Probing the epoch of reionization with high redshift quasars from VISTA and LSST

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Also https://github.com/richardgmcmahon/count_quasars forked from https://github.com/dhroth/count_quasars
Site choice:

Cerro Paranal (ESO) or Cerro Pachon (Gemini)
VISTA primary mirror delivered to VISTA telescope; April 2008

The VISTA Mirror

4.1 m diameter f/1 primary

ESO Press Photo 10c/08 (16 April 2008)

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Quasars and AGN with z>6.5

• Scientific motivation and background

• Foreground challenges and uncertainties in forecasts

• Need for BOTH LSST and near infra red imaging data (VISTA, Euclid) at both the catalogue and the image pixel level

• How we are getting ready (Raphael Shirley talk)
Scientific Motivation

- Epoch of Recombination: $z=1100$
- First stars “PopIII”: $z=30-20$
- Epoch of Reionization: $z=15-6$
- Epoch of peak galaxy and quasar activity: $z=2$

Cambridge 2023 March 27
Where are the Baryons?

90% of Baryons are a metal enriched in ionized Intergalactic or Circumgalactic medium, Shull+2013; Fukugita+1998

How do we detect them directly?
Redshift $z = 0.158$
$m(V) = 12.5$ [Vega, AB]
$m(K) = 9.8, 10.9$ [Vega, AB]

20th brightest source in 3CR radio catalogue
10 million stars are brighter in optical

Absolute Magnitude: $B = -27.5$
Black hole mass: $1.5 \times 10^9$ Solar Masses


20" (500 kpc)

ACS • HRC

Quasar 3C 273
Hubble Space Telescope • ACS HRC Coronagraph
Evolution of HI: 3C273 spectrum from HST/FOC $z=0$; $z=3.6$ QSO HIRES/Keck spectrum from M. Rauch (both are radio selected)
Heavy elements and HI neutral fraction

Figure 1. A high signal-to-noise spectrum of the quasar ULAS J1319+0959 at $z = 6.13$ from Becker et al. (2015), obtained with the X-Shooter spectrograph on the Very Large Telescope (VLT). The spectrum has been rebinned to 1.5 Å per pixel for presentation purposes.

The HI Neutral fraction of the IGM can be inferred in various ways.
High-z Quasars (HzQ) selection challenges

• Dropout: HzQ, flux blueward of the Ly$\alpha$ (1216 Angstroms) emission-line absorbed by neutral Hydrogen

• At $z = 6.5$, $\lambda_{\text{obs, Ly}\alpha} \sim 0.9\mu m$

• HzQ are rare

• Candidates are contaminated by artefacts (image and catalogue junk) and

• Gaussian scatter of foreground LT dwarfs (similar optical colours to HzQ but much more abundant)

• Morphologically misclassified foreground galaxies
Nuisance foreground objects: L and T Galactic stars
(20 Jupiter masses; interesting for other reasons)

- Very red spectrum rising in optical;
- Redder than M-star in optical

- Near IR Broad band colours are ‘blue’
- Similar to A star photometrically in JHK
- Spectrum is heavily absorbed in near IR
- Spectrum similar to Jupiter; water and Methane

Spectra from Stern et al, 2007
QSO model: E(B-V)=0.0, z=6.5

QSO model: E(B-V)=0.0, z=7.5
Visible and Infrared Survey Telescope for Astronomy (VISTA)

VISTA summary

- **Location**: ESO, Paranal, Chile
- **Aperture**: 4.2 m diameter f/1 primary
- **Field of view**: 1.65 degree diameter
- **Instrumentation**: VIRCAM — 8k x 8k mosaic near-infrared camera
- **Detectors**: 16 x 2k x 2k pixel (Raytheon VIRGO HgCdTe); 67 megapixels
- **Wavelength range**: 0.84–2.5 microns
- **Pixel scale**: 0.34 arcseconds/pixel

- **Surveys started**: March 2010
  Science Verification Oct 2009– Feb 2010

Sparse filled mosaic 90% x 42% spacing
VISTA Survey Coverage

Observing dates: 20091015 - 20220801
Cambridge Astronomy Survey Unit
# VISTA Large (>100deg²) Area ESO Public Surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg²)</th>
<th>5σ point source depth (AB mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td><strong>VISTA Hemisphere Survey</strong></td>
<td>18,000</td>
<td></td>
</tr>
<tr>
<td>1. VHS-DES</td>
<td>4500</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>60 secs per band</td>
<td></td>
</tr>
<tr>
<td>2. VHS ATLAS</td>
<td>5000</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>60 secs per band</td>
<td></td>
</tr>
<tr>
<td>3. VHS-GPS (5° &lt;</td>
<td>b</td>
<td>&lt; 30°)</td>
</tr>
<tr>
<td></td>
<td>60 secs per band</td>
<td></td>
</tr>
<tr>
<td><strong>VIKING</strong></td>
<td>1,500</td>
<td>23.1</td>
</tr>
<tr>
<td><strong>VVV (Galactic Centre)</strong></td>
<td>520</td>
<td>22.4</td>
</tr>
<tr>
<td><strong>VMC (Magellanic Clouds)</strong></td>
<td>184</td>
<td>23.3</td>
</tr>
</tbody>
</table>

VHS time allocation: initially 500+ nights on VISTA over 7 years: started 2010; finished 2022
LSST forecasts

• LSST Commissioning Phase Mini-Survey
• LSST Year 1 of 10 observations
Forecast for LSST Year 1 (15,000 deg$^2$)

- LSST $\gamma$ Y1 5σ depth (23.64mag)
  - $N(z>6.0) = 2800$
  - $N(z>6.5) = 700$
  - $N(z>7.0) = 55$
  - $N(z>7.5) = 0$

- VISTA J VHS–ATLAS 5σ depth (20.70mag)
  - $N(z>6.0) = 136$
  - $N(z>6.5) = 40$
  - $N(z>7.0) = 12$
  - $N(z>7.5) = 3$
VISTA: VEILS + VIDEO: 20deg$^2$
centred on 3 LSST Deep Drilling Fields
Banerji, Hoenig, Sullivan, Jarvis +

\begin{itemize}
  \item N(z>6.0) = 13
  \item N(z>6.5) = 3.9
  \item N(z>7.0) = 1.0
  \item N(z>7.5) = 0.2
\end{itemize}
Summary

• LSST will transform the study of the high redshift Universe as traced by quasars in the redshift range 6.0 to 7.5
  • Near IR photometry from VISTA will be essential for efficient rejection of foreground low mass galactic stars

• Pixel level combination of LSST and near IR data from VISTA will be essential at z > 6.5 quasar selection and ‘reliable’ photometric classification prior to spectroscopy to confirm classification
  • Spectroscopic follow-up of only a subset possible
  • LSST from Year 2 onwards may help by adding variability since luminous AGN vary by 0.1mags rms on “rest-frame year” timescale
  • LSST limits on lack of proper motion could be a useful (Gaia not useful since z>6 quasars are not detectable in Gaia wavebands)

• Euclid will be deeper in near IR flux but expectations for z>8 are low in medium term since footprint growth rate is 3000 deg² per year.
EXTRA SLIDES
Example Selection Method:

- classical colour based preselection on DES + VISTA catalogues;
  - J band limit for z>6.5 sample selection;
  - J < 21.0
- Probabilistic SED based classification with listdriven forced flux based photometry on DES (g, r, i) and WISE (W1, W2) to go below catalogue limits (Reed, et al. 2017)