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Brown Dwarfs and High-redshift Quasars in the UKIDSS – Unlikely Neighbors in the Infrared

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Abstract. Over the ~ 5 years of its full operations, the SDSS rapidly broke high redshift quasar and brown dwarf discovery barriers by exploiting the advantages of the near-infrared/optical z filter, combined with a high efficiency and large-area imaging array. During this time, dedicated searches by our group and collaborators revealed many new quasars at $z \sim 5-6$ and new L/T brown dwarfs using the i-dropout technique. Both of these samples probed new parameter spaces and signficantly expanded our understanding of the properties and environments of such rare objects. The *UKIRT* Infrared Deep Sky Survey (UKIDSS) offers the possibility to continue such interesting discoveries to even higher redshift (quasars) and lower temperatures and masses (brown dwarfs). We discuss the attributes of the survey that makes such rare object discovery possible, and the challenges and techniques required to identify such objects from the sea of candidates in such large datasets.

1. Introduction

Over the past ~ 5 years, dedicated searches by our group and our collaborators have revealed many new quasars at $z \sim 5-6$ and new L/T brown dwarfs using the i-dropout technique (Chiu et al. 2005, 2006; Fan et al. 2004; Knapp et al. 2004; Leggett et al. 2001). The discovery of high redshift quasars at $z \sim 6$ has allowed direct observations of the onset of the epoch of reionization, and in the case of brown dwarfs, the coolest, lowest mass stellar objects have demonstrated new physical and atmospheric chemical properties only previously speculated. Both of these samples have led to productive followup efforts, with spatially and spectroscopically detailed analyses of the newly discovered objects (such as Liu et al. 2006; Chiu et al. 2006; Golimowski et al. 2004).

High-redshift quasars and brown dwarfs are typically discovered using multiband imaging of large sky surveys. As objects displaying rising flux towards 1 μm, they present unusually red broadband photometric colors compared to normal stars which dominate sky fields. In the case of high-redshift quasars, this red flux profile is caused by significant absorption of a quasar's intrinsic ultraviolet emission by intergalactic medium (IGM) gas along the line of sight. For brown

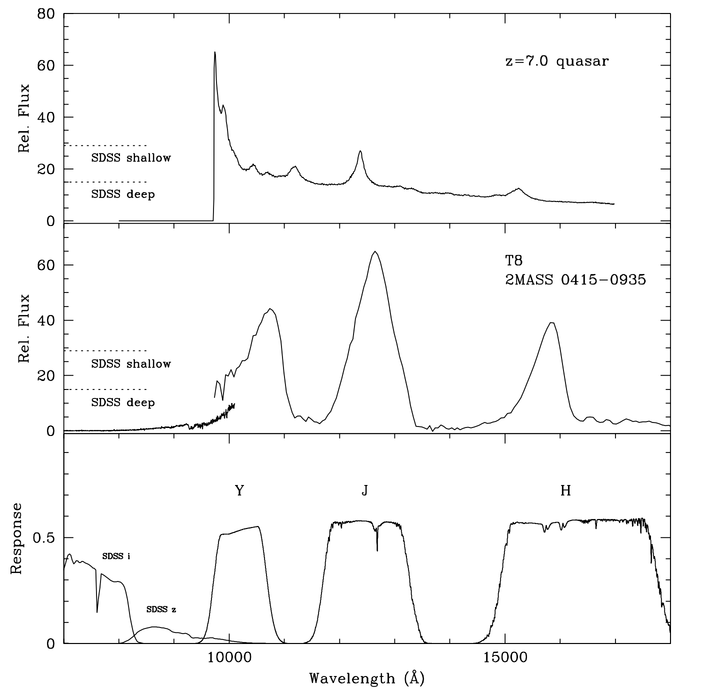

Figure 1. High-redshift quasars and very late type T dwarfs (and Y dwarfs) display nearly no flux in optical bands, but strong flux in the near-infrared. This dropout provides the main target selection criterion in optical/near-IR searches. 2MASS 0415-0935, T8, is constructed from an optical and near-IR spectrum. Model quasar at $z = 7.0$ is from simulation work in Chiu et al. (2005).

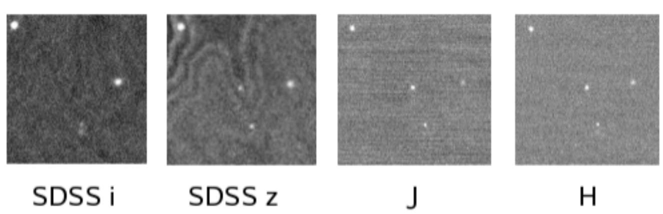

Figure 2. The SDSS i-dropout characteristic is shown for an example candidate object, in i/z optical bands, and J/H near-IR bands.

dwarfs, the surface chemical composition and very low temperature of these objects yields the gradually rising spectral energy distribution (SED) towards 1 μm. Figure 1 illustrates this. As a result, when imaged in filters such as SDSS i and z, these two types of objects are recognizable by their signature "i-dropout" feature – invisible in the i filter, but strongly detected in the z band (as seen in Figure 2).

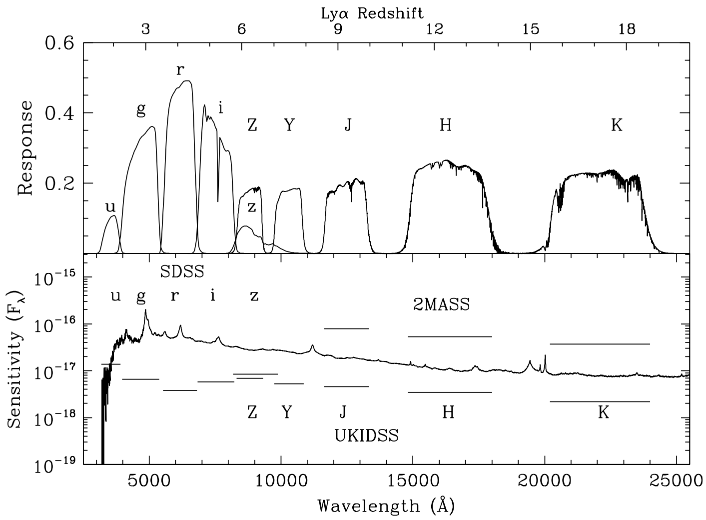

Figure 3. Top panel: throughputs of the SDSS and UKIDSS imaging systems. Note the novel UKIDSS Z and Y passbands, which have sharper cutoffs compared to SDSS z, and fill the wavelength gap between the SDSS and near-infrared JHK bands. For reference, the top axis scale indicates the wavelength position of quasar Lyα emission versus redshift. Bottom panel: horizontal lines indicate the resulting 5σ F_λ sensitivities (erg/s/cm^2/Å) and wavelength coverages of the SDSS and UKIDSS survey bands, in addition to the shallower 2MASS in JHK. A composite quasar spectrum shifted to redshift $z = 3$ and normalized to magnitude $i_{\rm AB} = 19.1$ is shown, demonstrating near-infrared detection in UKIDSS but not 2MASS.

Searches through the SDSS catalogs yielded many such objects (nearly two dozen quasars at $z > 5.8$ and ~ 100 L and T dwarfs), impressively extending the known frontier of quasars to $z \sim 6.4$ and of brown dwarfs to the coldest yet known (class T8). Combined with the Two Micron All-Sky Survey (2MASS), the SDSS allowed efficient selection of such interesting candidates for subsequent spectroscopic followup and classification. However, the SDSS has reached a natural barrier to further discovery, due to the intrinsic faintness of quasars at high-redshift and the band-shifting of flux beyond the SDSS z filter.

The *UKIRT* Infrared Deep Sky Survey (UKIDSS) and other planned near-infrared surveys such as VISTA provide the possibility of continuing the search for such rare objects towards even higher redshift and cooler temperatures. By extending the depth of wide-area imaging surveys three magnitudes deeper than 2MASS (UKIDSS JHK 5σ Vega limits = [19.5, 18.6, 18.2]), the UKIDSS opens a significant additional margin of opportunity to identify such objects through combination with the SDSS and other deeply imaged areas. UKIDSS was designed with such searches among its primary goals, and it has several attributes enhancing the utility of candidate selection.

Specifically, while the SDSS *ugriz* and MKO-based JHK filters are well-known and commonly used, the addition of the novel Z and Y filters of the UKIDSS are a relatively recent development and noteworthy. Proposed by

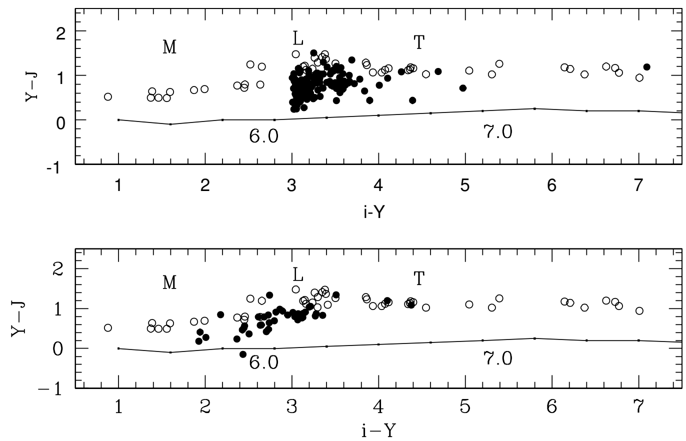

Figure 4. The panels illustrate how UKIDSS red object candidates at or below the SDSS detection limits (in $i-Y/Y-J$) can be separated into poor and promising targets (as well as artifacts removed) by using deeper imaging data. Top panel shows raw candidates (solid black points) extracted from UKIDSS , and that significant numbers ($\sim$ 80) of photometrically similar catalog objects must be observed down to a color decrement of interest (such as $i - Y > 3.0$). Dwarf stellar locus indicated by open circles with MLT labels, and quasar locus as solid line with numeric redshift labels. In the bottom panel, the addition of deep SDSS optical data, reaching > 1.5 mag deeper than the normal SDSS, immediately reveals the true color decrement of the candidates, and allows the most promising genuine objects to be efficiently selected for followup. An order of magnitude less followup effort is required to reach the same faintness/color limit.

Warren & Hewett (2002), and discussed extensively in Hewett et al. (2006), the UKIDSS Z and Y bands are defined by interference filters with sharp wavelength cutoffs and, coupled with the high sensitivity of modern infrared detectors, remedy some of the deficiencies in current imaging around $\sim 1\mu$m. The high throughput of the UKIDSS system at these wavelengths, combined with sharper band profiles, allow the more precise discrimination of potential quasar candidate redshifts and brown dwarf types, while avoiding unnecessary sky background contamination. The resulting F_λ sensitivity of the UKIDSS imaging is shown in the bottom panel of Figure 3, and compared with the SDSS as well as 2MASS sensitivities in the JHK bands. A composite quasar spectrum at $z = 3$ is also shown, illustrating the important capability of UKIDSS to detect the typical quasar near-infrared continuum, versus non-detection in 2MASS.

Because the UKIDSS planned area is coincident with the SDSS footprint, significant new followup opportunities are made available by regions such as the Southern Equatorial Stripe, located on the equator ($\pm 1.265^\circ$ in Declination) between $22^{\rm hr}$ and $4^{\rm hr}$ in Right Ascension (RA). This region, covered by multiply imaged areas of the SDSS, reaches up to 1.5 magnitudes deeper than the normal SDSS surveyed area. The advantage of deeper SDSS imaging is critical for discovery of new dropout objects, as it not only improves the number of candidates available (due to the natural luminosity function of candidates versus depth), more importantly, allows the rejection of numerous undesirable candidates. These contaminants range from cosmic rays and imaging artifacts to normal Galactic stars which, for example, have fluxes just below the normal SDSS detection limits in i and may be scattered into selections due to photometric errors. Deeper imaging reveals these faintly detected contaminants (often numbering dozens or scores per desired candidate), and allows them to be rejected. Figure 1 illustrates this shallow versus deep imaging advantage. With this deeper photometric information, closely ranked candidates (clustering near the SDSS detection limit) are also more clearly separated by their color decrement and priority for followup (see for example, Figure 4).

As UKIDSS continues to produce imaged areas and object catalogs towards its goal of 4000 sq. degrees to a depth of $K = 18.2$, the combination of deep optical imaging with this new high quality near-infrared database will continue to allow the discovery of interesting distant and nearby objects in the red.

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