Studying the complex absorption profiles of Si IV in 21 HiBALQSO spectra

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Abstract. We investigate the physical conditions and kinematics of broad absorption line region clouds of Si IV in 21 HiBAL Quasars. We use the Danezis et al. method [1], [2], [3] in order to fit and analyze the broad absorption troughs of Si IV resonance lines in the UV region of the electromagnetic spectrum. We find that the BAL flow is not smooth but instead plasma clouds are formed in it. BAL troughs present multicomponent structure which indicates the existence of more than one absorbing cloud in the line of sight, where every absorbing cloud produces a Si IV doublet. We show that the blending of these doublets produces the apparent broad absorption troughs we observe. One of our main achievements is that we managed to decompose and deblend each complex absorption trough to the individual doublets that it consists of. Apart from that, we succeeded in deblending the resonance lines of every doublet. By achieving accurate fits to the BAL troughs we calculated some physical and kinematical parameters that describe the plasma clouds in the line of sight. These parameters are: the radial outflow velocities of the clouds, the random velocities of ions inside each plasma cloud, the apparent optical depth in the center of every absorption component, the FWHM and the equivalent width. As a final step we correlate these physical parameters in order to draw useful conclusions.

1. Introduction

Broad absorption line quasars (BALQSOs) are a subtype of QSOs, defined by the presence of broad and blue-shifted absorption features with typical velocities of 0.1c (e.g. [4]). The intrinsic fraction of BALQSOs from the total quasar population is estimated to be about 15-20% [5], [6] although this fraction rises to 17-23%, after correcting for optical/UV selection effects [7], [8]. High – ionization BAL quasars (HiBALQSOs) show absorption from C IV, N V, Si IV and Lyα (in order of decreasing typical strength (λ_{\text{vac}}> 1215 Å) and are classified by means of their UV C IV 1549 BAL profile.

Broad absorption line QSOs (BALQSOs) are a marvellous manifestation of outflows which are a fundamental characteristic of AGNs and are very commonly detected e.g. [9], [6], [10], [11], [12], [13], [14] and references therein. Observationally BAL quasars show troughs characterized by FWHM \sim 2000 – 20,000 km s^{-1} wide arising from resonance line absorption in gas with blueshifted (outflowing) velocities up to 66,000 km s^{-1} [15]. The structure of the absorption troughs ranges from...
apparently very smooth (P-Cygni like) troughs to multiple troughs which set in at very near zero outflow velocity [16], [17] and/or complexes of many individual absorption lines [18]. Usually these absorption features are of the P-Cygni type, although in some cases the absorption features are detached from the emission line by as much as 30,000 km s\(^{-1}\). The absorption in the majority of cases is at wavelengths shortward of line center, which indicates that the absorbing gas is flowing outward from the nucleus, and the high ionization level and high outflow velocities of the gas strongly suggest that these systems are closely associated with the nuclear regions (these lines are called intrinsic). However, there are cases that absorption is redshifted [19]. So, one of the difficulties in understanding the outflows (or inflows) revealed by absorption features in quasar spectra is their amazing diversity.

BALQSOs also present Narrow Absorption Lines (NALs) which have widths of several hundreds of km s\(^{-1}\) (FWHM < 2\(\times\)300 km s\(^{-1}\), [20]). A useful (but physically arbitrary) definition of NALs is that they are narrow enough not to blend important UV doublets, e.g., the CIV pair with separation ~ 500 km s\(^{-1}\). Thus we require FWHM < 200 to 300 km s\(^{-1}\). NALs with velocity shifts v < 5000 km s\(^{-1}\) from systemic are also called “associated” absorption lines (AALs) because of their plausible physical relationship to the AGN [10]. So narrow lines are separated into two subcategories: narrow lines far from the emission redshift \(z_a << z_e\) and narrow associated lines near the emission redshift \(z_a \approx z_e\). Narrow lines \(z_a << z_e\) which are due to gas clouds unrelated to the quasar that coincidentally fall along our line of sight to the quasar. On the other hand \(z_a \approx z_e\) systems could be either intervening or intrinsic. This means that these systems are due to gaseous regions within the host galaxy of the quasar or within a galaxy cluster which contains the quasar. These absorbers may not be ejected from the quasar, but are still affected by the quasar luminosity and environment.

However there are absorption lines with intermediate widths (FWHM ~ 300 – 2000 km s\(^{-1}\), [10]) which are called mini-BALs and are as common as BALs [21]. They appear at the same range of blueshifted velocities as the BALs, and they also clearly form in AGN outflows. Mini-BALs could represent a completely different type of absorber, or a particular line of sight through the same absorbers that we observe in other cases as BALs. Examples of high-velocity mini-BALs can be found in [22] and [23].

In this work we use the Danezis et al. method [1], [2], [3], which has been applied successfully to the spectra of hot emission stars, in order to deblend the observed complex features to their components and to calculate a number of physical parameters of the regions that create them. Here we study the absorption lines of Si IV \(\lambda\lambda\) 1393.755, 1402.77 Å in the spectra of 21 HiBALQSOs.

2. Data and method of analysis
The 21 QSOs were selected from the SDSS catalogue of broad line QSOs of Reichard et al. study [6]. We need to point out that in order to conclude to the final 21 HiBALQSOs, we used two criteria. Because this current work is a part of a wider study of HiBALQSO C IV and Si IV emission and absorption resonance lines, we demanded the redshift to be high enough \((1.813 < z < 3.777)\) so that the Si IV doublet would lie within the wavelength range that the spectra cover. Another criterion we applied is that the BALQSOs, had blended C IV and Si IV doublets. From the HiBALQSOs that meet these two criteria we chose randomly 21. The spectra were taken from the Sloan Digital Sky Survey (SDSS) Data Release 7 and they cover the optical range 3800-9200 Å, at a resolution of 1800-2100. The SDSS imaging survey uses a wide-field multi-CCD camera [25]. In table 1, one can see in the first column the SDSS name of each BALQSO, in column 2 there is the modified Julian date, plate and fiber, and in the third column the redshift.

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3. Spectral fitting

The first step in the fitting process is the identification of spectral lines in the studied wavelength range in order to identify possible blends between the absorption troughs. Then we determine the continuum for which we use the power law indices derived by [11]. We observed that among the 21 HiBALQSOs there are cases that present multiple troughs or detached troughs or troughs consisting of multiple kinematic components (more than one doublet) which set in at very near zero outflow velocity and extend up ~ 25000 km s\(^{-1}\).

In order to fit the Si IV absorption troughs we choose the most appropriate distribution among the following: Gauss, Lorentz, Voigt or the new Rotation [1] and Gauss-Rotation [2] distributions. In this study performing \(x^2\) tests, we found that the best fit is achieved by using the Gauss distribution.

We observed two types of absorption troughs. In the first case the absorption trough is fitted using only one Si IV doublet, which is created by an individual absorbing region (cloud). However, in the second case we have troughs which cannot be simulated adequately using only one Si IV doublet but are fitted by using more than one doublet. In this situation the absorption trough is produced by more than one cloud. This means that the line function that describes the observed profile comes from the solution of the radiative transfer equation through more than one cloud [1], [2], [3]. As for the number of doublets we increase them until a standard \(F - test\) yields no further significant gain (95% confidence level) in the goodness of the fit, as measured by the reduced \(x^2\). We must point out that we fit each doublet member using a Gaussian, i.e. a Gaussian for the red and a Gaussian for the blue component of a doublet.

During the fitting process we require that for a given trough the Si IV resonance lines should have almost the same width and the same outflow velocity. The width (FWHM) and central positions (\(V_{\text{outflow}}\)) of the two Gaussians have been fit simultaneously to reproduce the Si IV absorption troughs. As for the ratio of optical depths between the blue and the red component of a doublet, according to theory it is \(\sim 2:1\) (see [26], [27]). However, because the doublets’ members are blended, the ratio of their optical depths is not always 2 (see also [26]). So, by relaxing the constraint of optical depth

### Table 1. SDSS HiBALQSO Catalogue

| # | SDSS Object      | Redshift | MJD-Plate-Fiber |
|---|------------------|----------|----------------|
| 1 | J023252.80-001351.2 | 2.025    | 51820-0407-158 |
| 2 | J015024.44+004432.9 | 1.990    | 51793-0402-485 |
| 3 | J031828.91-001523.2 | 1.990    | 51929-0413-170 |
| 4 | J001502.26+001212.4 | 2.857    | 51795-0389-465 |
| 5 | J001025.90+005447.6 | 2.845    | 51795-0389-332 |
| 6 | J003551.98+005726.4 | 1.905    | 51793-0392-449 |
| 7 | J015048.83+004126.2 | 3.703    | 51793-0402-505 |
| 8 | J004041.39-005537.3 | 2.092    | 51794-0393-298 |
| 9 | J004732.73+002111.3 | 2.879    | 51794-0393-588 |
| 10| J005419.99+002727.9 | 2.522    | 51876-0394-514 |
| 11| J010336.40-005508.7 | 2.442    | 51816-0396-297 |
| 12| J000103.85-104630.2 | 2.081    | 52143-650-133  |
| 13| J102517.58+003422.0 | 1.888    | 51941-0272-501 |
| 14| J004323.43-001552.4 | 2.806    | 51794-0393-181 |
| 15| J104109.86+001051.8 | 2.259    | 51913-0274-482 |
| 16| J110041.20+003631.9 | 2.017    | 51908-0277-437 |
| 17| J000056.89-010409.7 | 2.111    | 51791-0387-098 |
| 18| J001438.28-010750.1 | 1.813    | 51795-0389-211 |
| 19| J023908.99-002121.4 | 3.777    | 51821-0408-179 |
| 20| J104841.03+000042.8 | 2.022    | 51909-0276-310 |
| 21| J00913.77-095754.5  | 2.076    | 52141-651-519  |
between the doublet lines, we perform repeated fits and compare the results by $x^2$ test, in order to conclude to the best fit.

In the studied spectra we observed that the whole Si IV absorbing region comprises of one or more absorption doublets. This means that the whole Si IV absorbing region is created by more than one discrete cloud. If we want to fit the whole Si IV spectral region we need to solve the radiative transfer equation for a complex atmosphere that contains more than one discrete cloud. So, we need an interpolation polynomial which includes the line functions of every individual line ([1], [2], [3]). From this interpolation polynomial, in this current analysis we calculate the outflow velocity ($V_{outflow}$), the random velocities ($V_{rand}$), the apparent optical depth ($\tau_{app}$), the full width at half maximum (FWHM) and the equivalent width (EW) of each individual blue and red component of a doublet.

In figure 1, we give two examples of fitted spectra. In both cases the doublets’ names are provided (A, B, C, D). Below the fit we present the residuals. Below the residuals the different components that compose the final profile are shown (with blue colour we indicate the 1393.755 Å line and with red colour the 1402.77 Å line)

4. Results

In our study we identified up to five Si IV absorbing clouds. One HiBALQSO has four absorbing clouds, one HiBALQSO has three absorbing clouds, ten HiBALQSOs have two absorbing clouds and nine HiBALQSOs have one cloud. In this study we calculated for every one of the 21 HiBALQSOs the following parameters: the outflow velocities ($V_{outflow}$), the random velocities ($V_{rand}$), the apparent optical depth ($\tau_{app}$), the full width at half maximum (FWHM) and the equivalent width (EW) of each individual blue and red component of a doublet. We classify the calculated outflow velocities in five classes. The first one has the value of 24090 km s$^{-1}$, the second one has values between 13551 and 17208 km s$^{-1}$, the third one between 7744 and 10325 km s$^{-1}$, the forth one between 5377 and 6883 km s$^{-1}$ and the fifth one between 2151 and 4732 km s$^{-1}$. Based on this classification we also classify the random velocities ($V_{rand}$), the FWHM, the apparent optical depth ($\tau_{app}$) and the equivalent width (EW). In table 2, we present the mean values and the errors of the calculated parameters of these five classes.

| Class | $<V_{outflow}>$ (km s$^{-1}$) | $<V_{rand}>$ (km s$^{-1}$) | $<\text{FWHM}>$ (km s$^{-1}$) | $<\text{EW}>$ (Å) |
|-------|-----------------------------|-----------------------------|-----------------------------|---------------------|
| 1     | 24090 ± 2170                | 2280 ± 114                  | 4190 ± 230                  | 2.40 ± 0.05         |
| 2     | 14430 ± 520                 | 1530 ± 78                   | 3040 ± 180                  | 2.30 ± 0.05         |
| 3     | 8640 ± 220                  | 1460 ± 82                   | 2820 ± 160                  | 2.60 ± 0.05         |
| 4     | 6110 ± 260                  | 580 ± 72                    | 1190 ± 70                   | 2.50 ± 0.05         |
| 5     | 3460 ± 110                  | 410 ± 90                    | 960 ± 50                    | 3.10 ± 0.06         |

5. Discussion and conclusions

In the majority of cases the Si IV resonance lines where blended. By deblending them, we managed to calculate the apparent optical depth of the blue as well as the red component of the doublet. The ratio of optical depths $\tau_b/\tau_r$ is not 2 as specified by atomic physics ($\tau_b/\tau_r = (g_b f_b \lambda_b)/(g_r f_r \lambda_r) \approx 2$, where $\lambda_b$, $\lambda_r$ are the transitions’ wavelengths, $f_b, f_r$ are the oscillator strengths and $g_b, g_r$ are the statistical weights of the levels [27]). In fact this ratio ranges from $\sim 1.1$-1.2 which indicates that the broad absorption troughs present non-black saturation. Non-black saturation is an indication of partial coverage of the background source by the absorbing clouds. This phenomenon occurs when the absorbing clouds are smaller than the background source, allowing part of the light from the source to reach the observer unabsorbed. This effect also indicates that all absorption lines are intrinsic to the QSO. This picture is further justified by the width of the lines (FWHM > 300 km s$^{-1}$).
Figure 5. Two examples of fitted spectra. In both cases the doublet’s names are provided (A, B, C, D). Below the fit the residuals are presented. Below the residuals the different components that compose the final profile are shown (with blue colour we indicate the 1393.755 Å line and with red colour the 1402.77 Å line).
In figure 2a we can see that the apparent optical depth (of the blue component) of the lines decreases as the outflow velocity increases. This fact can be interpreted in two different ways. There is the possibility that, as the clouds accelerate outwards, its typical density will decrease which can explain why the optical depths decrease as the outflow velocity increases. According to this picture it seems that absorption is stronger at lower velocity. This picture is supported by figure 3a which shows that the equivalent width of resonance lines decreases with increasing outflow velocity. However, we cannot be sure that this is the real case because the decrease in the apparent optical depths can be due to a decrease in the covering fraction. So, in order to conclude we need to calculate the true optical depths as well as the covering fractions.

The widths (FWHM) of the Si IV resonance lines range from 960-4190 km s$^{-1}$, a range of values which exceeds the thermal width by many orders of magnitude for silicon in a $10^4$-$10^5$ K gas. Therefore, the broad line environment encompasses a range of non-thermal velocities along our line of sight. These velocities are possibly due to bulk or turbulent motions involved with the absorbing flow. Indeed, outflow lines tend to have profiles that are broad and smooth compared to thermal widths ([28], [29], [30], [31], see [32] for a possible explanation of how turbulent motions broaden the lines). In figure 2b, we present the behaviour of FWHM as a function of outflow velocities where we

![Figure 2](image-url)
can see that the FWHM increases with increasing outflow velocity. In order to explain the increase of FWHM with increasing outflow velocity we can assume that temperature rises to extreme values and so the medium would be extremely hot that would dissolve the clouds. Apart from that, such a medium would be unable to absorb any Si IV photon. On the other hand we can assume that the turbulent velocities are not constant along the line of sight but instead are increasing as the clouds accelerate outswards.

Figure 3b indicates that lines with high FWHM (higher FWHM corresponds to higher outflow velocity according to figure 2b) have low values of optical depths. This means that absorption lines at high outflow velocities tend to be broader but shallower. Whether this is an evolutionary effect of clouds or a geometrical effect (due to changes in the covering factor) or a combination needs to be checked in order to reach to conclusions using time variability of independent HiBALQSOs and calculations of the covering fractions.

Figure 3. (a) Mean equivalent width as a function of mean outflow velocity between the studied HiBALQSOs. (b) Mean apparent optical depth as a function of mean FWHM. In all graphs we give the equation of the curve, the coefficient of determination $R^2$, the adjusted $R^2$, the SSE (sum of squares due to error) and the RMSE (root mean square due to error).

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