

Finding the Most Distant Quasars Using Bayesian Selection Methods

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Abstract. Quasars, the brightly glowing disks of material that can form around the super-massive black holes at the centres of large galaxies, are amongst the most luminous astronomical objects known and so can be seen at great distances. The most distant known quasars are seen as they were when the Universe was less than a billion years old (i.e., $\sim 7\%$ of its current age). Such distant quasars are, however, very rare, and so are difficult to distinguish from the billions of other comparably-bright sources in the night sky. In searching for the most distant quasars in a recent astronomical sky survey (the UKIRT Infrared Deep Sky Survey, UKIDSS), there were $\sim 10^3$ apparently plausible candidates for each expected quasar, far too many to reobserve with other telescopes. The solution to this problem was to apply Bayesian model comparison, making models of the quasar population and the dominant contaminating population (Galactic stars) to utilise the information content in the survey measurements. The result was an extremely efficient selection procedure that was used to quickly identify the most promising UKIDSS candidates, one of which was subsequently confirmed as the most distant quasar known to date.

Key words and phrases: Astrostatistics, Bayesian methods, model comparison, astronomy.

1. INTRODUCTION

Quasars (e.g., Rees, 1984) are amongst the most extraordinary astronomical objects known, the result of material falling into the huge black holes that lie at the centre of most galaxies (including the Milky Way). Galaxies' central black holes typically have masses of $M_{\text{BH}} \gtrsim 10^6 M_{\odot}$ (where $M_{\odot} = 1.99 \times 10^{30}$ kg is the mass of the Sun); but these black holes are mostly quiescent (as is currently the case in the Milky Way). Galaxies' central black holes only grow appreciably when there is a gravitational disturbance, possibly from other nearby galaxies, that forces gas and stars off their otherwise stable orbits. In the process of falling into the black hole, this disturbed material becomes compressed, forming a dense accretion disk which is heated

to extreme temperatures of $\gtrsim 10^4$ K. Even though such accretion disks are typically only a billionth the size of their host galaxies (having radii more comparable to that of the Solar System), their thermal glow can be brighter than all the stars in a galaxy, and the brightest quasars have luminosities of $L \simeq 10^{15} L_{\odot}$ (where $L_{\odot} = 3.84 \times 10^{26}$ W is the total power output of the Sun). At cosmological distances it is often the case that the host galaxy is too faint to be seen, leaving only the bright point of light that is the glowing accretion disk—it is these sources that are called quasars.¹

As a result of their high luminosities, quasars have been amongst the most distant astronomical objects known ever since their discovery (Schmidt, 1963). Due to the finite speed of light, they are also seen as they were when the Universe was much younger, and distant quasars (DQs) can be used to reveal the conditions in

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¹“Quasar” is a contraction of “quasi-stellar object,” the name given to these astronomical sources before their true nature was understood. The fact that quasars, like stars, appear as unresolved point-sources is one reason they can be difficult to identify.

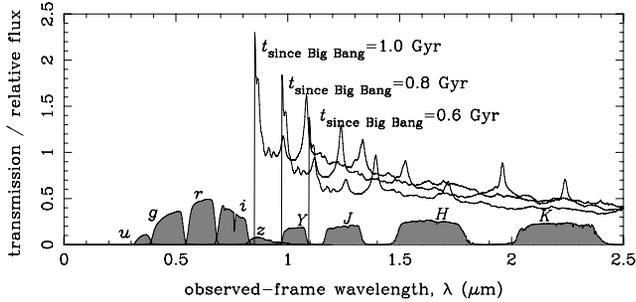


FIG. 1. Simulated spectra of DQs compared to the transmission curves of the SDSS optical filters (u , g , r , i , z) and the UKIDSS near-infrared filters (Y , J , H , K). The three quasars are at different distances and hence different look-back times, as labelled. The normalisation is arbitrary, although the decrease in flux level with distance is realistic. The least distant of these quasars might be seen in SDSS images (specifically the z band), but the most distant would not. All three simulated quasars would be visible in appropriately deep UKIDSS exposures.

the early Universe. At present, the most distant known quasars (e.g., Fan et al., 2006b, Willott et al., 2010, Mortlock et al., 2011) are so far away that they are seen as they were when the Universe was less than 1 billion years old (i.e., less than 7% of its current age of 13.8 billion years). The remainder of this article only concerns DQs in the first billion years of the Universe; although millions of more nearby quasars have been catalogued, it is only the most distant (or otherwise unusual) that are important as single objects.

No current telescopes can resolve DQs as anything other than point-sources, but they are sufficiently bright that they can be observed spectroscopically, with the light separated into different wavelengths. As illustrated in Figure 1, such observations can reveal both the constituents of the quasars themselves and the properties of the material along the lines-of-sight to them (e.g., Fan et al., 2006a). The most important example of this is the distinct break at an observed-frame wavelength of $\sim 1 \mu\text{m}$ that can be seen in all three simulated quasar spectra shown in Figure 1. This break comes about as the light at shorter wavelengths is absorbed by neutral hydrogen atoms that were present in the early Universe. But by ~ 1 billion years after the Big Bang the hydrogen in the Universe had been almost completely ionised, as the first generations of stars—and quasars—emitted sufficient ultraviolet radiation to separate electrons from protons. The rest-frame wavelength of the break is at $0.1216 \mu\text{m}$, but the wavelength of all light is increased by the cosmological expansion; the Universe is a factor of ~ 7 larger now than it was when it was 1 billion years old, and so the breaks in the

spectra of these quasars are seen at an observed-frame wavelength of $\sim 7 \times 0.1216 \mu\text{m} \simeq 0.85 \mu\text{m}$. The spectra of older quasars, including the break, are redshifted by even more, hence the systematic shift with age seen in Figure 1. More importantly, it is exactly these observations of DQs that currently provide the most direct evidence that the hydrogen in the early Universe was indeed neutral (e.g., Fan et al., 2006a).

There is hence a great incentive to find quasars at ever greater distances. Unfortunately, such DQs are incredibly rare, with a number density on the sky of only one per $\sim 200 \text{ deg}^2$ (which is ~ 1000 times the solid angle subtended by the Moon). This would not pose a problem if there were no other astronomical objects in the night sky, but quasars are generally seen as unresolved point-sources, and there are many billions of other point-sources (mainly stars in the Milky Way galaxy) of comparable flux² in the night sky. Hence, it would be impossible to distinguish a DQ (or any type of rare object) in a single astronomical image; but it is possible to make observations of the same region of sky using different filters, which can be combined to give an estimate of a source’s colour.³

A key fact behind all the quasar selection methods considered here—both heuristic and Bayesian—is that DQs can be differentiated from stars on the basis of their measured colours. This is particularly true for DQs because of the sharp break in their spectra described above—most astronomical sources exhibit spectra which vary much more smoothly with wavelength. Unfortunately, observational noise and the sheer variety of astronomical sources combine to render colour-based discrimination imprecise, hence the

²The basic quantity of brightness measured by a telescope is flux density, averaged over the range of wavelengths or frequencies to which the detector is sensitive. Several different definitions of flux density are used, but here it is defined as energy per unit area, per unit time, per unit frequency. A standard astronomical unit for flux density, used here, is the millijansky, denoted μJy , which is equal to $10^{-32} \text{ W m}^{-2} \text{ Hz}^{-1}$. Further, as all astronomical measurements involve averaging over a finite range of wavelengths or frequencies, the term “flux” is used here as a convenient shorthand for flux density.

³The negative logarithm of the ratio of (measured) fluxes in different bands is referred to as colour in astronomy. One utility of this quantity is that a source’s colours are largely independent of its distance, so they provide information about its intrinsic properties even if the distance is not known. Distances to astronomical objects are often unknown, and in some sense the main aim of the Bayesian selection procedure described in Section 3.2 is to determine whether a source is thousands of light years from Earth or billions of light years from Earth.

need for some thought to be put into the selection methods. This is best illustrated by example, as in Section 2, which describes the properties of a recent astronomical survey that was, in part, designed to find quasars more distant than any previously known. However, it quickly became apparent that the simple methods that had previously been used to select candidate DQs would not work because the level of contamination was too high, and so a Bayesian selection method was developed (Section 3). The results of this approach are then described in Section 4.

2. DATA

The DQ searches described here are based on images of the sky taken during large astronomical surveys. This is currently the dominant mode of observational astronomy. Rather than the traditional practice of using telescopes to obtain bespoke measurements of objects of interest, a survey involves taking images of a large, usually contiguous, region of sky and then using automated image-processing techniques to identify and characterise the sources that have been detected. A single exposure is sufficient to measure the positions and morphological characteristics of the detected sources, but it is usual (particularly in the optical and near-infrared bands considered here) to obtain measurements in each of several filters so that some information about the sources' colours is also obtained. The DQ search discussed here was based on optical (Section 2.1) and near-infrared (Section 2.2) surveys of the same area of sky, the data from which were combined to give the full wavelength coverage shown in Figure 1.

2.1 SDSS

The Sloan Digital Sky Survey (SDSS; York et al., 2000) is one of the most ambitious astronomical projects ever undertaken: over a period of several years a quarter of the sky was imaged in each of the five optical filters (denoted u , g , r , i and z) shown in Figure 1. These filters span the wavelength range from $\sim 0.3 \mu\text{m}$ to $\sim 1.0 \mu\text{m}$ and so a DQ would appear invisible in all but the longest wavelength filter (i.e., the z band).

One of the most important results of SDSS was the discovery of quasars seen as they were when the Universe was ~ 1 billion years old. These objects were identified by searching for sources which are detected in the z -band images but undetected in the u , g , r and i filters (Fan et al., 2001, 2003). However, more ancient quasars could not be discovered by an optical survey such as SDSS because, as shown in Figure 1, these

sources are only visible at the longer near-infrared wavelengths. If the SDSS were to be expanded to cover more of the sky, it would detect more such DQs, and a similar but more sensitive optical survey would find fainter quasars of the same age; but no optical survey can detect significantly more distant objects—progress can only be made by observing at longer wavelengths.

2.2 UKIDSS

The UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al., 2007) is the largest astronomical survey ever undertaken at near-infrared wavelengths (i.e., just longer than $1 \mu\text{m}$). UKIDSS consists of five sub-projects, including the Large Area Survey (LAS), which was designed specifically to be a near-infrared counterpart to SDSS.

Essentially all the area covered by the LAS observations had already been observed by SDSS and so the two surveys' catalogues could be combined. As the surveys also have comparable sensitivities (in the sense that the majority of sources bright enough to be detected in one survey are also detectable in the other), the cross-matched catalogue provides measured fluxes in the nine filters shown in Figure 1. These measurements are denoted $\{\hat{F}_b\} = \{\hat{F}_u, \hat{F}_g, \hat{F}_r, \hat{F}_i, \hat{F}_z, \hat{F}_Y, \hat{F}_J, \hat{F}_H, \hat{F}_K\}$, where b is the index of the band and the hat denotes that these are estimators constructed from the raw data. As such, while the true flux (in any band, b) satisfies $F_b \geq 0$, it is possible that $\hat{F}_b < 0$ due to the stochastic nature of the measurement process (specifically, the subtraction of an uncertain background level from the original images). Equally important, all these measurements have known uncertainties, $\{\sigma_b\} = \{\sigma_u, \sigma_g, \sigma_r, \sigma_i, \sigma_z, \sigma_Y, \sigma_J, \sigma_H, \sigma_K\}$, although these are not only different in each band, but also different in each image that makes up the survey. Taken together, the availability of $\{\hat{F}_b\}$ and $\{\sigma_b\}$ means that it is possible to evaluate the likelihood accurately for each detected source (see Section 3.2).

From the point of view of a search for DQs, the critical point is that UKIDSS makes measurements at sufficiently long wavelengths that it could detect quasars at greater distances—and hence look-back times—than optical surveys like SDSS. This was one of the main science goals of the UKIDSS LAS. While the UKIDSS data is demonstrably of sufficient quality to detect any such DQs that might have been in the area observed (Dye et al., 2006), actually distinguishing them from the millions of other sources in the UKIDSS catalogue proved to be a more challenging problem than was initially expected.

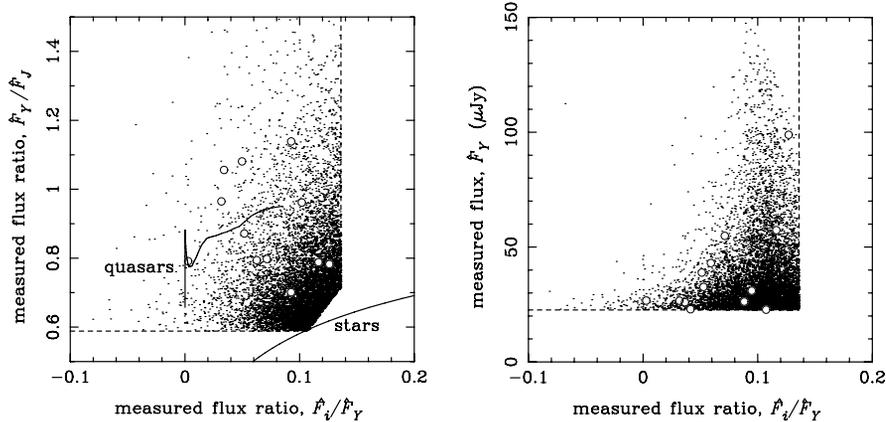


FIG. 2. Observed photometric properties of the $\sim 10^4$ sources in the UKIDSS–SDSS survey which have measured colours (in the i , Y and J bands) consistent with being DQs. The 13 large symbols are the confirmed DQs. The dashed lines indicate the data cuts which were applied before any more refined selection criteria were applied. The two solid curves in the left-hand panel illustrate the ranges of intrinsic colours expected of DQs and stars.

3. CANDIDATE SELECTION

The cross-matched UKIDSS–SDSS sample described above includes $\sim 2 \times 10^7$ catalogued sources over $\sim 5.5\%$ of the sky; given previous measurements of the target DQ population, the expectation was that ~ 10 of these would be quasars in the first billion years of the Universe, with maybe one or two beyond the distance limit that the SDSS could reach. The first major step in the search process is to select a set of candidates that is reasonably complete (i.e., contains most or all of the DQs in the initial sample) but small enough that follow-up measurements can be made to obtain decisive classifications. These reobservations can be either photometry (requiring less telescope time) or spectroscopy (to provide a decisive classification), but in either case it is only feasible to follow-up a few hundred sources at most. Hence, the initial catalogue must be reduced by a factor of $\sim 10^{-5}$ on the basis of the available UKIDSS–SDSS survey data alone. The numbers alone make this a challenging data-mining problem; the complications of real astronomical data only make a difficult situation worse.

The initial approach to this selection problem was to focus on the astronomical considerations, with little regard to any underlying statistical principles. Any catalogued source that was completely inconsistent with being a DQ was discarded. This included the following: sources with colours in the i , z , Y and J bands that had values close to zero (and hence no break); objects whose images were visibly extended (as evidenced by various image summary statistics calculated during the automated data analysis process); and

sources that were sufficiently close on the sky to other, brighter sources that their measured fluxes were likely to be compromised. This process, while complicated in detail, is unremarkable conceptually, and previous searches for DQs (e.g., Warren, Hewett and Osmer, 1994, Fan et al., 2001, Willott et al., 2007) included a similar series of steps to obtain a clean sample of astronomical sources with reliable measured fluxes. The result of applying these heuristic, but automated, tests to the UKIDSS–SDSS data was the sample of $\sim 10^4$ catalogued sources shown, along with the colour and flux cuts, in Figure 2.

All these sources have measured fluxes that are broadly like those expected for DQs, but most are also obviously consistent with being Milky Way stars; as is all too clear from Figure 2, the two populations overlap in the UKIDSS–SDSS data space. In the previous DQ searches mentioned above the quasars’ colours were far more distinct, with the result that simple colour cuts generated sufficiently small candidate samples for follow-up observations. In the case of the UKIDSS–SDSS search, however, there was a need for some means of further prioritising the candidates using only the initial survey data.

3.1 Candidate Ranking Schemes

It is clear from the data in Figure 2 that not all the candidates which passed the basic colour cuts are equally promising. Most of the candidates are clustered next to the selection boundaries to the bottom-right of both plots, whereas the fraction of DQs increases towards the top-left, where there are also fewer sources. This

distribution is a convolution of the Galactic stars’ intrinsic colours with the measurement noise. This is why the spread in \hat{F}_i/\hat{F}_Y is broader for fainter sources (i.e., towards the bottom of the right panel of Figure 2): fainter objects’ colours are measured with less precision. Hence, an apparently dramatic—and promisingly low—value of \hat{F}_i/\hat{F}_Y is far less significant if, for example, $\hat{F}_Y \simeq 30 \mu\text{Jy}$ than if, for example, $\hat{F}_Y \simeq 100 \mu\text{Jy}$. It is not sufficient merely for an object to have the measured colours of a DQ; its photometry must also be *inconsistent* with it being a Galactic star. Indeed, the latter is in some ways a more stringent requirement for a good candidate, given that there are so many more stars than quasars. Combining these considerations gives a clear, if qualitative, scheme for prioritising the candidates: identify those which are extreme outliers from the stellar distribution but are also consistent with being DQs. The remaining challenge is to encode these ideas in a quantitative algorithm.

If the properties of the DQ and star populations were both known perfectly, then Bayesian methods would be optimal. But given that any highly ranked candidates would be reobserved to confirm their nature, there is no reason to prefer a principled statistical approach—it is only the relative ranking of the candidates which is important. Any method which systematically separated DQs from Galactic stars would suffice. Many options are possible, but all must include some measure of how likely it is that a source has been drawn from the dominant stellar population. An approach such as kernel density estimation would have some of the desired properties, but the distribution shown in Figure 2 only appears well sampled because it is seen in projection: there is valuable information in the other measured fluxes (particularly the z band). It is also problematic that most methods of inferring the density of the stars’ measured properties would effectively involve a convolution, broadening the distribution; the stars outnumber the DQs by such a large factor that even a small broadening could have a drastic effect. One way around this would be to instead attempt deconvolution, to instead infer the true distribution of star colours, to which noise could be added. However, the only sensible way to utilise this estimate of the stellar population would be as the population prior in the Bayesian calculation suggested above. The inevitable conclusion is that all potential ranking methods would either involve the loss of information (and, specifically, classifying power) or be equivalent to the Bayesian approach.

3.2 Bayesian Candidate Probabilities

The Bayesian quasar selection algorithm is based on the calculation of the probability, P_q , that a candidate is a DQ (as opposed to a Galactic star). This probability retains all the relevant information in the data (i.e., including the uncertainties), provided only that the models of the quasar and star populations are accurate. The various heuristic ranking schemes hinted at above are hence incorporated naturally, and the only arbitrary aspect of the resultant candidate list is the minimum probability chosen for follow-up.

The starting point for the calculation of the candidate probabilities is, of course, Bayes’ theorem, in this case applied to two hypotheses:⁴ that the candidate is a target DQ (q); that the target is a Galactic star (s). Given data on a source in the form of measured fluxes $\{\hat{F}_b\}$ in N_b bands, the probability that the source is a target quasar is

$$\begin{aligned}
 P_q &= \Pr(q|\{\hat{F}_b\}, \text{det}) \\
 &= (\Pr(q|\text{det})\Pr(\{\hat{F}_b\}|q, \text{det})) \\
 (3.1) \quad &/(\Pr(q|\text{det})\Pr(\{\hat{F}_b\}|q, \text{det}) \\
 &\quad + \Pr(s|\text{det})\Pr(\{\hat{F}_b\}|s, \text{det})),
 \end{aligned}$$

where $\Pr(q|\text{det})$ is the prior probability that the source is a quasar, $\Pr(s) = 1 - \Pr(q|\text{det})$ is the prior probability that it is a star, and $\Pr(\{\hat{F}_b\}|q)$ and $\Pr(\{\hat{F}_b\}|s)$ are the model-averaged likelihoods under each hypothesis. Here “det” indicates that all these probabilities are conditional on the fact that the source has been detected at all.

The requirement that only detected sources are considered is a critical and somewhat subtle ingredient in this formalism. It ensures that the prior distribution of each population’s parameters can be normalised unambiguously, while avoiding the meaningless notion of an unconditional prior probability of the nature of a source. Asked out of context, the question “What is the probability that a source is a DQ?” is ill-posed and

⁴As discussed in detail by Mortlock et al., 2012, there are many other potential explanations for an apparently promising candidate, including asteroids, supernovae and a range of nonastronomical phenomena that relate to problems with the detector or the data processing. These phenomena are difficult to model and easy to spot by visual inspection and sub-dominant compared to the stellar contamination, so were dealt with heuristically, rather than in a principled Bayesian way.

has no sensible answer. This immediately implies that it is impossible to determine the prior probability of a source being of a certain type without at least some constraining information, such as a range of fluxes or other observed properties. Thus, the similar question “What is the probability that a source which has been detected by UKIDSS is a DQ?” does have a well-defined answer, the numerical value of which could be estimated from the observed numbers of quasars and stars that have fluxes which are greater than the UKIDSS detection limit.

This would then be a reasonable empirical value for the quasar prior, although even here the answer depends on various other factors such as position in the sky.⁵ The implication is that, at least in principle, the population priors would have to be calculated for each source under consideration, a potentially significant complication. Fortunately, the variation in, for example, the numbers of stars with position on the sky within UKIDSS is generally small compared to the overall difference between the numbers of quasars and stars. This is illustrated by the fact that of the $\sim 10^7$ astronomical sources catalogued by the UKIDSS LAS, only ~ 10 are expected to be DQs. Hence, $\Pr(q|\text{det}) \simeq 10^{-6}$, which might seem an unusually extreme value for a prior, but is merely a reflection of just how rare DQs are.

In the full implementation described in [Mortlock et al. \(2012\)](#), empirical models for the star and quasar populations are developed which give both the priors and a component of the likelihood. Both populations exhibit a variety of observable properties, most obviously because both DQs and Galactic stars span a wide range of flux levels. Denoting the N_p parameters⁶ describing objects in population p (which is either q or s) as $\{\theta_{p,i}\} = \{\theta_{p,1}, \theta_{p,2}, \dots, \theta_{p,N_p}\}$, the model-averaged

⁵If a source is close on the sky to the Galactic plane (visible even to the naked eye as the Milky Way), then the number of contaminating stars above any flux limit is greatly increased, which should be reflected in an increase in $\Pr(s|\text{det})$ and a resultant decrease in $\Pr(q|\text{det})$. (The quasar population does not vary significantly with position on the sky because the target DQs are at cosmological distances at which the distribution of all objects is expected to be homogeneous and isotropic.)

⁶For quasars the population parameters are redshift and luminosity; for Galactic stars the population parameters are colour (which serves as an observable proxy for surface temperature) and luminosity.

likelihood for population p is

$$(3.2) \quad \Pr(\{\hat{F}_b\}|p, \text{det}) = \int \cdots \int \Pr(\{\theta_{p,i}\}|p) \Pr(\text{det}|\{\theta_{p,i}\}, p) \times \Pr(\{\hat{F}_b\}|\{\theta_{p,i}\}, p) d\theta_{p,1} d\theta_{p,2} \cdots d\theta_{p,N_p},$$

where $\Pr(\{\theta_{p,i}\}|p)$ is the prior which describes the distribution of intrinsic properties of objects of type p , $\Pr(\text{det}|\{\theta_{p,i}\}, p)$ is the probability that an object with the specific properties would be detected, and $\Pr(\{\hat{F}_b\}|\{\theta_{p,i}\}, p)$ is the likelihood.

The detection probability is calculated by approximating the source identification algorithm of the UKIDSS LAS as being equivalent to a hard cut in the measured flux that corresponds to a signal-to-noise ratio of 5 in the Y and J bands. Fortunately, it is not critical to model the source detection process accurately, as the other heuristic astronomical cuts (described at the start of Section 3) inevitably include effective flux limits as well. The main role of this term is to ensure that the populations’ parameter priors have a clear normalisation.

The likelihood must include information on how the parameters relate to observables, as well as describing the stochastic aspects of the measurement process. In the case of optical or near-infrared survey photometry, the dominant source of uncertainty is the additive background noise in the image (although the Poisson-distributed noise from the finite number of photons received is important for the brightest sources). The noise is approximately normal in flux units and, neglecting inter-band correlations, the likelihood is taken to be

$$(3.3) \quad \Pr(\{\hat{F}_b\}|\{\theta_{p,i}\}, p) = \prod_{b=1}^{N_b} \frac{1}{(2\pi)^{1/2} \sigma_b} \times \exp\left(-\frac{1}{2} \left(\frac{\hat{F}_b - F_{p,b}(\{\theta_{p,i}\})}{\sigma_b}\right)^2\right),$$

where $F_{p,b}(\{\theta_{p,i}\})$ is the predicted flux in band b for a population p source with properties $\{\theta_{p,i}\}$, and σ_b is the photometric uncertainty in band b .

This formalism for evaluating P_q is summarised in equations (3.1), (3.2) and (3.3). The primary computational task is evaluating the multidimensional integral to evaluate the model-averaged likelihoods, although as both the quasar and star models only have two parameters, a simple quadrature was sufficient (and ensured the complete repeatability that would not be provided by Monte Carlo techniques).

4. RESULTS

The above Bayesian selection method was applied to the sample of $\sim 10^4$ DQ candidates described in Section 3, giving a value of P_q for each source. Most of the apparently reasonable candidates (based on having colours in the i , Y and J bands consistent with those expected for DQs) had $P_q \ll 1$ and could immediately be rejected from further consideration. In general, the reason for this was that the measured fluxes, while being consistent with being a DQ, were also reasonably consistent with being an ordinary star (e.g., if the noise level was high), in which case the high prior probability of being a star is the dominant factor. A small fraction of the candidates have $P_q \simeq 1$ and remain viable; a requirement that $P_q \geq 0.1$ was made to define a concrete selection criterion. This cut left 1138 candidate DQs with $P_q \geq 0.1$.

The next stage of the process was to examine the actual images of the candidates with $P_q \geq 0.1$ to search for any anomalies⁷ that might make the measured photometry—and hence the likelihood—unreliable. (The approach employed can, again, be understood in terms of the information content of the data: the Bayesian ranking utilised all the information in the catalogued fluxes; the visual inspection made use of information in the images that was not captured in the catalogues.) Over 90% of the $P_q \geq 0.1$ candidates were hence rejected, leaving just 107 reliably measured sources with more than a 10% chance of being a DQ.

This sample of ~ 100 sources was, finally, sufficiently small that they could all be reobserved, and follow-up measurements were made of all 107 candidates in at least one of the i , z , Y and J bands. After each new measurement P_q was recalculated and the candidate discarded if the probability ever fell below 0.1. In most cases even a single measurement was sufficient to reject a candidate; in the remainder P_q tended to increase towards unity as more measurements were made. If $P_q \simeq 1$ after follow-up observations in (at least) the i , Y and J bands, then a spectrum was obtained to confirm the interpretation as a DQ (and to obtain its basic properties). This process is essentially 100% efficient, in the sense that all sources for which spectra have been obtained since the Bayesian selection method was adopted have been confirmed as quasars. This contrasts quite strongly with more

conventional approaches to this problem in which the number of spectroscopic observations per discovery was higher by a factor of between ~ 10 (e.g., Fan et al., 2001) and $\gtrsim 50$ (Glikman et al., 2008).

In total, six new DQs have been identified from the UKIDSS data in this way, and the seven previously known quasars in the UKIDSS area were successfully recovered (Mortlock et al., 2012). The new discoveries included ULAS J1120+0641 (Mortlock et al., 2011), which is currently the most distant quasar known. It is seen as it was just 0.75 billion years after the Big Bang. As the only bright source known that early in the history of the Universe, ULAS J1120+0641 is the target of a large number of follow-up science observations, including by the *Hubble Space Telescope*. ULAS J1120+0641 is currently one of the most important astronomical sources known, and Bayesian methods were critical to its discovery.

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⁷Anomalies have included the following: diffraction spikes from nearby bright stars; bad pixels in the detector; positional offsets; unresolved binary sources; the presence of a nearby galaxy indicating a probable supernova; etc.

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