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Multicomponent analysis of Si IV and C IV broad absorption profiles in the case of two BALQSOs.

Answering some important questions.

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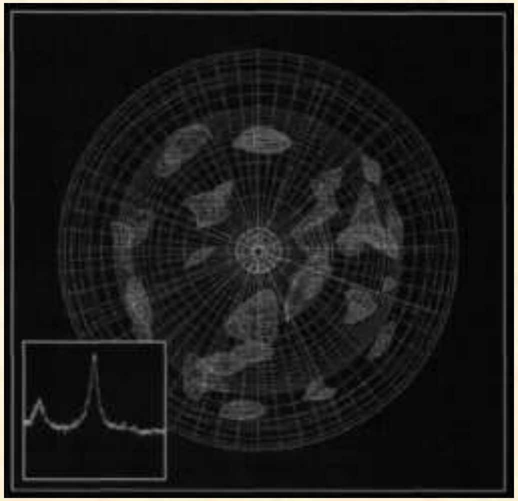
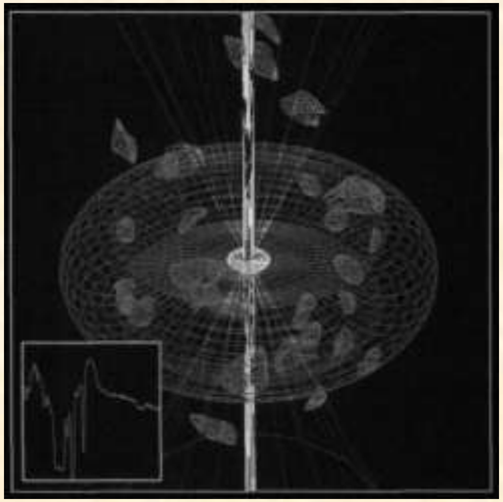
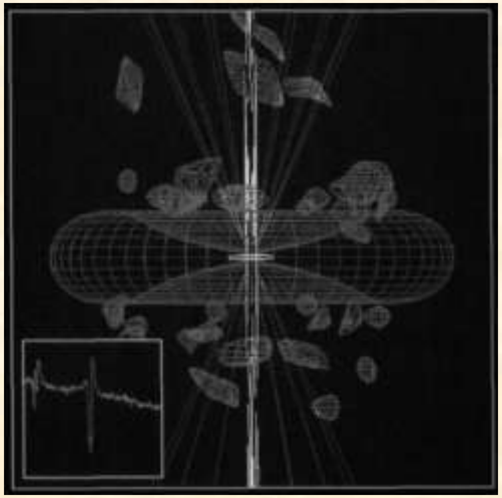


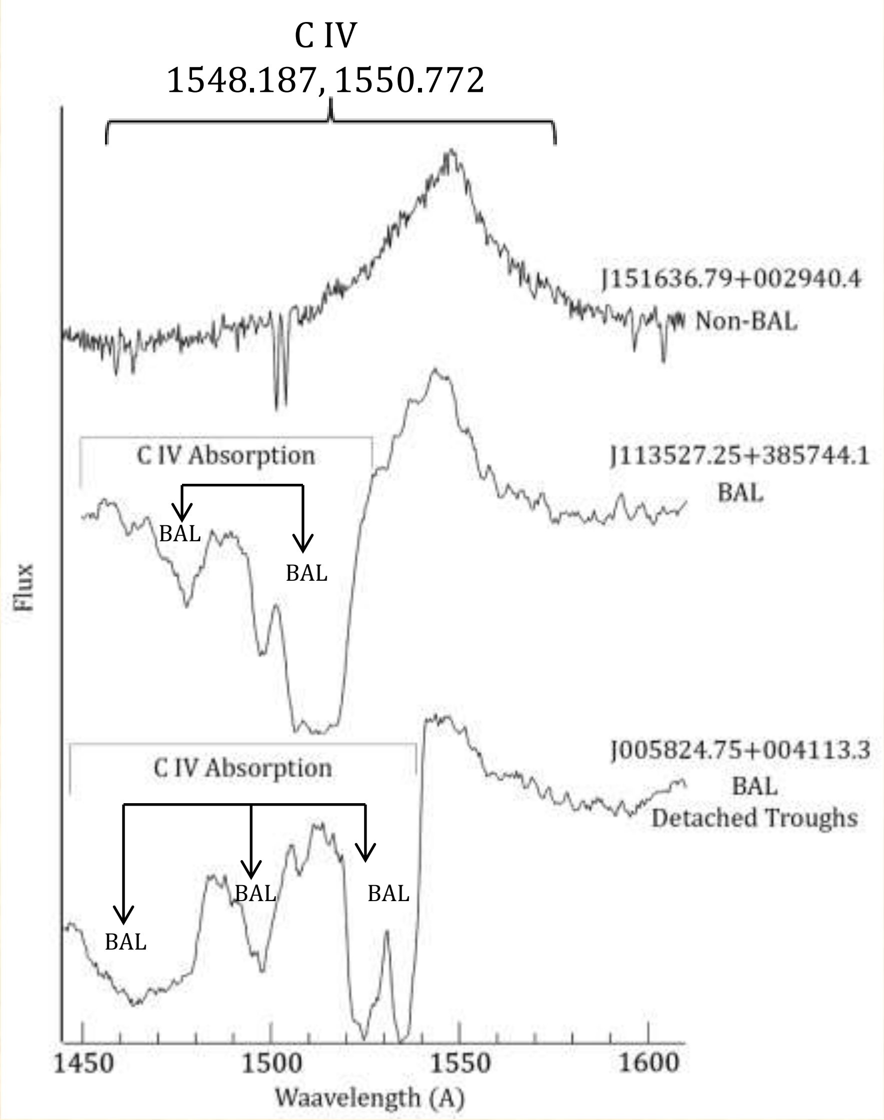




What are BALs
or
Broad Absorption Lines

BALs are Broad and complex absorption lines, which in the majority of cases are blueshifted relative to the AGN emission lines, implying outflow velocities from near 0 to as much as ~ 60,000 km/s (~ 0.2 c).

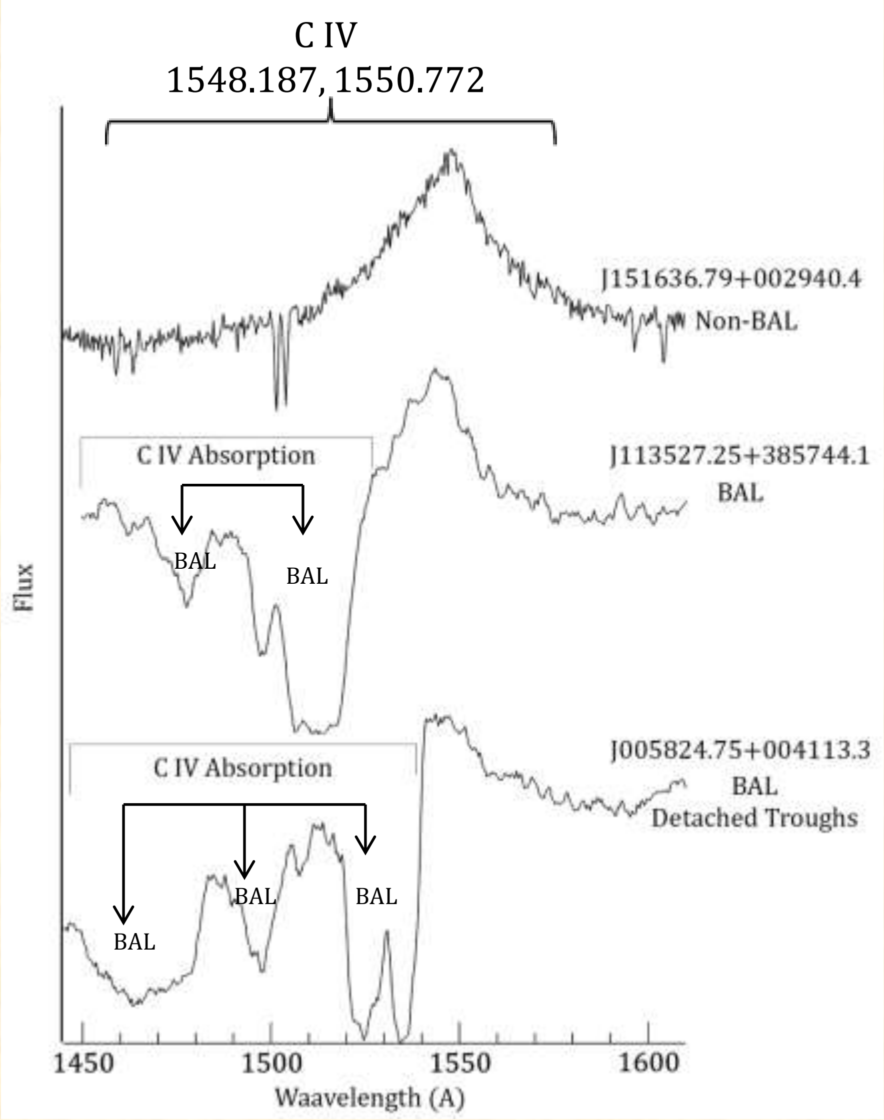
BALs identify high velocity outflows from the central engines that power the QSO.



A representative line width is ~10,000 km/s, although there is considerable diversity among BAL profiles.
Velocity widths ~> 3000 km/s and blueshifted velocity extrema~> 5000 km/s are usually considered minimum requirements for classification as a BAL.

Some BALs have several distinct absorption troughs, while others are strictly "detached" from the emission lines — such that the absorption appears only at blueshifts exceeding several thousand km/s.

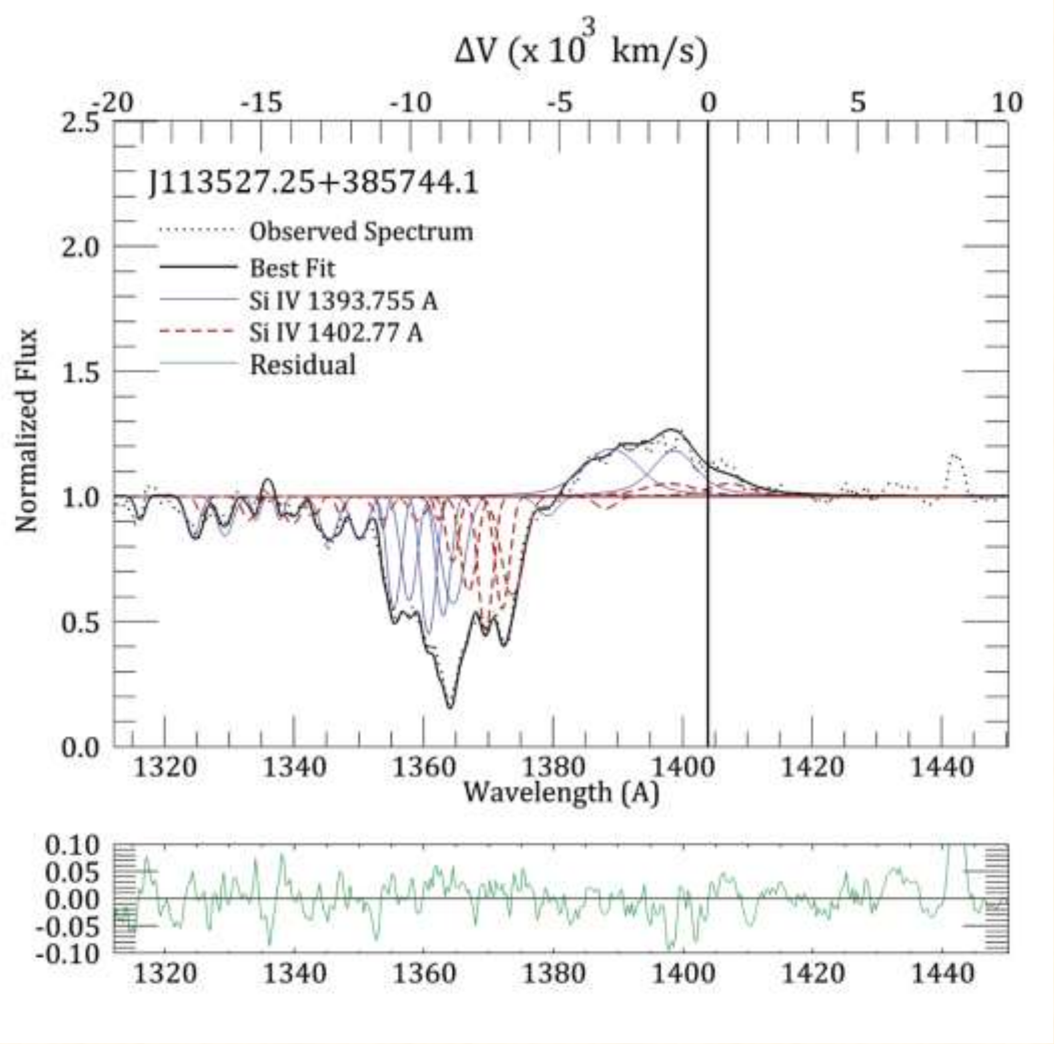
FWHM: 2000 – 20000 km/s
Voutflow ~ 66000 km/s
P-Cygni
Detached troughs up to ~ 30000 km/s



There are two opposing opinions about the origin of BALs:

i. a smooth continuous flow with the intensity depending only on optical depth effects (complete source coverage), e.g. Murray & Chiang 1995.

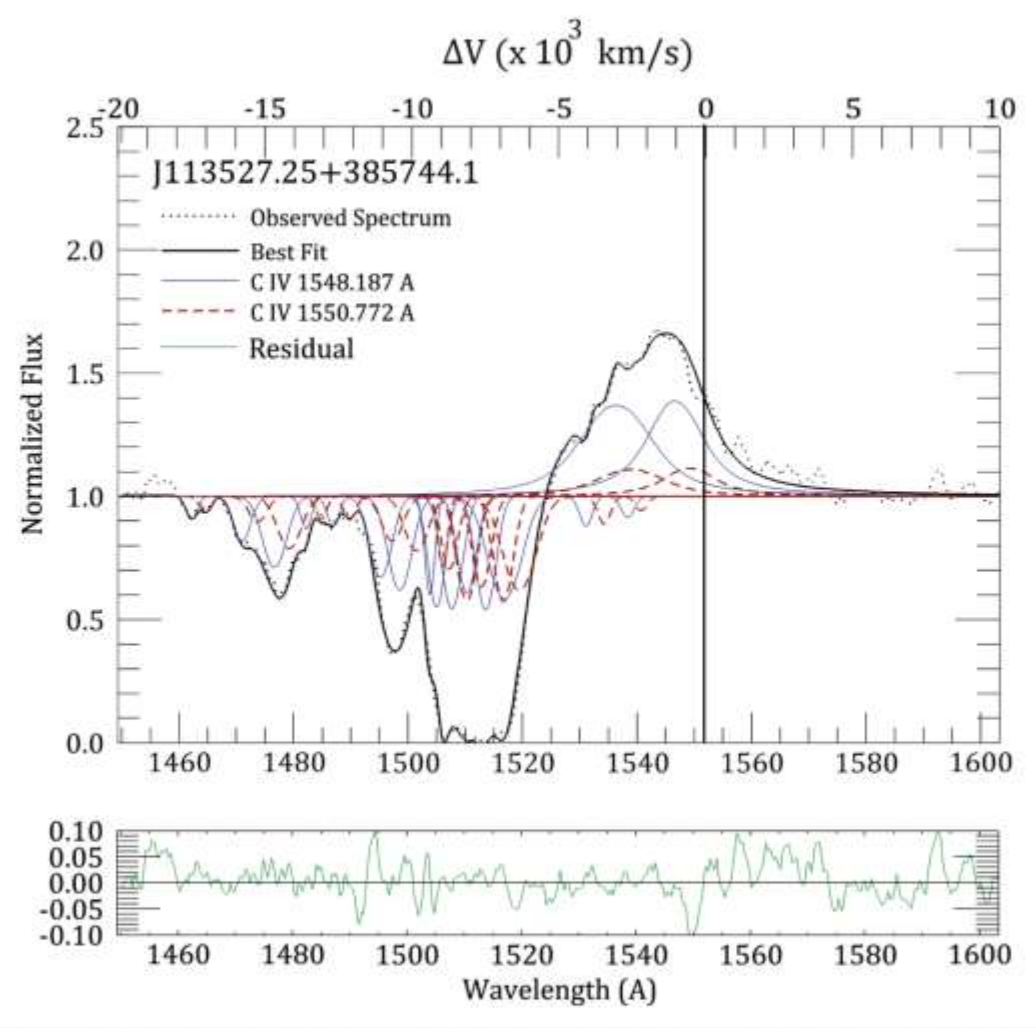
ii. a flow of many individual clouds (Turnshek 1984; McKee & Tarter 1975; Hamann et al. 2013; Capellupo et al. 2014; Lyratzi et al. 2011, , Lyratzi et al., 2010; Lyratzi et al., 2009).



According to the second point of view, the broad and complex profiles can be interpreted as the synthesis of a series of absorption components.

If the later holds then it implies the existence of independent absorbing regions that cover the continuum and/or emission line region along our line of sight.

These absorbing regions can be thought as overdensities or density enhancements in a wind [or interacting with the wind (Weyman, et al. 1985; Filiz Ak, et al. 2012)] produced by an accretion disc.



Open Questions

1. Physical Model of the structure of Broad Absorption Line Region (clouds, cloudlets, etc).

2. Mathematical Expression of the Physical Model able to simulate the BAL troughs and provide the physical parameters of BAL clouds.

3. Fitting Method:
   - Best Fit
   - Uniqueness of Fit - Fitting Criteria

4. Can all the previous be applied in observed BALQSO spectra. Are the values of calculated parameters accepted?

Proposed Physical Model

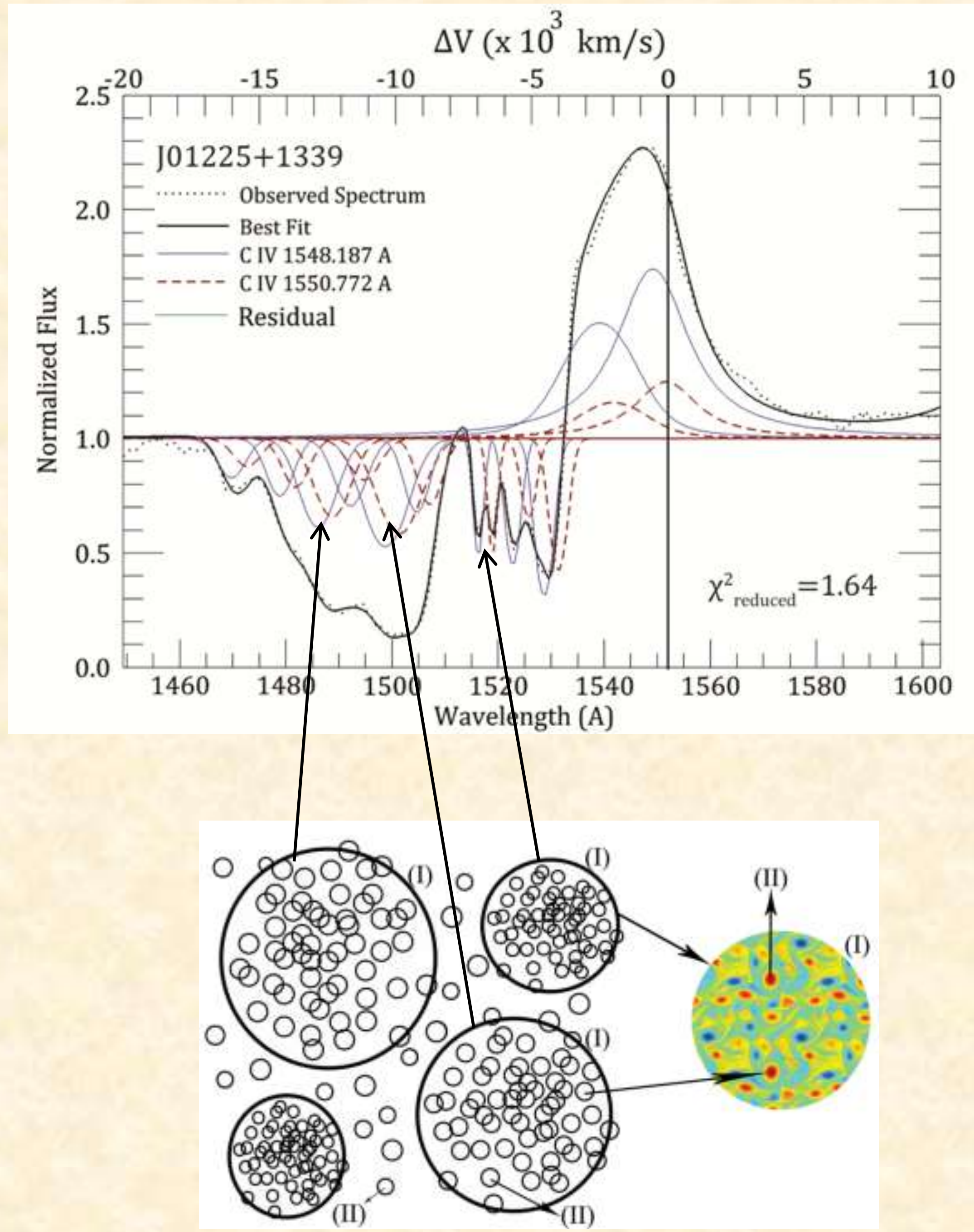
- Broad Absorption Lines (BALs) are complex, strong and unusually broad absorption troughs which appear remarkably smooth in high resolution spectra. BAL troughs cannot be simulated by a single distribution. Because of this characteristic, it has been proposed that BALs consist of a series of absorption components produced by density enhancements called clouds (Turnshek 1984; McKee & Tarter 1975; Hamann et al. 2013; Capellupo et al. 2014; Lyratzi et al. 2009; Lyratzi et al. 20010; Lyratzi et al. 2011). These clouds intercept the line of sight to the central engine that powers the QSO.

- The widths of lines produced by clouds are assumed to be due to thermal and microturbulent motions. $V_{thermal} \sim 20$ km/s for $T = 10^4 - 10^5$ K, $V_{turb} \sim 10^2$ km/s.

- The components we use in order to simulate the BAL profiles correspond to clouds (Regions I, Fig. 1) and they are quite broad (300 km/s $<$ FWHM $<$ 2300 km/s) compared to the thermal and microturbulent width.

- In order to explain this discrepancy we propose that clouds consist of subunits called cloud elements or cloudlets (cloud elements-regions II, Fig. 1), which are clustered.

- Each cloudlet produces an absorption line the width of which depends on thermal and microturbulent motions inside the cloudlet. The synthesis of all these narrow cloudlet lines that are very close in velocity space and overlap, produce a broad component corresponding to a cloud.



Mathematical Expression of the model

Solving the radiative transfer equation for such a complex plasma region – consisting of many clouds we concluded to eq. (1) (Danezis et al. 2003, ASS, 284, 1119, Danezis et al. 2007, PASJ, 59, 827-834).
This equation describes, for example, the synthesis of all the blue components of C IV (λ 1548.187). Applying eq. (1) once again we describe the synthesis of all red components of C IV (λ 1550.772 A).

$$\mathrm{I}_\lambda = \left[\mathrm{I}_{\lambda_0} \cdot \prod_i e^{-L_i \xi_i} + \sum_j S_{\lambda_{ej}} \left(1 - e^{-L_{ej}\xi_{ej}}\right)\right] \cdot \prod_g e^{-L_g \xi_g} \qquad \text{Eq. (1)}$$

i: is the number of absorbing clouds that cover the continuum (fully or partially), in the line of sight,
j: is the number of emitting clouds in the line of sight,
g: is the number of additional absorbing clouds that may cover the i absorbing clouds as well as the j emitting clouds,
I_{λ_0}: is the initial radiation intensity
$\prod_i \boldsymbol{exp\{-L_i \xi_i\}}$: is the factor that describes the synthesis of absorption lines produced by i clouds,
$\sum_j \boldsymbol{S_{\lambda_{ej}} \left(1 - exp\{-L_{ej}\xi_{ej}\}\right)}$: is the factor that describes the summation of emission lines produced by j clouds,
$\prod_g \exp\{-L_g \xi_g\}$: is the factor that describes absorbing clouds that may obscure both the i absorbing as well as the j emitting clouds,
L_i, L_{ej}, L_g : are the distribution functions of the absorption coefficients $k_{\lambda i}, k_{\lambda ej}, k_{\lambda g}$,
$k_{\lambda i}$: is the absorption coefficient of the i^{th} cloud in the line of sight,
$k_{\lambda ej}$: is the absorption coefficient of the j^{th} cloud in the line of sight,
$k_{\lambda g}$: is the absorption coefficient of the additional absorbing clouds that may cover the i and j clouds in the line of sight,
ξ: is the optical depth in the center of the spectral line,
$\mathrm{S}_{\lambda_{ej}}$: is the source function, that is constant during one observation

$$I_\lambda = \left[I_{\lambda_0} \cdot \prod_i e^{-L_i \xi_i} + \sum_j S_{\lambda_{ej}} \left(1 - e^{-L_{ej} \xi_{ej}}\right) \right] \cdot \prod_g e^{-L_g \xi_g}$$

The factors L_i, L_{ej}, L_g, can take the form of one of the following distributions, according to the physical conditions that prevail in the region that produces the spectral lines.

- Gauss
- Lorentz
- Voigt
- Rotation (Danezis et al., 2003, Danezis et al., 2009)
- Gauss-Rotation (Danezis et al., 2006, Danezis et al., 2007)

Direct calculations

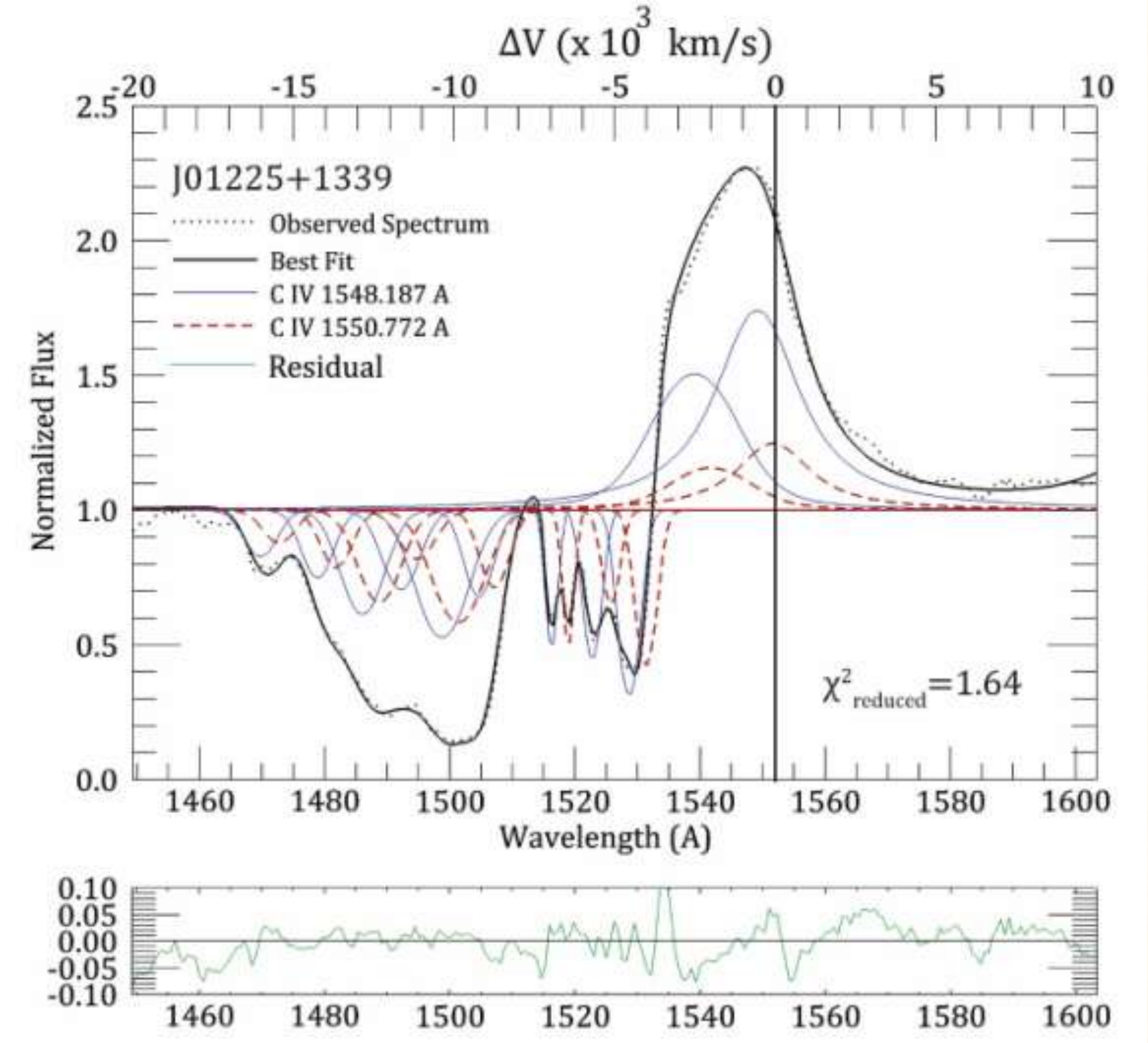
- Apparent radial velocities of absorbing or emitting density layers (V_{rad})
- The Gaussian typical deviation of the ion random motions (σ)
- The optical depth in the center of the absorption or emission components (ξ_i)

Indirect calculations

- The random velocities of the ions (V_{random})
- The FWHM
- Equivalent Width
- The column density (N)

Using Eq. (1)

Equation (1) can describe independently each one of the components (absorption/emission) of a spectral line. For example in the case of Si IV, C IV resonance lines we apply eq. (1) twice.



Once for the blue member of CIV (1548.187 Å-blue). So eq. (1) contains all the line functions of the blue members.

Once for the red members of CIV (1550.772 Å-red). So eq. (1) contains all the line functions of the red members.

The synthesis of the two functions gives us the best fit of C IV.

We repeat the same process for Si IV.

Fitting Process

Distributions Used in the Fitting Process

Emission Lines: Voigt (pressure + random motions)
Absorption Lines: Gauss (random motions – thermal + turbulent)

Proposed Fitting Criteria (Constraints, Restrictions)-Absorption/Emission Lines

During the fitting process we set some criteria in order to find the exact number of components that are necessary to fit the Si IV and C IV absorbing regions. Through this process we ensure that the final fit is unique.

These criteria can be separated into two categories:

Criteria between the members of a doublet (C IV λλ 1548.187, 1550.772 and Si IV λλ 1393.755, 1402.77).

- The first set of criteria is applied to the members of resonance lines. We fit doublets because in the case of singlets we cannot be sure for the number of components that gives the best fit. In the case of singlets the more the components the better the fit.

Criteria between C IV and Si IV components at the same outflow velocity from the emission redshift.

The major problem of multicomponent fits is that the best-fit solution is not unique (Laor et al. 1994).

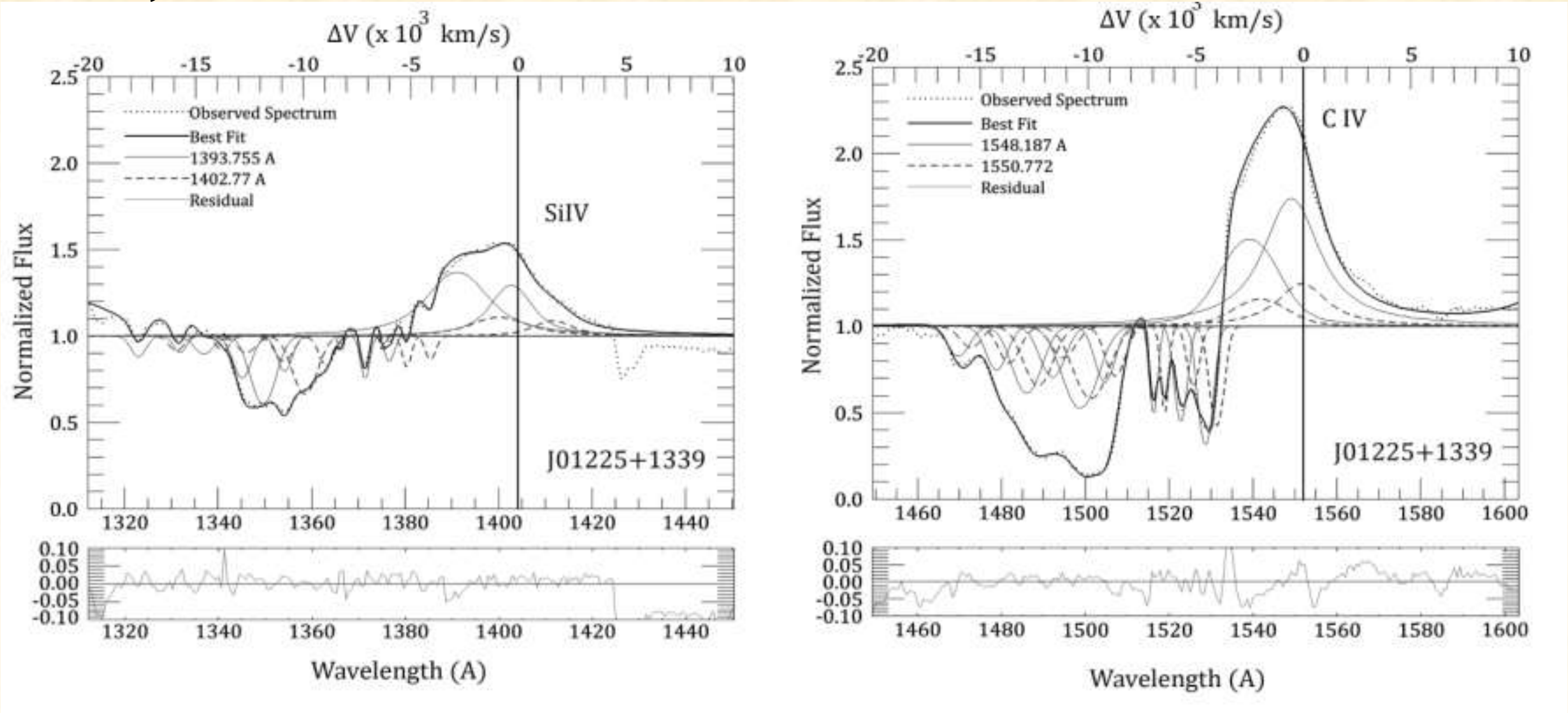
In the case of the UV Si IV and C IV resonance lines, their doublets are blended. This means that the fit will be highly degenerate unless both ions are fitted simultaneously.

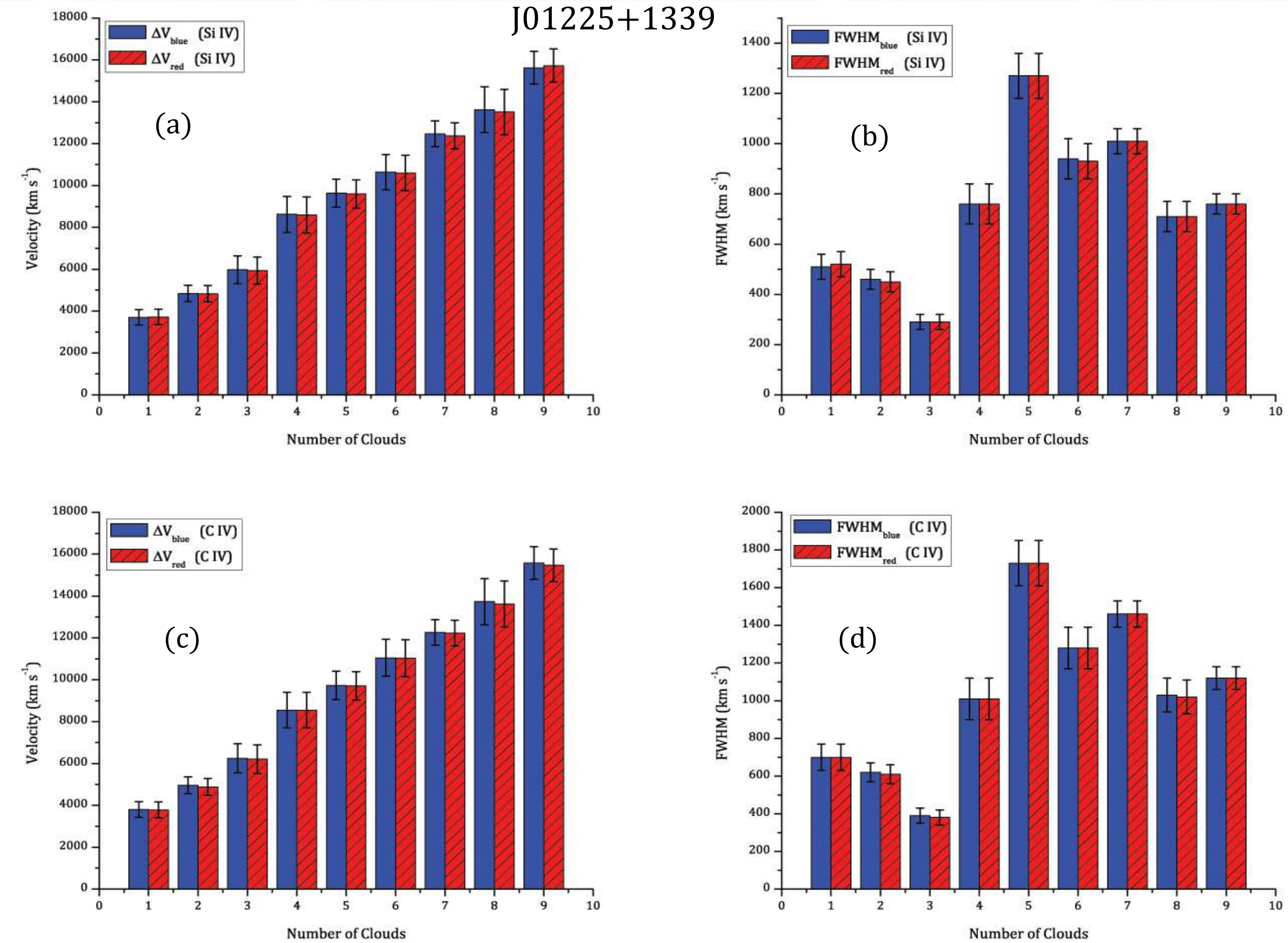
So in order to find a final solution, which is unique, and independent of initial parameter/guess we fit simultaneously Si IV and C IV doublets with parameters tied.

We assume that both Si IV and C IV follow the same kinematic structure.

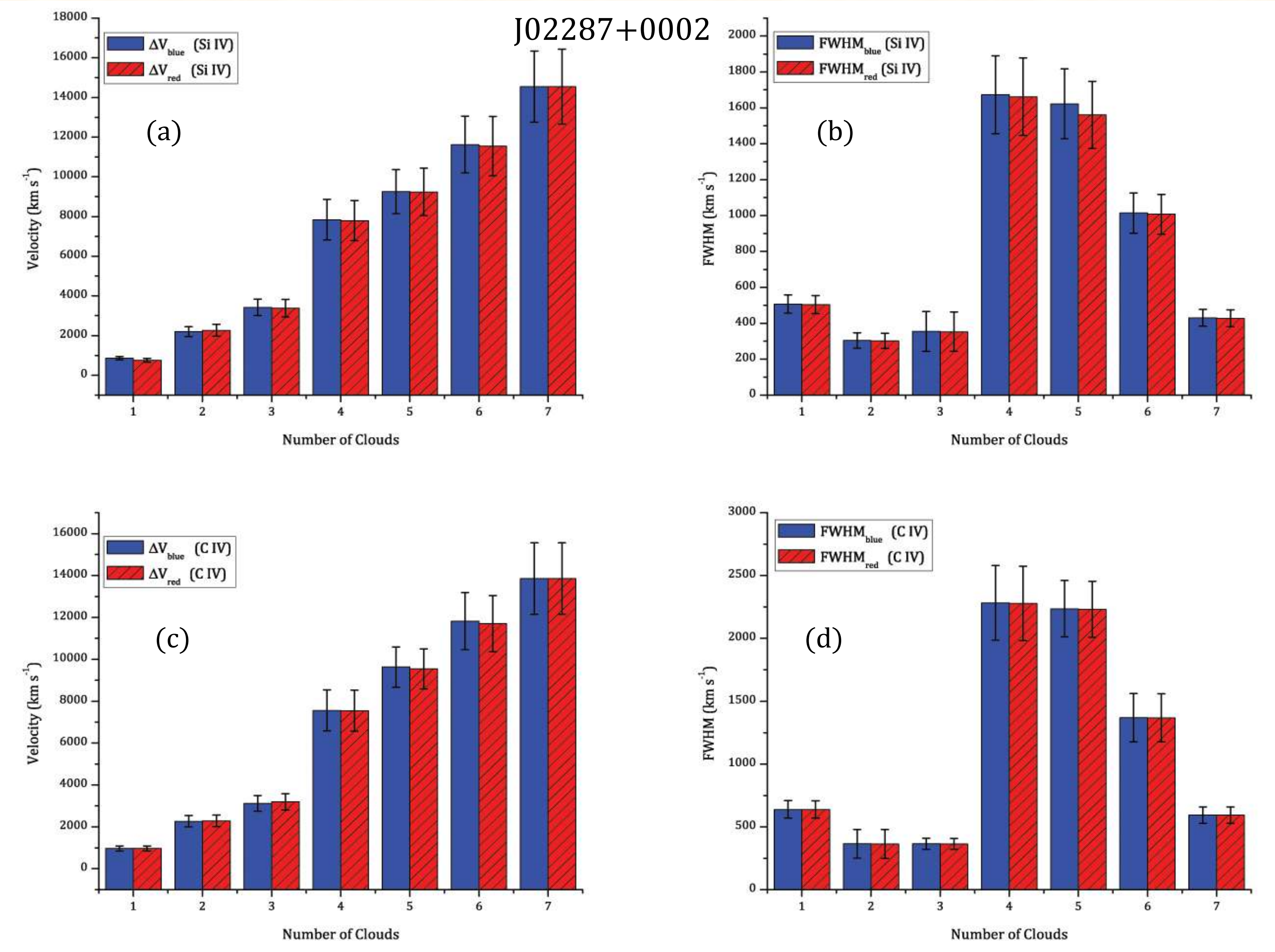
I) Criteria between the members of a doublet
(e.g. C IV λλ 1548.187, 1550.772 and Si IV λλ 1393.755, 1402.77).

- The width between the blue and the red member is exactly the same.
- The velocity shift of the blue member is exactly the same as the red component shift (the difference in velocities at line center must not differ from the expected doublet separation by more than one velocity bin)
- For emission lines the ratio of optical depths between the blue and the red member is $\tau_b/\tau_r = 2$ (as dictated by atomic physics).
- For absorption lines this ratio is free to vary $1{:}1 \le \tau_b/\tau_r \le 2{:}1$ (to account for non-black saturation)





(a) ΔV of Si IV blue and red members; (b) FWHM of Si IV blue and red members; (c) ΔV of C IV blue and red member; (d) FWHM of C IV blue and red members in the case of J01225+1339.



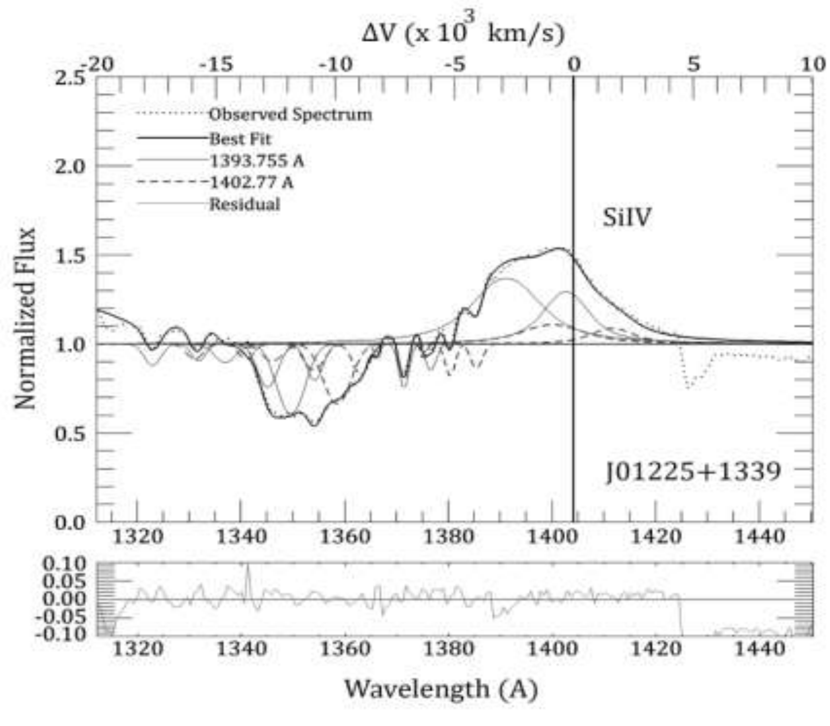
(a) ΔV of Si IV blue and red member; (b) FWHM of Si IV blue and red members; (c) ΔV of C IV blue and red member; (d) FWHM of C IV blue and red member in the case of J02287+0002.

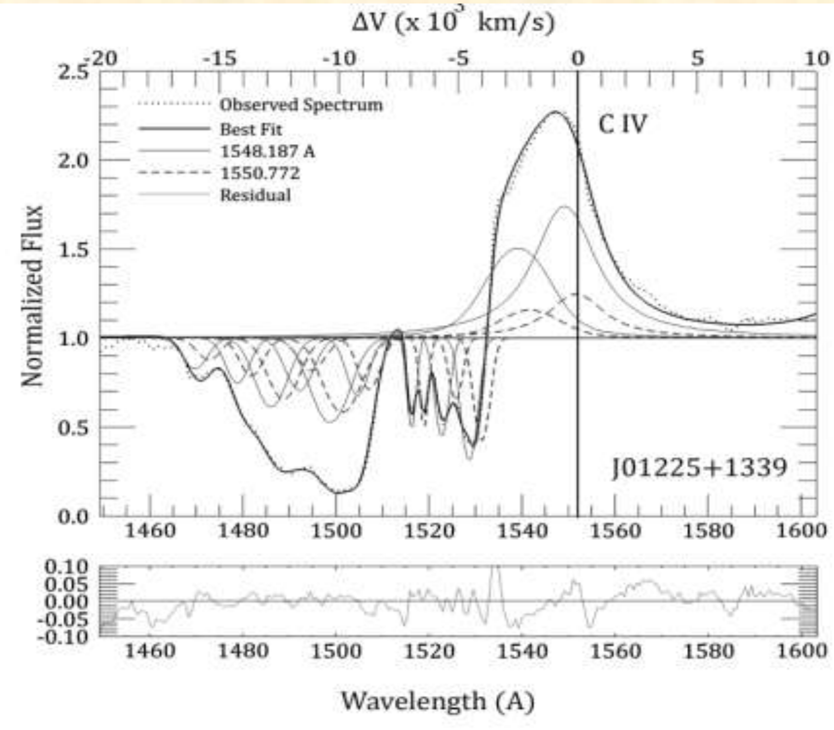
II) Criteria between C IV and Si IV components at the same outflow velocity from the emission redshift.

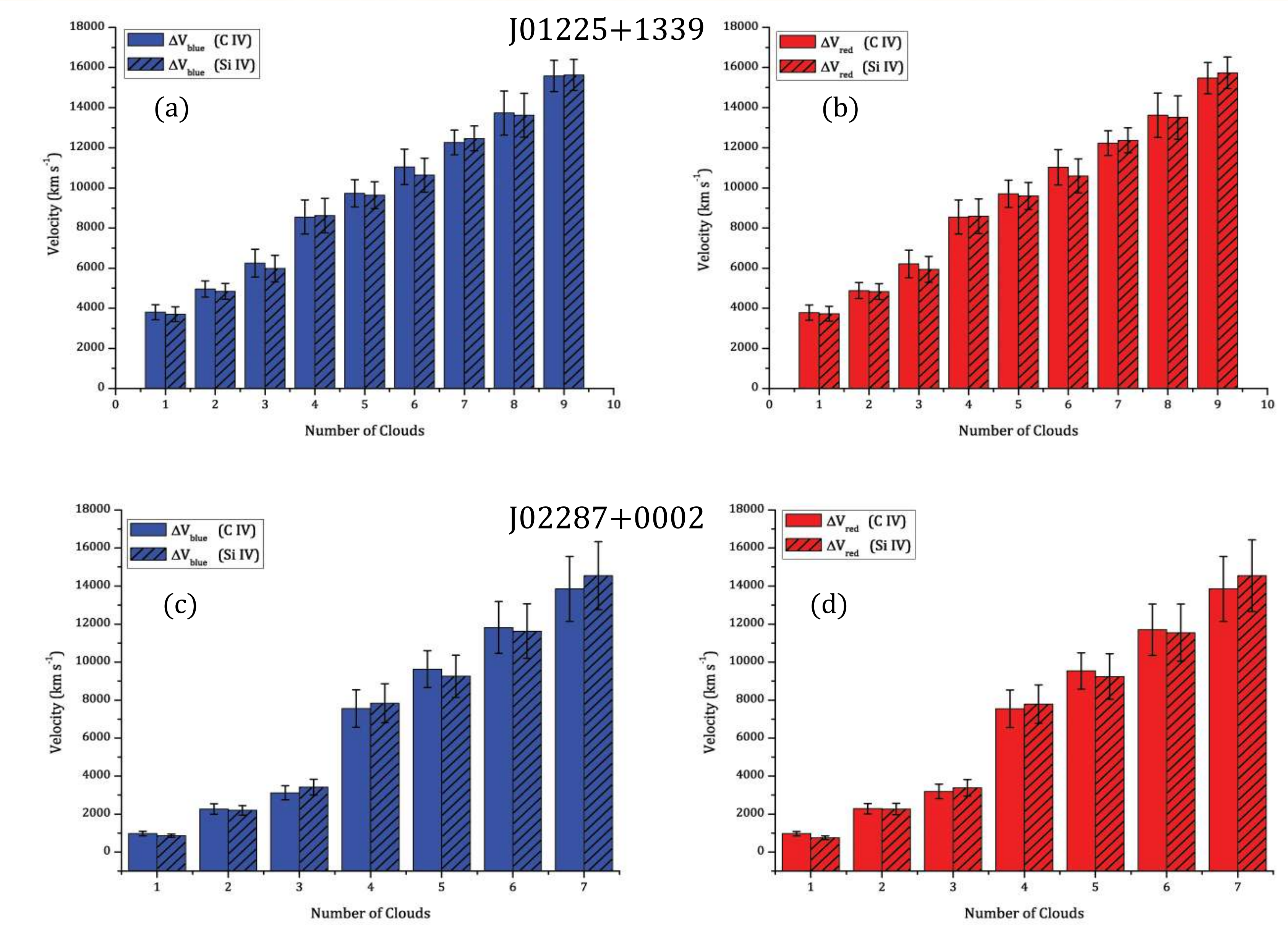
• Both C IV and Si IV BALs follow the same kinematic structure

• Each C IV doublet has its accompanying Si IV doublet at the same outflow velocity. This criterion is not restrictive as C IV might exhibit a doublet in a given velocity shift which might not be present is Si IV and vice versa (the difference in velocities at line center must not differ by more than one velocity bin).

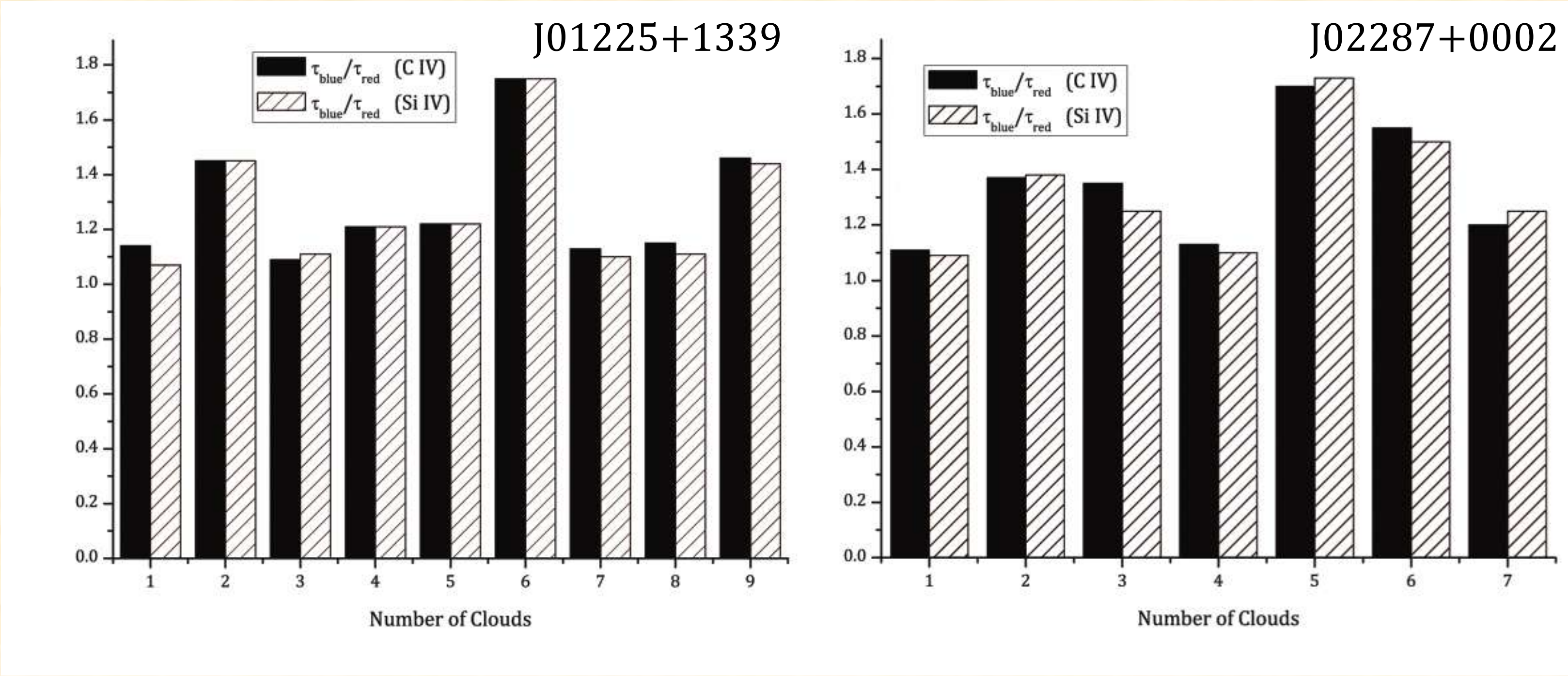
• The ratio of optical depths for a given C IV doublet at a given velocity shift ΔV should be the same as the ratio of optical depths of the corresponding Si IV doublet at the same velocity shift ΔV.







(a) ΔV of blue members of C IV and Si IV in J01225+1339; (b) ΔV of red members of C IV and Si IV in J01225+1339; (c) ΔV of blue members of C IV and Si IV in J02287+0002; (d) ΔV of red members of C IV and Si IV in J02287+0002.


J01225+1339
J02287+0002
τblue/τred (C IV)
τblue/τred (Si IV)
Number of Clouds

Best fits of the Si IV and C IV spectral regions of J01225+1339 and J02287+0002.

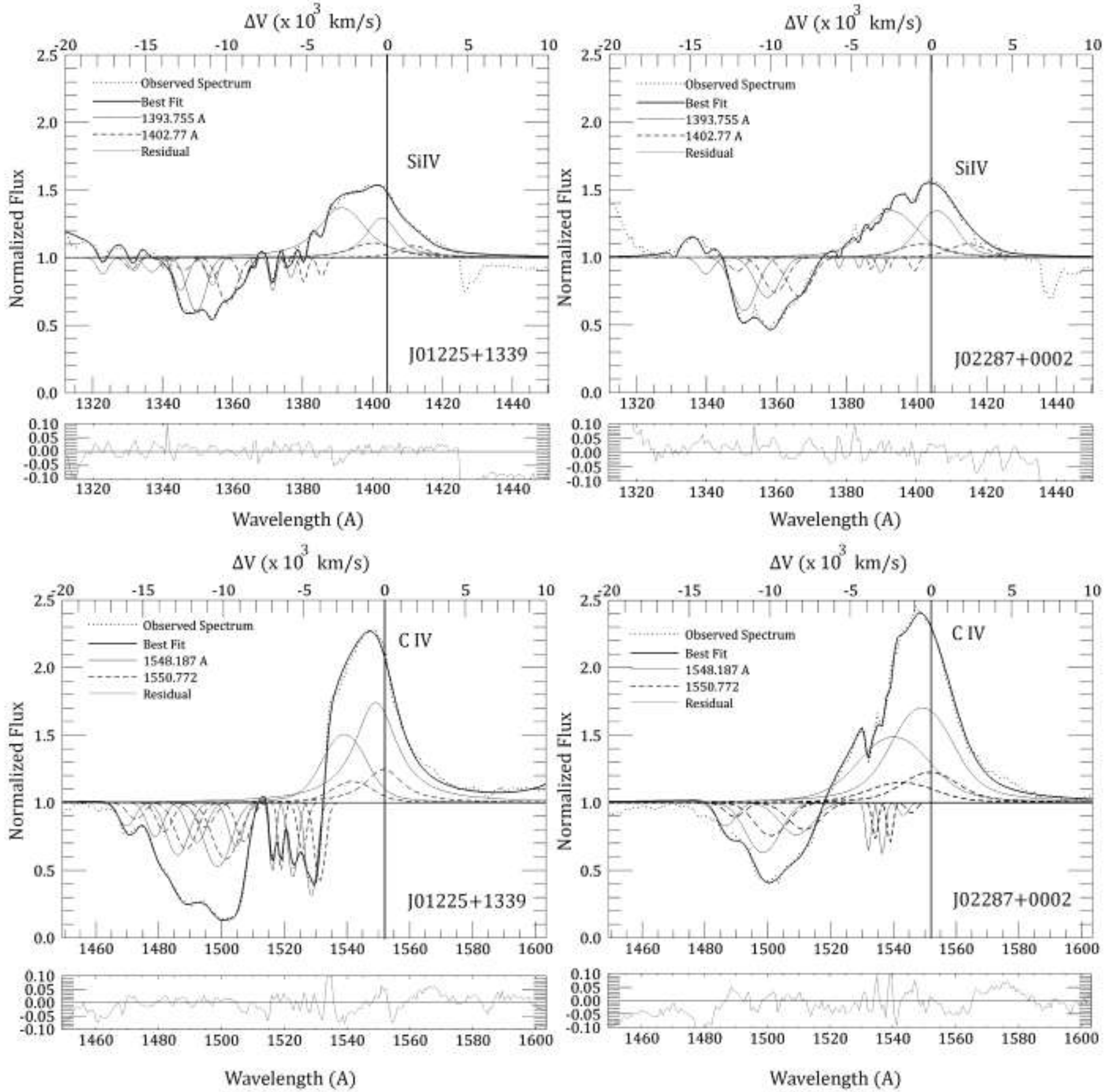
Dotted Line: Observed Spectrum

Thick Black Line: Best Fit

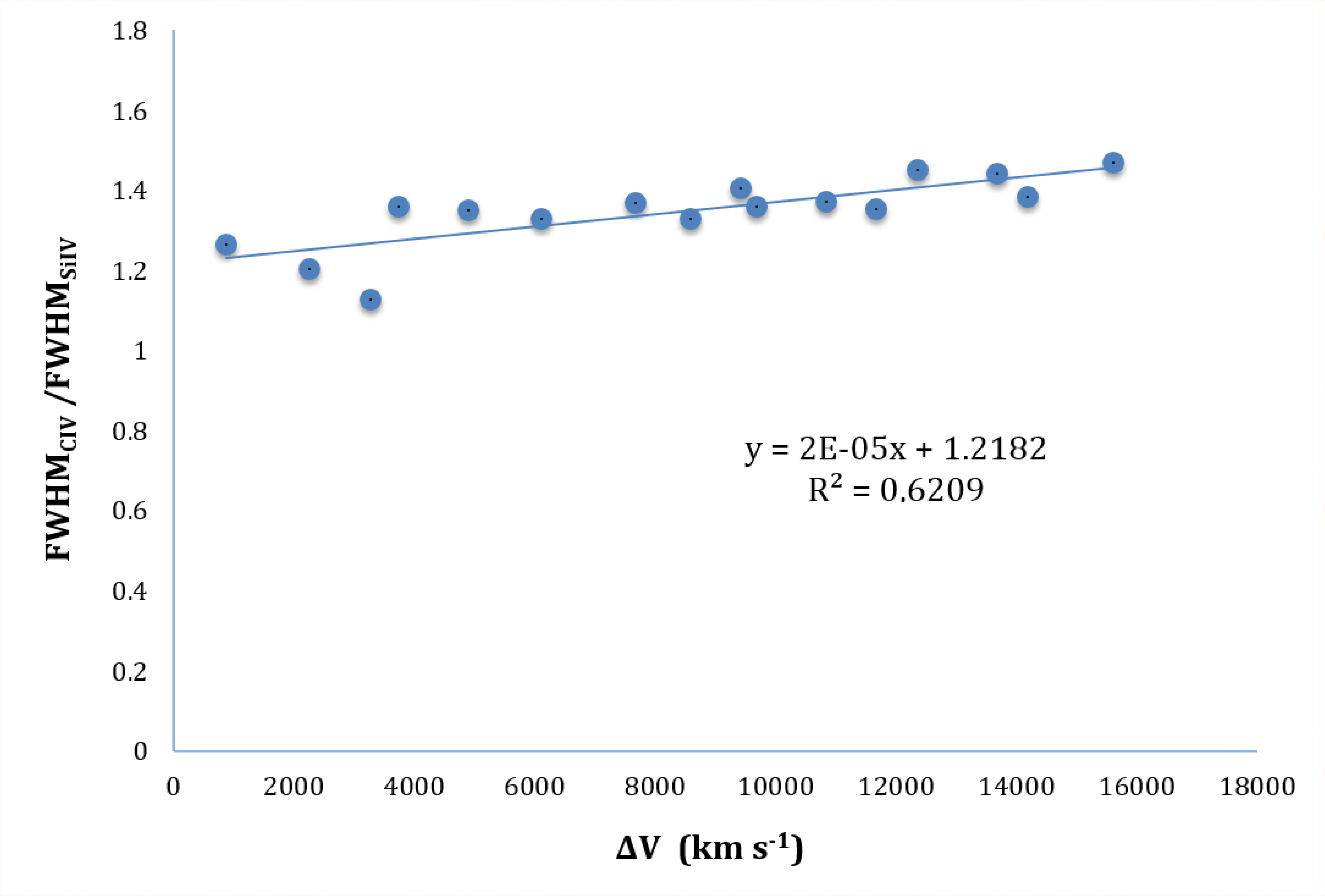
Blue Line: Shorter wvl member of the doublet

Red Line: Longer wvl member of the doublet

Green Line: Residual



J01225+1339												
	Si IV						C IV					
Cloud	ΔV_b (km/s)	ΔV_r (km/s)	$FWHM_b$ (km/s)	$FWHM_r$ (km/s)	τ_b	τ_r	ΔV_b (km/s)	ΔV_r (km/s)	$FWHM_b$ (km/s)	$FWHM_r$ (km/s)	τ_b	τ_r
1	3700±370	3720±370	510±50	520±50	0.16±0.03	0.15±0.03	3800±380	3780±380	700±70	700±70	1.05±0.16	0.92±0.28
2	4840±390	4830±390	460±40	450±40	0.29±0.12	0.20±0.08	4960±400	4880±400	620±50	610±50	0.71±0.16	0.49±0.11
3	5980±660	5940±650	290±30	290±30	0.10±0.07	0.09±0.06	6250±690	6210±690	390±40	380±40	0.72±0.14	0.66±0.17
4	8620±860	8590±860	760±80	760±80	0.23±0.07	0.19±0.06	8550±850	8550±850	1010±110	1010±110	0.40±0.07	0.33±0.07
5	9640±670	9600±670	1270±90	1270±90	0.50±0.20	0.41±0.16	9730±680	9710±680	1730±120	1730±1120	0.64±0.13	0.53±0.11
6	10640±850	10600±850	940±80	930±70	0.28±0.14	0.16±0.08	11050±880	11030±880	1280±110	1280±110	0.35±0.11	0.20±0.06
7	12470±620	12370±620	1010±50	1010±50	0.11±0.03	0.10±0.03	12270±610	12230±610	1460±70	1460±70	0.49±0.06	0.44±0.05
8	13620±1090	13510±1080	710±60	710±60	0.10±0.03	0.09±0.02	13730±1100	13620±1100	1030±90	1020±90	0.30±0.06	0.26±0.03
9	15630±780	15730±790	760±40	760±40	0.13±0.03	0.09±0.02	15580±780	15470±780	1120±60	1120±60	0.19±0.02	0.13±0.01
J02287+0002												
	Si IV						C IV					
Cloud	ΔV_b (km/s)	ΔV_r (km/s)	$FWHM_b$ (km/s)	$FWHM_r$ (km/s)	τ_b	τ_r	ΔV_b (km/s)	ΔV_r (km/s)	$FWHM_b$ (km/s)	$FWHM_r$ (km/s)	τ_b	τ_r
1	860±90	750±100	510±50	5010±50	0.12±0.01	0.11±0.01	970±120	970±120	640±70	640±70	0.10±0.01	0.09±0.01
2	2200±250	2270±300	300±40	300±40	0.11±0.01	0.08±0.01	2270±270	2280±280	370±110	370±110	0.48±0.05	0.35±0.05
3	3420±410	3380±440	360±110	350±110	0.11±0.01	0.08±0.01	3120±370	3190±380	370±40	370±40	0.42±0.04	0.31±0.04
4	7780±1020	7790±1010	1670±220	1660±210	0.35±0.04	0.32±0.03	7560±980	7550±980	2280±300	2280±300	0.27±0.02	0.24±0.02
5	9260±1110	9240±1200	1620±200	1600±190	0.52±0.06	0.30±0.04	9630±960	9550±950	2240±220	2230±220	0.46±0.03	0.27±0.03
6	11620±1430	11550±1500	1010±110	1010±100	0.15±0.02	0.10±0.01	11820±1360	11750±1350	1370±190	1370±190	0.17±0.01	0.11±0.01
7	14540±1790	14540±1890	430±50	430±50	0.05±0.01	0.04±0.01	13850±1700	13850±1700	590±70	590±70	0.11±0.01	0.09±0.01



In a group of 16 components we found that $FWHM_{CIV}/FWHM_{SiIV} = 1.34 \pm 0.1$

This work is part of a more extensive study of a larger sample of BALQSOs in order to extract generalized conclusions with respect to the physical parameters-conditions in BALRs.

Acknowledgments

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Thank you very much for your attention