follow-up imaging (as opposed to spectroscopy) can be seen by comparing Fig. 1 (c) and (d), which shows that routine photometric observations are sufficient to reveal that most candidates are just scattered M dwarfs.

Fortunately, follow-up photometry does not reject all the candidates, and to date UKIDSS DR3 has yielded four high-z quasars. These include the successful recovery of SDSS 0836+0054

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

(Fan *et al.* 2001) and SDSS 1411+1217 (Fan *et al.* 2004), as well as two new discoveries: ULAS J0203+0012 (Venemans *et al.* 2007), with $z = 5.86 \pm 0.01$ and $Y = 19.9 \pm 0.1$ (*i.e.*, at the limit of detectability in UKIDSS); and ULAS J1319+0950 (Mortlock *et al.* 2008b), with $z = 6.13 \pm 0.01$ and $Y = 19.2 \pm 0.1$. Spectra of both are shown in Fig. 2.

The identification of four $z \simeq 6$ quasars in the UKIDSS DR3 dataset is consistent with expectations from the Fan *et al.* (2001) quasar luminosity function, and thus represents a complete end–to–end verification of the survey. Aside from showing that the UKIDSS data are of the necessary quality, it also validates the cross-matching to the SDSS and 2MASS catalogues, and demonstrates that it is possible to produce a manageable candidate sample using almost completely automated procedures. Whilst it is unlikely that the first $z \simeq 7$ quasar is amongst the remaining UKIDSS DR3 candidates, the above successes give reason for confidence that several $z \gtrsim 6.4$ quasars will be in the increasingly complete LAS. More such discoveries will come in the next decade as VISTA and various longer wavelength surveys begin to make observations, and the detection of $z \simeq 7$ quasars may even become routine, but for the moment they represent the absolute limit of observational astronomy.

Acknowledgments

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