BSc in Physics

XSHOOTER spectroscopy of red quasars

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Abstract

In continuation of the previous discovery and investigation of the bias against red quasars, this bachelor project presents a study of 24 dusty quasar candidates. The reader is provided with an overview of relevant knowledge gained from other papers on the topic, before it introduces and explains the new target selection method used to choose these candidates from photometry. Furthermore, the project presents spectroscopic data gained with the X-shooter instrument and new software created to determine redshifts, equivalent widths, and column densities of HI absorption lines with associated errors from Monte Carlo simulation. This leads the project to the discovery of 10 DLAs and sub-DLAs, which via a Voigt fitting procedure are characterised with metallicities of iron, silicon, chromium and zink. In the light of a hidden component analysis, the project continues to discuss the validity of the resulting relative abundances and depletion curves. This allows the project to provide some positive evidence of similar behaviour in the ISM of DLAs and the dust in the ISM of Galactic absorbers.
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Introduction

A bias, a tendency, or simply just an error. It goes by many names, but none of them are pleasant in a scientific context. Independent of the name, it is hard to evade, and observational astrophysics provides illustrative examples of just that. In this subcategory of astrophysics, it has long been known that optically selected, flux-limited surveys feature an indisputable bias, known as the Malmquist bias [Malmquist, 1936]. This bias arises from the flux-limit, which prefers brighter, possibly more distant objects over dimmed and possibly closer objects. Hence, most of the neutral, dim gas at high redshift is practically invisible, and the process of gaining more knowledge on the evolution of the first stars and galaxies is complicated.

A powerful method to observe the distant, early galaxies is in form of absorption lines on spectra of very bright and even more distant objects. The quasars (QSOs) are a class of such objects. Even though the QSOs themselves are interesting targets, this bachelor project only describes them as background light sources in QSO absorption line systems. These systems are divided into subcategories based on the column density of neutral hydrogen in the foreground absorber, which will be discussed in more detail in Chapter 2. The category of highest column density ($N_{HI} \geq 10^{20.3}$ cm$^{-2}$, e.g. Wolfe et al., 1986), called Damped Lyman-α Absorbers (DLAs), consists almost entirely of neutral hydrogen and helium, but some metal pollution is also observed. Certain metals tend to deplete onto dust grains, which lowers their observed abundances in the gas phase and reveals that dust is present in the DLA [De Cia et al., 2016]. Given that it has been found that metallicity and optical extinction from dust correlates [Zafar and Watson, 2013], the net effect is that the dust bias favours lower metallicity DLA. In other words, it is expected that the current knowledge on the chemical evolution of the early universe is biased against high metallicity.

This bachelor project continues the work of previous studies (See Krogager et al., 2017 for a consensus report) on interpreting the consequences of re-
ducing the bias via use of a new target selection method [Heintz, 2019]. In Chapter 3, this method is described and used to find 24 dusty quasar candidates, which might include foreground absorbers. The data is reduced in Chapter 4, before the results are presented and analysed in Chapter 5, where it is also revealed that 7 out of these candidates contain DLAs and associated metal absorption lines. Therefore, the second half of Chapter 5 presents and analyses these systems in detail. Chapter 6 discusses the sources of error in the previous analysis, takes other studies of similar systems into account, and analyses how consistent the results of this project are with them. Finally, Chapter 7 contains the overall conclusion.
Quasar absorption line systems

Besides finding the reddened QSOs, which will be described in Chapter 3, it is essential to know the source of the reddening of the spectrum. This chapter provides the reader with an overview of the underlying knowledge that has already been gathered on this topic by previous papers and projects.

2.1 Spectroscopic classification

When looking into the distant, early universe, a very bright light source is needed. Often, QSOs provide just that, which makes it necessary to recognise these objects. Typically, the procedure is to examine the spectrum to check if it includes certain lines and then fitting a template to the observed spectrum via adding artificial extinction to the template. Based on data from 718 individual spectra observed in the Large Bright Quasar Survey [Francis et al., 1991], the most prominent emission lines in QSOs are Ly-\( \alpha \) \( \lambda \) 1216 Å, CIV \( \lambda \) 1549 Å, CIII \( \lambda \) 1909 Å and MgII \( \lambda \) 2798 Å. Hence, these are the lines this project uses to recognise QSOs. It is already known that the most widely used QSO template [Vanden Berk et al., 2001] is highly effected by host galaxy contamination, which makes it impossible to fit both the blue and the red part of the spectrum to dust-reddened QSOs as shown by Fynbo et al., 2013. Therefore, this project makes use of a new template. The new template is based on a selection of bright QSOs at high redshift and created by Selsing, J. et al., 2016. Via the use of bright QSOs, the relative effect of the contamination from the host galaxy is reduced and hence the template improved for the purpose of this project. The effect is also supported by their selection of QSOs covering from Ly\( \beta \) to H\( \alpha \), which allows the continuum on both sides of the Ly\( \alpha \) emission line to be properly fitted.
2.2 Damped Absorbers

As mentioned in the introduction, Lyman-\(\alpha\) absorption systems are divided into categories depending on their column density of neutral hydrogen, but also on the detection of metal absorption lines in their spectra. In this context, all elements heavier than hydrogen and helium are referred to as metals. Essentially, there are then two cases. If no metal lines are detected, it has long been known that the absorption system is of intergalactic origin at high redshift [Sargent et al., 1980]. This project focuses on the case where metal lines are detected. Here, observations are often divided into three subcategories defined by their column density of neutral hydrogen, as previously mentioned. The column density is defined as the total number of atoms the line-of-sight has encountered per surface unit and following the steps taken in Petitjean, 1998, this relation can be expressed as:

\[
\tau(\lambda) = 1.498 \cdot 10^{-2} \cdot \frac{Nf\lambda}{b} H(a, u)
\]

(2.1)

In this equation, \(b\) is the Doppler parameter, \(f\) is the oscillator strength, \(\tau(\lambda)\) the optical depth as a function of wavelength, and \(H(a, u)\) is the so-called Voigt function in the terms used by Petitjean, 1998. This function is a convolution of a Gaussian and a Lorentzian, which will be put into further use in Section 4.3. For now, it is sufficient to state that the column density hence indicates how many of the atoms in the absorber are neutral.

For the purpose of this project a column density of \(N_{HI}>10^{19}\) cm\(^{-2}\) is needed, because this implies that most of the hydrogen gas in the system is neutral. These kind of systems are often called sub-DLAs (e.g. Péroux et al., 2001) and characterised by observation of damped wings on the Lyman-\(\alpha\) absorption line. If the column density is \(N_{HI}>10^{20.3}\) cm\(^{-2}\), the system is no longer a sub-DLA but an actual DLA [Wolfe et al., 1986]. The sub-DLAs have column densities similar to the outskirts of local spiral galaxies, while the DLAs correspond to environments similar to more central regions in local spirals [Srianand and Petitjean, 1998]. Hence, it is assumed that both sub-DLAs and DLAs reveal galactic disks at high redshifts [Wolfe et al., 1986], but while DLAs are believed to be the outskirts of galaxies, sub-DLAs represents line-of-sights that are closer to the centrum. To justify why this project focuses on the sub-DLAs and DLAs rather than systems of lower column densities, the results of
recent measurements of the density parameter of DLAs are included. Based on column density distributions, it has been shown that $\Omega_{DLA} = 10^{-3}$ at redshifts $3.5 > z > 2$ [Noterdaeme, P. et al., 2009]. This density parameter is similar to the ones for baryons in present-day stars [Pérez-Ràfols, 2018], which leads to the hypothesis that DLAs are the main reservoirs for star formation in early galaxies and hence a crucial component in the process of understanding galaxy evolution.
As mentioned in the introduction, the current surveys of quasar absorption systems are biased against metal-rich absorbers due to the selection method. Since this is already known, new target selection methods are being developed. One of these has proved very efficient toward high Galactic latitudes and will be described in greater detail.

### 3.1 Target selection method

The data used in this project has been found via a new set of selection cuts. These cuts are based on a promising and relatively new target selection method [Heintz, 2019], but does not use the principle of zero proper motion. Instead, data from three different surveys has been collected.

![Figure 3.1:](image)

**Figure 3.1.:** The response per input photon for each of the filters used in the three different surveys. The four broad-band filters (u, g, r, and i) are from KiDS, the intermediate filters (Z, Y, J, H, and Ks) are from VIKING, and the outermost red filters (W1, W2, W3, and W4) are from WISE.

The first one is the Kilo-Degree Survey (KiDS), which is hosted at the Very Large Telescope Survey Telescope (VST) with four broad-band filters (u, g, r,
and i on Figure 3.1). In combination with the survey from the Visible and Infrared Survey Telescope for Astronomy (VISTA), called the VISTA Kilo-Degree Infrared Galaxy Survey (VIKING), another five filters (Z, Y, J, H, and K, on Figure 3.1) are added. The last of the three included surveys is the AllWISE Images Atlas based on the Wide-field Infrared Survey Explorer (WISE) mission, which contributes with yet another four bands (W1, W2, W3, and W4 on Figure 3.1). In other words, the selection method is purely based on photometry and hence so are the selection cuts. The method consists of five different cuts:

1. It is required that the apparent magnitude of the object in the u-filter $u$ and the apparent magnitude in the g-filter $g$ are related by $u - g > 1$, because the method aim to detect high redshift QSOs with $z > 2$ as background light sources. To see why this criterion corresponds to just that, it should be noted that the broad and characteristic QSO Ly-$\alpha$ emission line at $\lambda \sim 1216$ Å will be redshifted to $\lambda \gtrsim 3648$ Å, which is just about the limit between the u- and the g-filter. When the Ly-$\alpha$ emission is shifted from the u-filter to the g-filter, it corresponds to an increased flux in the g-filter, which is equal to a decrease in the apparent magnitude of this filter. Hence, the relation selects the desired QSO candidates.

2. It is required that the apparent magnitude of the object in the r-filter $r$ and the apparent magnitude in the Z-filter $Z$ are related by $r - Z > 0.5$ in order to select the dust-reddened sources. It has long been known that DLAs contain dust [Pei et al., 1991], but the composition of the dust grains are still a subject of further investigations. In order to explain the criterion and for the sake of simplicity, this project will assume the scattering theory proposed by Mie [Carroll and Ostlie, 2017], where all dust grains are spherical with a radius $a$ and hence a geometrical cross section $\sigma_g = \pi a^2$. If the wavelength of the emitted light $\lambda$ is in the same order of magnitude as the dust grains, Mie scattering says that $\sigma_g \propto a^3/\lambda$. Hence, the flux in the r-filter will be smaller compared to the flux in the Z-filter, if the background QSO is reddened by dust. Remembering that smaller flux equals larger apparent magnitude, this criterion selects the desired QSO candidates.

3. It is required that the apparent magnitude of the object in the W1-filter $W1$ and the apparent magnitude in the W2-filter $W2$ are related by $0.6 < W1 - W2 < 1.2$. The lower limit is determined from the median
WISE colour of Active Galactic Nuclei (AGN) in the sample of 4509 AGNs and 38092 Seyfert galaxies presented in Nikutta et al., 2014. Referring to their Table 1, it is seen how the lower limit excludes stellar contamination, also from star forming regions. Yet, this limit still includes some of the high-redshift QSOs [Stern et al., 2012]. The upper limit is determined from the median WISE colour of QSOs in the Nikutta et al., 2014 sample of 14795 QSOs. Thus, this criterion removes stellar contamination, while maintaining some of the high-redshift QSOs selected from the other criteria.

4. It is required that the apparent magnitude of the object in the W2-filter $W_2$ and the apparent magnitude in the W3-filter $W_3$ are related by $2.2 < W_2 - W_3 < 4.2$. These limitations are also due to the attempt to exclude stellar contamination as presented in Table 1 in Nikutta et al., 2014.

5. It is required that the apparent magnitude of the object in the J-filter $J$ and the apparent magnitude in the K-filter $K$ are related by $J - K > 0$, because Krogager et al., 2016 observed a significant amount of stellar contamination, even after introducing the criteria above. Further, they observed that most of the contamination had $J - K < 0$, which will then be deselected with the above-mentioned relation.

Figure 3.2.: Galactic coordinates of the 24 QSO candidates (black dots) and of the SGP (red dots). The coordinates for the SGP are from the SAO Encyclopedia provided by Swinburne University of Technology.
With these five criteria, 24 dusty QSO candidates were selected from the surveys. They are marked on Figure 3.2 with black dots, while the South Galactic Pole (SGP) is marked with a red dot.

3.2 Facilities

The subsequent spectroscopy of the candidates was made with the X-shooter instrument on the Very Large Telescope (VLT) at ESO Paranal Observatory in Chile [Vernet, J. et al., 2011]. With its broad range on wavelength going from 3000-25000 Å, X-shooter is a well-suited spectrograph for observing QSOs and their broad range of emission. The ability to do multi-wavelength on X-shooter is constructed by three spectroscopic arms: UVB in the range 3000-5595 Å, VIS in the range 5595-10240 Å, and NIR in the range 10240-24800 Å. When it was first put to action in 2009, it was the most sensitive instrument of its kind, and hence observation time on X-shooter is still in great demand. As a result, the data for this project has been observed as a ‘filler’ program. A filler program consists of relatively bright targets that can be observed even with bad seeing. Furthermore, the observing time must not exceed an hour in order to ensure that the actual timetable for the night is followed. As a consequence of this, these observations have been conducted throughout the summer and autumn of 2019 under suboptimal conditions.
When observations with X-shooter are performed, a whole set of calibration files are conducted as well in order to account for the noise from the charge-coupled device (CCD). The CCD is a semi-conductor device meaning that unlike its predecessor, the photographic film, the CCD has linear response. One photon simply equals one electron, but the capture of photons is not 100% efficient. Hence, the calibration files consist of bias frames, dark frames, and flat-fields to compensate for this.

4.1 Calibration

The bias frame is a 0 s exposure of the CCD, while the CCD is not exposed to any light. Hence, the outcome is solely the read noise from the pixel-to-pixel structure of the CCD, which allows the observer to estimate the signal to noise ratio (S/N). Besides the effects from the CCD efficiency, the motions of the atoms in the material of the CCD will also cause charge depositions, just like the ones from photons. The procedure to account for this 'dark current' is to record dark frames, which essentially is the same thing as the exposure of the target itself, except for the fact that the shutter is kept closed. Most importantly, dark frames must be conducted with the exact same exposure time and CCD temperature as the target frames to ensure the same amount of thermal noise.

On top of this is the fact that the deviation from total linear response is not even across the CCD. This is mainly coursed by two effects. First, the quantum efficiency of each pixel is not the same. Every pixel on the CCD are very similar in size, varying at about 15 to 25 microns from one CCD to another, but common to all is that it is about the magnitude where quantum effects are no longer neglectable. Even if this were not the case, there would still be variations due to the second and more macroscopic source of error. This error arises from the optics of the telescope that may be disturbed by dust.
on the CCD or caused by vignetting. Hence, a flat field is often conducted on the twilight sky or inside the telescope dome to ensure an even distribution of light so that the variations merely reflects these two sources of errors [Sparke and Gallagher, 2019].

When these effects of the CCD are taken into account, wavelength calibrations and relative flux calibrations are made. On X-shooter, this is done via an internal calibration unit equipped with different lamps, for which the wavelength and flux are known. All data, including both science, flat, bias, dark and calibration frames, from the described observations with X-Shooter has been collected via the ESO User Portal. For the time being, the standard way of reducing the frames is via the instrument specific ESO pipeline, but a new open source spectroscopic data reduction software based on python is gaining grounds with its improved techniques [Eilers et al., 2020]. The software is called PypeIt [Prochaska et al., 2019] and will be used in this project.

4.2 PypeIt

Released in October last year, this software is designed to provide an adjustable, easy way to reduce spectroscopic data taken with a list of served instruments, including X-Shooter at VLT. It requires the user to provide the calibration frames and the science frames, whereafter it produces a setup file. Before the file is run end-to-end, the user need to comment out the frametypes that are not recognized by the software. Considerable time was spend testing PypIt during this project, but unfortunately PypeIt still suffers from some teething troubles, which is why the reductions used for further analysis in this project are kindly provided by Kasper E. Heintz.

4.3 Measurements

Given that python is generally more used to write software for astrophysics [Momcheva and Tollerud, 2015], I have for this project developed a python-based software for determining redshifts $z$, equivalent widths $w$ of QSO absorption lines ($w > 0$) and QSO emission lines ($w < 0$) as well as column densities of HI absorption lines $N_{HI}$ in QAL systems. The scripts are gathered
under the joint name pyzar and can be found on GitHub*. When running the
main.py file, the user is presented with three options: Lines and equivalent
widths, Redshift determination from lines or Column density and extinction.

If the user chooses to do Lines and equivalent widths, the script requires
more information on the specific choice of reduction tool. So far, only reduced
spectra from either the ESO pipeline or PypeIt are supported. The script then
calls the relevant LoadData.py file, which includes an interactive and user-
friendly function that allows the files from the reduction to be chosen from
a list. For the ESO pipeline files, the files must be in fits format including
either the ultraviolet (UVB), the visual (VIS) or the near-infrared (NIR) 1D
spectrum and the original header from the pipeline reduction. If the user
has chosen a PypeIt reduction, the files must also be divided into UVB, VIS
and NIR but should be in dat or txt format. It should be noted that from
a standard reduction with either of the reduction tools, the output files will
satisfy these criteria just like that. The function saves the loaded spectra in
python’s dictionary format including indications of telluric lines as a zip-file,
before it returns the combined spectrum. Next, the spectrum, consisting of
matching wavelengths, fluxes and error bars on the fluxes, is given as input
parameter to the EQW.py file. Using a pyspeckit class called Spectrum, the
script displays a scaleable plot of the spectrum and requires the user to select
wavelength intervals for the continuum and the line fitting. This is done in
order to determine the observed equivalent width \( w_{\text{obs}} \) defined as in Petitjean,
1998:

\[
w_{\text{obs}} = \int \frac{I_c - I}{I_c} d\lambda
\]

(4.1)

In this equation, \( I \) is the observed spectral intensity, which is given from
the loaded spectrum, and \( I_c \) is the interpolation of the original continuum over the
absorption line as defined by the pyspeckit baseline-function. The intervals
for the continuum interpolation must be defined for each line area individually,
because of pyspeckit’s problem handling several lines at once. Furthermore, it
is important that as much absorption-free continuum as possible is included in
the baseline interpolation for the best result of the numerical integration. This
process returns a .png-file for the user to inspect, exemplified by Figure 4.1 on
the following page. The black line is the loaded spectrum from eKVRQ0302-
3032, one of the dusty QSO candidates, saved as the Spectrum class, while
the red line shows the combined result from the baseline fit, noted as \( b1 \) in

*https://github.com/svejlgaard/pyzar
the upper left corner, and the Voigt profile fit, noted with four characteristic constants on the centre right part of the figure. Here, $A(0)$ is the maximum deviation from the baseline flux, $\Delta x(0)$ is the centre of the absorption line fit, $\sigma_G$ is the variance of the Gaussian part, and $\sigma_L$ is the variance of the Lorentzian part. In this specific example, the best fit does not include the wing-effect from the Lorentzian distribution, which means that the fitting procedure does not include an uncertainty on $\sigma_L$. The blue area shows the FWHM of the line profile, where the equivalent width will be calculated. Via Monte-Carlo simulations of this procedure, the centrum of the measured line and equivalent width are both returned with error bars of $1\sigma$ in a \texttt{EQUX} table, which is returned as a file in \texttt{txt} format.

**Figure 4.1.** The returned .\text{png}-file from the \texttt{EQW.py} routine. The black line is the loaded spectrum from eKVRQ0302-3032, while the red line is the combined result from the baseline fit (called b1 on this figure) and the Voigt profile fit (represented by the four constants on the centre right part of this figure). The blue area shows the FWHM of the line profile, where the equivalent will be calculated.

Choosing *Redshift determination from lines* requires that the user via a similar interactive function provides a \texttt{EQUX} table, similar to the one returned from \texttt{EQW.py} with four columns: An empty column, the centrum of the measured line with error, the equivalent width with error and another empty column. The main script then runs the \texttt{Restframe.py} file, where a list of likely QSO absorption lines and characteristic QSO emission lines based on the NIST database [Kramida and Fuhr, 2020] is provided. Next, the user must insert
an approximate value of the redshift of the given system. It is important to note that the QSO and any potential foreground absorber must be treated separately in this function. Via user-provided estimates of the origin of the measured lines, the function returns a new version of the $\text{H}_\text{I}$ $\text{X}$ table, in which three columns are included: Name and wavelength of line, equivalent width in the rest frame $w_{\text{rest}} = w_{\text{obs}}/(1 + z_{\text{sys}})$ and redshift $z_{\text{sys}}$. All values are returned with error estimates from the Monte-Carlo simulation.

If a foreground absorber is detected, the user can choose to determine Column density and extinction. The user must now again chose to (re)load either an ESO pipeline reduction or a PypeIt reduction. Provided with the redshift of the quasar as well as the number and redshifts of DLAs, the main file runs the ColumnExtinction.py file, which by use of a SciPy function called curve_fit fits a Voigt profile to the spectrum. This Voigt profile, defined as $H(a,x)$, is based on the analytical approximation to the Voigt-Hjerting function as presented by García [García, 2006] in his erratum. To optimize this fitting procedure for the extinction, the ColumnExtinction function cuts out the area between the SIV and MgII QSO emission lines, where there is typically less noise and absorption on the continuum. For the optimization of the column density fit, the area around the foreground absorber HI line is also selected. Furthermore, the fitting is performed with an initial guess for the column densities, while the extinction is determined. It is decided to do so and not the other way around, because it produces a better fit parameter for the column densities. The function then returns a figure with the spectrum, the non-reddened fit and the reddened fit as well as the fit parameter values and their errors.

### 4.4 VoigtFit

In order to fit the metal lines of absorption systems, another python-based software is used. The program is called VoigtFit and is created by Krogager, 2018†. The program is based on a parameter file template that must provide the program information about the system, including the redshift of the foreground absorber and the velocity components of the detected lines. Once this is done, the program opens an interactive window, where the user can

---

†https://github.com/jkrogager/VoigtFit
mask regions not to be included in the following Chebyshev Polynomial fitting procedure. Via these fits, the program estimates the curve of growth (COG). The COG is the relation between the equivalent width $w$ of a line and its column density $N$ at a given value of the Doppler parameter $b$ as mentioned in Section 2.2 [Petitjean, 1998]. Furthermore, it is characterised by three prominent regions with different dependencies of $b$. The optically thin line region corresponds to low values of $N$, where the COG is linear and independent of $b$. Here, the Gaussian part of the Voigt profile with its core is responsible for the growth in $w$. The interpretation of this behaviour is that the increased amount of atoms generates a higher random motion and hence a higher temperature in the absorbing gas. In the other end of the COG, the saturated line region with larger values of $N$ is also linear and independent of $b$. These lines are however very optically thick, and hence it is no longer broadened by the Gaussian core of the Voigt profile, but by the wings from the Lorentzian part. In terms of the physical interpretation, the increased amount of atoms is now contributing to the pressure of the absorbing gas. In between these two regions is the third region, where the lines are saturated but not yet to a degree, where the Lorentzian part strongly dominates. This region induces a well known source of error that will be discussed in Section 6.3.

Including the estimated values from the COG, the output from VoigtFit consists of several different files, of which three are relevant to this project. The .cont-file includes the Chebyshev Polynomial coefficients, which is used to calculate the Doppler parameter $b$ and the column density $N$ in the .fit-file. The last relevant file is the .pdf-file, which includes a plot of the spectrum and the fit.
Results

Based on the use of the criteria described in Section 3.1 and the tools described in Chapter 4, the following chapter will present what is learned from the observations. In the table below, an overview is presented, while the individual fits are presented in Appendix A.

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>Redshift</th>
<th>$A_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>eHAQ1407+0140</td>
<td>BAL QSO</td>
<td>3.748 ± 0.001</td>
<td>0.635 ± 0.005</td>
</tr>
<tr>
<td>eHAQ1447+0008</td>
<td>QSO</td>
<td>0.541 ± 0.001</td>
<td>2.59 ± 0.03</td>
</tr>
<tr>
<td>eHAQ1450-0207</td>
<td>QSO</td>
<td>1.32 ± 0.01</td>
<td>0.513 ± 0.004</td>
</tr>
<tr>
<td>RQ0007-3223</td>
<td>QSO + DLA</td>
<td>3.658 ± 0.007</td>
<td>0.000 ± 0.005</td>
</tr>
<tr>
<td>RQ2328-3231</td>
<td>QSO + DLA</td>
<td>3.5836 ± 0.0002</td>
<td>0.00 ± 0.05</td>
</tr>
<tr>
<td>RQ0214-3246</td>
<td>BAL QSO</td>
<td>1.728 ± 0.001</td>
<td>∼ 0.1^*</td>
</tr>
<tr>
<td>RQ0239-3314</td>
<td>BAL QSO</td>
<td>3.158 ± 0.004</td>
<td>∼ 0.4^*</td>
</tr>
<tr>
<td>RQ0302-3032</td>
<td>QSO + ass. DLA</td>
<td>2.769 ± 0.005</td>
<td>0.582 ± 0.003</td>
</tr>
<tr>
<td>RQ0317-3348</td>
<td>QSO</td>
<td>2.782 ± 0.002</td>
<td>0.930 ± 0.005</td>
</tr>
<tr>
<td>RQ2237-3419</td>
<td>QSO + DLA</td>
<td>2.462 ± 0.003</td>
<td>0.669 ± 0.003</td>
</tr>
<tr>
<td>RQ2243-2951</td>
<td>QSO + DLA</td>
<td>3.441 ± 0.003</td>
<td>0.25 ± 0.04</td>
</tr>
<tr>
<td>RQ2243-3228</td>
<td>QSO + DLA</td>
<td>2.286 ± 0.004</td>
<td>0.522 ± 0.002</td>
</tr>
<tr>
<td>RQ2244-3111</td>
<td>QSO</td>
<td>1.54 ± 0.05</td>
<td>0.487 ± 0.002</td>
</tr>
<tr>
<td>RQ2244-3210</td>
<td>QSO</td>
<td>1.054 ± 0.004</td>
<td>0.99 ± 0.02</td>
</tr>
<tr>
<td>RQ2245-2945</td>
<td>QSO + ass. abs.</td>
<td>2.376 ± 0.003</td>
<td>0.638 ± 0.003</td>
</tr>
<tr>
<td>RQ2254-3419</td>
<td>QSO + DLA x 3</td>
<td>2.639 ± 0.002</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>RQ2258-3045</td>
<td>QSO</td>
<td>1.385 ± 0.002</td>
<td>0.80 ± 0.01</td>
</tr>
<tr>
<td>RQ2305-3015</td>
<td>QSO</td>
<td>2.5473 ± 0.0005</td>
<td>0.301 ± 0.003</td>
</tr>
<tr>
<td>RQ2305-3428</td>
<td>QSO</td>
<td>2.81 ± 0.08</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>RQ2309-2949</td>
<td>BAL QSO</td>
<td>2.283 ± 0.006</td>
<td>0.600 ± 0.002</td>
</tr>
<tr>
<td>RQ2309-3005</td>
<td>QSO</td>
<td>2.983 ± 0.006</td>
<td>0.201 ± 0.001</td>
</tr>
<tr>
<td>RQ2321-3120</td>
<td>QSO</td>
<td>0.579 ± 0.006</td>
<td>∼ 0.5^*</td>
</tr>
<tr>
<td>RQ2323-3250</td>
<td>BAL QSO</td>
<td>2.831 ± 0.003</td>
<td>0.351 ± 0.004</td>
</tr>
<tr>
<td>RQ2352-3103</td>
<td>QSO + DLA</td>
<td>3.07 ± 0.03</td>
<td>0.250 ± 0.003</td>
</tr>
</tbody>
</table>

^*See Notes on individual objects
5.1 Notes on individual objects

eHAQ1407+0140

This is a broad absorption line (BAL) QSO, which is a sub-class of QSOs with very strong outflows causing P-cygni-like absorption on the blue side of the emission lines from the QSO. There are no prominent features in the UVB, but in the VIS a broad emission line is detected along with three BALs in the NIR part of the spectrum. Based on the interpretation of the lines as C \textsc{iii}, Ly-\(\alpha\), C \textsc{iv}, and Mg \textsc{ii} respectively, this QSO has a weighted redshift average \( z = 3.748 \pm 0.001 \). It is well-described with a dust-reddening corresponding to \( A_V = 0.635 \pm 0.005 \) from the Selsing template.

eHAQ1447+0008

This is a QSO. It is faint in the UVB, but bright in the VIS and the NIR, where it shows five emission lines interpreted from the shortest to the highest wavelength as H-\(\beta\), the O \textsc{iii} doublet, and H-\(\alpha\). This interpretation yields a weighted redshift average \( z = 0.541 \pm 0.001 \). The Selsing template suits the spectrum well with a dust-reddening of \( A_V = 2.59 \pm 0.03 \), which makes this QSO the most dust obscured in this sample.

eHAQ1450-0207

This is a QSO with a weak continuum in the UVB and the VIS and two bright emission lines in the NIR. The weighted redshift average \( z = 1.32 \pm 0.01 \) is determined from the interpretation of the lines as H-\(\beta\) and H-\(\alpha\). With the Selsing template, a dust-reddening of \( A_V = 0.513 \pm 0.004 \) is needed in order to fit the spectrum.
This spectrum contains a QSO and an absorption system. Characterised by a bright continuum with emission lines in the VIS and in the NIR from Ly-\(\alpha\), Si IV, C IV, C III, and Mg II, the QSO has a weighted redshift average \(z = 3.658 \pm 0.007\). For the Selsing template to fit the spectrum, no extinction from dust is needed within an 1 \(\sigma\) uncertainty of 0.005 magnitudes. Furthermore, several metal lines and a broad, winged Ly-\(\alpha\) absorption line are interpreted as a single sub-DLA with weighted redshift average \(z = 2.818 \pm 0.008\) and column density \(N_{HI} = 10^{20.19 \pm 0.04}\) cm\(^{-2}\). This absorption system will be investigated further.

This is the clearest spectrum in the sample. It contains a QSO and an absorption system, both with many clear features. Based on Ly-\(\alpha\), C IV, and C III in the VIS, the QSO has a weighted redshift average \(z = 3.5836 \pm 0.0002\), while several metal absorption lines and a winged Ly-\(\alpha\) absorption line are interpreted as a single sub-DLA with weighted redshift average \(z = 3.0804 \pm 0.0003\) and column density \(N_{HI} = 10^{19.303 \pm 0.001}\) cm\(^{-2}\). The characteristics of this sub-DLA will be investigated further. The system does not need dust-reddening within an 1 \(\sigma\) uncertainty of 0.05 magnitudes to fit the Selsing template.

This is a BAL QSO with a narrow Ly-\(\alpha\) emission line. A clear continuum throughout all three filters are seen, while the BAL lines primarily are detected in the UVB. Based on C III and H-\(\alpha\), the weighted redshift average is \(z = 1.728 \pm 0.001\). In the UVB, it should also be noticed that the flux dive and hence the extinction is too steep to be fitted by the Selsing template. This indicates that the QSO is dust-reddened by dust grains of another composition. Given that the overestimation of the flux is in the blue part of the spectrum, this observation suggests that the dust grains are smaller than assumed by the template used in this project. The fitted value of the dust extinction \(A_V \sim 0.1\) should therefore be interpreted as a rough estimate.
RQ023-3314

This spectrum shows a BAL QSO with a Lyman-$\alpha$ forest that is not well described by the Selsing template. This might be due to outflows from the QSO itself. Based on emission lines in the VIS from Ly-$\alpha$, C $\text{IV}$, and C $\text{III}$ the weighted redshift average is $z = 3.158 \pm 0.004$. Similar to RQ0124-3246, the dust-reddening of $A_V \sim 0.4$ should only be seen as a rough estimate.

RQ0302-3032

This spectrum consist of a QSO and an associated sub-DLA. With its strong metal lines, the spectrum differs significantly from the other spectra in this sample. The weighted redshift average of the QSO $z = 2.769 \pm 0.005$ is based on Ly-$\alpha$ emission in the UVB as well as C $\text{IV}$ and C $\text{III}$ emission in the VIS. The associated sub-DLA includes many different metal absorption lines and Ly-$\alpha$ at weighted redshift average $z = 2.742 \pm 0.002$. A dust-reddening of $A_V = 0.582 \pm 0.003$ and column density of $N_{HI} = 10^{20.2 \pm 0.1}$ cm$^{-2}$ yields the best fit to the Selsing template.

RQ0317-3348

This spectrum is very poor. As mentioned in Section 3.2, the spectra are conducted via a filler program, so it is expected that some of the spectra will be very affected by this. Hence, not much information can be extracted from this spectrum, and the best estimate of the redshift is determined by use of the template as well. From fitting the template to the Ly-$\alpha$ line, the redshift is $z = 2.782 \pm 0.002$ and the dust-reddening is $A_V = 0.930 \pm 0.005$.

RQ2237-3419

This spectrum shows a clear continuum from a QSO throughout the spectrum and absorption from a single foreground object. In the UVB, a weak Ly-$\alpha$ emission line as well as a clear C $\text{IV}$ emission line is detected, while the VIS
shows C III and Mg II and the NIR H-α. On this basis, the weighted redshift average is \( z = 2.462 \pm 0.003 \) with a dust-reddening of \( A_V = 0.669 \pm 0.003 \) from the Selsing template fit. Furthermore, the UVB includes a broadened and winged Ly-α absorption line with a column density of \( N_{HI} = 10^{20.6 \pm 0.2} \) cm\(^{-2}\). Along with several metal absorption lines, this provides a weighted redshift average \( z = 2.324 \pm 0.006 \) of the DLA, and it will be investigated further.

**RQ2243-2951**

This is a QSO with a foreground absorption system. Based on Ly-α in the UVB, C IV and C III in the VIS, and H-γ in the NIR, the weighted redshift average is \( z = 3.441 \pm 0.003 \). The foreground absorber is classified as a DLA based on Ly-α and several metal absorption lines as well as its column density \( N_{HI} = 10^{20.3 \pm 0.2} \) cm\(^{-2}\). The DLA's weighted redshift average is \( z = 2.632 \pm 0.006 \). The best template fit returns a dust extinction value \( A_V = 0.25 \pm 0.4 \). Further investigations of this object will follow.

**RQ2243-3228**

This spectrum reveals a QSO and a foreground absorber. In the UVB, Ly-α and C IV emission is observed, while the NIR shows H-β, O III, and H-α. From this interpretation of the emission lines and the Selsing template fit, the redshift of the QSO is \( z = 2.2864 \pm 0.004 \) with a dust extinction of \( A_V = 0.522 \pm 0.002 \). The foreground absorber is classified as a sub-DLA with column density \( N_{HI} = 10^{19.8 \pm 0.6} \) cm\(^{-2}\), but the signal is very weak, where the Ly-α absorption line would be. This makes the fitting procedure more difficult and the outcome less descriptive. Despite this, the sub-DLA will be investigated further.

**RQ2244-3111**

This is a QSO. It has a bright emission line in the NIR and a weak emission line in the UVB, which are interpreted as H-α and C III. Along with some associated metal absorption lines, the weighted redshift average is \( z = 1.54 \pm 0.05 \). The
Selsing template fits the spectrum with a dust-reddening of $A_V = 0.487 \pm 0.002$.

**RQ2244-3210**

This is a QSO. It has two bright emission lines in the NIR, interpreted as O $\text{III}$ and H-α, as well as a weak emission line in the UVB, interpreted as C $\text{III}$. With this interpretation, the weighted redshift average is $z = 1.054 \pm 0.004$ and $A_V = 0.99 \pm 0.02$ from the template fitting procedure.

**RQ2245-2945**

This is a rich QSO spectrum with associated absorption, meaning that there is absorption at the redshift of the QSO. It is quiet a puzzling case, because there is an emission line source next to the trace, which can be seen in the NIR spectrum. However, this project will not go into further details on this, but only interpret the QSO emission lines. These are Ly-α and O $\text{III}$, which means that the weighted redshift average is $z = 2.376 \pm 0.003$. From the Selsing template, the extinction from dust is $A_V = 0.638 \pm 0.003$, but this estimate may be affected by the light from the nearby source.

**RQ2254-3419**

This is a QSO with three foreground absorption systems. The QSO itself has a clear continuum throughout the whole wavelength band with several recognisable, bright emission lines. Based on Ly-α, C $\text{IV}$, C $\text{III}$, and O $\text{III}$, the weighted average redshift is $z = 2.639 \pm 0.002$ without dust-reddening within a 1 $\sigma$ uncertainty of 0.01 magnitude. The lowest Ly-α absorption line is a broadened and winged line with column density $N_{HI} = 10^{20.42\pm0.07}$ cm$^{-2}$ from a DLA at weighted redshift average $z = 1.816 \pm 0.004$. It has several associated metal lines, which is also the case for the second lowest Ly-α absorption line. This line is also broadened, but does not have the same extension of its wings. From the template fitting, it has a column density of $N_{HI} = 10^{20.3\pm0.6}$ cm$^{-2}$ and weighted redshift average $z = 2.530 \pm 0.001$. The highest Ly-α absorption line is also broadened and winged with column density $N_{HI} = 10^{19.91\pm0.03}$ cm$^{-2}$.
and based on its metal absorption lines interpreted as $z = 2.562 \pm 0.001$. This system with its many foreground absorbers will be investigated and discussed further.

**RQ2258-3045**

This is a QSO with a significantly dust-reddened spectrum. It shows a strong emission line in the NIR and two strong absorption lines in the VIS, which are interpreted as respectively H-$\alpha$ and the Mg II doublet. This makes the weighted redshift average $z = 1.385 \pm 0.002$ and the Selsing template fitted dust-reddening $A_V = 0.80 \pm 0.01$.

**RQ2305-3015**

This is a bright QSO without any evident metal lines. It has two clear emission lines, which are interpreted as H-$\alpha$ in the NIR and Ly-$\alpha$ in the UVB. Based on these lines, the weighted redshift average is $z = 2.5473 \pm 0.0005$ and the best fit to the Selsing template requires a dust-reddening of $A_V = 0.301 \pm 0.003$.

**RQ2305-3428**

This QSO is weak in the VIS, but clear in the NIR. It shows two clear emission lines in the UVB, which are interpreted as Ly-$\alpha$ and N V. This leads to a weighted redshift average is $z = 2.81 \pm 0.08$ and a dust-reddening of $A_V = 0.94 \pm 0.04$.

**RQ2309-2949**

This is a BAL QSO with a very bright H-$\alpha$ in the NIR. Furthermore, the emission lines in the VIS are interpreted as Mg II and C III, while the BAL lines in the UVB are interpreted as C IV, Si IV, and Ly-$\alpha$. Based on these lines, the
weighted redshift average is \( z = 2.283 \pm 0.006 \), and from the template fitting
the extinction from dust is \( A_V = 0.600 \pm 0.002 \).

**RQ2309-3005**

This is a very noisy QSO spectrum with some weak metal lines and some
very weak quasar lines. Based on Ly-\( \alpha \), the weighted redshift average is
\( z = 2.983 \pm 0.006 \) with dust-reddening \( A_V = 0.201 \pm 0.001 \).

**RQ2321-3120**

Similar to RQ0214-3246 and RQ+239-3314, this QSO has a very steep extinc-
tion in the UVB continuum. Because the assumed extinction curve is poorly
applicable, the dust-reddening from the Selsing template fitting of \( A_V \sim 0.5 \)
should only be seen as a rough estimate. It has bright lines in the NIR and in
the VIS, which are interpreted as H-\( \beta \) and H-\( \alpha \). This yields a weighted redshift
average \( z = 0.579 \pm 0.006 \).

**RQ2323-3250**

This is a BAL QSO with its characteristic lines in both the UVB and the VIS.
The ones in the UVB are interpreted as Ly-\( \alpha \) and N v, while the one in the
VIS is interpreted as C iv. With these lines, the weighted redshift average
\( z = 2.831 \pm 0.003 \) and dust-reddening \( A_V = 0.351 \pm 0.004 \).

**RQ2352-3103**

This is a QSO with a foreground absorption system including very strong metal
lines. Based on three of the characteristic QSO emission lines, Ly-\( \alpha \), C iv, and
Si iv, the weighted redshift average is \( z = 3.07 \pm 0.03 \) with dust-reddening of
\( A_V = 0.250 \pm 0.003 \). The foreground object has a broadened and winged Ly-\( \alpha \)
absorption line of column density \( N_{HI} = 10^{21.0 \pm 0.03} \) cm\(^{-2} \), which categorises
it as a DLA. This line and the additional metal lines has a weighted redshift average $z = 2.168 \pm 0.005$. Because of its DLA, this target will be investigated further.
### 5.2 Absorption systems

Based on the analysis of each spectrum, the following targets are selected for further analysis and summarized in the table below:

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>$z_{sys}$</th>
<th>log($N_{sys}$)</th>
<th>[Fe/H]</th>
<th>[Si/H]</th>
<th>[Cr/H]</th>
<th>[Zn/H]</th>
<th>b (km/s)</th>
<th>X</th>
<th>log($N_X$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ0007-3223</td>
<td>sub-DLA</td>
<td>2.818 ± 0.008</td>
<td>20.19 ± 0.04</td>
<td>-0.16 ± 0.04</td>
<td>-0.31 ± 0.03</td>
<td>-0.49 ± 0.04</td>
<td>-0.13 ± 0.05</td>
<td>70 ± 15</td>
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<tr>
<td>RQ2328-3231</td>
<td>sub-DLA</td>
<td>3.0804 ± 0.0003</td>
<td>19.303 ± 0.001</td>
<td>-0.48 ± 0.04</td>
<td>-1.44 ± 0.03</td>
<td>-0.71 ± 0.01</td>
<td>-0.11 ± 0.05</td>
<td>38 ± 12</td>
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<tr>
<td>RQ2237-3419</td>
<td>DLA</td>
<td>2.324 ± 0.006</td>
<td>20.6 ± 0.2</td>
<td>-1.8 ± 0.3</td>
<td>-0.7 ± 0.1</td>
<td>-1.57 ± 0.08</td>
<td>-0.16 ± 0.06</td>
<td>18.1 ± 0.4</td>
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<tr>
<td>RQ2243-2951</td>
<td>DLA</td>
<td>2.632 ± 0.006</td>
<td>20.3 ± 0.2</td>
<td>-0.19 ± 0.04</td>
<td>-0.4 ± 0.1</td>
<td>-0.31 ± 0.05</td>
<td>-0.43 ± 0.02</td>
<td>12 ± 7</td>
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<tr>
<td>RQ2243-3228</td>
<td>sub-DLA</td>
<td>1.799 ± 0.002</td>
<td>19.8 ± 0.6</td>
<td>-0.8 ± 0.3</td>
<td>-0.61 ± 0.09</td>
<td>-0.7 ± 0.5</td>
<td>-0.88 ± 0.04</td>
<td>46.4 ± 0.6</td>
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*Notes: X denotes different elements measured.*
<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Fe</th>
<th>Si</th>
<th>Cr</th>
<th>Zn</th>
<th>20 ± 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ2254-3419 (a) DLA</td>
<td>1.816 ± 0.004</td>
<td>20.42 ± 0.07</td>
<td>-1.19 ± 0.04</td>
<td>-0.78 ± 0.03</td>
<td>-0.83 ± 0.05</td>
<td>-0.37 ± 0.03</td>
</tr>
<tr>
<td>RQ2254-3419 (b) DLA</td>
<td>2.530 ± 0.001</td>
<td>20.3 ± 0.6</td>
<td>-1.3 ± 0.1</td>
<td>-0.4 ± 0.1</td>
<td>-0.9 ± 0.2</td>
<td>-0.21 ± 0.08</td>
</tr>
<tr>
<td>RQ2254-3419 (c) sub-DLA</td>
<td>2.562 ± 0.001</td>
<td>19.91 ± 0.03</td>
<td>-0.84 ± 0.04</td>
<td>-0.45 ± 0.03</td>
<td>-1.26 ± 0.04</td>
<td>-0.23 ± 0.06</td>
</tr>
<tr>
<td>RQ2352-3103 DLA</td>
<td>2.168 ± 0.005</td>
<td>21.0 ± 0.3</td>
<td>-1.5 ± 0.1</td>
<td>-</td>
<td>-1.46 ± 0.08</td>
<td>-0.4 ± 0.1</td>
</tr>
<tr>
<td>RQ0302-3032 sub-DLA</td>
<td>2.742 ± 0.002</td>
<td>20.2 ± 0.1</td>
<td>-1.06 ± 0.04</td>
<td>-0.44 ± 0.03</td>
<td>-1.64 ± 0.04</td>
<td>-0.29 ± 0.01</td>
</tr>
</tbody>
</table>
5.3 Notes on individual DLAs

RQ0007-3223

This sub-DLA has two high column density velocity components and one less dominant component based on the results from the Voigt fit. Inferred from the metal absorption lines listed in the table on Figure 5.1, the weighted redshift average is $z=2.818 \pm 0.008$. Despite a considerable amount of noise around the Cr II and Zn II lines, these lines are still statistically significant, while both the Fe II and Si II lines are clear indicators of high metallicity. The resulting metallicity values based on the Voigt fit are $[\text{Fe/H}]=-0.16 \pm 0.04$, $[\text{Si/H}]=-0.31 \pm 0.03$, $[\text{Cr/H}]=-0.49 \pm 0.04$, and $[\text{Zn/H}]=-0.13 \pm 0.05$. However, these values should only be taken as lower bounds given the high velocity components, which will be explored further in Chapter 6. The same applies to the metallicities presented for the other DLAs. Another thing that applies to the other DLAs as well as this one is the fact that the spread on redshift seems too large. Even when the error bars on individual lines are taken into account, it is still statistically significant and hence calls for further discussion. This will be provided in Section 6.2.

<table>
<thead>
<tr>
<th>Transition</th>
<th>EW, [Å]</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe II λ 1144</td>
<td>1.3 ± 0.1</td>
<td>2.8399 ± 0.0003</td>
</tr>
<tr>
<td>P II λ 1152</td>
<td>2.0 ± 0.1</td>
<td>2.8275 ± 0.0002</td>
</tr>
<tr>
<td>Si II λ 1304</td>
<td>1.75 ± 0.06</td>
<td>2.8100 ± 0.0003</td>
</tr>
<tr>
<td>Cu II λ 1358</td>
<td>2.7 ± 0.1</td>
<td>2.8334 ± 0.0002</td>
</tr>
<tr>
<td>Si II λ 1526</td>
<td>0.56 ± 0.07</td>
<td>2.82 ± 0.03</td>
</tr>
<tr>
<td>Fe II λ 1611</td>
<td>0.5 ± 0.1</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.26 ± 0.06</td>
<td>2.82 ± 0.04</td>
</tr>
<tr>
<td>Cr II λ 2056</td>
<td>0.18 ± 0.04</td>
<td>2.82 ± 0.08</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.2 ± 0.1</td>
<td>2.83 ± 0.03</td>
</tr>
<tr>
<td>Mg I λ 2852</td>
<td>5 ± 3</td>
<td>2.83 ± 0.05</td>
</tr>
<tr>
<td>Fe I λ 3021</td>
<td>2.4 ± 0.8</td>
<td>2.754 ± 0.0003</td>
</tr>
</tbody>
</table>

Figure 5.1.: On the left is a velocity plots of lines found in RQ0007-3223 that are commonly used for characterising and comparing DLAs. Remarkably broad Fe II line and Si II line. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.
This sub-DLA has several velocity components according to the Voigt fit, but might include even more different components, given that the fit does not provide a satisfactory description of the absorption lines, e.g. Fe II seen on Figure 5.2. On the right of this figure, the redshift measurements of the metal absorption lines are listed and based on those, the weighted redshift average is z = 3.0804 ± 0.0003. The Si II lines are relatively small compared to the other Si II lines in this survey, which results in a lower metallicity. From the Voigt fit, it is [Si/H] = -1.44 ± 0.03, while [Fe/H] = -0.48 ± 0.04, [Cr/H] = -0.71 ± 0.01, and [Zn/H] = -0.11 ± 0.05.

<table>
<thead>
<tr>
<th>Transition</th>
<th>EW, [Å]</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV λ 1403</td>
<td>0.52 ± 0.03</td>
<td>3.1114 ± 0.0004</td>
</tr>
<tr>
<td>Ni II λ 1454</td>
<td>0.12 ± 0.02</td>
<td>3.0900 ± 0.0006</td>
</tr>
<tr>
<td>Si II λ 1526</td>
<td>0.51 ± 0.03</td>
<td>3.054 ± 0.001</td>
</tr>
<tr>
<td>Fe II λ 1611</td>
<td>0.26 ± 0.02</td>
<td>3.082 ± 0.001</td>
</tr>
<tr>
<td>Ni II λ 1741</td>
<td>0.642 ± 0.007</td>
<td>3.0392 ± 0.0008</td>
</tr>
<tr>
<td>Si II λ 1808</td>
<td>0.13 ± 0.01</td>
<td>3.0420 ± 0.0003</td>
</tr>
<tr>
<td>Fe I λ 1934</td>
<td>0.06 ± 0.02</td>
<td>3.056 ± 0.001</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2026</td>
<td>0.20 ± 0.01</td>
<td>3.0635 ± 0.0002</td>
</tr>
<tr>
<td>Cr II λ 2056</td>
<td>0.25 ± 0.02</td>
<td>3.06 ± 0.06</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.33 ± 0.03</td>
<td>3.10 ± 0.02</td>
</tr>
<tr>
<td>Fe II λ 2344</td>
<td>2.73 ± 0.06</td>
<td>3.057 ± 0.003</td>
</tr>
<tr>
<td>Fe II λ 2374</td>
<td>1.38 ± 0.04</td>
<td>3.094 ± 0.009</td>
</tr>
<tr>
<td>Mg II λ 2796</td>
<td>2.1 ± 0.2</td>
<td>3.0731 ± 0.0005</td>
</tr>
<tr>
<td>Mg II λ 2803</td>
<td>1.07 ± 0.05</td>
<td>3.0140 ± 0.0002</td>
</tr>
</tbody>
</table>

Figure 5.2.: On the left is a velocity plots of lines found in RQ2328-3231 that are commonly used for characterising and comparing DLAs. The fit (red line) does not provide an adequate description of the Feii 2344 line. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

RQ2237-3419

This DLA has two prominent velocity components based on the results from the Voigt fit. From Figure 5.3, it is seen that absorption lines from Cr II are almost untraceable and hence consistent with the low fit value of [Cr/H] = -1.57 ± 0.08. The Fe II lines also result in a low fit value of [Fe/H] = -1.8 ± 0.3, while the remaining lines induce [Si/H] = -0.7 ± 0.1 and [Zn/H] = -0.16 ± 0.06. From the measurement of redshift via the metal absorption lines, the weighted redshift average of this DLA is z = 2.324 ± 0.006.
Figure 5.3.: On the left is a velocity plots of lines found in RQ2237-3419 that are commonly used for characterising and comparing DLAs. The Cr II lines are almost untraceable, and the Fe II lines are relatively small. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

**RQ2243-2951**

This DLA has two velocity components based on the results from the Voigt fit. On Figure 5.4, these two components are clearly seen on the Fe II line plots as well as the Si II line plot, indicating sturdiness in the fit. Overall, this DLA has high metallicity with [Fe/H] = -0.19 ± 0.04, [Si/H] = -0.4 ± 0.1, [Cr/H] = -0.31 ± 0.05, and [Zn/H] = -0.43 ± 0.02. The absorption lines listed in the table result in a weighted redshift average of z = 2.632 ± 0.006.

<table>
<thead>
<tr>
<th>Transition</th>
<th>EW, [Å]</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni II λ 1454</td>
<td>7 ± 1</td>
<td>2.294 ± 0.009</td>
</tr>
<tr>
<td>Si II λ 1526</td>
<td>1.5 ± 0.1</td>
<td>2.354 ± 0.002</td>
</tr>
<tr>
<td>Fe II λ 1611</td>
<td>1.7 ± 0.2</td>
<td>2.306 ± 0.004</td>
</tr>
<tr>
<td>Ni II λ 1709</td>
<td>6 ± 1</td>
<td>2.359 ± 0.008</td>
</tr>
<tr>
<td>Si II λ 1808</td>
<td>0.6 ± 0.1</td>
<td>2.330 ± 0.005</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2026</td>
<td>0.62 ± 0.09</td>
<td>2.32 ± 0.09</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.20 ± 0.05</td>
<td>2.32 ± 0.01</td>
</tr>
<tr>
<td>Cr II λ 2066</td>
<td>0.25 ± 0.05</td>
<td>2.360 ± 0.004</td>
</tr>
<tr>
<td>Fe II λ 2344</td>
<td>1.8 ± 0.3</td>
<td>2.326 ± 0.004</td>
</tr>
<tr>
<td>Fe II λ 2374</td>
<td>1.3 ± 0.3</td>
<td>2.325 ± 0.007</td>
</tr>
<tr>
<td>Fe II λ 2382</td>
<td>1.7 ± 0.7</td>
<td>2.323 ± 0.002</td>
</tr>
<tr>
<td>Fe II λ 2586</td>
<td>1.4 ± 0.2</td>
<td>2.33 ± 0.04</td>
</tr>
<tr>
<td>Fe II λ 2600</td>
<td>1.9 ± 0.3</td>
<td>2.326 ± 0.008</td>
</tr>
</tbody>
</table>
Figure 5.4.: On the left are velocity plots of lines found in RQ2243-2951 that are commonly used for characterising and comparing DLAs. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

RQ2243-3228

This sub-DLA has two prominent velocity components based on the Voigt fitting procedure. Further, it has a noticeably broad Si II line, which results in [Si/H] = -0.61 ± 0.09. Given that the other lines result in [Fe/H] = -0.8 ± 0.3, [Cr/H] = -0.7 ± 0.5, and [Zn/H] = -0.88 ± 0.04, this is the highest metallicity for this DLA. On the basis of the lines presented in the table on Figure 5.5, the weighted redshift average is z = 1.799 ± 0.002.

Figure 5.5.: On the left are velocity plots of lines found in RQ2243-3228 that are commonly used for characterising and comparing DLAs. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.
This system contains three foreground absorbers. The absorber closest to the background QSO is a sub-DLA (c) and has three different velocity components according to the Voigt fit. On Figure 5.6, most of the Fe II lines are well described by the fit (red line), but some misalignments, e.g. on Fe II 1608, indicate underlying problems to be discussed in Chapter 6. From the Voigt fit, the metallicity is \([\text{Fe/H}] = -0.84 \pm 0.04, [\text{Si/H}] = -0.45 \pm 0.04, [\text{Cr/H}] = -1.26 \pm 0.04, \text{and } [\text{Zn/H}] = -0.23 \pm 0.06\). The metal absorption lines on the corresponding table is basis for the weighted redshift average \(z = 2.562 \pm 0.001\). Next is a DLA (b) with two different velocity components. This number of components is however conflicted by the fact that the Voigt fit (red line) does not completely describe the spectrum in a satisfactory way, e.g. the broad Si II 1260 line on Figure 5.7. Based on this fit, the metallicity is given as \([\text{Fe/H}] = -1.3 \pm 0.1, [\text{Si/H}] = -0.4 \pm 0.1, [\text{Cr/H}] = -0.9 \pm 0.2, \text{and } [\text{Zn/H}] = -0.21 \pm 0.08\). Inferred from the metal absorption lines on the figure below, the weighted redshift average of this DLA is \(2.530 \pm 0.001\).
The last DLA (a) in this spectrum has been fitted by the Voigt fitting procedure via three different velocity components. On this basis, the metallicity is given as \([\text{Fe/H}] = -1.19 \pm 0.04\), \([\text{Si/H}] = -0.78 \pm 0.03\), \([\text{Cr/H}] = -0.83 \pm 0.05\), and \([\text{Zn/H}] = -0.37 \pm 0.03\). The metal absorption lines in the table on Figure 5.8 result in a weighted redshift average of \(z = 1.816 \pm 0.004\).

### Table 5.1: Metal Absorption Lines and Equivalent Widths

<table>
<thead>
<tr>
<th>Transition</th>
<th>EW, [Å]</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si II λ 1260</td>
<td>2.5 ± 0.1</td>
<td>2.5211 ± 0.0002</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2026</td>
<td>0.23 ± 0.05</td>
<td>2.532 ± 0.004</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.29 ± 0.02</td>
<td>2.525 ± 0.008</td>
</tr>
<tr>
<td>Fe II λ 2249</td>
<td>1.36 ± 0.05</td>
<td>2.50 ± 0.01</td>
</tr>
<tr>
<td>Fe II λ 2374</td>
<td>0.69 ± 0.03</td>
<td>2.5382 ± 0.0003</td>
</tr>
<tr>
<td>Fe II λ 2382</td>
<td>2.42 ± 0.04</td>
<td>2.5256 ± 0.0007</td>
</tr>
<tr>
<td>Fe II λ 2600</td>
<td>0.28 ± 0.03</td>
<td>2.5300 ± 0.0001</td>
</tr>
<tr>
<td>Mg II λ 2796</td>
<td>2.36 ± 0.07</td>
<td>2.5392 ± 0.0005</td>
</tr>
<tr>
<td>Mg II λ 2803</td>
<td>1.93 ± 0.07</td>
<td>2.5389 ± 0.0007</td>
</tr>
</tbody>
</table>

#### Figure 5.7.
On the left are velocity plots of lines found in DLA (b) of RQ2254-3419 with \(z = 2.530 \pm 0.001\) that are commonly used for characterising and comparing DLAs. Here, the fit of the Si II reveals why the metallicity should only be seen as a lower bound. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

#### Figure 5.8.
On the left are velocity plots of lines found in DLA (a) of RQ2254-3419 with \(z = 1.816 \pm 0.004\) that are commonly used for characterising and comparing DLAs. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.
This DLA is described by four different velocity components according to the Voigt fit. With its broad metal lines seen on Figure 5.9, masking has been necessary to reduce the noise impact and impact from other lines, which will statistically be more distinct, when integrating over a larger wavelength interval. Contrary to all the other DLAs in this survey, no Si lines have been detected. The resulting values are [Fe/H] = -1.5 ± 0.1, [Cr/H] = 1.46 ± 0.08, and [Zn/H] = 0.4 ± 0.1. Based on the table of measured absorption lines, the weighted redshift average is $z = 2.168 ± 0.005$.

**Figure 5.9.** On the left are velocity plots of lines found in RQ2352-3103 that are commonly used for characterising and comparing DLAs. The light grey lines are masked part of the spectrum. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

### RQ0302-3032

This DLA is described by two velocity components according to the Voigt fit, but from Figure 5.10 it is seen that some lines are not well described by this fit, e.g. Si II 1304. Along with similar observations in the other DLAs of this project, this is a strong motivation for looking into more details of the fitting procedure. The resulting values from the fit are [Fe/H] = -1.06 ± 0.04, [Si/H] = -0.44 ± 0.03, [Cr/H] = -1.64 ± 0.04, and [Zn/H] = -0.29 ± 0.01. Inferred

<table>
<thead>
<tr>
<th>Transition</th>
<th>EW, [Å]</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al II λ 1670</td>
<td>2.66 ± 0.07</td>
<td>2.173 ± 0.005</td>
</tr>
<tr>
<td>Fe II λ 1611</td>
<td>2.20 ± 0.04</td>
<td>2.20 ± 0.01</td>
</tr>
<tr>
<td>Fe II λ 1608</td>
<td>1.37 ± 0.05</td>
<td>2.176 ± 0.004</td>
</tr>
<tr>
<td>Al II λ 1854</td>
<td>0.9 ± 0.1</td>
<td>2.1735 ± 0.0004</td>
</tr>
<tr>
<td>Cr II λ 2056</td>
<td>0.23 ± 0.06</td>
<td>2.174 ± 0.006</td>
</tr>
<tr>
<td>Cr II, Zn II λ 2062</td>
<td>0.37 ± 0.05</td>
<td>2.173 ± 0.005</td>
</tr>
<tr>
<td>Cr II λ 2066</td>
<td>0.16 ± 0.01</td>
<td>2.173 ± 0.007</td>
</tr>
<tr>
<td>Fe II λ 2344</td>
<td>2.44 ± 0.05</td>
<td>2.1733 ± 0.0003</td>
</tr>
<tr>
<td>Fe II λ 2374</td>
<td>1.49 ± 0.07</td>
<td>2.1730 ± 0.0005</td>
</tr>
<tr>
<td>Fe II λ 2382</td>
<td>2.02 ± 0.06</td>
<td>2.1733 ± 0.0003</td>
</tr>
<tr>
<td>Fe II λ 2586</td>
<td>2.51 ± 0.06</td>
<td>2.1742 ± 0.0003</td>
</tr>
<tr>
<td>Fe II λ 2600</td>
<td>3.11 ± 0.05</td>
<td>2.174 ± 0.0003</td>
</tr>
<tr>
<td>Mg II λ 2796</td>
<td>4.48 ± 0.08</td>
<td>2.1742 ± 0.0004</td>
</tr>
<tr>
<td>Mg II λ 2803</td>
<td>4.05 ± 0.07</td>
<td>2.1742 ± 0.0004</td>
</tr>
</tbody>
</table>

5.3 Notes on individual DLAs
from the metal absorption lines on the table in Figure 5.10, the weighted redshift average is $z = 2.742 \pm 0.002$.

![Figure 5.10](image)

**Figure 5.10:** On the left are velocity plots of lines found in RQ0302-3032 that are commonly used for characterising and comparing DLAs. The misalignment of fit from spectrum is revealing underlying problems. On the right, a list of the most prominent metal absorption features, their equivalent width and redshift.

### 5.4 Depletion

As mentioned in Chapter 2, sub-DLAs and DLAs are often linked to the regions in the outskirts of early galaxies. Therefore, it is relevant to compare the dust in these targets with known Galactic absorbers. A way of doing so is to compare the dust depletion of elements. Dust depletion is a process induced by the reactivity between elements and dust grains, which ties the elements to the dust grains in the solid-phase. Hence, the elements are removed from the gas-phase and no longer visible in the spectrum. Inspired by De Cia et al., 2016, this project uses [Zn/Fe] as a dust depletion tracer and investigates the expected similarities with the dust depletion in Galactic absorbers. Therefore, it should be noted that these results turns on the reliability of [Zn/Fe] as a dust depletion tracer. The reliability depends on two criteria: How well does the depletion of iron represent the total amount of dust and how well does iron and zink trace each other. This project will not go into further details of whether or not these criteria are satisfied, but illustrate this as another possible uncertainty and rely on the production of positive evidence made by De Cia, A. et al., 2013 throughout the presentation of results.
Figure 5.11: Relative abundances for all the DLAs in this survey are marked with different symbols and error bars, showing their value and error along both axes. The red lines show the results of linear fits with parameters $A_1 = -0.2 \pm 0.1$ and $B_1 = -1.0 \pm 0.2$ for Cr (top) and $A_1 = -0.08 \pm 0.08$ and $B_1 = -0.37 \pm 0.09$ for Si (bottom). The grey areas correspond to 2 $\sigma$ on the fit.

On Figure 5.11, the observed relative abundances of [Cr/Zn] and [Si/Zn] are plotted versus [Zn/Fe]. The errors are calculated via error propagation of the errors returned from the Voigt fitting procedure, while the red line shows a linear fit with slope $B_1$ and intersection $A_1$ to the data points, in which uncertainty along both axes are included. Around the red line is a grey area corresponding to 2 $\sigma$ on the fit parameters. [Cr/Zn] has slope $B_1 = -1.0 \pm 0.2$ and intersection $A_1 = -0.2 \pm 0.1$, while [Si/Zn] has slope $B_1 = -0.37 \pm 0.09$ and intersection $A_1 = -0.08 \pm 0.08$.

From here, it is of great interest to translate this into a measure of the depletion. To do so, this project uses the result of the derivations in the previously mentioned paper by De Cia et al., 2016, which is presented in their Equation 4:

$$\delta_X + \alpha_X = A_1 + B_1 \cdot [\text{Zn/Fe}] + B_{\delta_{\text{Zn}}} \cdot [\text{Zn/Fe}]$$

On the right hand side of the equation, $A_1$ and $B_1$ are defined as in this project, while $B_{\delta_{\text{Zn}}} = -0.27 \pm 0.03$ is the slope of the observed depletion of Zn in individual Galactic absorbers [Jenkins, 2009]. On the left hand side, $\delta_X$ is the depletion of element $X$, while $\alpha_X$ is a term to correct for nucleosynthetic over- or under-abundance. Under the assumed criteria for the quality of [Zn/Fe] as a dust depletion tracer, the correcting term corresponds to the intersection $B_1$ on Figure 5.11. The resulting values are described by another linear fit with slope $B_2$ and intersection $A_2$. For chromium, the data is described by $B_2 = $
Another suggestion from this analysis is that depletion depends on the element. To see why this is also expected to be the case, the electron configuration of chromium, silicon, and zink will be analysed briefly. Chromium has 24 electrons meaning that the first 18 electrons are distributed like the noble gas argon and the last 6 will for the sake of stability be divided into a half full 3d orbital and a half full 4s orbital [Fynbo, 2000]. Continuing to silicon, it has 14 electrons distributed with 10 electrons like in the noble gas neon and the last 4 divided into a full 3s orbital and a 3p orbital with 2 out of 6 possible electrons. Lastly, zink has 30 electrons, which are distributed so that the 18 first electrons resemble the noble gas argon and the remaining 12 fill up a 3d orbital and a 4s orbital. The result of this distribution is that zink characterises as strongly 'noble gas like'. To sum up, chromium has 6 less tightly bound electrons, where silicon only has 4 and zink has none. From a simplified chemical view, this supports the expectation of chromium being more reactive and hence more exposed to depletion than silicon, while zink should be closest to unaffected of these three.
Discussion

In this chapter, all the individual analyses of and results from the observed DLAs will be gathered in a unified comparison with current literature and papers on QAL systems.

6.1 Bias

As mentioned in the introduction, it is a well-known problem that previous selection methods have been sided against quasars hiding behind dusty foreground absorbers and hence against high metallicity absorption systems. Inspired by Figure 4 in the paper by Fynbo et al., 2017, this project will use Figure 6.1 to analyse the bias further. On Figure 6.1, the black contour lines are $2.5 < z < 3.5$ QSO $g - r$ versus $u - g$ and $J - K_s$ colour-colour distributions from the SDSS / Baryon Oscillation Spectroscopic Survey (BOSS) data release 12 as presented in Eisenstein et al., 2011, while the red and olive coloured stars are respectively cool dwarf colours and normal stars colours from Hewett et al., 2006. Furthermore, the small, brown dots are data from 150 High $A_V$ Quasar (HAQ) survey presented in Krogager et al., 2015, and the straight lines are reddening vectors for a QSO with $z = 3$, reddened by either the SMC, the LMC or the MW extinction curves as parametrized in Pei, 1992 at foreground absorber redshift of $z = 2.0$ for the light-blue lines and $z = 2.5$ for the orange lines. The diamonds marked on the lines correspond to $A_V$ of 0.5, 1.0, 1.5, and 2.0, innermost to the outermost. This project contributes to the plot with the red and blue dots. The blue dots are either normal quasars or quasars reddened by other means (Lyman-blanketting, dust in the host galaxy, etc.), while the red dots are systems reddened by DLAs or sub-DLAs.

From this contribution, several points can be deduced. First, it is seen that the data presented here confirms that the dusty quasars are shifted away from the QSO locus and towards the stellar track. In order words, this provide positive evidence to the existing suspicion of intervening absorbers effectively
disguising themselves and their background light source. It is also worth noticing the differences between the dust-reddened and the DLA-reddened objects. The second point is that the DLA-reddened objects seem to be more effected by this shift than the other reddened QSOs. Among these other QSOs, 11 out of 16 are no longer within the QSO locus or are no longer separable from the stellar track in the $g - r$ versus $u - g$ that is traditionally used. For the DLA-reddened objects, the same ratio is 6 out of 7. In continuation of this point, it should be noted that this might just reflect the different sample sizes of the two populations of objects. To support this suggestion, more data from both populations would be needed, which will be cumbersome taken into account the mentioned bias and the suggestion from Fynbo et al., 2017 that only a few percent of the reddening of QSO will be caused by a foreground DLA.

Figure 6.1.: A colour-colour plot with optical colour to the left and near-infrared to the right. On the $u - g$ plot, the stellar track (represented by the olive stars for normal stars and red stars for cool dwarfs) lies closer to the targets (represented by blue dots for dust-reddened QSOs and red dots for DLA-reddened QSOs) than the quasar locus (represented by the black lines). This problem is solved in the $J - K_s$ plot where the targets are clearly separated from the stars.
6.2 Redshift spread

Figure 6.1 assumes that the targets found via the selection cuts actually are individual DLAs or sub-DLAs. Has this project provided evidence for that? As noted in Section 5.3, the redshift spreads on all of the sub-DLAs and DLAs are larger than accounted for by the error bars. There might be several reasons to this, but the main one is very likely to be found in the data reduction.

When fitting the individual lines in a spectrum, pyzar and hence this project uses the pyspeckit fitting procedure as well as wavelength intervals provided by the user for the baseline fit and the line profile fit. To maintain a reasonable run time of the script as a whole, these wavelengths are only determined by the user once, after which the Monte Carlo simulation includes detecting the absorption line on the baseline fit. This procedure has one great disadvantage: Local minima. If the chi square function has several local minima over the provided baseline interval, it has no way of knowing, which one is the global. This is especially a likely problem for noisy data, and most of the data presented in this project includes noise. Hence, the fitting procedure can easily get overconfident, if it strikes the local minimum before the global minimum, which results in very small error bars on a value that might not be correct.

As a future solution to this problem, one could imagine implementing a controlled gradient descent where the fit is told to take several steps on the curve opposite to the gradient whenever it finds a minimum. This explorative optimization technique would depend less on the user provided start conditions for the fit and hence uncover more of the function. However given that this not yet implemented, it is expected that the error bars are underestimated, which contributes positively to the verification of the DLAs as individual systems.

6.3 Curve of growth

When these important kind of absorption systems are found and their spectroscopic data analysed, the next trouble in line turns up. As stressed by Prochaska, 2006, the conclusions regarding the column densities are very likely to be underestimated. To explain why this is the case and to motivate further error analysis, the intermediate region of the COG will be analysed. In
this region, the COG is flattened with a strong dependence of $b$. This difference in the conversion from $w$ to $N$ becomes a significant error, when several velocity components broaden the measured, effective value of $b$. When this is the case, an apparently saturated line will be treated in the Lorentzian region, even though it is actually on the flat part of the COG. As a consequence, the resulting value of $N$ will be too small. To analyse whether or not this effect has an impact on the results of this project, the following section contains a hidden component analysis (HCA).

### 6.4 Hidden component analysis

This HCA is executed as described by Prochaska and Wolfe, 1996, which consists of comparing the apparent column density per unit velocity $N_a(v)$ for several absorption lines for the same ion. If this comparison reveals that the stronger transition has a smaller value of $N_a(v)$, it indicates that a hidden component or hidden saturation is present. To gain a rough insight into whether or not this is the case for the results presented in this project, the Fe II absorption lines from RQ2352-3103 will be analysed. These lines are chosen, because Figure 5.9 shows that they seem to be optically thick. First, the apparent column density per unit velocity $N_a(v)$ is calculated via the definition presented in Prochaska and Wolfe, 1996:

$$N_a(v) = \frac{m_e c \tau_a(v)}{\pi e^2 f \lambda_{rest}}$$

(6.1)

Here $\tau_a = \ln(I_i(v)/I_a(v))$ is the apparent optical depth, $f$ is the oscillator strength, $\lambda_{rest}$ is the rest frame wavelength of the transition, while $I_i(v)$ and $I_a(v)$ are the intrinsic and measured intensity respectively. The result is presented on Figure 6.2. Based on the oscillator strengths presented in Table 3 in Prochaska and Wolfe, 1996, the transition from weakest to strongest are: Fe II 2374 with $f = 0.02818$, Fe II 2586 with $f = 0.0619$, Fe II 2344 with $f = 0.1097$, and Fe II 2382 with $f = 0.3006$. When comparing this to the measured values for $N_a(v)$, the order is exactly reversed almost all the way throughout the relevant velocity interval. Hence, Figure 6.2 provides positive evidence that there are hidden components present in these absorption lines and that the metallicity presented in Section 5.3 should accordingly be regarded as a lower
limit. If this result covers the rest of the survey presented here, which is most likely because of the observed line profiles, the same applies to the rest of the metallicity values. Therefore, it is of great interest to gain high resolution spectra of these targets and hence enable smaller velocity components to be resolved.

![Graph showing line profiles](image_url)

**Figure 6.2.** The result of the HCA of RQ2352-3103 based on Fe II 2374 with \( f = 0.02818 \), Fe II 2586 with \( f = 0.06119 \), Fe II 2344 with \( f = 0.1097 \), and Fe II 2382 with \( f = 0.3006 \). Because of the reverse relation between the oscillator strength and the apparent column density, this provides evidence for hidden components or hidden saturation.

Is it then only possible for these values to be underestimated? It has been stressed by Fynbo, 2000 that the condition of the hydrogen in a DLA is crucial to the accuracy of determining its metallicity. Two problems are pointed out. Say a significant amount of hydrogen is in molecular form, then this amount will practically be invisible on the spectrum. This is due to the symmetry of molecular hydrogen, meaning that it requires highly energetic collisions to ionize and hence molecular hydrogen reemits light in the ultraviolet region below 1000 Å. Practically, this region is impossible to reach for our sources because of dust and high redshifts. This causes the column density of hydrogen to be underestimated, which induces overestimation of the metallicity based on column density measurements of the metal in question. Detection of CO emission can indicate whether or not molecular hydrogen is significantly present. Second, one can imagine that a significant amount of hydrogen is already excited, meaning that it is ionized even before the photons from the background DLA interact with it. This will again result in an underestimation of
the column density of hydrogen and hence an overestimation of the metallicity as well as the dust-to-gas ratio. Referring to Howk and Sembach, 1999, the lowest column density DLAs and the sub-DLAs will be most effected by this.

6.5 Follow-up observations

Considering all the above mentioned sources of error, the uncertainties provided by the Monte Carlo error simulation are most likely too optimistic. By providing the reader with the discussed possibilities of gaining more conservative limits on the metallicity values, the results of this project should be read as a motivation to do follow-up observations on these targets with higher resolution in order to resolve what might be hidden in this data. Despite the uncertainties, the values of the slopes agree within $1\sigma$ with the slopes for Galactic absorbers [Jenkins, 2009], suggesting that the DLAs and Galactic absorbers have strong similarities in their ways of regulating dust production. In other words, the dust production seem to depend strongly on the amount of available metals. Further, the slope values for both $\delta_{Cr}$ and $\delta_{Si}$ agree within $1\sigma$ with the corresponding values from Galactic absorbers. This suggests similar behaviour in the dust grains in these absorbers and the DLAs.
Conclusion

As an attempt to address the currently existing bias against dusty QSOs and hence high metallicity DLAs, this project has studied 24 dusty QSOs candidates found via a new selection method based on photometry. Follow-up spectroscopy with X-shooter has been reduced via a new reduction software called PypeIt and kindly provided by Kasper E. Heintz. In the spirit of new selection cuts and new software, this project presents a new simple, python-based tool called pyzar and uses it to determine redshifts, equivalent widths, and column densities of HI absorption lines with associated errors from Monte Carlo simulations. The results of these measurements leads the project to detection of 10 DLAs and sub-DLAs, which are exposed to further analysis via the VoigtFit tool. From this fitting procedure, the velocity components and the related column densities of the metal absorption lines are determined. These values are used to determine the metallicity of iron, silicon, chromium, and zink for each DLA.

In the final chapter, the project presents a discussion of the results. It is confirmed on a colour-colour plot that the bulk of the QSO candidates are shifted onto the stellar track in the optical, while also noted that it seems to effect the DLA-reddened targets more than the ones reddened by other means. Via a hidden component analysis of the target RQ2352-3103, it is shown that hidden saturation is present in the spectrum and made probable that this might also be the case for the rest of the DLAs. If hidden saturation is present, this would explain the high values of the velocity parameter. Lastly, it is shown that the relative abundances of the DLAs in this project agree with the relative abundances of Galactic absorbers, which indicates that dust production depends on the amount of available metals. Given that the depletion fitting values agrees as well, it provides positive evidence that the ISM of DLAs behaves very similary to dust in the ISM in the Galactic absorbers.


eHAQ1407+0140

Observed wavelength [Å]
0.0
0.2
0.4
0.6
0.8
1.0

Flux [erg s⁻¹ cm⁻² Å⁻¹]
$10^{16}$

eHAQ1447+0008

Observed wavelength [Å]
0.0
0.2
0.4
0.6
0.8
1.0

Flux [erg s⁻¹ cm⁻² Å⁻¹]
$10^{16}$
Appendix A

Observed wavelength [Å]

Flux [erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\)]

1044 × 10\(^3\) 6 × 10\(^3\) 2 × 10\(^4\)

eKVRQ0239-3314

eKVRQ0302-3032

eKVRQ0317-3348
Appendix A
Observed wavelength [Å]
Flux [erg s\(^{-1}\) cm\(^{-1}\) Å\(^{-1}\)]

KV-RQ2328-3231