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

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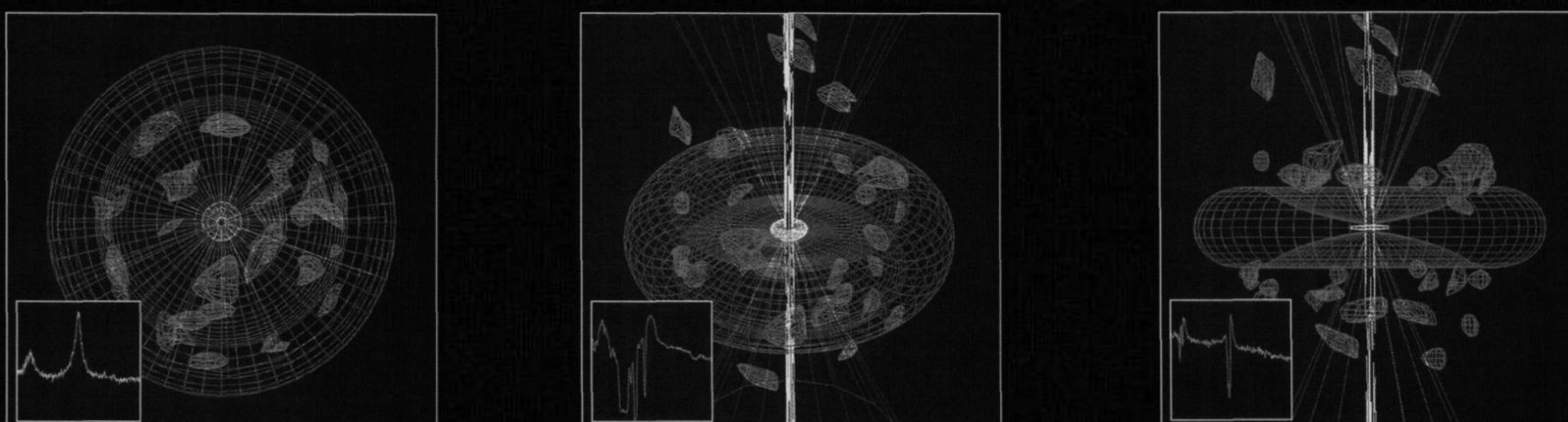
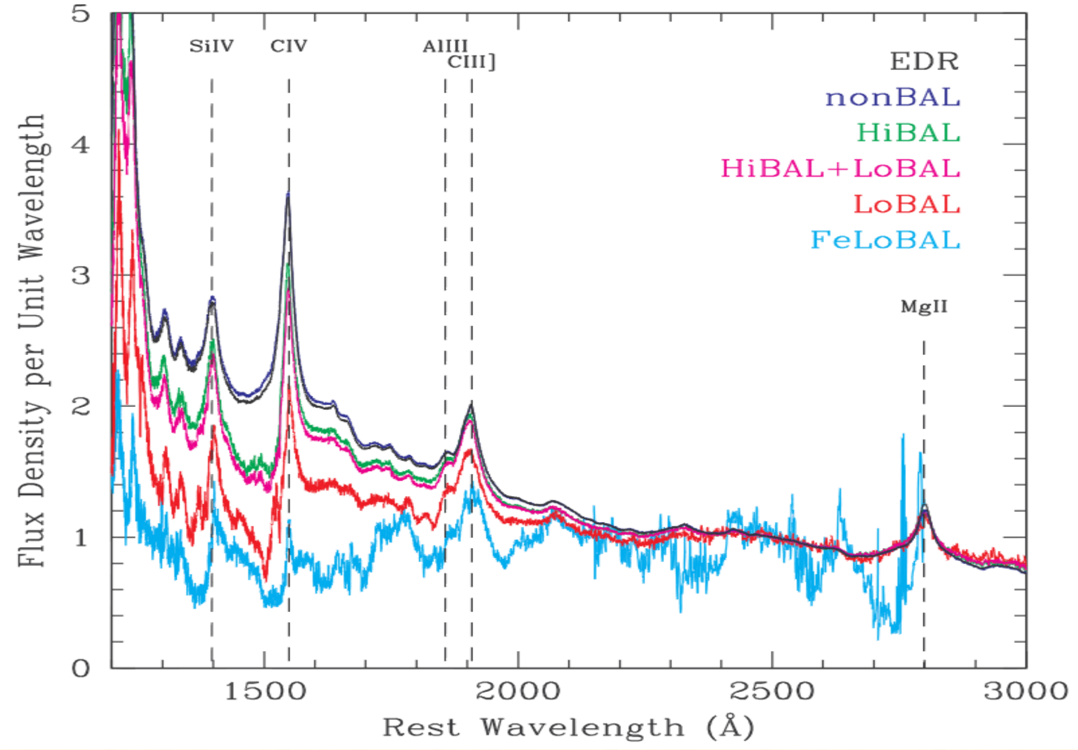


Spectral Classification of BALQSOs

- High-ionization BALs (HiBALs) contain strong, broad absorption high-ionization lines such as C IV, Si IV, N V, Lyα

- Low ionization BALQSOs (LoBALs) contain HiBAL features but also have absorption from low-ionization lines such as Mg II.

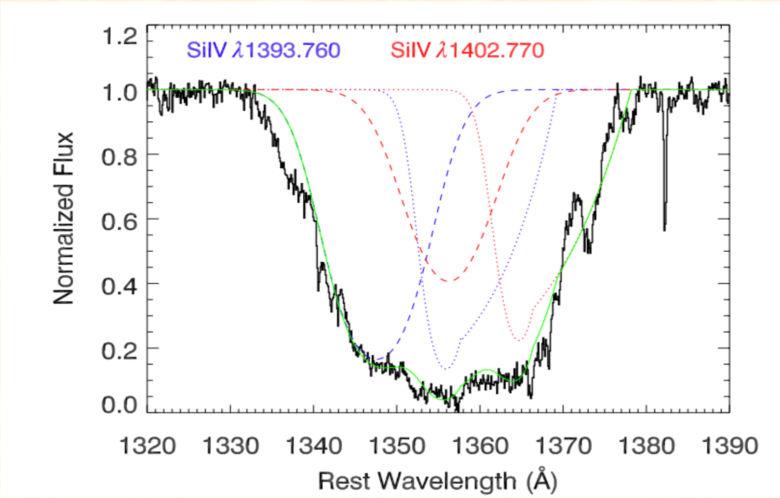
- FeloBALQSOs LoBALs with excited-state Fe II or Fe III absorption



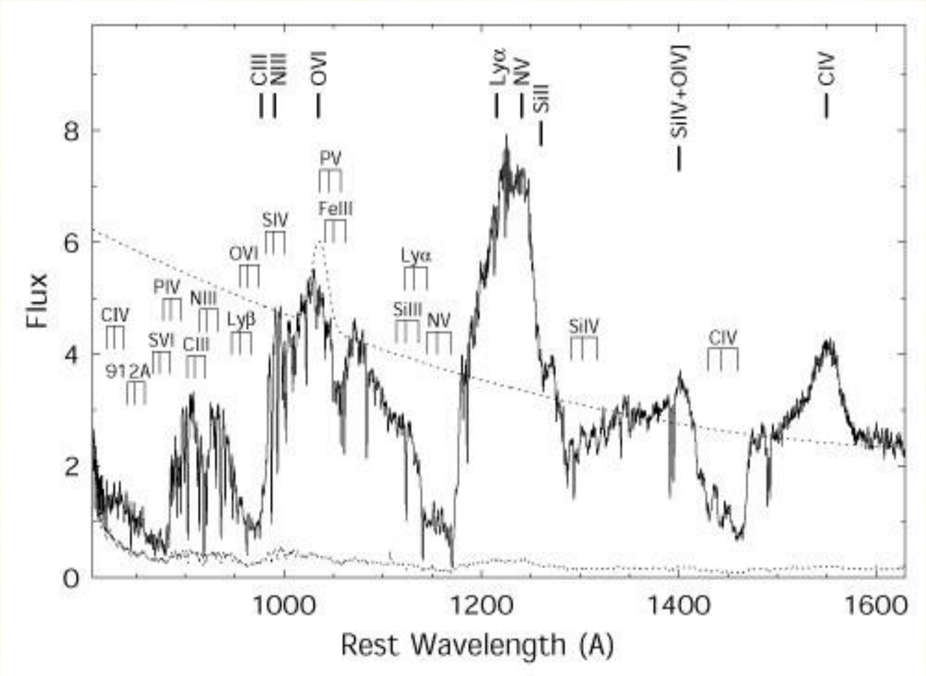
Reichard et al. 2003

BALQSOs

FWHM: 200 – 20000 km/s
Voutflow ~ 66000 km/s
P-Cygni
Detached troughs up to ~ 30000 km/s

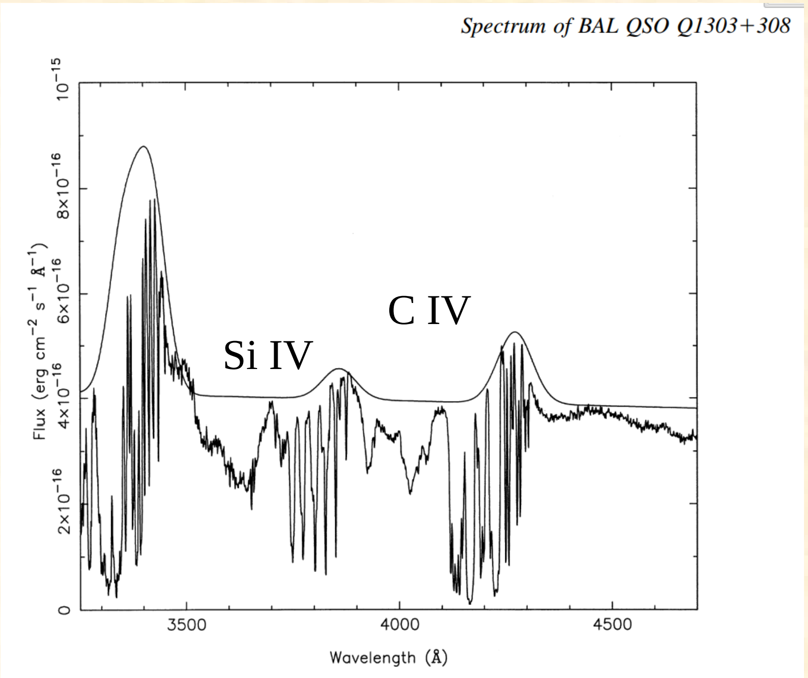


Benoit C. J. Borguet et al. AJ 2013



Hamann ARAA 1997

BALQSO with NALs



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.

E. Y. Vilkoviskij and M. J. Irwin, MNRAS 2001

NALs

FWHM < 200 – 300 km/s

Mini - BALs

However there are absorption lines with intermediate widths (FWHM ~ 300 – 2000 km/s, Hamann & Sabra 2004) which are called mini-BALs and are as common as BALs (Rodriguez et al. 2011).

Data

#	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	J000913.77-095754.5	2.076	52141-651-519

Model and Spectral Fitting

In this work we use the Danezis et al. model (Danezis et al. 2003, 2007 and Lyratzi et al. 2007) in order to analyze the Si IV absorption troughs.

Fitting

1. Identification of lines. Searching for possible blends.
2. Fitting the continuum (using a power law with spectral indices derived by Trump et al. 2006) .
3. Identification of troughs in the Si IV spectral region: Multiple troughs, detached troughs. Checking the appropriate distribution among, Gauss, Lorentz, Voigt, Rotation (Danezis et al. 2003) and Gauss – Rotation (Danezis et al. 2006, 2007). In this study performing x^2 tests, we found that the best fit is achieved by using the Gauss distribution.
4. 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.
5. As for the number of doublets, in the trough, 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 .

6. 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 ($V_{outflow}$) of the two Gaussians have been fit simultaneously to reproduce the Si IV absorption troughs.

7. As for the ratio of optical depths between the blue and the red component of a doublet, according to theory it is ~ 2:1 (Borguet et al. 2013, Arav et al. 2001). So, by relaxing the constraint of optical depth between the doublet lines, we perform repeated fits and compare the results by x^2 test, in order to conclude to the best fit.

8. 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.

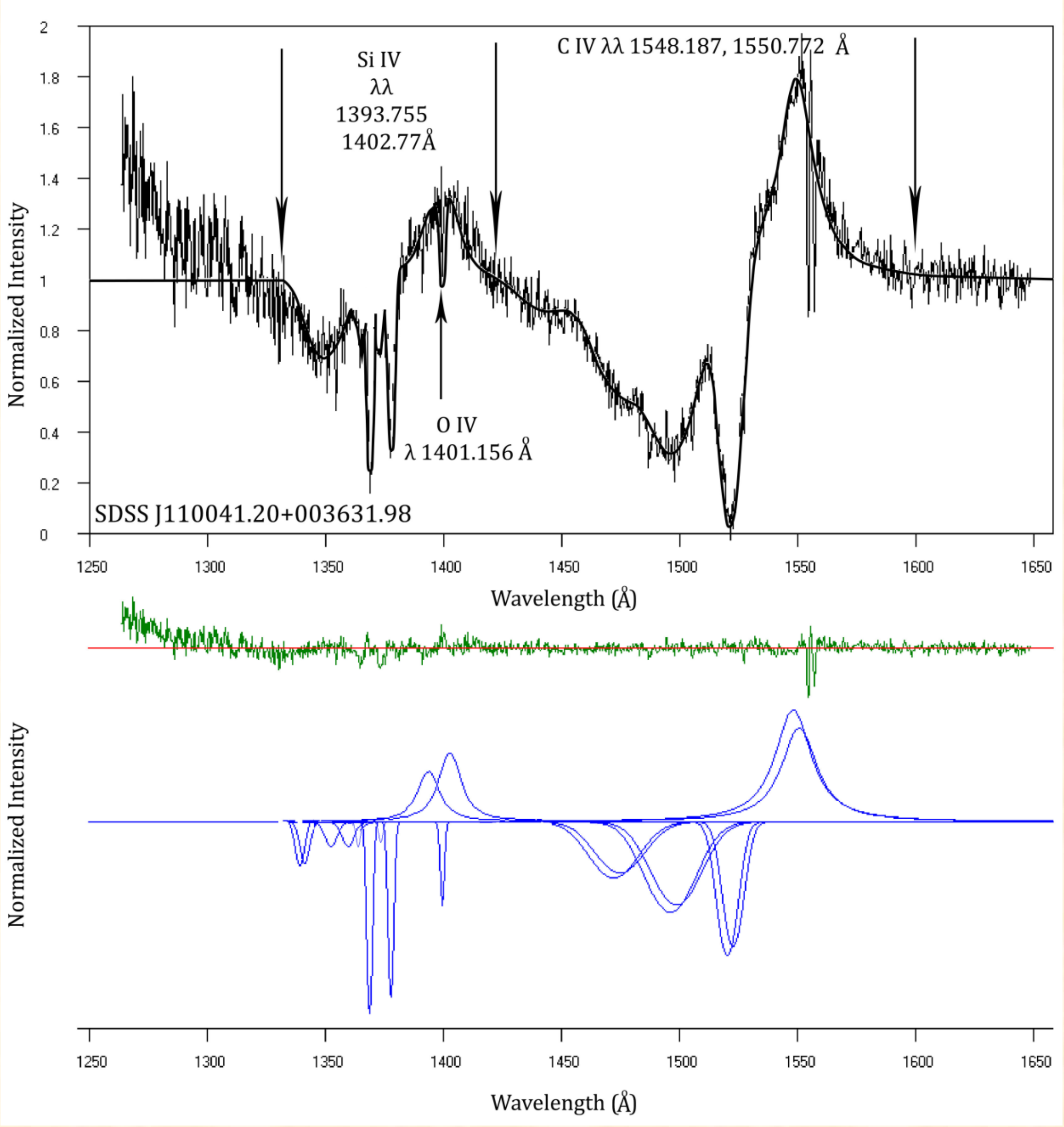
9. We use an interpolation polynomial which includes the line functions of every individual line (Danezis et al., 2003, 2007; Lyratzi et al., 2007).

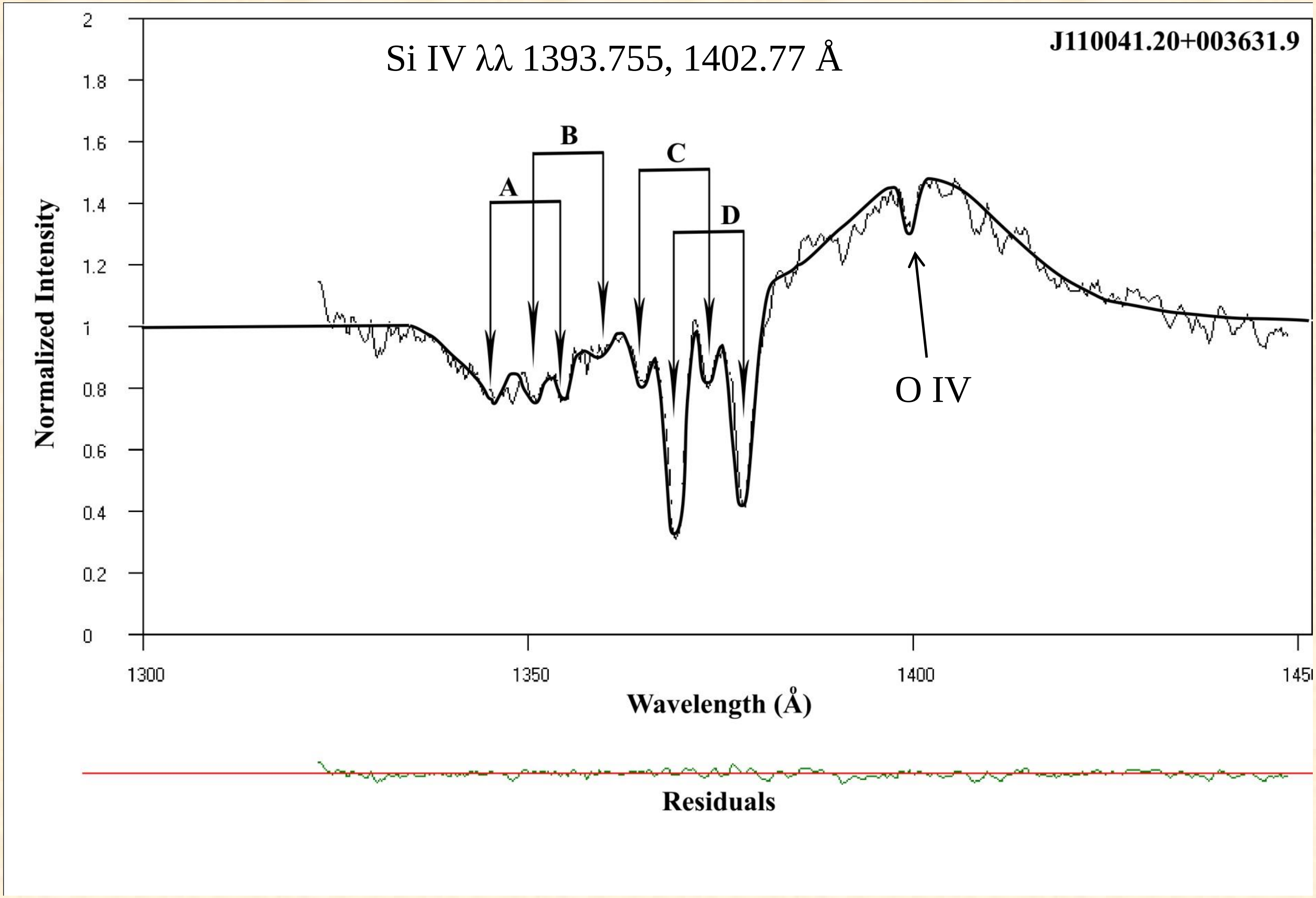
10. From this interpolation polynomial, in this current analysis we calculate the outflow velocity ($V_{outflow}$), the random velocities (V_{rand}), the optical depth (τ), the full width at half maximum (FWHM) and the equivalent width (EW) of each individual blue and red component of a doublet.

Examples of Studied Spectra and their Fit

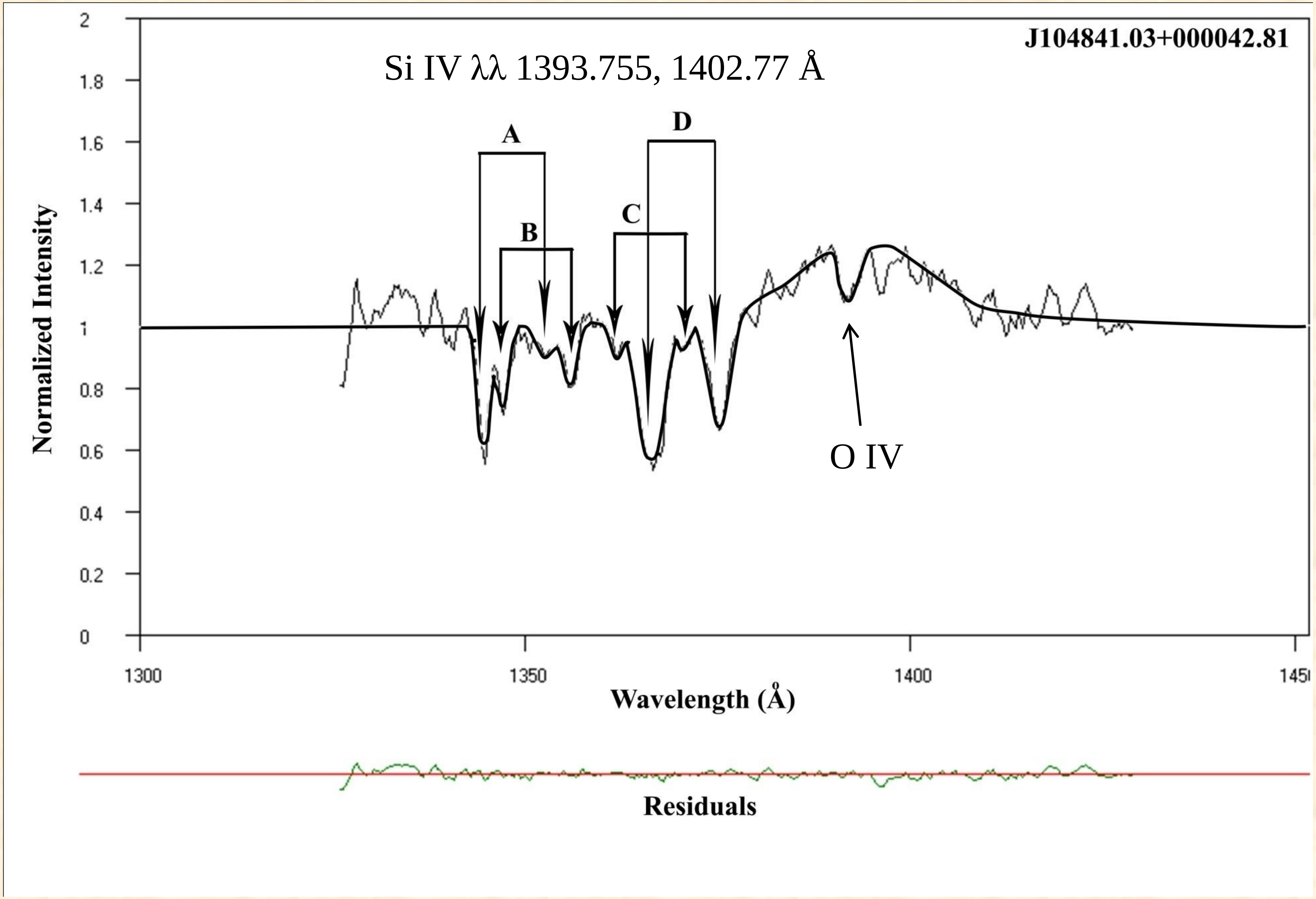
Black Line: Model Fit

Blue Line: Individual Components





Si IV λλ 1393.755, 1402.77 Å
J110041.20+003631.9
A
B
C
D
O IV
Normalized Intensity
Wavelength (Å)
Residuals
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1300
1350
1400


J104841.03+000042.81
Si IV λλ 1393.755, 1402.77 Å
A
B
C
D
O IV
Normalized Intensity
Wavelength (Å)
Residuals

Results

#	SDSS Name	Vrad1 (km/s)	Vrad2 (km/s)	Vrad3 (km/s)	Vrad4 (km/s)	Vrad5 (km/s)
1	J000103.85-104630.2			7959	15487	24091
2	J004323.43-001552.4			9034	17208	
3	J023908.99-002121.42			8819	17208	
4	J001502.26+001212.4			9034	16778	
5	J031828.91-001523.17		6883		14627	
6	J010336.40-005508.7	3657			13551	
7	J110041.20+003631.98		5377	10325		
8	J104841.03+000042.81		6023	10217		
9	J001025.90+005447.6			9464		
10	J004732.73+002111.3	4087		9034		
11	J004041.39-005537.3			9034		
12	102517.58+003422.17			8604		
13	J104109.86+001051.76	2151		8174		
14	J023252.80-001351.17			8174		
15	J005419.99+002727.9			7744		
16	J003551.98+005726.4	4409	6668			
17	J000056.89-010409.7	2581	6238			
18	J015048.83+004126.29	3656				
19	J000913.77-095754.5	4732				
20	J001438.28-010750.1	3226				
21	J015024.44+004432.99	2796				

In our study we identified up to five Si IV absorbing clouds.

One HiBALQSO has three clouds,
Eleven HiBALQSOs have two clouds
Nine HiBALQSOs have one cloud.

In this study we calculated for every one of the 21 HiBALQSOs the following parameters:

- outflow velocities ($V_{outflow}$),
- random velocities (V_{rand}),
- apparent optical depth (τ),
- full width at half maximum (FWHM)
- equivalent width (EW)

of each individual blue and red component of a doublet.

We classify the calculated outflow velocities in five classes.

Based on this classification we also classify the random velocities (V_{rand}), the FWHM, the apparent optical depth ($\tau_{apparent}$) and the equivalent width (EW).

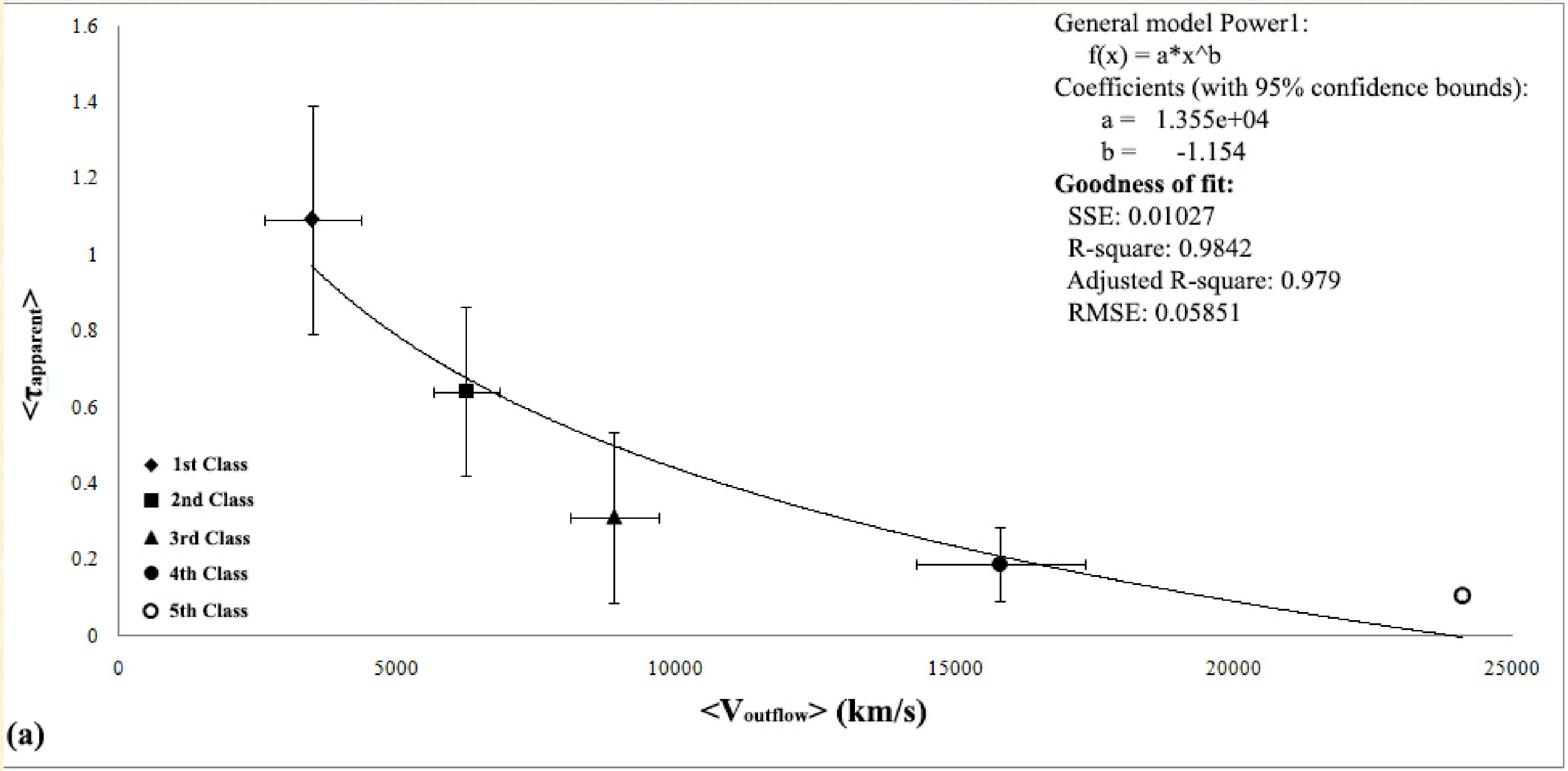
Class	**$\langle V_{outflow} \rangle$ (km/s)**	**$\langle V_{random} \rangle$ (km/s)**	**<FWHM> (km/s)**	**$\langle \tau_{app} \rangle$**	**<EW> (Å)**
1	24090 ± 0	2280 ± 0	4190 ± 0	0.1 ± 0.0	2.4 ± 0.0
2	14430 ± 2865	1550 ± 350	3040 ± 213	0.2 ± 0.1	2.3 ± 0.3
3	8640 ± 551	1630 ± 320	2820 ± 225	0.3 ± 0.2	2.6 ± 0.3
4	6110 ± 610	1430 ± 290	1190 ± 107	0.6 ± 0.2	2.5 ± 0.3
5	3460 ± 921	420 ± 90	960 ± 48	1.2 ± 0.3	3.1 ± 0.4

DISCUSSION AND CONCLUSIONS

Blended Doublets: By deblending them we calculated the apparent optical depths of the blue and red component of each doublet. The ratio $\tau_b/\tau_r \neq 2$. In fact it ranges from 1.1 – 1.3. → 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.

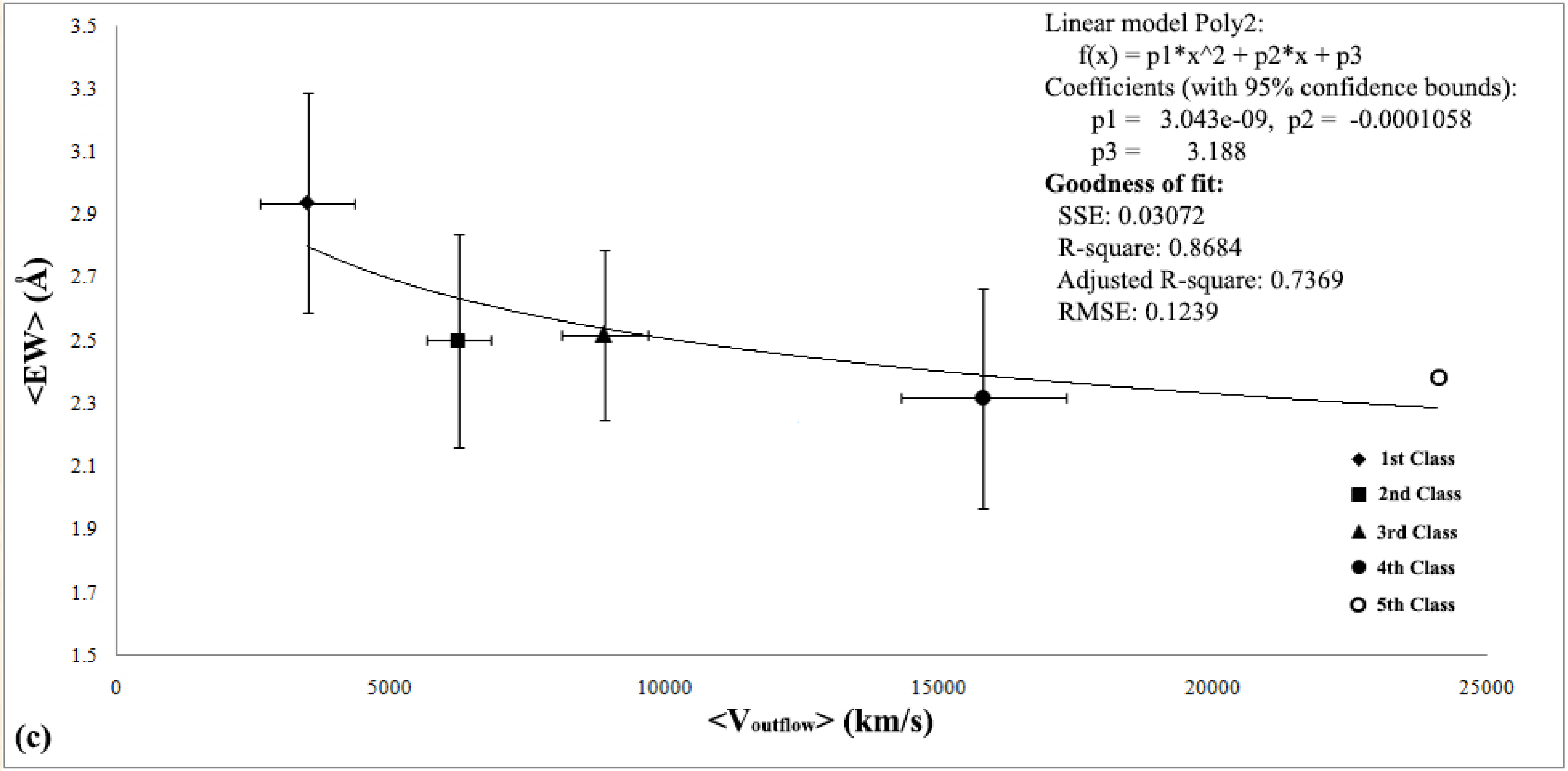
Diagrams showing the correlations between the calculated physical parameters



The apparent optical depth of the lines decreases as the outflow velocity increases.

Possible Explanations

1. 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 Fig. 1c which shows the equivalent width of resonance lines decreases with increasing outflow velocity.
2. 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 which exceed 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 nonthermal velocities along our line of sight. These velocities are possibly due to bulk or turbulent motions involved with the absorbing flow.

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 outwards.

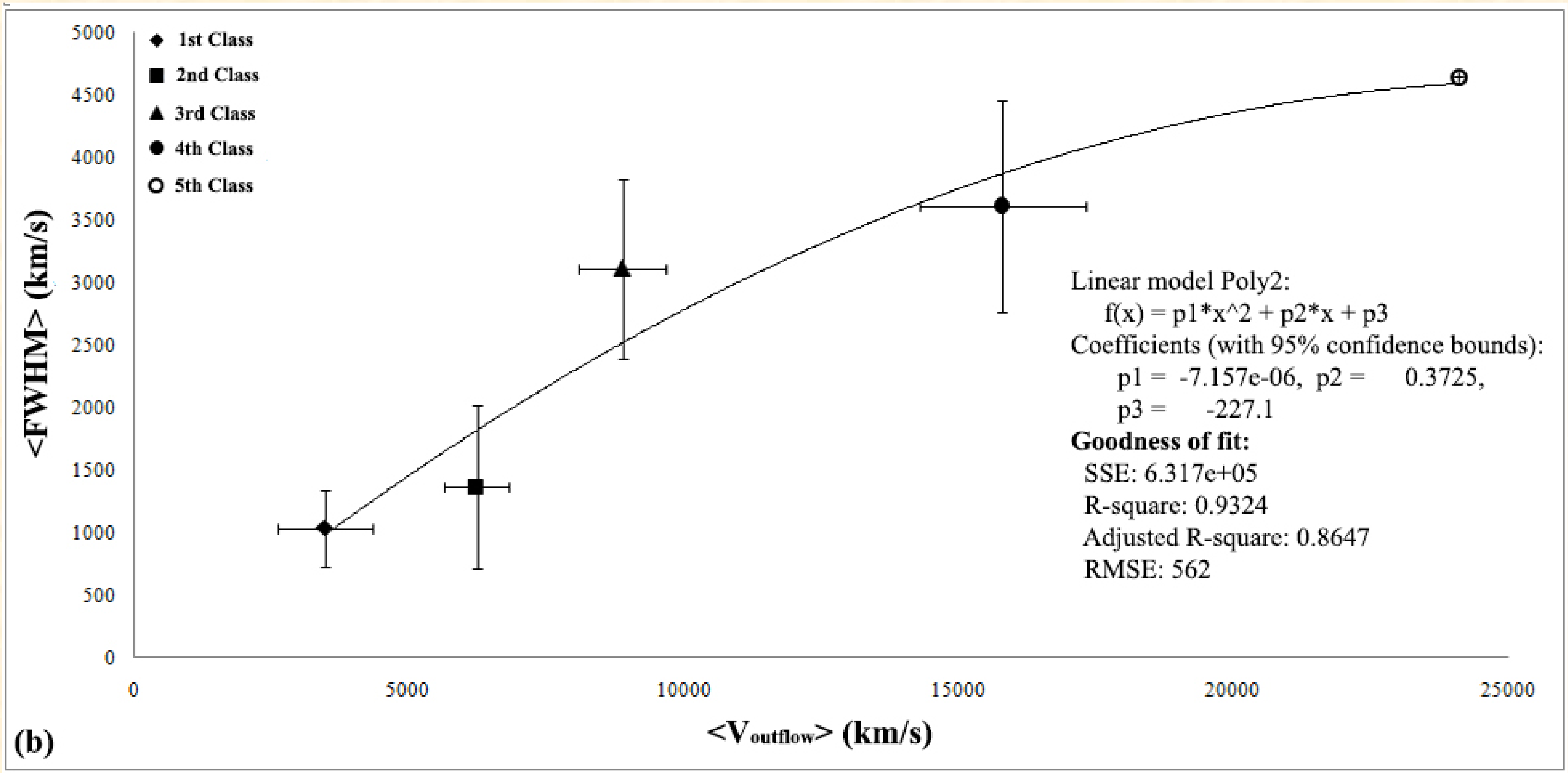
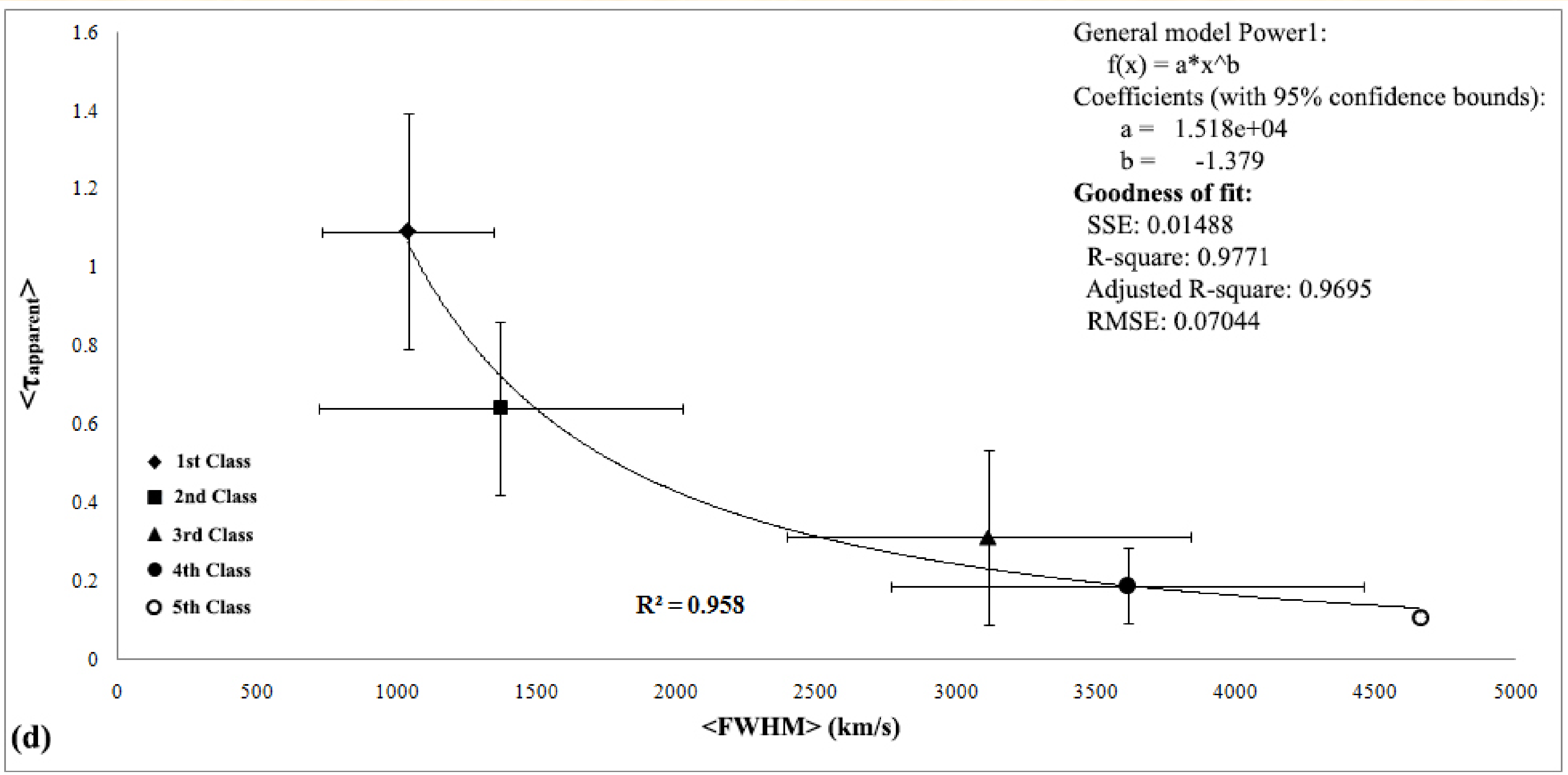


Figure 1d indicates that lines with high FWHM (higher FWHM corresponds to higher outflow velocity according to Fig. 1b) have low values of optical depths. This means that absorption lines at high outflow velocities tend to be broader but shallower. Whether this is an evolutionary effect of clouds or 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.



Future Work

1.The study of a greater sample of HiBALQSOs

2.Calculation of all the previously mentioned physical parameters in the case of one more spectral line (Lyα, N V)

3. Calculate the true optical depths, the covering fractions and the apparent and true column densities for comparisons.

4. Investigate whether clouds cover the continuum source, or the Broad Emission Line Region or both.

Acknowledgments

This research project is progressing at the University of Athens, Department of Astrophysics, Astronomy and Mechanics, under the financial support of the Ted and Erica Spyropoulos Foundation and the Special Account for Research Grants, which we thank very much. Finally, we would like to thank Prof. Jack Sulentic and Prof. Paola Marziani for kindly providing us with both VLT BALQSO spectra as well as for their useful and detailed comments on our work.

Thank you very much!