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 < ∼20.2) and area coverage (∼4000 deg²) to
detect several redshift z ∼ 6.4 quasars. The Third Data Release (DR3) included ∼1000 deg²
of LAS observations which have so far yielded two previously known z ∼ 6 quasars and two
new discoveries: ULAS J0203+0012, at z = 5.72; and ULAS J1319+0950, at 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 also probe the intervening matter via absorption. The
most striking demonstration of this has come from studies of redshift z ∼ 6 quasars (Fan et al.
2001; Willott et al. 2007), which have revealed a sharp increase in the Lyα optical depth beyond
z ∼ 5.7 (e.g., Becker et al. 2001). Combined with the results from the Wilkinson Microwave
Anisotropy Probe 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 at z ∼ 7. The most distant quasars known at present (e.g.,
CFHQS J2329−0301, at z = 6.43, Willott et al. 2007; SDSS 1148+5251, at 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 ∼ 6 photons with wavelengths shorter
than the Lyα transition at λ = 0.1216 µm 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 at $z \gtrsim 6.4$ are destined to remain invisible to CCD-based surveys. Combined with the low numbers of $z \gtrsim 6$ quasars (e.g., a surface density of $\sim 0.02$ deg$^{-2}$; Jiang et al. 2007) 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 $\sim 2 \times 10^4$ 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 ($\sim 4000$ 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 $0.97 \mu m \lesssim \lambda \lesssim 1.07 \mu m$ (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 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 (WSA; Hambly et al. 2008). The Third Data Release (DR3), made available in December 2007 to ESO, includes $\sim 1000$ 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 $\sim 99$ 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 acquisition or subsequent processing, but in many cases the underlying cause can be identified and accounted for, finally leaving the sample of predominantly real sources seen in Fig. 1 (b).

Critically, this sample is 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 (Fan et al. 2001) and SDSS 1411+1217 (Fan et al. 2004), as well as two new discoveries:

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*The WSA is located at [http://surveys.roe.ac.uk/wsa/](http://surveys.roe.ac.uk/wsa/).*
ULAS J0203+0012 (Venemans et al. 2007), at $z = 5.72 \pm 0.01$ and with $Y = 19.9 \pm 0.1$ (i.e., at the limit of detectability in UKIDSS); and ULAS J1319+0950 (Mortlock et al. 2008b), at $z = 6.13 \pm 0.01$ and with $Y = 19.10 \pm 0.03$. 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.

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*The initial redshift estimate of $z = 5.86$ was revised to $z = 5.72$ after ULAS J0203+0012 was found to be broad absorption line quasar (Mortlock et al. 2008b).*