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Citation for published version:
Banerji, M, McMahon, RG, Hewett, PC, Gonzalez-Solares, E & Koposov, SE 2013, 'Hyper-luminous Reddened Broad-Line Quasars at z~2 from the VISTA Hemisphere Survey and WISE All Sky Survey', Monthly Notices of the Royal Astronomical Society. https://doi.org/10.1093/mnrasl/sls023

Digital Object Identifier (DOI):
10.1093/mnrasl/sls023

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published in:
Monthly Notices of the Royal Astronomical Society

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Hyper-luminous Reddened Broad-Line Quasars at $z \sim 2$
from the VISTA Hemisphere Survey and WISE All Sky Survey

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ABSTRACT

We present the first sample of spectroscopically confirmed heavily reddened broad-line quasars selected using the new near infra-red VISTA Hemisphere Survey and WISE All-Sky Survey. Observations of four candidates with $(J-K) > 2.5$ and $K \leq 16.5$ over $\sim 180$ deg$^2$, leads to confirmation that two are highly dust-reddened broad-line Type 1 quasars at $z \sim 2$. The typical dust extinctions are $A_V \sim 2–2.5$ mags. We measure black-hole masses of $\sim 10^9 M_\odot$ and extinction corrected bolometric luminosities of $\sim 10^{47}$ erg/s, making these among the brightest Type 1 quasars currently known. Despite this, these quasars lie well below the detection limits of wide-field optical surveys like the SDSS with $i_{AB} > 22$. We also present WISE photometry at 3–22 $\mu$m, for our full sample of spectroscopically confirmedreddened quasars including those selected from the UKIDSS Large Area Survey (Banerji et al. 2012a). We demonstrate that the rest-frame infrared SEDs of these reddened quasars are similar to UV-luminous Type 1 quasars with significant hot dust emission and starburst quasar hosts like Mrk231. The average 12$\mu$m flux density of our reddened quasars is similar to that of the recently discovered HyLIRG WISE1814+3412 ($z = 2.452$) at similar redshifts, with two of our reddened quasars also having comparable 22$\mu$m flux densities to this extreme HyLIRG. These optically faint, heavily reddened broad-line quasars are therefore among the most mid infrared luminous galaxies at $z \sim 2$, now being discovered using WISE.

Key words: galaxies:active, (galaxies:) quasars: emission lines, (galaxies:) quasars: general, (galaxies:) quasars: individual

1 INTRODUCTION

Dust-reddened broad-line quasars could represent the crucial missing link between massive ultraluminous starbursts identified in far infrared and submillimeter surveys, and UV-luminous quasars in optical surveys. The study of these rare transitioning systems, has gained new impetus with the advent of sensitive wide-field infrared surveys such as the UKIDSS Large Area Survey (LAS) (Lawrence et al. 2007), VISTA Hemisphere Survey (VHS; McMahon et al. in prep) and Wide Infrared Survey Explorer (WISE) All Sky Survey (Wright et al. 2010). In our previous work (Banerji et al. (2012); B12 hereafter), we used the UKIDSS LAS to find a population of heavily dust-reddened ($(J-K) > 2.5$ (Vega)) quasars at $z \sim 2$ corresponding to the main epoch of black-hole growth in the Universe. This new sample of 12 confirmed reddened quasars was the first to be assembled using a pure near infrared (NIR) selection and pushed 2 mags fainter than previous studies using 2MASS, which had selected quasars that were considerably less red ($(J-K) > 1.7 - 2$) (Glikman et al. 2007; Cutri et al. 2001).

Sensitive NIR surveys at 1–2$\mu$m are well suited to searching for broad-line quasars at $z \sim 2$, with significant

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amounts of dust in their host galaxy. At these redshifts, the NIR colours sample a portion of the rest-frame spectral energy distribution (SED) at ~0.3–0.8μm that is very sensitive to dust extinction within the quasar host, but not to the hot-dust emission from the molecular torus at 1–3μm (Hyland \& Allen 1982; Neugebauer et al. 1987). Ground-based NIR imaging also allows discrimination of luminous Type 1 broad-line quasars that typically appear unresolved, and the less luminous Type 2 sources where the host galaxy is often resolved.

Our aim in this work is to use initial data from the new VISTA Hemisphere Survey and the WISE All Sky Survey completed this year, to devise a colour selection criterion for reddened broad-line quasars and subsequently test this selection method via spectroscopic follow-up of a small pilot sample. The infra-red colour scheme we use, should in principle be effective at isolating dust-reddened broad line quasars and the current study offers the first practical demonstration of this selection using new data from VHS and WISE. In addition, we also investigate the rest-frame infra-red SEDs of our full sample of reddened (J−K > 2.5) quasars using data from the WISE All Sky Release. Throughout this paper we assume a flat concordance cosmology with H₀ = 70 kms⁻¹ Mpc⁻¹, ΩM = 0.3 and ΩΛ = 0.7. All magnitudes are in the Vega system unless otherwise stated.

2 PHOTOMETRIC DATA

2.1 VISTA Hemisphere Survey (VHS)

VHS is a NIR photometric survey being conducted using the VISTA telescope in Chile, that aims to survey 18,000 deg² of the southern celestial hemisphere to a depth 30 times fainter than the 2MASS survey in at least two wavebands (J and K). In the South Galactic Cap, 4500 deg² will be imaged deeper, including the H-band, and will have supplemental deep griY imaging provided by the Dark Energy Survey. The remainder of the high galactic latitude sky will be imaged at YJHK and combined with optical photometry from the VST-ATLAS survey. In this work, we use ~180 deg² data from the VHS VST-ATLAS overlap region at 205° <RA< 245° and −9° <DEC< −4.5°. The VHS data in this region reaches average 5σ K-band depths of 18.2 (Vega).

2.2 WISE

The WISE satellite has conducted an all-sky survey at mid infrared wavelengths between 3.4μm and 22μm (Wright et al. 2010). WISE specific mid-IR colour selection criteria for isolating both populations of obscured and unobscured AGN have been devised (Assef et al. 2011; Stern et al. 2012; Assef et al. 2012). These authors propose a colour-cut of [W1–W2] > 0.8–0.85 with a more conservative cut of [W1–W2] > 0.7 suffering from less incompleteness but also prone to higher levels of contamination from populations of dusty and normal star-forming galaxies. These colour criteria have been shown to be extremely effective in selecting AGN at intermediate redshifts but become incomplete when H₀ moves into the W1 band at z ≥ 3.4. The WISE selection identifies AGN independent of their reddening and so needs to be combined with additional colour information at shorter wavelengths in order to distinguish highly reddened quasars from those that are unobscured at UV and optical wavelengths. In addition, morphological information from ground-based NIR surveys can be used to separate dusty broad-line quasars from Type 2 AGN.

2.3 This Sample

Our aim is to test the effectiveness of a joint VHS+WISE colour selection in isolating highly reddened quasars at z~2. We therefore identify reddened quasar candidates that satisfy the following selection criteria:

- (J−K) > 2.5 and 13 < K < 17 (Vega). A bright sample with 13 < K ≤ 16.5 (Vega) is prioritized for spectroscopic follow-up. The (J−K) colour-cut corresponds roughly to E(B−V) > 0.5 at z ~ 2.
- Unresolved or stellar-like point source classifications in the VHS NIR images. This corresponds to mergedclass = −1 in the VHS catalogues.
- Signal-to-noise of >10 in the K-band in order to ensure reliable morphological classifications.
- Candidates are required to be red in all the NIR bands - i.e. J > H & H > K.

The above NIR only selection criteria produces ~600 candidates with K < 17, 447 of which are at K ≤ 16.5. Many of these sources are expected to be spurious. In order to clean the sample, it is matched to the WISE All-Sky source catalogue using a matching radius of 3" and requiring a >3σ detection in both the WISE 3.4 and 4.6μm bands. This reduces the candidate list to 321 sources. The VHS+WISE detected sources are then required to satisfy the additional criterion of [W1−W2] > 0.85, which produces 11 candidate reddened quasars with 13 < K < 17, seven of which are at 13 < K ≤ 16.5. Finally, the images for all candidates are visually inspected to create the sample for spectroscopic follow-up. This visual inspection eliminates two sources with a close neighbour in the J-band, which may be affecting the J-band photometry, leaving five candidates, which are summarised in Table I.

Before presenting results of our spectroscopic follow-up, we first look at the expected effectiveness of our colour selection criteria presented above. In Figure I we show our red quasar candidates from VHS+WISE, with 13 < K < 17 in the (J−K) versus (W1−W2) colour-colour plane as well as our sample of already confirmed such reddened quasars from B12. Also shown are all point-like sources over the same area, down to the same flux limit in the K-band, 142 known UV-luminous quasar, and an evolving elliptical galaxy template modelled as a simple stellar population with zform = 5, 0000 RAS, MNRAS 000, 000–000, C

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Reddened Quasars from VHS and WISE

3

VHS (J−Ks) Vega

WISE [3.4−4.6 µm] Vega

Figure 1. (J−K) versus (W1-W2) colour selection of our red quasar candidates. All stellar objects over 180 deg², are shown in grey. The greyscale represents the density of these objects while the 1% of outliers in the distribution are shown as the individual grey points. Known UV-luminous quasars, local Ultraluminous Infrared Galaxies (ULIRGs) from the IRAS 1Jy sample and known LT dwarf stars have also been plotted. We also show the tracks of a typical unreddened quasar as well as an elliptical galaxy template with a formation redshift of z = 5. Our reddened quasar candidates are marked as the red circles. The small filled circles represent the spectroscopically confirmed sample from B12, the two large filled circles are the 2 new confirmed quasars presented in this work and the open circles represent all candidates presented in this study down to K < 17.

Table 1. Sample of 13 < K ⩽ 16.5 and (J−K) > 2.5 reddened quasar candidates from VHS and WISE.

| Name       | RA   | DEC  | KVega | Redshift |
|------------|------|------|-------|----------|
| VHSJ1350−0503 | 13:50:37.24 | −05:03:59.4 | 15.97 | 2.176    |
| VHSJ1409−0830 | 14:09:29.08 | −08:30:58.7 | 16.50 | 2.300    |
| VHSJ1504−0442 | 15:04:46.25 | −04:42:14.1 | 16.50 | No Spec  |
| VHSJ1518−0501 | 15:18:37.85 | −05:01:38.3 | 16.13 | –        |
| VHSJ1543−0439 | 15:43:21.91 | −04:39:08.6 | 16.43 | –        |

3 SPECTROSCOPIC FOLLOW-UP

Spectra were taken for four out of our five reddened quasar candidates using GNIRS, the NIR spectrograph on Gemini-North. We used GNIRS in cross-dispersed mode in order to obtain the widest wavelength coverage. Each target was observed for 20 minutes using 4 exposures of 5 minutes with the target dithered along the slit in a classical ABBA pattern for purposes of sky subtraction. We used the short camera (0.15″/pix) and the 31.7 lines/mm grating with a 1″ slit. This provided coverage over 0.9–2.5µm across six orders. Only the two reddest orders are used here corresponding to the atmospheric windows at 1.6µm and 2.2µm. The instrumental resolution is measured to be ~10Å or 160 km/s from the sky lines. All data were reduced using standard GNIRS pipelines (v1.11) and utilising the Image Reduction and Analysis Facility (IRAF).

Out of the four reddened quasar candidates observed, two are confirmed to be broad line quasars at z~2. The spectra can be seen in Figure 2 along with the best-fit SEDs derived by fitting to the broadband photometry as in B12. We derive dust extinctions, bolometric luminosities and black-hole masses for these two quasars using the methods outlined in B12. These are summarised in Table 2. These properties are fairly typical of our sample of reddened quasars selected from the UKIDSS-LAS (B12). Crucially however, the VHS targets are in the southern hemisphere and therefore suitable for detailed follow-up using ALMA. Optical spectroscopy is needed to confirm the identity of the two sources where no lines were seen in the NIR. These could be

using an updated version of Bruzual & Charlot (2003) and the publicly available web-based tool EzGA1.

1 http://www.baryons.org/ezgal/
β

in our sample range from µinfrared SED at 1–3 power-law exponents of βrest-frame optical SED at 0.3–1 µ0 while the reddened QSO1 template has β3.

photometric catalogue for all 14 quasars is shown in Table 2. We now consider the mid infrared SEDs of all our spectroscopically confirmed reddened quasars in our sample, and compare them to standard templates of the Polletta et al. (2007) QSO1 template assuming ionisation of the highly compact starbursts with buried AGN, or quasars at z < 1.2, 1.75 < z < 2.00 or z > 2.8.

4 MID-INFRARED SEDS OF REDDENED BROAD-LINE QUASARS

We now consider the mid infrared SEDs of all our spectroscopically confirmed reddened quasars including those selected from the UKIDSS-LAS in B12. In Figure 2 we show the SEDs of all 14 spectroscopically confirmed reddened quasars in our sample, and compare them to standard templates from Polletta et al. (2007), including a reddened version of the Polletta et al. (2007) QSO1 template assuming E(B−V) = 0.8 and an SMC-like extinction curve. The SEDs are all normalised to a value of 1 at 1 µm, the well known inflection point in the quasar SED (Elvis et al. 1994). The full photometric catalogue for all 14 quasars is shown in Table 3.

We fit two power-laws of the form νFν ∝ νβ to the rest-frame optical SED at 0.3–1 µm as well as the rest-frame infrared SED at 1–3 µm. The QSO1 template has βopt = 0.68 and βNIR = −0.55. Mrk231 has optical and infrared power-law exponents of βopt = −0.91 and βNIR = −0.77, while the reddened QSO1 template has βopt = −2.27 and βNIR = −1.26. The rest-frame optical power law exponents in our sample range from −6 to −0.4 with a median of βopt = −1.47, considerably steeper than the standard QSO1 template. The different values of βopt reflect the different dust extinction values in our sample of reddened quasars. The median value of βNIR in our sample is −0.54, consistent with the standard QSO1 template. The infrared slope is therefore not particularly sensitive to dust extinction. Some quasars have steeper infrared slopes consistent with the Mrk231 and reddened QSO1 templates.

The well-known minimum in the quasar SED at ~1 µm (Elvis et al. 1994) is clearly seen in the rest-frame SEDs, and these observations demonstrate the importance of this feature on the rest-frame NIR colours. At redshifts of ~0.5 where the 2MASS survey has found significant numbers of red quasars (Glikman et al. 2007), this minimum falls in the J-band therefore making the (J − K) colours of the quasars red irrespective of the amount of dust.

In Figure 4 we also compare the WISE flux densities of our reddened quasars to the recently discovered Hyperluminous Infrared Galaxy (HyLIRG), WISE1814+3412 (Eisenhardt et al. 2012) at a similar redshift (z = 2.452). Our quasars are considerably bluer in terms of their W2-W3/W4 colours but the median 12 µm flux density is 1.46 mJy comparable to 1.86 mJy in the case of WISE1814+3412. Two of our most highly reddened quasars ULASJ1234+0907 and ULASJ1539+0557 (B12) at z = 2.503 and z = 2.658, also have observed 22 µm flux densities of >10 mJy, comparable to this very luminous HyLIRG. These reddened Type 1 quasars are therefore among the most mid-infrared luminous sources at z ~ 2, now being discovered using the WISE All Sky Survey.

5 CONCLUSIONS

We have presented results from a search for reddened broad-line quasars using data from the new infrared VISTA Hemisphere Survey and WISE All Sky Survey. We spectroscopically confirm two new reddened quasars in the VHS at z~2 over an area of 180 deg2. The quasars have broad lines, large bolometric luminosities and black-hole masses, and dust ex-

Figure 2. NIR spectra of our two confirmed dusty broad-line quasars at z~2 from VHS+WISE. The region of low atmospheric transmission between the H– and K-bands is shown as the shaded rectangular area. Vertical lines mark the expected positions of emission lines - in order of increasing wavelength - Hβ (4861Å), [OII] 4959Å, 5007Å and Hα (6563Å).
Table 3. AB Magnitudes in the UKIDSS Y J HK and WISE 3.4, 4.6, 12 and 22µm bands for all reddened quasars, along with errors on these magnitudes. The full table is published in the online version of this paper.

| Name             | Y     | J     | H     | K     | 3.4µm | 4.6µm | 12µm | 22µm |
|------------------|-------|-------|-------|-------|-------|-------|------|------|
| ULASJ1234+0907   | 26.38±0.84 | 22.38±0.29 | 20.37±0.21 | 18.05±0.03 | 17.20±0.03 | 16.28±0.04 | 14.34±0.04 | 13.90±0.17 |
| ULASJ1539+0557   | 21.75±0.36 | 21.02±0.20 | 19.18±0.08 | 17.74±0.02 | 16.85±0.03 | 16.23±0.03 | 14.27±0.03 | 13.18±0.06 |

Figure 3. Normalised SEDs in terms of \( \nu F_\nu \), of all our reddened quasars corrected to the rest-frame and compared to standard SED templates from Polletta et al. (2007). All SEDs have been normalised to a flux density of 1 at 1µm.

Figure 4. Rest-frame SEDs of our reddened quasars compared to the newly discovered hyperluminous infrared galaxy WISE 1814+3412 (\( z = 2.452 \)) from Eisenhardt et al. (2012). Our reddened quasars have comparable W3 fluxes to this HyLIRG at similar redshifts, with two of our most highly reddened sources also showing comparable W4 flux densities.

ACKNOWLEDGEMENTS

We thank the referee for useful comments. MB, RGM and PCH acknowledge support from the STFC funded Galaxy Formation and Evolution programme at the Institute of Astronomy. Based on observations obtained as part of the VISTA Hemisphere Survey, ESO Program, 179.A-2010 (PI: McMahon) and observations obtained at the Gemini Observatory: GN-2012A-Q-86 (PI:Banerji).

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