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Near and Mid-infrared properties of known $z \geq 5$ Quasars

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ABSTRACT
We assemble a catalogue of 463 spectroscopically confirmed very high ($z \geq 5.00$) redshift quasars and report their near ($zZyYJHK_s$ and K) infrared and mid-infrared (WISE) properties. Using archival WFCAM/UKIRT and VIRCAM/VISTA data we check for photometric variability in the near-infrared that might be expected from super-Eddington accretion and find *blah*. Extrapolating the known quasar luminosity function we suggest that x% of the possibly detected $z \geq 5$ quasars in the current datasets have been discovered. All the data, analysis codes and plots used and generated here can be found at: `github.com/d80b2t/VHzQ`.

Key words: Astronomical data bases: surveys – Quasars: general – galaxies: evolution – galaxies: infrared.

1 INTRODUCTION

Very high redshift quasars (VHzQ; defined here to have redshifts $z \geq 5.00$) are excellent probes of the early Universe. This includes studies of the Epoch of Reionization for hydrogen (see e.g. Fan et al. 2006; Mortlock 2016, for reviews), the formation and build-up of supermassive black holes (e.g., Rees 1984; Wyithe & Loeb 2003; Volonteri 2010; Agarwal et al. 2016; Valiante et al. 2018; Latif et al. 2018; Wise et al. 2019) and early metal enrichment (see e.g., Simcoe et al. 2012; Chen et al. 2017; Bosman et al. 2017).

Super-critical accretion, where $\dot{M} > \dot{M}_{\rm Edd}$, is a viable mechanism to explain the high, potentially super-Eddington, luminosity and rapid growth of supermassive black holes in the early universe (e.g., Alexander & Natarajan 2014; Madau et al. 2014; Volonteri et al. 2015; Pezzulli et al. 2016; Lupi et al. 2016; Pezzulli et al. 2017; Takeo et al. 2018). Thus, one could expect VHzQs to potentially vary in luminosity as they go through phases of super-critical accretion. These signatures of photometric variability should be looked for, noting the rest-frame optical emission is redshifted into the observed near-infrared (NIR) at redshifts $z > 5$. Fortunately, data are now in place from deep, wide-field NIR instruments and surveys such as the Wide Field Camera (WFCAM) instrument on the United Kingdom Infra-Red Telescope (UKIRT) in the Northern Hemisphere and the VISTA InfraRed CAMera (VIRCAM) on the Visible and Infrared Survey Telescope for Astronomy (VISTA) in the Southern Hemisphere, that are necessary for identifying VHzQs.

Quasars are known to be prodigious emitters of infrared emission, thought to be from the thermal emission of dust grains heated by continuum emission from the accretion disc (e.g., Richards et al. 2006; Leipski et al. 2014; Hill et al. 2014; Hickox et al. 2017). Observations in the mid-infrared, e.g. ∼3-30μm allow discrimination between AGN[1] and passive galaxies due to the 1.6μm "bump" entering the MIR at $z \approx 0.8 - 0.9$ (e.g., Wright et al. 1994; Sawicki 2002; Lacy et al. 2004; Stern et al. 2005; Richards et al. 2006; Timlin et al. 2016) as well as between AGN and star-forming galaxies due to the presence of Polycyclic Aromatic Hydrocarbon (PAHs) at $\lambda > 3\mu$m (e.g., Yan et al. 2007; Tielens 2008).

Jiang et al. (2006) and Jiang et al. (2010) report on the discovery of a quasar without hot-dust emission in a sample of 21 $z \approx 6$ quasars. Such apparently hot-dust-free quasars have no counterparts at low redshift. Moreover, those authors demonstrate that the hot-dust abundance in the 21 quasars builds up in tandem with the growth of the central black hole. But understanding how dust first forms and appears in the central engine remains an open question (Wang et al. 2008, 2011).

WISE mapped the sky in 4 passbands, in bands centered at wavelengths of 3.4, 4.6, 12, and 23μm. The all sky 'ALLWISE' catalogue release, contains nearly 750 million detections at high-significance[2], of which over 4.5M AGN candidates have been identified with 90% reliability (Assef

[1] Historically, "quasars" and "Active Galactic Nuclei (AGN)" have described different luminosity/classes of objects. In recognition of the fact that both terms describe accreting supermassive black holes, we use these terms interchangeably, with a preference for quasar, since we are generally in the higher-L regime (e.g. Haardt et al. 2016).
[2] wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec2_1.html

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et al. 2018). Blain et al. (2013) presented WISE mid-infrared (MIR) detections of 17 (55%) of the then known 31 quasars at $z > 6$. However, Blain et al. (2013) was compiled with the WISE 'All-Sky' data release, as opposed to the superior AllWISE catalogues. That sample only examined the 31 known $z > 6$ quasars; our sample has 170 objects with redshift $z \geq 6.00$ (with 108 detected in WISE). Bañados et al. (2016) reports WISE W1, W2, W3 and W4 magnitudes for the Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1, PS1; Kaiser et al. 2002, 2010), but with no further investigation into the reddest WISE waveband for the VHzQs.

Critically, we now have available to us new W1 and W2 photometry from the 'unWISE Source Catalog' (Schlafly et al. 2019), a WISE-selected catalogue that is based on significantly deeper imaging and has a more extensive modeling of crowded regions than the ALLWISE release. For the first time in a catalogue, unWISE takes advantage of the ongoing mid-IR Near-Earth Object Wide-Field Infrared Survey Explorer Reactivation mission (NEOWISE-R; Mainzer et al. 2014), and achieves depths ~0.7 mag deeper than ALLWISE (in W1/2). This additional depth is a significant advantage in the detection and study of VHzQs in the 3-5 micron regime.

Here we present for the first time the combined near-infrared properties (from UKIRT and VIRCAM) and the new mid-infrared unWISE for all the spectroscopically known $z \geq 5.00$ quasars. Our motivations are numerous and include: *(i)* establishing the first complete catalogue of $z > 5.00$ quasars since the pioneering work from SDSS; *(ii)* utilizing all the WFCAM and VISTA near-infrared photometry available for the quasars; *(iii)* making the first study of near- and mid-IR variability of the VHzQ population and *(iv)* establishing the photometric properties for upcoming surveys and telescopes including the Large Synoptic Survey Telescope (LSST)Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper. [3], ESA *Euclid*[4] and the *James Webb Space Telescope* (JWST)[5,6,7,8]. We chose redshift $z = 5.00$ as our lower redshift limit due to a combination of garnishing a large sample, adequately spanning physical properties (e.g. luminosity, age of the Universe) and to highlight the parts of $L - z$ parameter space where $z > 5$ quasars still wait to be discovered.

This paper is organized as follows. In Section 2, we present the assembled list of the 463 $z \geq 5.00$ VHzQs that we have compiled. We then give a high-level overview of the photometric surveys and datasets we use and present the photometry of the VHzQs. In Section 3 we investigate the variability properties of the VHzQs, looking for evidence of super-critical accretion. In Section 4 we calculate how many $z > 5$ quasars we should expect to find in current datasets. We conclude in Section 5 and present all the necessary details to obtain our dataset in the Appendices.

[3] lsst.org; [4] sci.esa.int/euclid; [5] jwst.nasa.gov; [6] sci.esa.int/jwst; [7] www.asc-csa.gc.ca/eng/satellites/jwst; [8] jwst.stsci.edu.

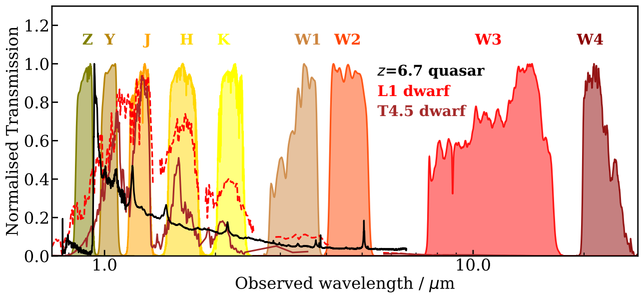

Figure 1. The spectral bands used in this paper. The $ZYJHK$ filter curves are from UKIRT/WFCAM. The $ZYJHK_s$ VISTA/VIRCAM filter curves are similar, but not identical to these. The WISE passbands W1-4 are presented, though without the Brown et al. (2014) W4 recalibration. The quasar spectrum is a composite based on Vanden Berk et al. (2001) and Bañados et al. (2016). The L and T dwarf spectra are from Cushing et al. (2006).

We present all our photometry and magnitudes on the AB zero-point system (Oke & Gunn 1983; Fukugita et al. 1996). This includes the near-infrared, as well as the mid-infrared magnitudes. These magnitudes are *not* Galactic extinction corrected. We use a flat ΛCDM cosmology with $H_0 = 67.7$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.307$, and $\Omega_\Lambda = 0.693$ Planck Collaboration (2016) to be consistent with Bañados et al. (2016) and all logarithms are to the base 10.

2 METHOD AND DATA

Quasars are generally identified by photometric selection followed by spectroscopic confirmation. Here, we reverse this method obtaining first a list of spectroscopic quasars and then obtain photometric information.

We have compiled a list of 463 quasars with redshifts $z \geq 5.00$. We use all the $z \geq 5.00$ quasars that have been discovered, spectroscopically confirmed and published as of 2018 December 31 (MJD 58483). We then obtain optical, near-infrared and mid-infrared photometry for the spectral dataset. The near-infrared data comes from two sources: first, the WFCAM (Casali et al. 2007) on the UKIRT, primarly, but not exclusively, as part of the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). And second, data from the VIRCAM on the VISTA (Emerson et al. 2006; Dalton et al. 2006). The mid-infrared, $\lambda = 3 - 30\mu$m wavelength data is from the the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010; Cutri 2013) mission. For reference, Figure 1 displays the wavelength and normalised transmission of the filters in question.

2.1 Spectroscopy

We compile the list of all known, spectroscopically confirmed quasars from the literature. This list was complied from a range of surveys and papers. Specifically, we use

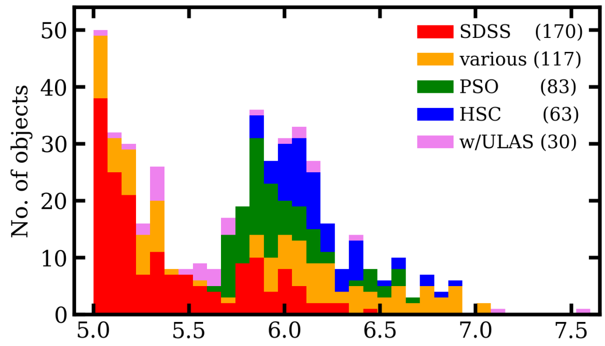

Figure 2. The redshift distribution $N(z)$ of the VHzQ sample. The bins are $\delta z = 0.075$ in width and have the data stacked on top of each other.

data from: Bañados et al. (2014, 2016, 2018), Becker et al. (2015), Calura et al. (2014), Carilli et al. (2007, 2010), Carnall et al. (2015), Cool et al. (2006), De Rosa et al. (2011), Fan et al. (2000, 2001, 2003, 2004, 2006, 2018), Goto (2006), Ikeda et al. (2017), Jiang et al. (2008, 2009, 2015, 2016), Kashikawa et al. (2015), Koptelova et al. (2017), Kim et al. (2015, 2018), Kurk et al. (2007, 2009), Leipski et al. (2014), Mahabal et al. (2005), Matsuoka et al. (2016, 2018a,b), Mazzucchelli et al. (2017), Morganson et al. (2012), Mortlock et al. (2009, 2011), McGreer et al. (2006, 2013), Reed et al. (2015, 2017), Stern et al. (2007), Tang et al. (2017), Venemans et al. (2007, 2012, 2013, 2015b,a, 2016), Wang et al. (2016, 2017, 2018b,a), Willott et al. (2007, 2009, 2010, 2013, 2015), Wu et al. (2015) Yang et al. (2018b,a) and Zeimann et al. (2011).

Most of these objects are easily identified by their broad Lyα emission line, N V emission and characteristic shape blueward of 1215Å in the rest-frame. As we shall see, some of the recently discovered objects are close to the galaxy luminosity function characteristic luminosity M^*, and some have relatively weak or maybe even completely absorbed Lyα (e.g. Figures 7 and 10 in Bañados et al. 2016). We leave aside detailed investigation and discussion into spectral features and line strengths, and take as given the published spectra and redshift identifications.

The breakdown of how many VHzQ each survey reports is given in Table 1. The Sloan Digital Sky Survey (SDSS) and the Pan-STARRS1 (PS1; PSO in Table 1) survey and alone identified over half (54.6%) of the VHzQ population. Data from the Hyper Suprime-Cam (HSC) on the Subaru telescope is responsible for 13.6% of our dataset (HSC+SHELLQs in Table 1). The combination of surveys is also vital for identifying VHzQs. The UKIDSS Large Area Survey (ULAS) on its own, or in combination with other surveys is responsible for 6.5% of the sample (SUV+ULAS) including the highest-z object. Where more than one survey is used for the high-redshift identification (e.g. via shorter-band veto and longer wavelength detection) we follow the discovery paper naming convention.

The redshifts for the VHzQs generally come from the measurement of broad UV/optical emission lines. There are far infra-red emission lines e.g. C II 158 μm available for several objects, but at the level of our current analysis broadline redshifts are sufficient.

Survey	# VHzQs	(%)	Survey reference
ATLAS	4	(0.86)	Shanks et al. (2015)
CFHQS	20	(4.32)	Willott et al. (2007)
DELS^a	16	(3.46)	Dey et al. (2018)
ELAIS	1	(0.22)	Väisänen et al. (2000)
FIRST	1	(0.22)	Becker et al. (1995)
HSC	8	(1.73)	Miyazaki et al. (2018)
IMS	5	(1.08)	Kim et al. (2015)
MMT	12	(2.59)	McGreer et al. (2013)
NDWFS	1	(0.22)	Jannuzi & Dey (1999)
PSO	83	(17.93)	Kaiser et al. (2002, 2010)
RD	1	(0.22)	Mahabal et al. (2005)
SDSS	170	(36.72)	Stoughton et al. (2002)
SDWISE^b	27	(5.83)	Wang et al. (2016)
SHELLQs	55	(11.88)	Matsuoka et al. (2016)
SUV^c	20	(4.32)	Yang et al. (2017)
UHS	1	(0.22)	Wang et al. (2017)
ULAS	10	(2.16)	Lawrence et al. (2007)
VDES^d	17	(3.67)	Reed et al. (2017)
VHS	1	(0.22)	Wang et al. (2018a)
VIK	9	(1.94)	Edge et al. (2013)
VIMOS	1	(0.22)	Le Fèvre et al. (2003)

Table 1. The source and number of the VHzQ, with the key survey reference also given. Recent survey name and acronyms include: ^{a}DESI Legacy Imaging Survey; ^{b}SDWISE = SDSS+WISE; ^{c}SUV = SDSS-ULAS/VHS; ^{d}VDES = VHS/VIKING+DES;

$z \geq$	Age / Myr	No. of objects
5.00	1180	463
5.70	1000	267
6.00	937	170
6.19	900	86
6.50	845	40
6.78	800	14
7.00	767	4
7.50	700	1

Table 2. The number of objects at or above a given redshift. The age of the Universe in Megayears is also given.

The number of objects at or above various redshifts, along with the corresponding age of the Universe is given in Table 2.

The $N(z)$ redshift histogram is given for the sample in Figure 2. We split the contribution up by survey. For clarity we show the individual surveys of SDSS, PS1, HSC, the ULAS detection, and tally the remaining surveys together ("various").

2.2 Near-infrared photometry

The near-infrared data in this paper comes from the Wide Field Astronomy Unit's (WFAU) Science Archives for UKIRT-WFCAM, the WFCAM Science Archive (WSA; Hambly et al. 2008) and VISTA-VIRCAM, the VISTA Science Archive (VSA; Cross et al. 2012). These archives were developed for the VISTA Data Flow System (VDFS Emerson et al. 2004).

We access both the WSA and the VSA and include all non-proprietary WFCAM data, which covers all public surveys and PI projects from Semester 05A (2005-05-01) to 2017-Jan-01, and all non-proprietary VISTA data, which

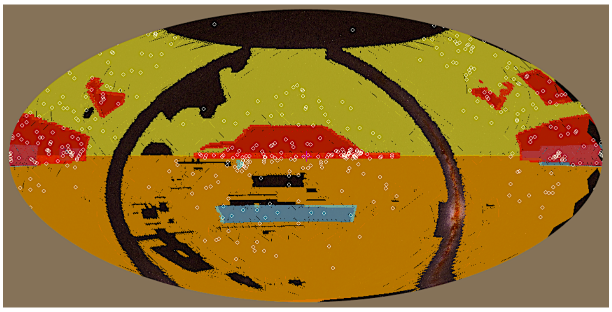

Figure 3. The coverage maps for VHS (DR6; orange), UHS (DR1; olive), VIKING (DR5; blue) and ULAS (DR11; red), the most recent public releases of the 4 main surveys. The VHzQs are given by white diamonds.

covers all public surveys and PI projects from science verification on 2009-Oct-15 to 2017-Jan-01.

Here we are not just querying the WSA or VSA data tables. We are taking a list of objects (positions) are performing matched aperture ("forced") photometry on the NIR imaging data. As such, we generate a set of tables that are different in subtle ways to the regular "Detection" tables. The two most important tables for our needs are the `[w/v]serv1000MapRemeasurement` and `[w/v]serv1000MapRemeasAver`.

We produce and provide a two new databases with all the necessary quantities and measurements to fully reproduce our tables, figures and results herein. Moreover, these databases report considerably more information than we report here. Full documentation can be found at the WSA Schema Browser and the VSA Schema Browser.

2.2.1 *Averaging matched photometry*

The data was processed using a matched-aperture photometry method where flux is measured at the spectroscopic position of the quasar, without necessarily knowing if there is a formal detection in the NIR photometry beforehand. The matched-aperture pipeline is discussed in Cross et al. (2013) and with fuller details to appear in a forthcoming paper (Cross et al., 2019, in prep).

We query the WSA and VSA performing matched-aperture photometry at the positions of our 463 VHzQs. This database is world-readable and we give the full recipe and relevant SQL queries for accessing both databases in Appendix B as well as online.

The photometry in a single epoch image often has low signal-to-noise. The advantage of matched aperture photometry on quasars is that co-adding is relatively simple if each epoch is taken in the same aperture and the aperture photometry has been corrected to total. Indeed, the standard aperture corrections work well for point sources. Coadding using the matched-aperture photometry can give better results for the photometry, where the individual epochs are taken from multiple projects with different field-centres and orientations and point-spread functions since the individual epoch scattered light, pixel distortion and aperture corrections can be applied with the correct weighting.

We average the aperture corrected calibrated fluxes (e.g. **aperJky3**), and then convert to magnitudes.

$$\bar{F} = \frac{\sum_i^N (w_i\, F_i)}{\sum_i^N w_i} \tag{1}$$

where F_i is the i^{th} epoch measurement of a parameter to be averaged such as the aperture corrected calibrated flux in a $1''$ aperture (**aperJky3**) and $\bar{F}$ is the weighted mean average of this parameter. The weight for each epoch $w_i = 1/(\sigma_F)^2$ if the epoch is included and $w_i = 0$ if an epoch is excluded for quality control purposes. The weights of each epoch in each averaged catalogue are tabulated in the `[w]serv1000MapAverageWeights`.

We calculate a set of averaged catalogues, for each pointing and filter, based on the requirements in `RequiredMapAverages`, in these cases over time spans of 7, 14, 30, 91, 183 days, 365 days, 730 days, over 10 epochs and over all epochs. The averaging process starts at the first epoch and works onwards from there. Again, we present these measurements in the new SQL tables.

We detect 359 unique quasars in the WFCAM WSA database, 220 quasars are detected in the VISTA VSA database with 130 objects in common with both WFCAM and VISTA data. We give the necessary SQL queries syntax at `d80b2t/VHzQ`.

2.3 MIR data

The MIR data for this study comes from the Wide-field Infrared Survey Explorer (WISE) mission, and we utlize data from the WISE cryogenic and the Near-Earth Object WISE (NEOWISE; Mainzer et al. 2011) post-cryogenic and NEOWISE Reactivation Mission (NEOWISE-R Mainzer et al. 2014) survey phases.

We use data from the the beginning of the WISE mission (2010 January; Wright et al. 2010) through the fifth-year of NEOWISE-R operations (Mainzer et al. 2011, 2018 December;). There are several major data releases and catalogues based on the WISE mission. Here we use two: the WISE AllWISE Data release and the recently released "unWISE Catalog" Schlafly et al. (2019). The AllWISE program combines the W1 and W2 Single-exposure data from all WISE survey phases (4-Band Cryo, 3-Band Cryo and Post-Cryo; 2010-01-07 thru 2011-02-01) survey phases, and the W3 and W4 from the 4-Band Cryo phase. The unWISE effort[9] is the unblurred coadds of the WISE imaging using the AllWISE and NEOWISE-R stacked data (Lang 2014; Meisner et al. 2018a,b).

For the two shorter WISE bands, $\lambda_{\rm eff}3.37\mu$m W1 and $\lambda_{\rm eff}4.62\mu$m W2 we generally report the deeper, unblurred unWISE coadd data. For the two longer WISE bands, $\lambda_{\rm eff}12.1\mu$m and $\lambda_{\rm eff}22.8\mu$m we use the ALLWISE Data Release.

Previous works (e.g., Krawczyk et al. 2013; Ross et al. 2015; Bilicki et al. 2016) found that cross-matches performed with a radius of 2-3" between the user catalogue and WISE was a good compromise between completeness and contamination (see e.g. Figure 4 of Krawczyk et al. 2013). We thus

[9] http://unwise.me

use a cross-match radius of 2.75". When querying the ALLWISE catalogues, "Cone Search Radius" in the ALLWISE table search was set to 2.75" for the Spatial Constraints. The "One to One Match" was "not" checked; although possible, we consider it highly unlikely there would be more than one MIR source contributing to the flux of a single UV/optically bright rest-frame quasar. Investigating this in detail is very interesting but left to a future study.

Knowing we have secure detections in the near-infrared bands, and wanting to boost the number of WISE W3/W4 detections, we allow ourselves to be less conservative in querying the ALLWISE catalogues and also query the AllWISE Reject Table. However, with the exception of one object (SHELLQs J1208-0200), the ALLWISE Reject Table does not contain any further W3/W4 detection informationn.

All fluxes in the unWISE catalog are reported there are in "Vega nanoMaggies", with the Vega magnitude of a source is given by

$$m_{\rm Vega} = 22.5 - 2.5\log(f), \tag{2}$$

where f is the source flux. The absolute calibration for unWISE is ultimately inherited from AllWISE through the calibration of Meisner et al. (2017). This inheritance depends on details of the PSF normalization at large radii, which is uncertain. Subtracting 4 millimag from the unWISE W1, and 32 millimag from unWISE W2 fluxes improves the agreement between unWISE and AllWISE fluxes.

Thus to convert unWISE Vega magnitudes onto the AB system, we have:

$$\begin{aligned} \mathrm{W1}_{\rm AB,unWISE} &= 22.5 - 2.5\log(f_{\rm W1}) - 0.004 + 2.699 \\ \mathrm{W2}_{\rm AB,unWISE} &= 22.5 - 2.5\log(f_{\rm W2}) - 0.032 + 3.339. \end{aligned}$$

For the our MIR variability investigations, we do not use the unWISE coadds, but instead use the AllWISE catalogue and the NEOWISE 2019 Data Release. NEOWISE 2019 makes available the 3.4 and 4.6 m (W1 and W2) single-exposure images and extracted source information that was acquired up until 2018 December 13 (MJD 58465) including the fifth year of survey operations of NEOWISE. These fifth year NEOWISE data products are concatenated with those from the first four years into a single archive from 2013 December 13 (MJD 56639).

The WISE scan pattern leads to coverage of the full-sky approximately once every six months (a"sky pass"), but the satellite was placed in hibernation in 2011 February and then reactivated in 2013 October. Hence, our light curves have a cadence of 6 months with a 32 month sampling gap.

Table 3 represents the culmination of this effort, and we now exam the assembly of its contents in more detail.

survey	qsoName	ra	dec	redshift	Z	Y	J	H	K	W1
PSO	J000.3401+26.8358	0.34011	26.83588	5.75	-1000.00 ± -1000.000	-1000.00 ± -1000.000	19.28 ± 0.062	-1000.00 ± -1000.000	-1000.00 ± -1000.000	16.280 ± 0.02
SDSS	J0002+2550	0.66412	25.84304	5.82	-1000.00 ± -1000.000	-1000.00 ± -1000.000	19.37 ± 0.069	-1000.00 ± -1000.000	-1000.00 ± -1000.000	16.250 ± 0.02
SDWISE	J0008+3616	2.21429	36.27041	5.17	-1000.00 ± -1000.000	-1000.00 ± -1000.000	19.33 ± 0.063	-1000.00 ± -1000.000	-1000.00 ± -1000.000	16.018 ± 0.02
PSO	J002.3786+32.8702	2.37870	32.87026	6.10	-1000.00 ± -1000.000	-1000.00 ± -1000.000	20.99 ± 0.249	-1000.00 ± -1000.000	-1000.00 ± -1000.000	17.951 ± 0.10
SDSS	J0012+3632	3.13700	36.53781	5.44	-1000.00 ± -1000.000	-1000.00 ± -1000.000	19.01 ± 0.049	-1000.00 ± -1000.000	-1000.00 ± -1000.000	15.821 ± 0.01
PSO	J004.3936+17.0862	4.39361	17.08630	5.80	-1000.00 ± -1000.000	-1000.00 ± -1000.000	20.56 ± 0.202	-1000.00 ± -1000.000	-1000.00 ± -1000.000	17.834 ± 0.10
PSO	J006.1240+39.2219	6.12404	39.22193	6.62	-1000.00 ± -1000.000	-1000.00 ± -1000.000	21.28 ± 0.422	-1000.00 ± -1000.000	-1000.00 ± -1000.000	17.364 ± 0.06
SDWISE	J0025-0145	6.36183	-1.75903	5.07	-1000.00 ± -1000.000	-1000.00 ± -1000.000	-1000.00 ± -1000.000	17.74 ± 0.004	-1000.00 ± -1000.000	14.851 ± 0.00
PSO	J007.0273+04.9571	7.02733	4.95712	6.00	-1000.00 ± -1000.000	20.33 ± 0.056	20.23 ± 0.074	20.29 ± 0.108	20.19 ± 0.105	17.178 ± 0.06
SDWISE	J0031+0710	7.85775	7.17692	5.33	-1000.00 ± -1000.000	20.03 ± 0.082	20.20 ± 0.146	19.49 ± 0.106	19.61 ± 0.123	16.658 ± 0.03

Table 3. The first ten of 463 very high-z quasars with near and mid-infrared photometry.

Selection	number detected (%)
Any band ($ZYJHK/K_s$)	449 (97.0)
Z-band	75 (16.2)
Y-band	273 (59.0)
J-band	447 (96.5)
H-band	269 (58.1)
K or Ks-band	322 (69.5)

Table 4. Detection rate of VHzQs in the near-infrared. For the 14 objects that have no NIR detections, 3 have been observed but are not in our queried time range, 6 have not been observed yet and 5 objects are too far north to be visible by UKIRT.

3 RESULTS

Having collated the sample of 463 VHzQs, and obtained their near- and mid-infrared photometry we report here the various photometric properties of the quasars.

First, we will concentrate on detection rate in the infrared, go on to report on the colour-redshift and colour-colour properties of our sample and then report on how the current sample populates the luminosity-redshift Lz-plane.

3.1 Detection Rates in the NIR

Table 4 gives the detection rates for the VHzQs in the NIR $YJHK/K_s$-bands. The first thing to note is that the coverage of the NIR surveys for example from the UKIDSS LAS and VISTA VHS, does not overlap the full area for where the VHzQs are detected.

There are 14 objects that have no NIR detections. 3 of these (PSOJ053.9605-15.7956, PSO J056.7168-16.4769 and DELSJ0411-0907) have been observed (by VHS) but are out of our queried time range (for which the data is publicly available). 6 objects have not been observed (or at least the data is not in the WSA/VSA archives yet) and 5 objects are at a declination $\delta \geq +60$ deg are too far north for UKIRT and cannot be observed.

3.1.1 Comparing WFCAM and VISTA

There are 130 overlapping QSOs between WFCAM and VISTA. We used the `VegaToAB` values to put these objects on the same AB system, and for each object compared the two measurements. First, we calculated the weighted average (calibrated flux) in each filter of both and calculated the ratio and difference between each measurement and the average. Then for each filter we calculated the weighted average of the differences (in mag) for each instrument to see if there were significant offsets. The results are given in Table 6. The only filter with a significant offset is the Y-band. All of the VISTA averages are negative and all of the WFCAM ones are positive. The Ks versus K band comparison may be affected the different shapes of the filters, with K being significantly wider than K_s.

We have also checked for quasars with large differences in magnitude between the WSA and VSA. Objects were selected where the average flux was $> 0.$ and > 5 average flux error. In order to account for large errors in either the WFCAM or VISTA photometry, objects with deltaMag$< 2\times$ deltaMagErr in either WSA or VSA were removed. This selects two quasars with large, δmag > 0.2mag differences between the WSA and VSA. These are SDSSJ0349+0034 and SDSSJ2220-0101. For SDSSJ0349+0034 has a WSA K-band magnitude of 19.13±-0.24, while for the VSA K_s-band this is 18.36±0.10 mag. For SDSSJ2220-0101, in J-band WSA = 22.23±0.15, for the VSA = 19.38±0.04.

abs(VIRCAM - WFCAM)	millimags	no. of objects
Z	23.2	3
Y	57.3	53
J	2.1	106
H	45.8	96
K_s/K	25.2	110

Table 5. Comparing the magnitudes in different WFCAM/UKIRT and VIRCAM/VISTA near-infrared bands.

$z \geq$	unWISE		ALLWISE	
	W1	W2	W3	W4
5.00	362 (78.2%)	308 (66.5%)	51 (11.0%)	10 (2.2%)
5.70	186 (69.4%)	151 (56.3%)	15 (5.6%)	2 (0.7%)
6.00	109 (63.7%)	91 (53.2%)	8 (4.7%)	2 (1.2%)
6.19	63 (72.4%)	47 (54.0%)	3 (3.4%)	2 (2.3%)
6.50	34 (85.0%)	26 (65.0%)	1 (2.5%)	2 (5.0%)
6.78	12 (85.7%)	9 (64.3%)	0 (0.0%)	0 (0.0%)
7.00	4 (100.0%)	4 (100.0%)	0 (0.0%)	0 (0.0%)
7.50	1 (100.0%)	1 (100.0%)	0 (0.0%)	0 (0.0%)

Table 6. Detection rates in the mid-infrared bands from WISE as a function of redshift. A signal-to-noise cut of `w`x`snr`> 3.0 has been used for each band.

3.2 Detection Rates in the MIR

Unlike the NIR coverage, the WISE satellite and mission performed an all-sky survey, so the location of every VHzQ in our dataset is covered. However, the depth of the WISE survey depends heavily on sky location, with locations near the Ecliptic Poles having the highest number of exposures.

Before reporting on the detection rates, we investigate this effect using the AllWISE Source Catalog. Figure 5 shows the WISE ALLWISE magnitude versus signal-to-noise, colour coded by `w`x`cov` the mean coverage depth, in each corresponding band. In the two shorter bands W1/2 we see the clear and expected trend for brighter objects to have larger SNR, and also for the higher signal to noise for objects with more exposures at a given magnitude. The behaviour for the W3/4 bands is different, with two populations clearly evident in W3 and although a bit more mixed, also in W4. With the suggested split at SNR> 2, and no obvious R.A./Declination dependence seen, this behaviour is explained by the fact that there are non-detectiopns in W3/4 for objects (with high W1/2 SNR) that are reported in the ALLWISE catalogue.

For the 362 VHzQ with coverage detections, the mean number of exposures for the W1/2 bands is 32.0 and 31.5, respectively, with a minimum number of exposures 17 and 12, and the maximum number or exposures being 114 (for both bands). For the W3/4 filters, the corresponding mean, minimum and maximum exposure are 17.4 and 17.5, 5.8 and 6.8 and 69 (for both bands). These values are directly from the `w`x`cov` entries in the WISE ALLWISE catalogue.

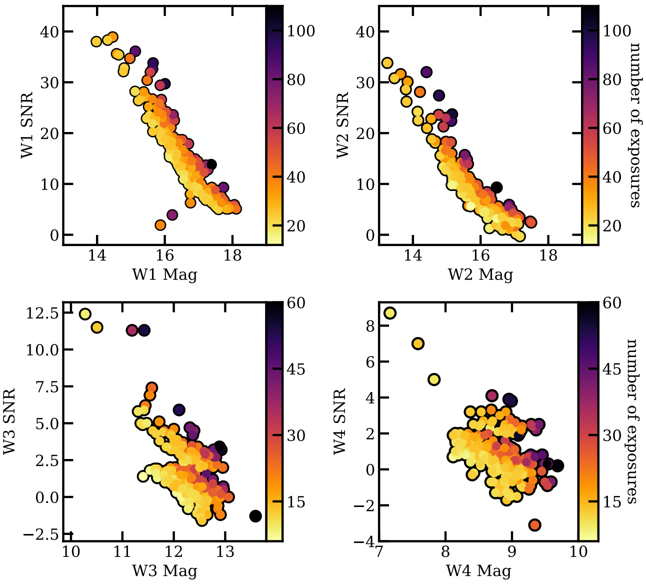

Figure 4. WISE W1/2/3/4 `wxmpro` magnitude against signal-to-noise, colour coded by `wxcov` the mean coverage depth, in each corresponding band.

Selection	number detected (%)
W1 SNR > 3.0	362 (xxz.9)
W2 SNR > 3.0	255 (60.1)
W1 ∧ W2 SNR > 2.0	
W3 SNR > 2.0	99 (23.3)
W4 SNR > 2.0	29 (6.8)
Any W1/2/3/4 SNR > 2.0	
W1/2 SNR < 2.0 ∧ W3 SNR > 2.0	

Table 7.

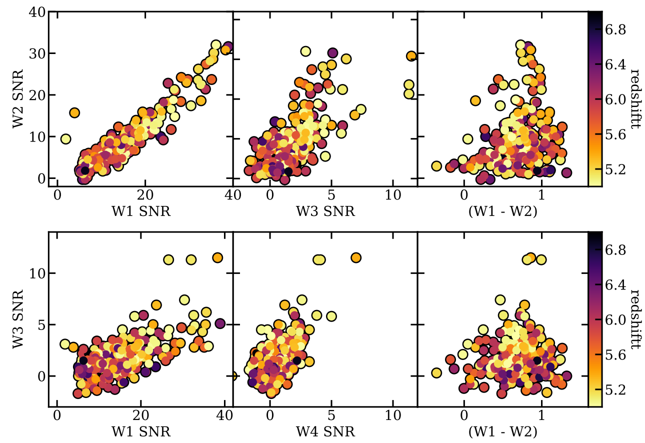

Figure 5. WISE signal-to-noise measures for the four bands, as well as for (W1-W2) colour. The points are colour coded by redshift.

Table 7 gives the detection rates for the VHzQs in the MIR WISE W1-4 bands.

Blain et al. (2013)

Recently, Assef et al. (2018) released two large catalogues of AGN candidates identified across 30,000 deg^2 of extragalactic sky from the WISE AllWISE Data Release. The "R90" catalogue, is contains 4.5M AGN candidates at 90% reliability (and ≈150 AGN candidates per deg^2) while the "C75" catalogue consists of 20.9M AGN candidates at 75% completeness (and (≈700 AGN candidates per deg^2). Crossmatching out catalogue of 463 VHzQs with these catalogues, produces 42 matches with the R90 sample and 98 matches with the C75 sample. Both catalogues unsurprisingly match to the ultraluminous quasar SDSS J0100+2802 (Wu et al. 2015) while the C75, but not the R90 catalogue mathes to ULAS J1120+0641 (Mortlock et al. 2011). Neither catalogue matches J1342+0928 (Bañados et al. 2018).

Very High-z Quasars Detected in WISE W3 and W4.

3.3 Variability

VHzQs, if accreting at, or above the Eddington Limit, might well have have large values of changing mass accretion rate, $\dot{m}_{\rm accr}$. A consequence of this would be that these quasar exhibit signs of variability, most likely showing up in their UV/optical rest-frame spectra. We look for evidence of this variability signature in the NIR and MIR light-curves of the VHzQs. As a guide, C IV enters the Y-band at redshift z=5.32 and exits at z=5.99, and enters the J-band at redshift $z = 6.55$ and exits at z=7.57. Mg II enters the H-band at redshift $z = 4.33$ and exits at $z = 5.37$ and enters the K-band at redshift $z = 6.25$ and exits at 7.50.

Using the extended datasets described in Section 2.2 and **??**, we

Figure 7 gives the number of NEOWISE-R epochs and detections there are for each VHzQ, while Figure **??** presents three examples of the MIR lightcurves and associated colour changes. Here we show J0100+2802 (Wu et al. 2015), J0224-4711 and J1626+2751. **NJC: What about NIR light-curves / combined light-curves**

At least 8 original observations across at least 30 days in either WSA or VSA per band, calibrated flux greater than zero over the whole time, and the error on the average flux is 8 times lower than this.

Thenn a requirement of SNR> 3 per 'average' epoch, where 'average epoch' is then dependenet o nthe averaging timescales (whcih as we see can vary).

Then calculate the clipped median and standard deviation,

$$1.48 \times \sigma_{median}/\bar{\epsilon} \quad (3)$$

where $\bar{\epsilon}$ is the mean of the error in each point in the light curve, divided by the total number of points. With this definition, although some of the objects have very well sampled, 'average' light curves where you are averaging over e.g. a month, or two weeks.

Longer time-series, better SNR and moreover, $(1 + z)$. Just selecting things that would Doing this independtly in each band...

objiD 164 is SDSSJ1000+0234, faint; very faint. SHELLQsJ0220-0432: (qso59) show this too. CFHQSJ0216-0455

4 SURFACE DENSITY OF VHZQS

One interesting question to ask is given the compilation of VHzQs assembled here, are there bright $z > 5.00$ quasars

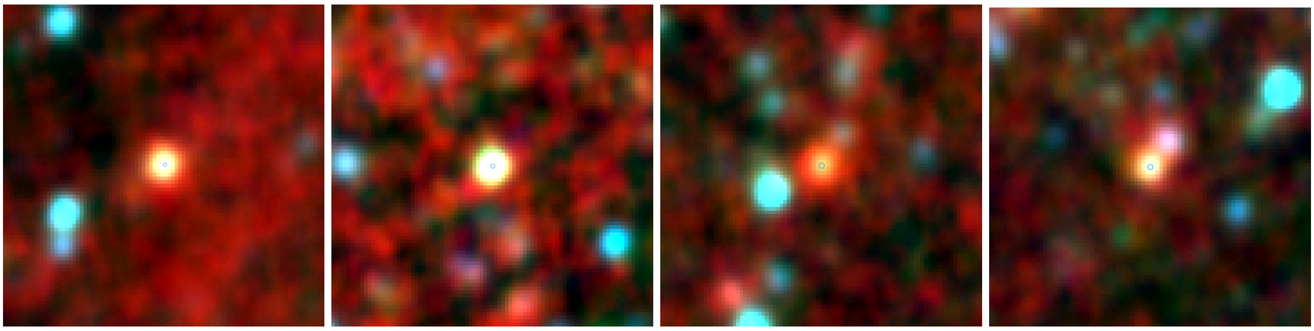

Figure 6. (a) UHS J0439+1634 (b) SDSS J0100+280 (c) SDSS J1443+3623 (d) SDSS J1623+4705

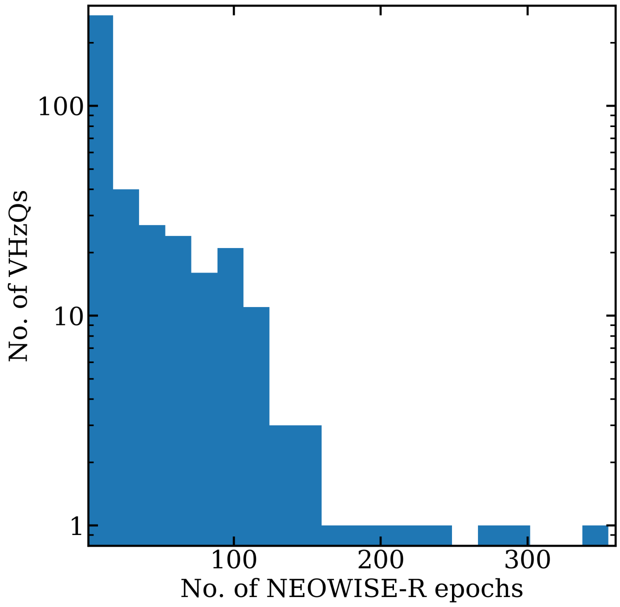

Figure 7. Histogram showing the number of NEOWISE-R epochs and detections there are for each VHzQ.

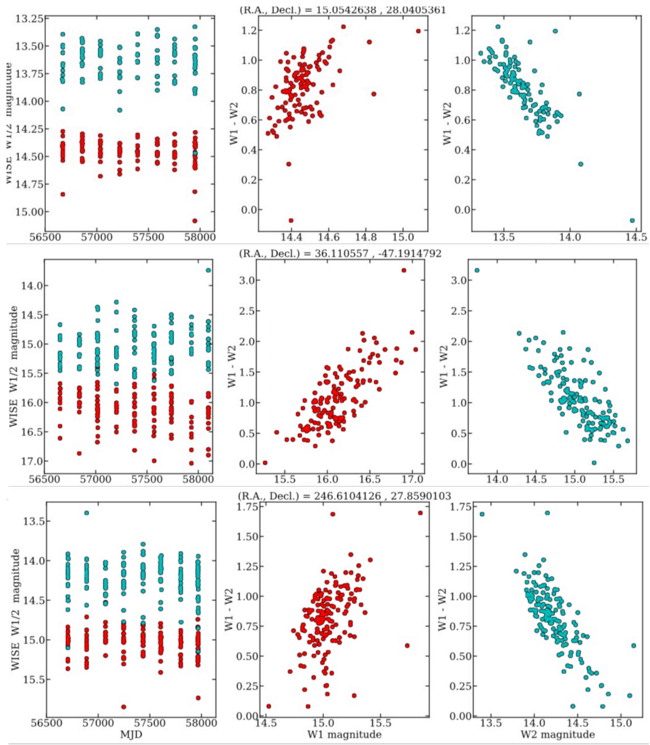

Figure 8. Here we show the MIR NEOWISE-R for J0100+2802 (Wu et al. 2015), J0224-4711 and J1626+2751. Red points are the W1 band; cyan points the W2 band.

that are in *current* photometric datasets, and if so, how many are still to be discovered and confirmed spectroscopically?

VHS, Area 1: 150<RA/deg< 200 annd -40 <Decl./deg< -20: Y=21.1 mag, J=20.6 mag, H=20.3 mag, K_s=19.8 mag (all AB). Area 2: 10<RA/deg<60, -60 <Dec< -40: J=21.2 mag, H=20.6 mag, K_s=20.2 mag.

VIKING is more uniform, so I calculated the averages over the whole area: Z=22.7 mag, Y=21.9 mag, J=21.4 mag, H=21.2 mag, Ks=21.1 mag.

Following Fan et al. (2001) and McGreer et al. (2013), we use use an exponential decline to describe the space density of VHzQs at high redshifts, e.g.

$$\rho(z, \mathrm{M}_{1450} \propto 10^{k(z)} \quad (4)$$

where z is the sample redshift.

UHS J-band depth 19.6 (Vega; Dye et al. 2018)

VISTA HEMISPHERE SURVEY DATA RELEASE 1 Release date (will be set by ESO) PROPOSAL ESO No.: 179.A-2010 PRINCIPAL INVESTIGATOR: Richard McMahon Authors: R. McMahon, M. Banerji, N. Lodieu for the VHS Collaboration

The aim of the Vista Hemisphere Survey (VHS) is to carry out a near Infra-Red survey, which when combined with other VISTA Public Surveys will result in coverage of the whole southern celestial hemisphere (∼20,000 deg^2) to a depth 30 times fainter than 2MASS/DENIS in at least two wavebands (J and K$_s$), with an exposure time of 60 seconds per waveband to produce median 5 point source (Vega) limits of J = 20.2 and K_S = 18.1. In the South Galactic Cap, ∼5000 deg^2 will be imaged deeper with an exposure time of 120 seconds and also including the H band producing median 5σ point limits of: J = 20.6; H = 19.8; K$_s$ = 18.5. In this 5000 deg^2 region of sky deep multi-band optical (grizY) imaging data will be provided by the Dark Energy Survey (DES). The remainder of the high galactic

[H]

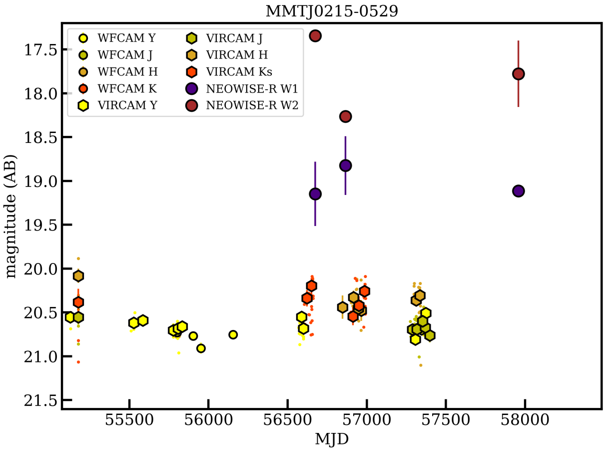

Figure 9. MMTJ0215-0529

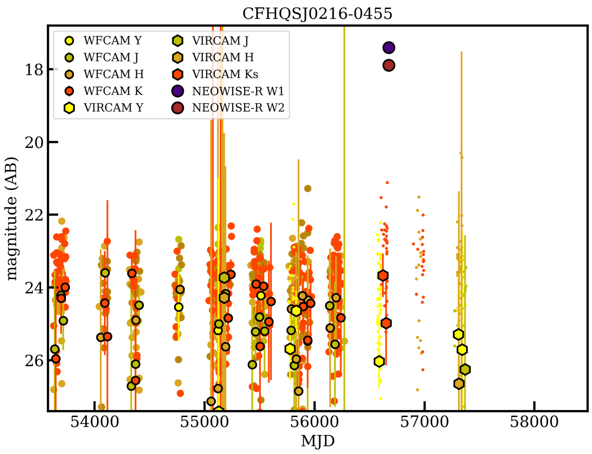

Figure 10. CFHQSJ0216-0455

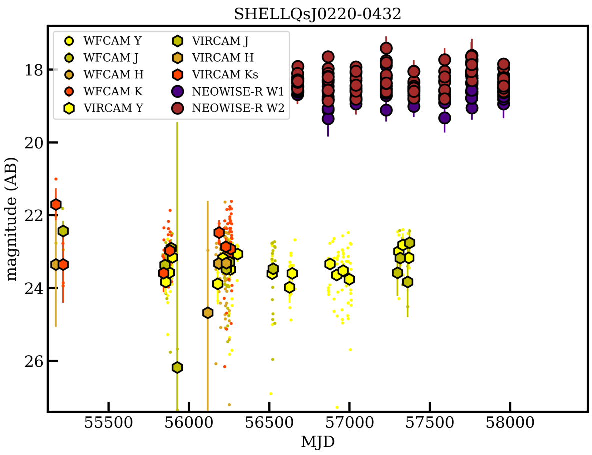

Figure 11. SHELLQsJ0220-0432

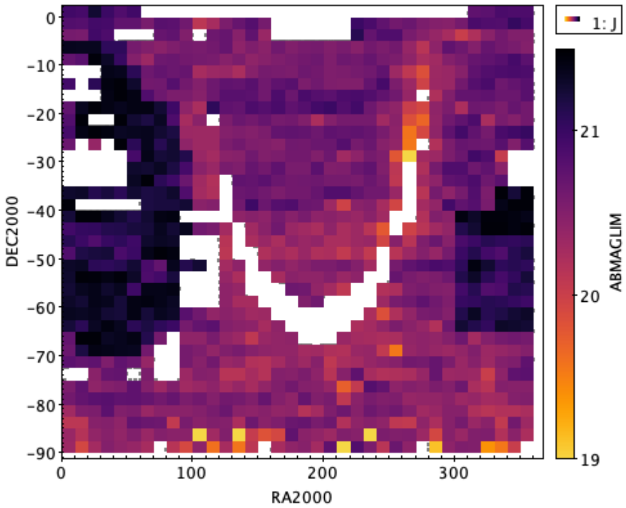

Figure 12. The calculated average `AB MAGLIM` in the VHS. As one can see, VHS is not completely uniform. The are 3 areas with different filter sets, and the depths changed in 2 of these areas, particularly in J and K_s. Y and H are almost uniform, but the coverage is much less.

latitude ($|b|$ >30°) sky will be imaged in YJHK for 60sec per band to be combined with ugriz waveband observations from the VST ATLAS survey.

VHS YJHK 99.99, 21.2, 21.2, 20.6, 20.0 (9)

`ABmagLimits` for each survey in the database.

5 DISCUSSION AND CONCLUSIONS

In this study, we have, for the first time, ompiled the list of all $z > 5$ spectroscopically confirmed quasars. We have assemble the NIR $(y/Y, J, H, K/K_s)$ and MIR (WISE W1/2/3/4) photometry for these objects, given their detection rates and SEDs. We find that:

We can gain a good appreciation for what these missions will discover by collating the datasets we currently have.

- Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam porta sodales est, vel cursus risus porta non. Vivamus vel pretium velit. Sed fringilla suscipit felis, nec iaculis lacus convallis ac.
- Fusce pellentesque condimentum dolor, quis vehicula tortor hendrerit sed. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos himenaeos. Etiam interdum tristique diam eu blandit. Donec in lacinia libero.
- Sed elit massa, eleifend non sodales a, commodo ut felis. Sed id pretium felis. Vestibulum et turpis vitae quam aliquam convallis. Sed id ligula eu nulla ultrices tempus. Phasellus mattis erat quis metus dignissim malesuada. Nulla tincidunt quam volutpat nibh facilisis euismod. Cras vel auctor neque. Nam quis diam risus.

Nunc lacus nibh, convallis ac lobortis ut, tempus ac lectus. Maecenas eu elit massa. Nulla vel lacus lorem. Proin et lobortis tortor. Phasellus ultrices nisl non enim porttitor dictum. Curabitur nec nunc ac nibh ornare elementum. Nunc ultrices hendrerit ultricies. Aliquam dapibus semper est et gravida. Etiam cursus, massa eget tempor elementum, lectus urna feugiat nisi, eget sagittis.

Author Contributions

N.P.R. initiated the project, compiled the list of $z > 5.00$ quasars, wrote most of the analysis code, developed the the plotting scripts, and developed and wrote the initial and subsequent drafts of the manuscript. N.J.G.C. supplied the critical near-infrared expertise and database for which the bulk of the project relies. N.J.G.C. also contributed directly to the writing of the manuscript.

Availability of Data and computer analysis codes

All materials, databases, data tables and code are fully available at: `https://github.com/d80b2t/VHzQ`

ACKNOWLEDGEMENTS

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This paper heavily used TOPCAT (v4.4) (Taylor 2005, 2011). This research made use of `Astropy`, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; The Astropy Collaboration et al. 2018).

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This project used data obtained with the Dark Energy Camera (DECam) and the NOAO Data Lab, The Data Lab is operated by the National Optical Astronomy Observatory, the national center for ground-based nighttime astronomy in the United States operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, and NEOWISE, which is a project of the Jet Propulsion Laboratory/California Institute of Technology. WISE and NEOWISE are funded by the National Aeronautics and Space Administration.

CasJobs was originally developed by the Johns Hopkins University/ Sloan Digital Sky Survey (JHU/SDSS) team. With their permission, MAST used version 3.5.16 to construct CasJobs-based tools for GALEX, Kepler, the Hubble Source Catalog, and PanSTARRS.

This research has made use of the SVO Filter Profile Service (http://svo2.cab.inta-csic.es/theory/fps/) supported from the Spanish MINECO through grant AyA2014-55216 The SVO Filter Profile Service[10] describes the Spanish VO Filter Profile Service. The Filter Profile Service Access Protocol. Rodrigo, C., Solano, E. http://ivoa.net/documents/Notes/SVOFPSDAL/index.html

APPENDIX A: NEAR-INFRARED WFCAM SCIENCE ARCHIVE SQL QUERIES

Here we give the receipe and SQL that returned the near-infrared photometry for the VHzQs from the WFCAM Science Archive.

The data are on the WFCAM Science Archive: `wsa.roe.ac.uk`. Access the User Login form `wsa.roe.ac.uk/login.html` with these credentials::

- Username: `WSERV1000`
- password: `highzqso`
- community: `nonsurvey`

Then going to the `Free Form SQL Query` page the Database release `WSERV1000v20180716` can be accessed which contains all the data we use here.

We *nota bene* a few things. First, the quantity `aperJky3` and `aperJky3Err` are found in the `wserv1000MapRemeasAver` and `wserv1000MapRemeasurement`, so care has to be taken to return unique column names (otherwise e.g. astropy.io.fits will crash). As such, we alias `aver.aperJky3` to `aperJky3Aver` and likewise for the error quantity. Aliases will be necessary in some cases anyway, because some queries can be done sensibly on multiple instances of the same table. Other times, one may join tables on quantities such as `catalogueID` or `apertureID`, where you are meaning the same thing, but aliases would again be sensible.

Second, the `RA` and `DEC` values returned by the WSA are in radians, if used directly. To return values in degrees, use a selection with an alias, e.g. `RA as RADeg` and `DEC as DECDeg`.

[10] Rodrigo, C., Solano, E., Bayo, A. http://ivoa.net/documents/Notes/SVOFPS/index.html

Then the following SQL will return the values in Table **??**.

```
SELECT
qso.qsoName,  qso.ra as raJ2000, qso.dec as decJ2000,
aver.apertureID,  aver.aperJky3 as aperJky3Aver,
aver.aperJky3Err as aperJky3AverErr, aver.sumWeight,
aver.ppErrBits as ppErrBitsAver, m.mjdObs,
m.filterID, remeas.aperJky3,
remeas.aperJky3Err,
w.weight, remeas.ppErrBits,
m.project

FROM
finalQsoCatalogue as qso,
MapApertureIDshighzQsoMap as ma,
wserv1000MapRemeasAver as aver,
wserv1000MapRemeasurement as remeas,
MapProvenance as v,
wserv1000MapAverageWeights as w,
MapFrameStatus as mfs,
Multiframe as m

WHERE
qso.qsoID=ma.objectID and
ma.apertureID=aver.apertureID and
aver.apertureID=remeas.apertureID and
aver.catalogueID=v.combicatID and
v.avSetupID=1 and
v.catalogueID=remeas.catalogueID and
w.combicatID=v.combicatID and
w.catalogueID=v.catalogueID and
w.apertureID=aver.apertureID and
mfs.catalogueID=remeas.catalogueID and
m.multiframeID=mfs.multiframeID and
mfs.programmeID=10999 and
mfs.mapID=1
order by v.combicatID, m.mjdObs
```

APPENDIX B: NEAR-INFRARED VISTA SCIENCE ARCHIVE SQL QUERIES

In a very similar manner to the WSA, we give here the details on how to access the VISTA Science Archive (VSA)

At the VSA Login, enter with these credentials::

- Username: `VSERV1000`
- password: `highzqso`
- community: `proprietary`

Then head to the Freeform SQL Query page where the database release to use is `VSERV1000v20180716`.

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