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Long term variability of Si IV and C IV broad absorption troughs of 10 BALQSOs

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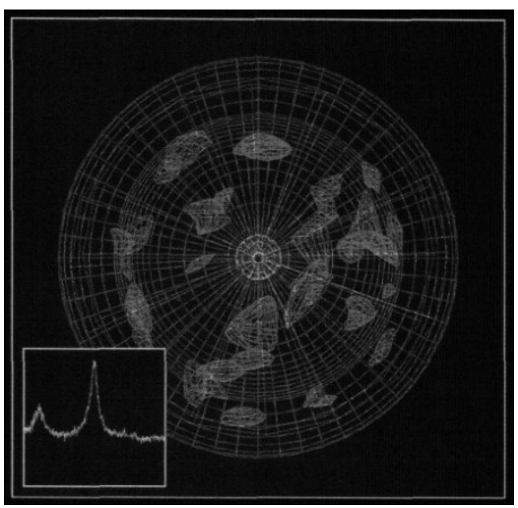
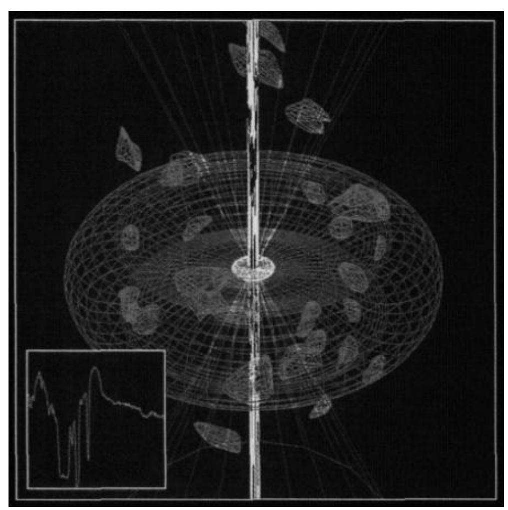
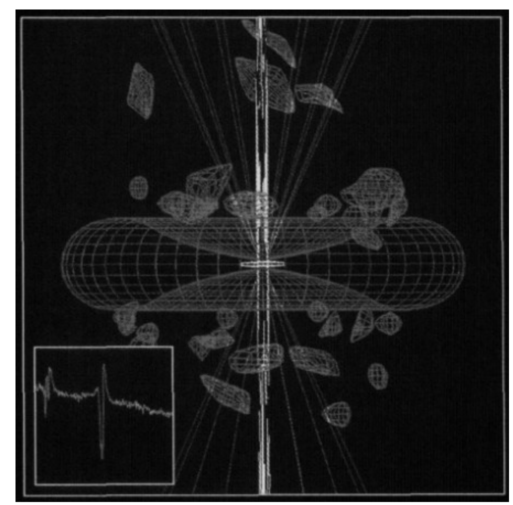




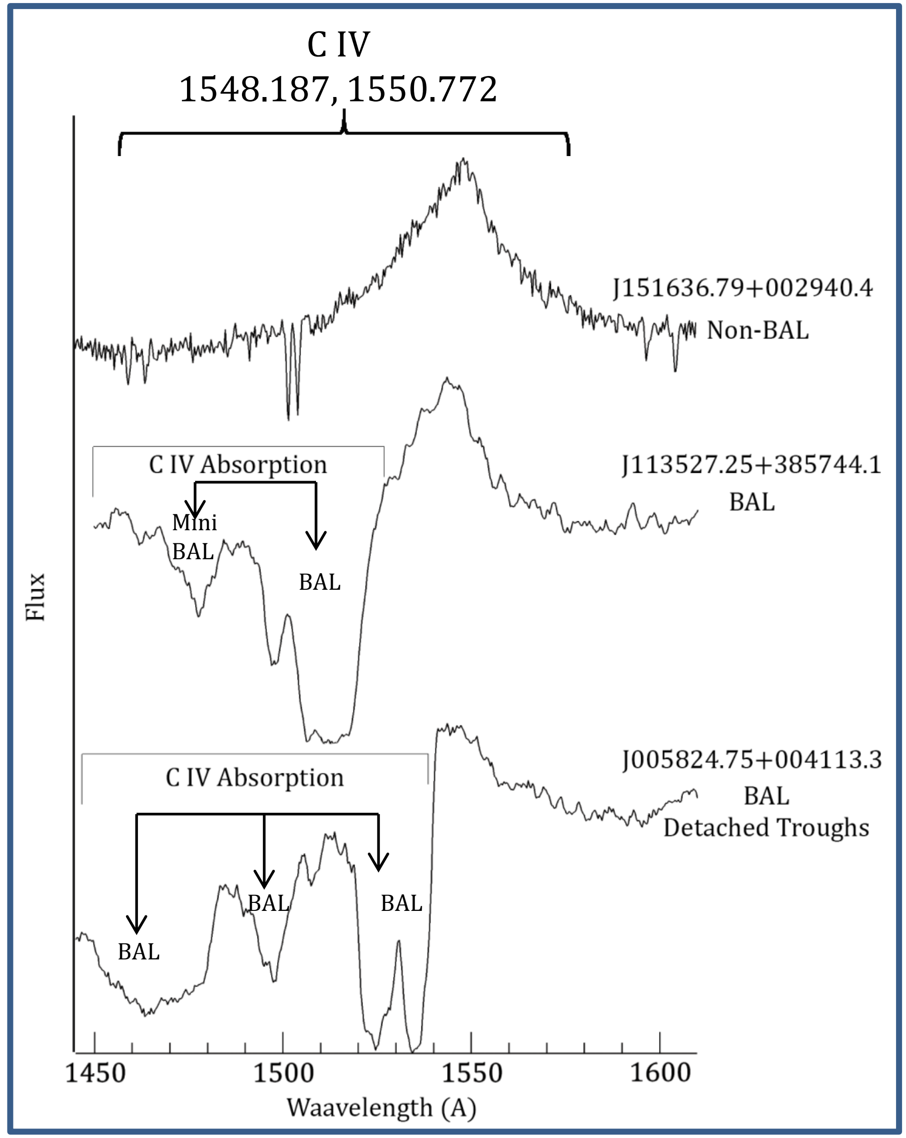


Definition and properties of BALs
(Broad Absorption Lines)

BALs are **broad and complex absorption troughs**, which in the majority of cases are blueshifted with respect to the coresponding emission lines implying outflow velocities from near 0 to as much as ~ 60,000 km/s (~ 0.2 c).

A representative line width is ~10,000 km/s, although there is considerable diversity among BAL profiles.

FWHM: 2000 – 20000 km/s
Voutflow ~ 0.2c
P-Cygni
Detached troughs up to ~ 30000 km/s

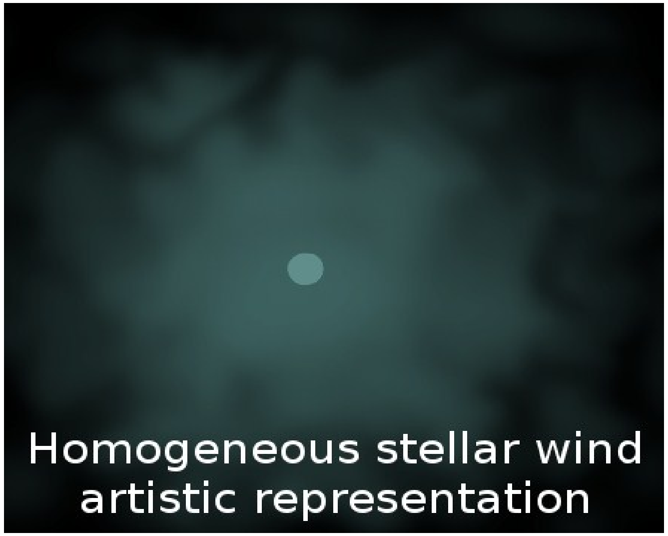


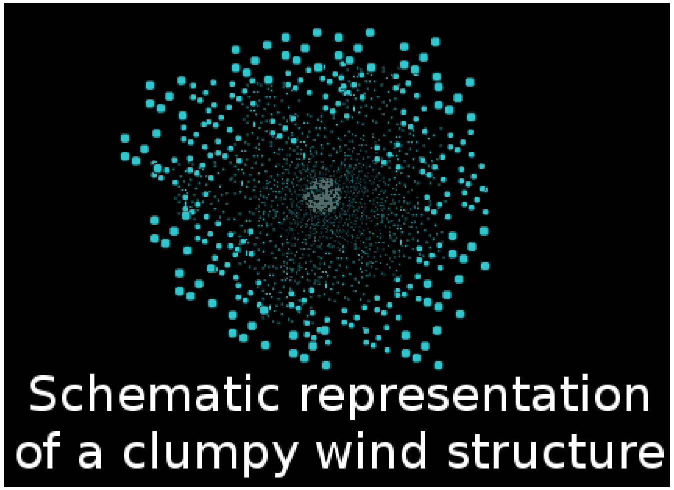
The Origin of BALs

There are two opposing opinions about the origin of BALs:

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

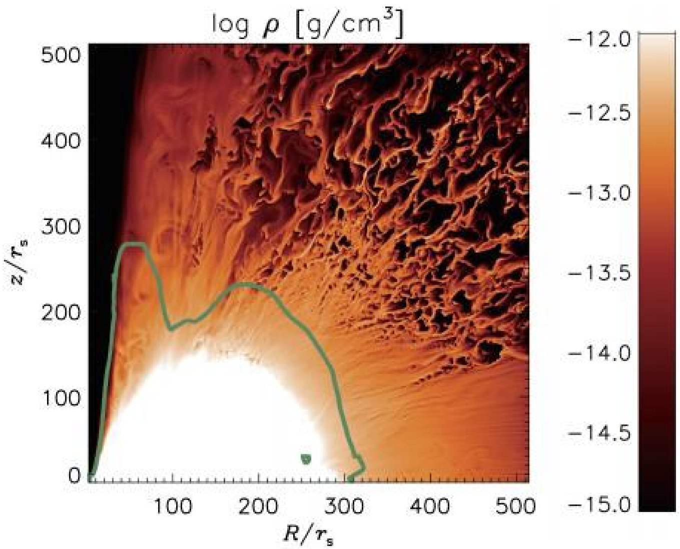
ii. a **flow of many individual clouds – clumpy wind structure** (McKee, & Tarter 1975; Turnshek 1984; Lyratzi et al. 2009, 2010, 2011; Hamann et al. 2013; Capellupo, Hamann & Barlow 2014), which are optically thick and **very small compared with the size of the central continuum source**.



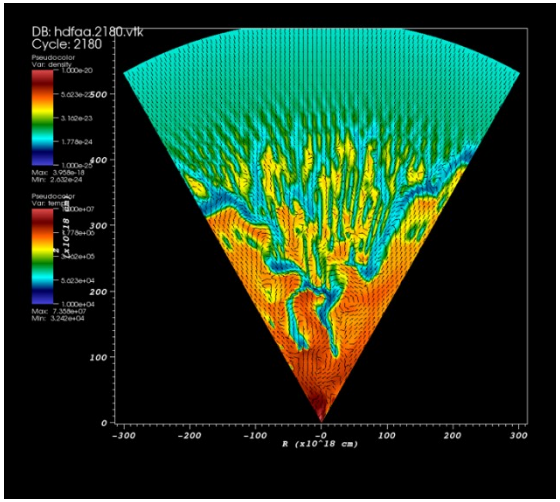


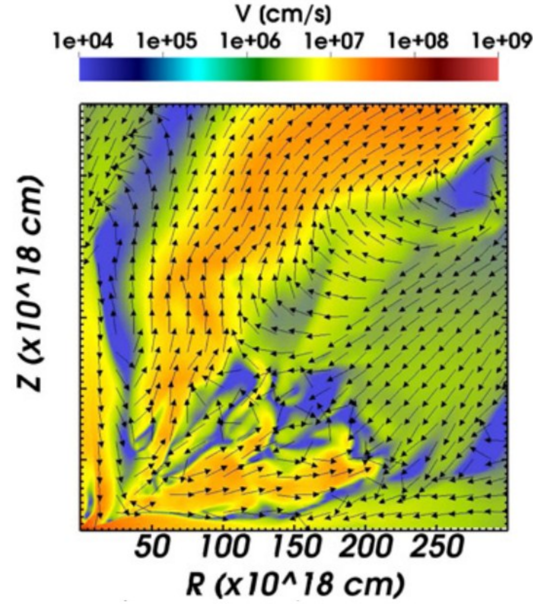
Arguments favoring cloud scenario

1. From a theoretical point of view, clumpy outflows due to instabilities in the highly turbulent medium have been predicted by numerical simulations of Takeuchi, Ohsuga & Mineshige (2013), Moscibrodzka & Proga (2013), Waters & Proga (2016).



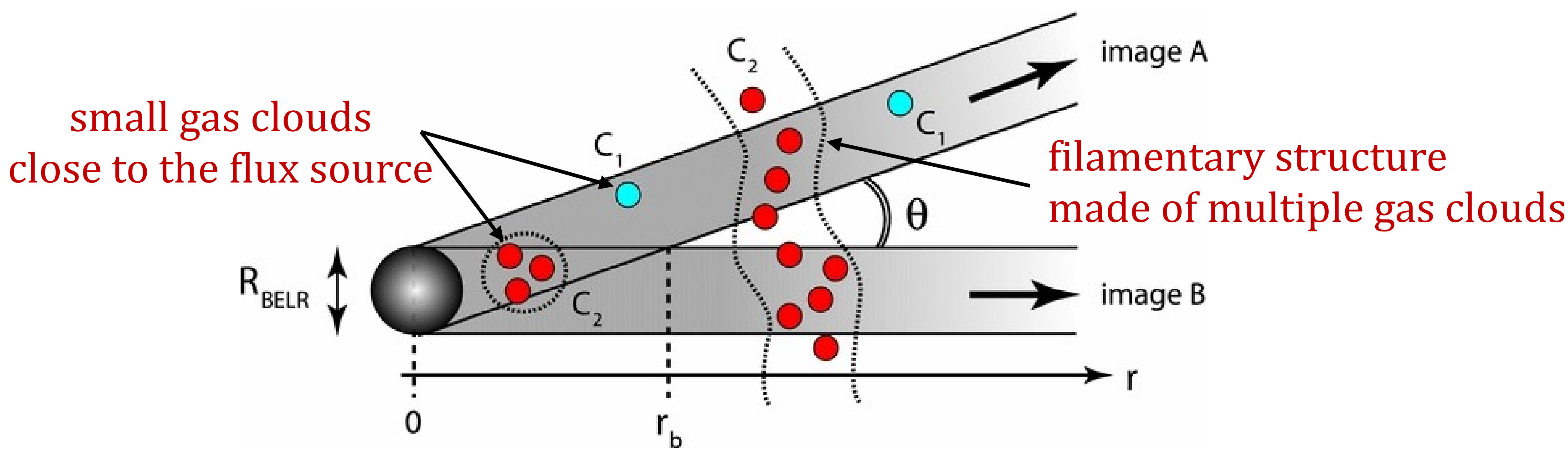
Takeuchi, S., et al. 2013, PASJ,65,88





Moscibrodzka & Proga (2013)
Waters & Proga (2016).

3. Misawa et al. (2014) by observing multiple sightlines with the aid of strong gravitational lensing resolved the clumpy structure of the outflow winds in the quasar SDSS J1029+2623. Through their observations they **rejected the hypothesis of a smooth homogenous outflow and concluded to complex small structures inside the outflow** from the galactic nucleus. They proposed two different structures for the clumpy outflow: a) **small gas clouds close to the flux source** and b) filamentary (or sheet-like) structure made of **multiple clumpy gas clouds.**



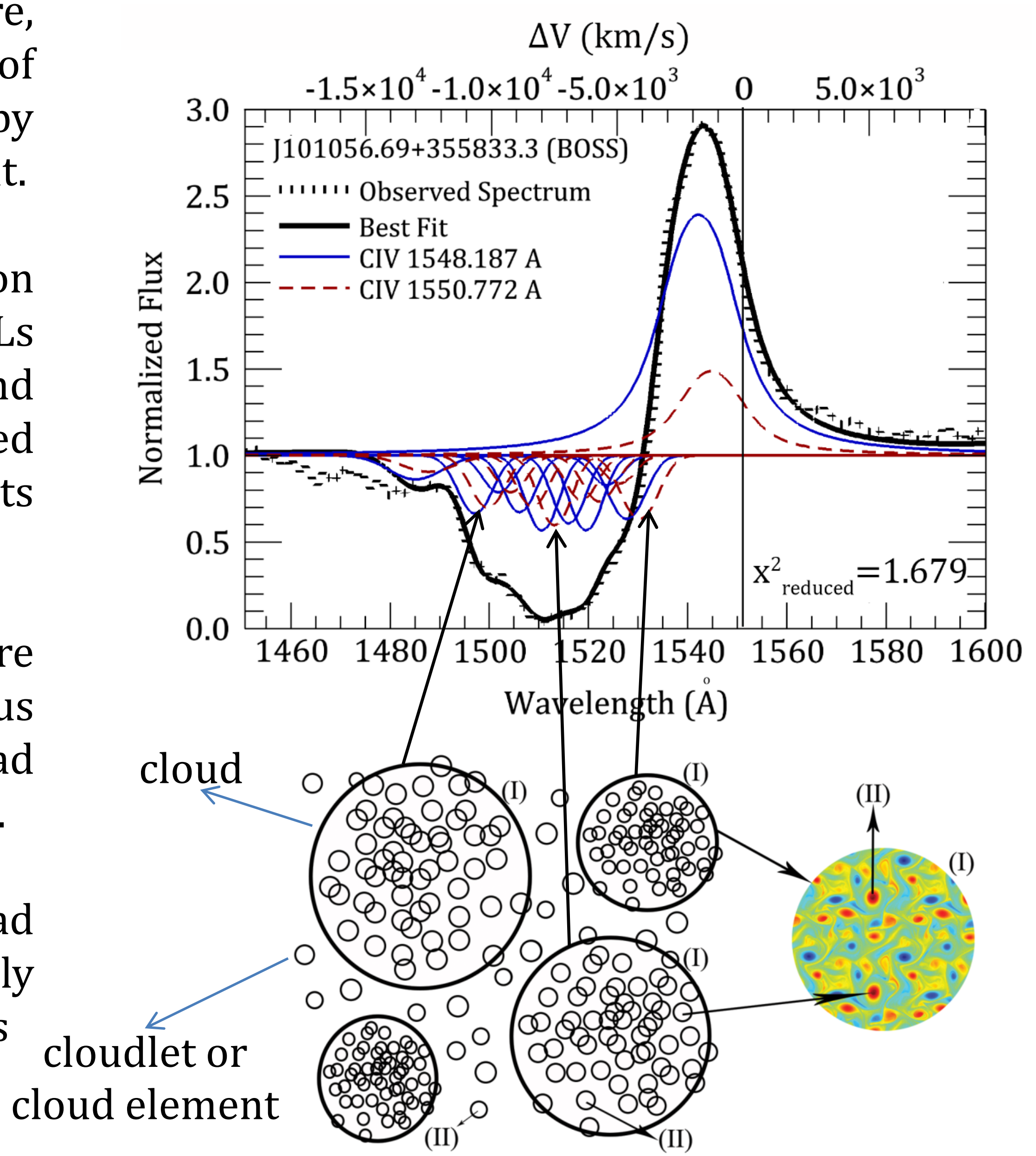
Our Proposed Physical Model (Stathopoulos et al. 2015)

BALs are of multicomponent nature, i.e. BALs are the synthesis of absorption components produced by independent clouds in the line of sight.

As the widths of absorption components we use to simulate BALs are larger than the thermal and microturbulent widths, we proposed that clouds are clusters of subunits called cloudlets or cloud elements.

Cloudlet absorption components are close in velocity space thus overlapping producing broad components corresponding to clouds.

The synthesis of clouds' broad components produce the remarkably broad absorption troughs called BALs



Variability of BALs

BAL variability is commonly manifested as changes in the absorption strength (Hamann et al. 1997a; Srianand & Petitjean 2001; Misawa et al. 2005; Lundgren et al. 2007; Hall et al. 2011; Capellupo et al. 2012a,b, 2013; FilizAk et al. 2013; Vivek et al. 2014) **and/or appearance/disappearance of absorption troughs** (Hamann et al. 2008; Rodrıguez et al. 2011; Vivek et al. 2012a,b; Hamann et al. 2013b).

The variability of these absorption troughs is attributed to one of the following mechanisms:

1. Changes in the acceleration profile and/or geometry of the outflow due to change in the driving force or mass-loss rate
2. Line of sight acceleration of a shell of material from a continual flow
3. **Changes in the ionization state** as a function of velocity [changes in the ionization state of the gas result in change on the column density of the absorbing ion (Wildy et al. 2015)]
4. **Transverse motion of the absorbing cloud(s)** relative to the line of sight (Gabel et al. 2003; Hall et al. 2007; Lundgren et al. 2007; Capellupo et al. 2011; Vivek et al. 2012a).

The most dominant and competing mechanisms are 3 and 4

However, the actual situation may be a complex mixture of changing ionization and cloud movements (Capellupo et al. 2012b).

BAL Variability Studies

Usually, BAL variability studies are performed in two ways:

1. By studying the **variation of the whole absorption trough** by measuring the variability of the fractional EW of the whole trough (Lundgren et al. 2007, Gibson et al. 2010, Welling et al. 2014, Wildy, Goad & Allen 2014).

2. By studying the **variation within portions of a trough**, (breaking BALs to velocity intervals and measuring their variability)
   Interval widths
   Velocity intervals width ≈ 1200 km/s: Capellupo et al. (2011), Gibson et al. (2008).
   Velocity intervals width ≈ 275 km/s: FilizAk. et al. (2013)
   Velocity intervals width ≈ 774 km/s: He Zhi-Cheng et al. (2015)

However, both cases, i.e. studying the variation of the whole absorption trough and studying independently the variation of parts of the absorption defined as described above, have a disadvantage. **The variation measured in these ways does not correspond to the variation of the properties of the physical structures of the BAL QSO environment that create the observed absorption.**

Our proposed method

1. We proposed (Danezis et al. 2003, 2007, 2009, Lyratzi et al. 2007, 2009, Stathopoulos et al. 2015) that **BAL troughs are of multicomponent origin**, i.e. BALs are the product of a series of absorption components produced by a clumpy outflow.

2. In order to analyze Si IV and C IV BAL troughs to the number of components they consist of we use:

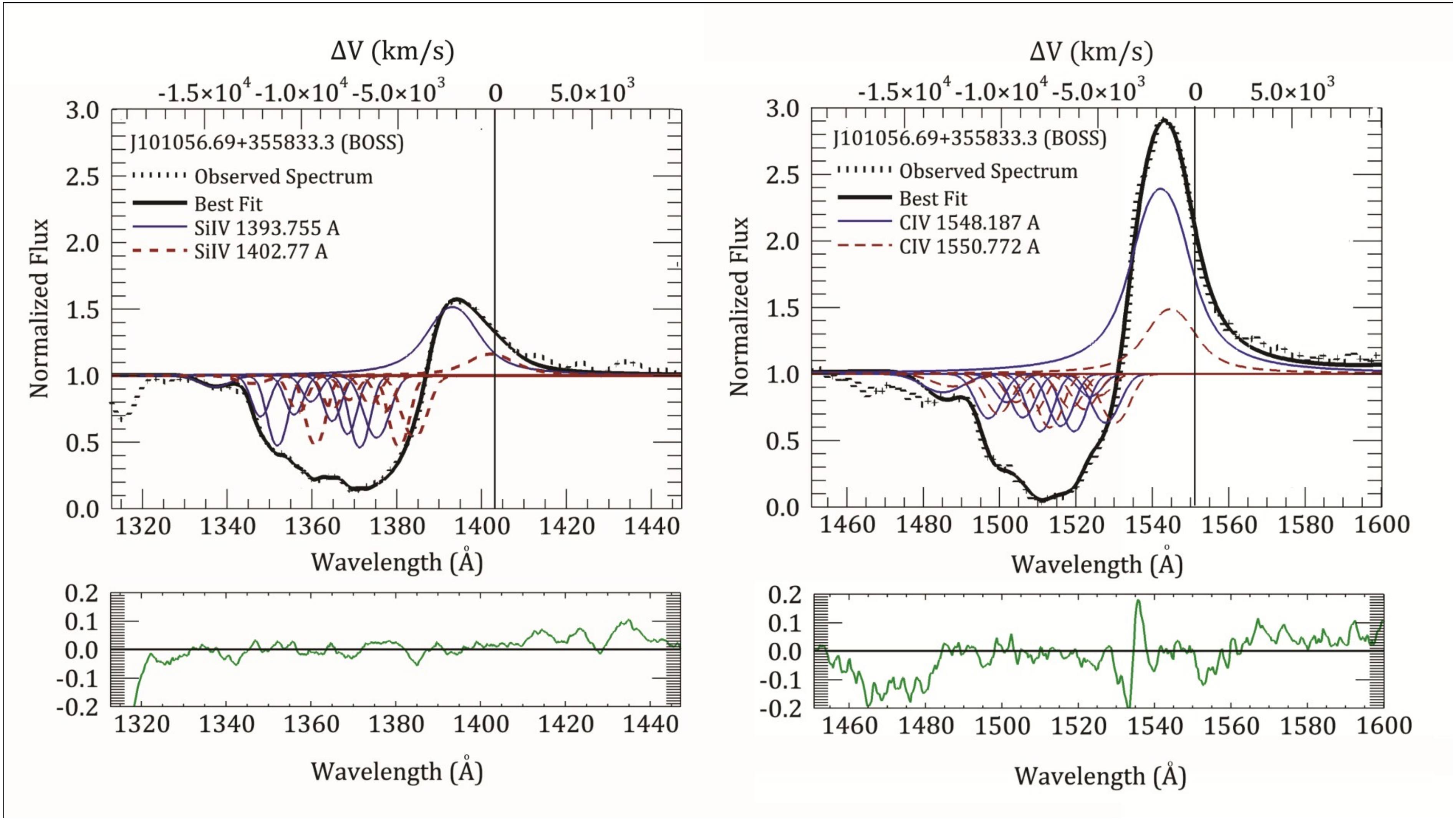
i. the model of Danezis et. al. (2003, 2006, 2007), Lyratzi et al. 2007

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

ii. the fitting criteria proposed by Stathopoulos et al. (2015). These **criteria ensure that the number of components used to reproduce BALs are uniquely determined**.

3. Thus, we have the ability to study the variability of each individual component i.e. the variability of each absorbing system (clump, cloud) in the line of sight.

4. As a result the BAL trough is not studied as a whole, but in parts. However, **these parts are not arbitrarily selected, but each one of them is an actual absorption component which is created by a real physical structure (cloud) in the BAL QSOs environment**. So, each actual absorption component of a BAL can be studied independently.



Dotted line: Observed spectrum

Black line: Best fits of Si IV (left) and C IV (right) broad absorption troughs.

Blue line: short wavelength (blue) components (Si IV λ 1393.755 Å and C IV λ 1548.187 Å)

Red dashed line: longer wavelength (red) components (Si IV λ 1402.77 Å and C IV λ 1550.772 Å)

Green line: residual

In order to compare the strengths of the fitted components between the spectra of two different epochs, we define a measurement of the deviation between two components, in units of σ using the following equation (Ak et al. 2013).

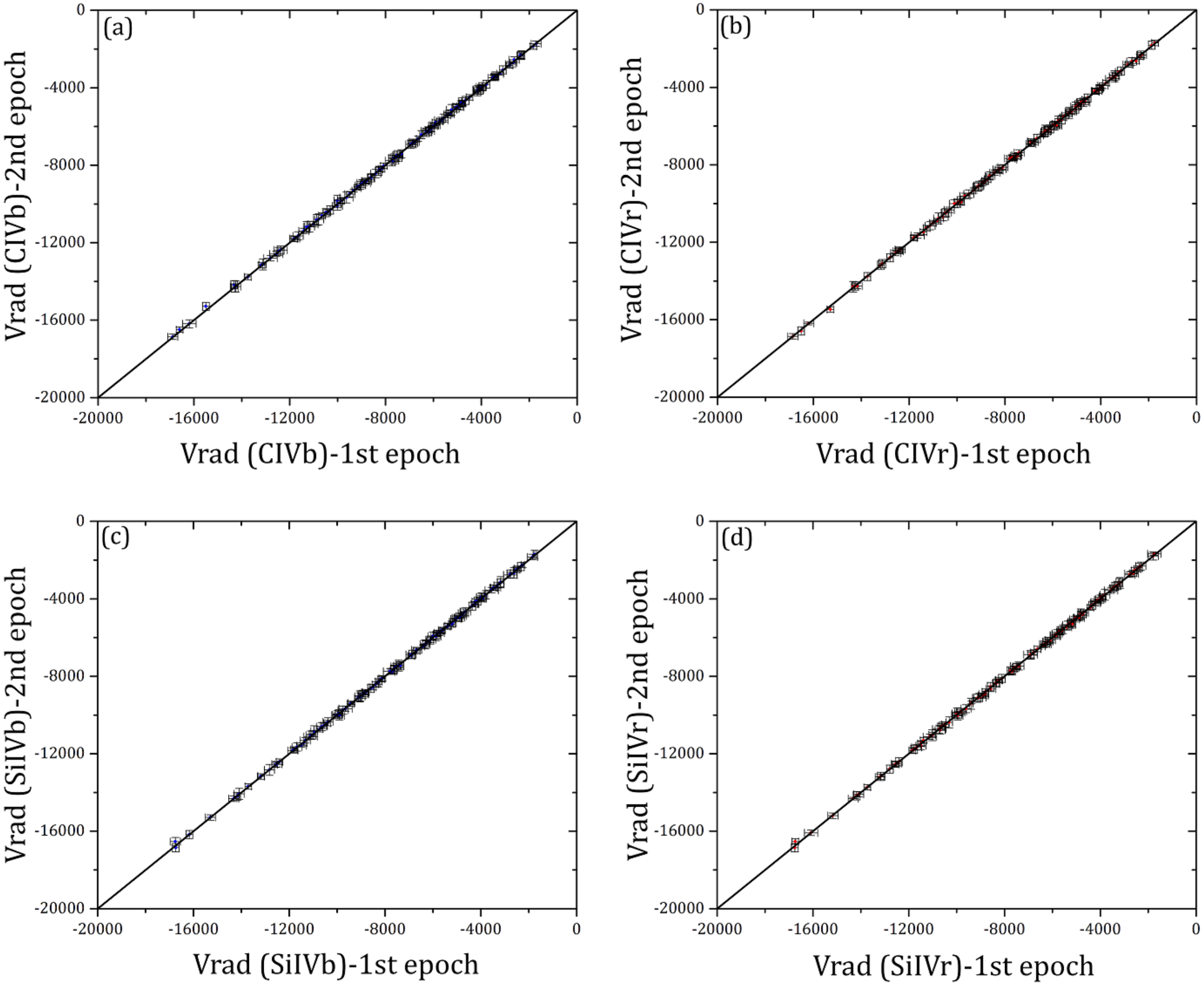
$$N_{\sigma}(\lambda) = \frac{\tau_2 - \tau_1}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

where τ_1, τ_2 are the optical depths (at line centers) of the components under comparison and σ_1, σ_2 are the uncertainties in each optical depth.

We identify variable components of BAL troughs when an absorption component is detected with $|N_{\sigma}|\geq 1$ in the core of the component.

Results

Radial Velocities



1. We do not find any evidence of acceleration or deceleration as the velocity shifts of individual components for all studied BALQSOs do not change as a function of time [consistent with Lundgren et al. (2007), Gibson et al. (2008), Capellupo et al. 2011].

Figure 1.

FWHM

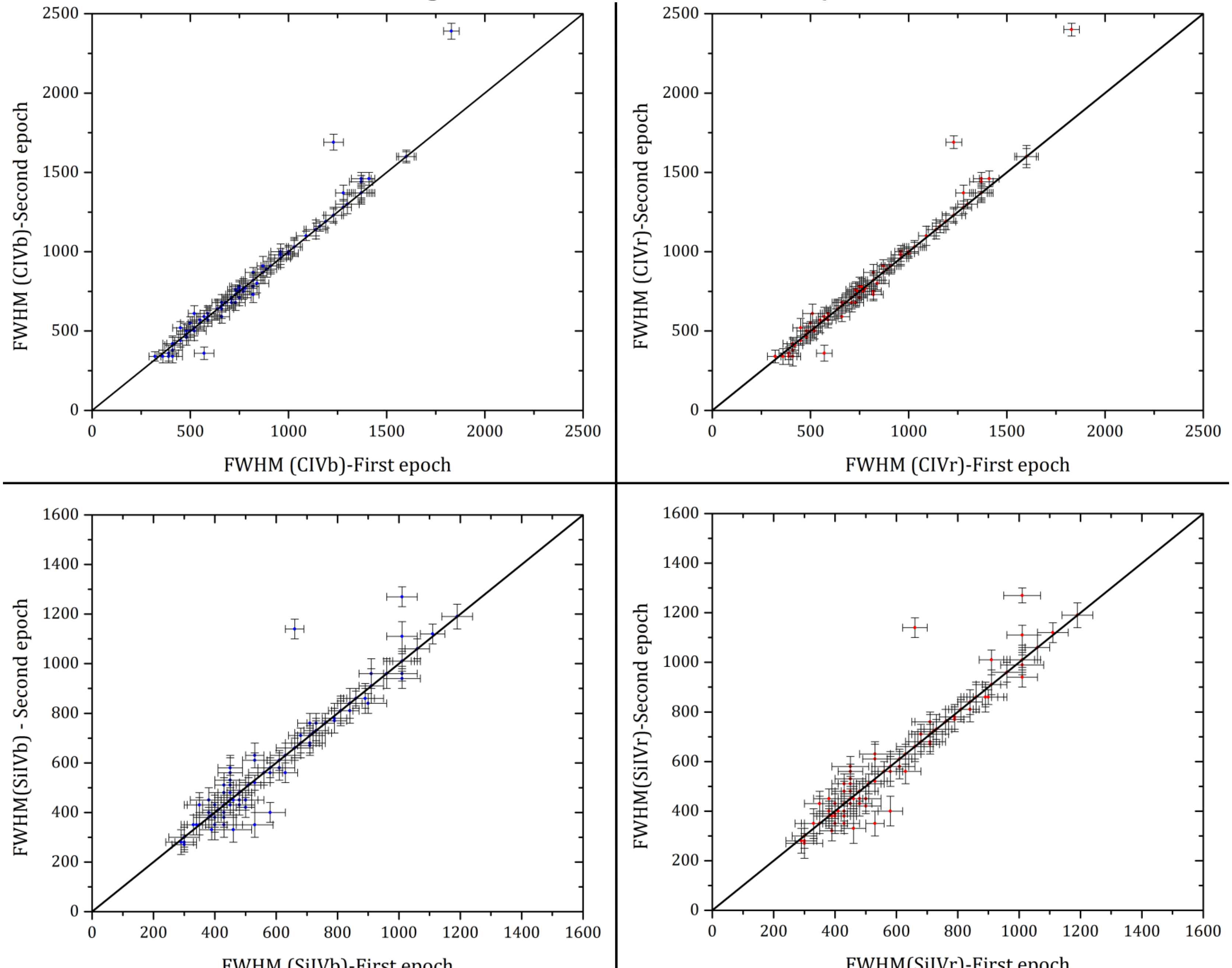
2. FWHMs of individual components remain constant as a function of time.

The widths (FWHM) of the components that the BAL troughs are analyzed into are much larger than the thermal widths for a gas of 10^4-10^5 K.

Therefore the absorbers may have a range of non-thermal line of sight velocities or the so called clouds are clusters of subunits called cloudlets (Stathopoulos et al. 2015). However a mixed scenario of course cannot be ruled out.

The fact that the widths of the components, that compose the BAL troughs of Si IV and C IV, remain constant between two epochs for all BALQSOs, indicates that the structure and/or the internal velocity field of the absorbers remains constant over time.

Figure 2. FWHM variability



Optical Depths

3. All variable components show variations in the optical depths at line centers which are also manifested as variations in the EW of the components.

Because FWHM=const over time, the variations of EW follow exactly the variations of optical depths.

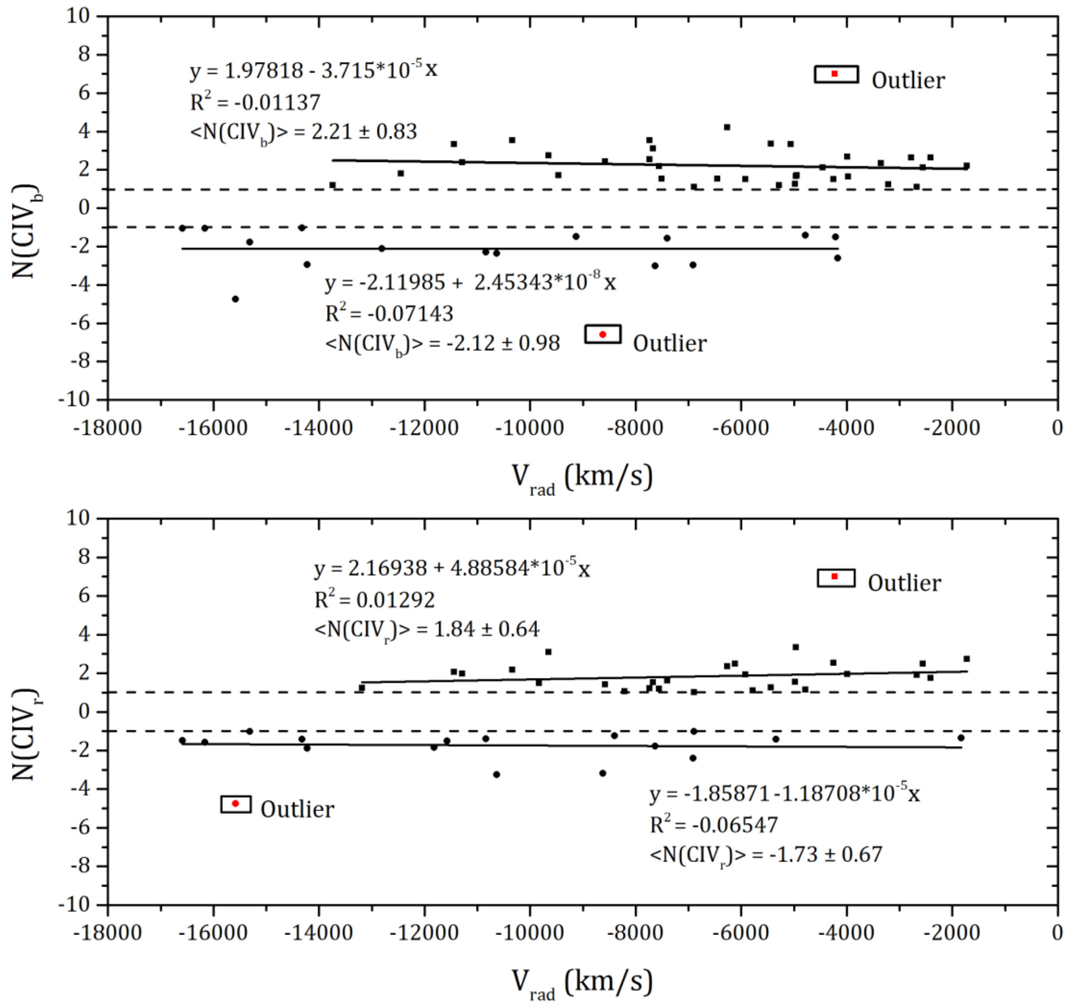


Figure 3. Variability measure N versus radial velocity (only for components with |N|≥1) for C IV blue and red components

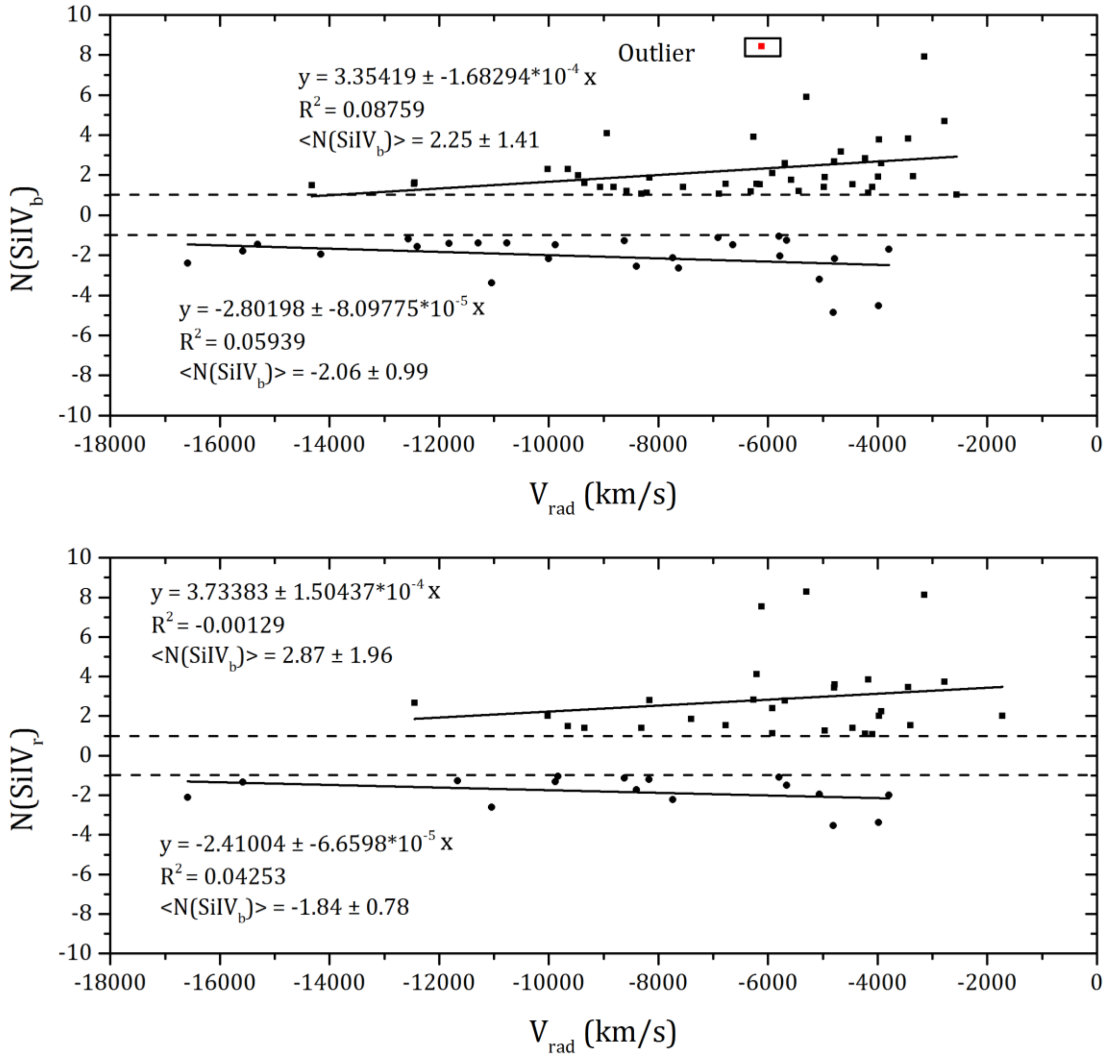
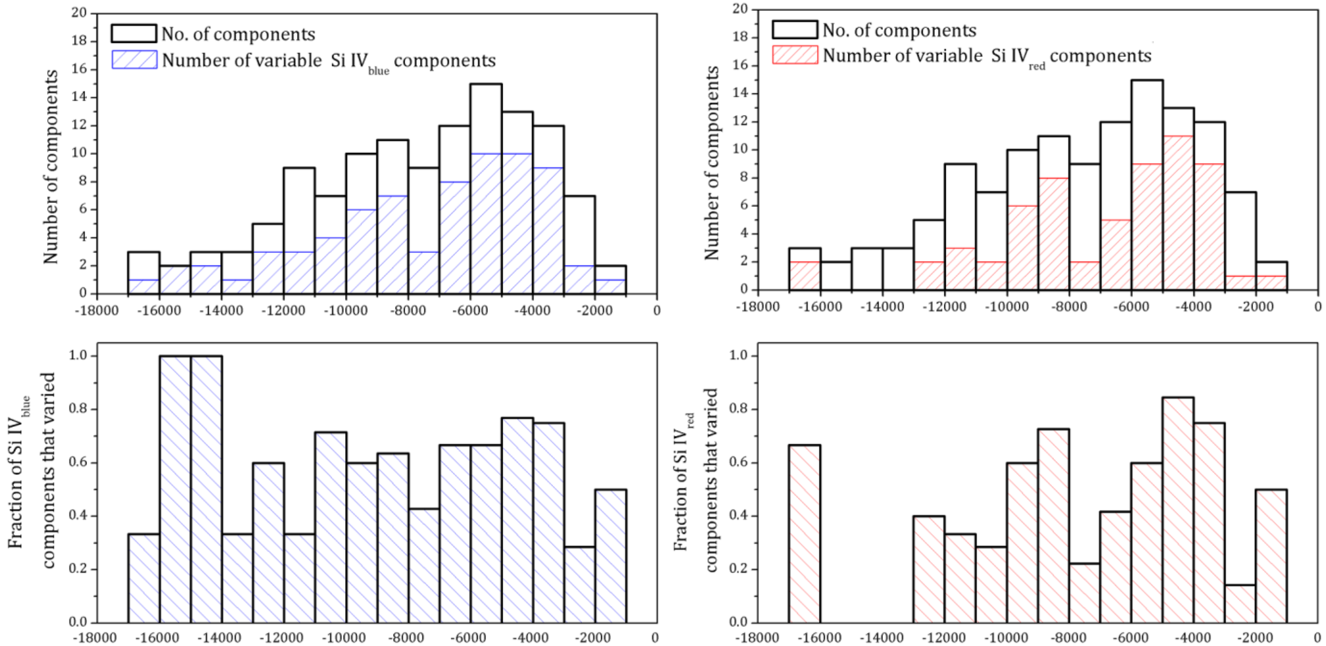


Figure 4. Variability measure N versus radial velocity (only for components with |N|≥1) for Si IV blue and red components

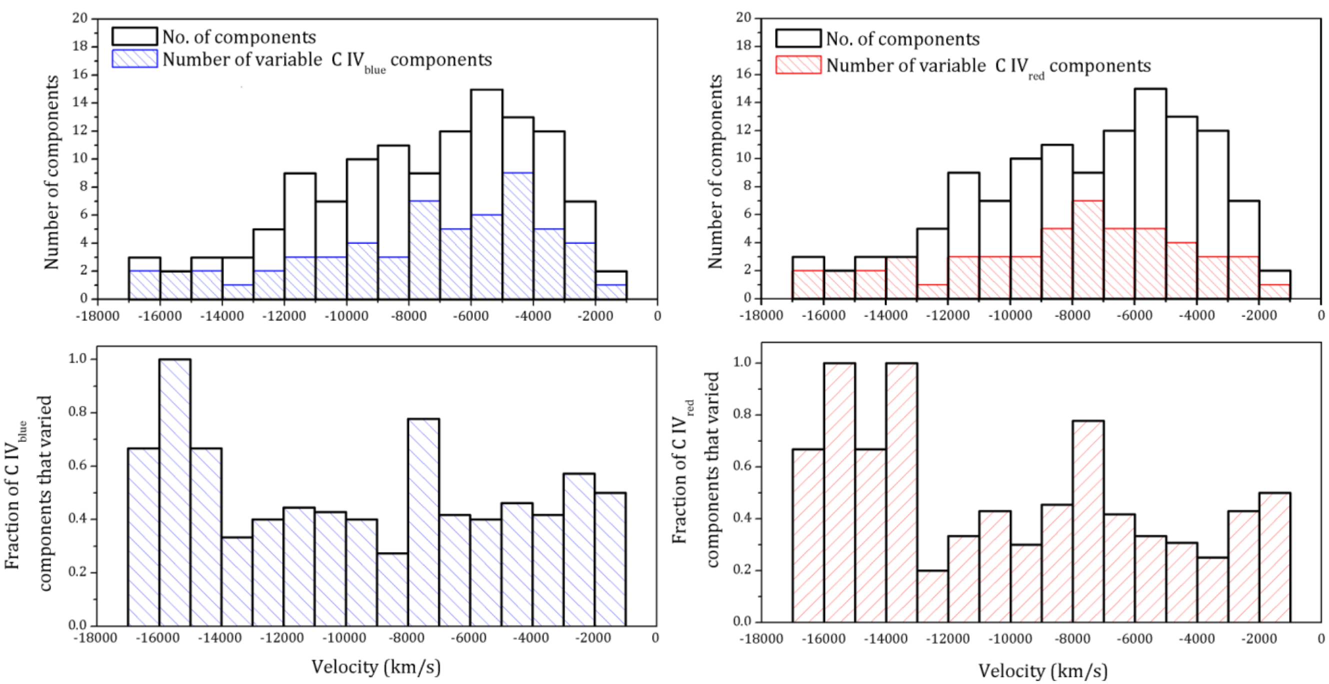
4. Incidence of variability in Si IV and C IV blue and red components



Si IV

Black line: number of observed components in each velocity bin.
Dashed line: number of variable components in each velocity bin

Fraction of variable components (number of variable components divided by the number of observed components)



C IV

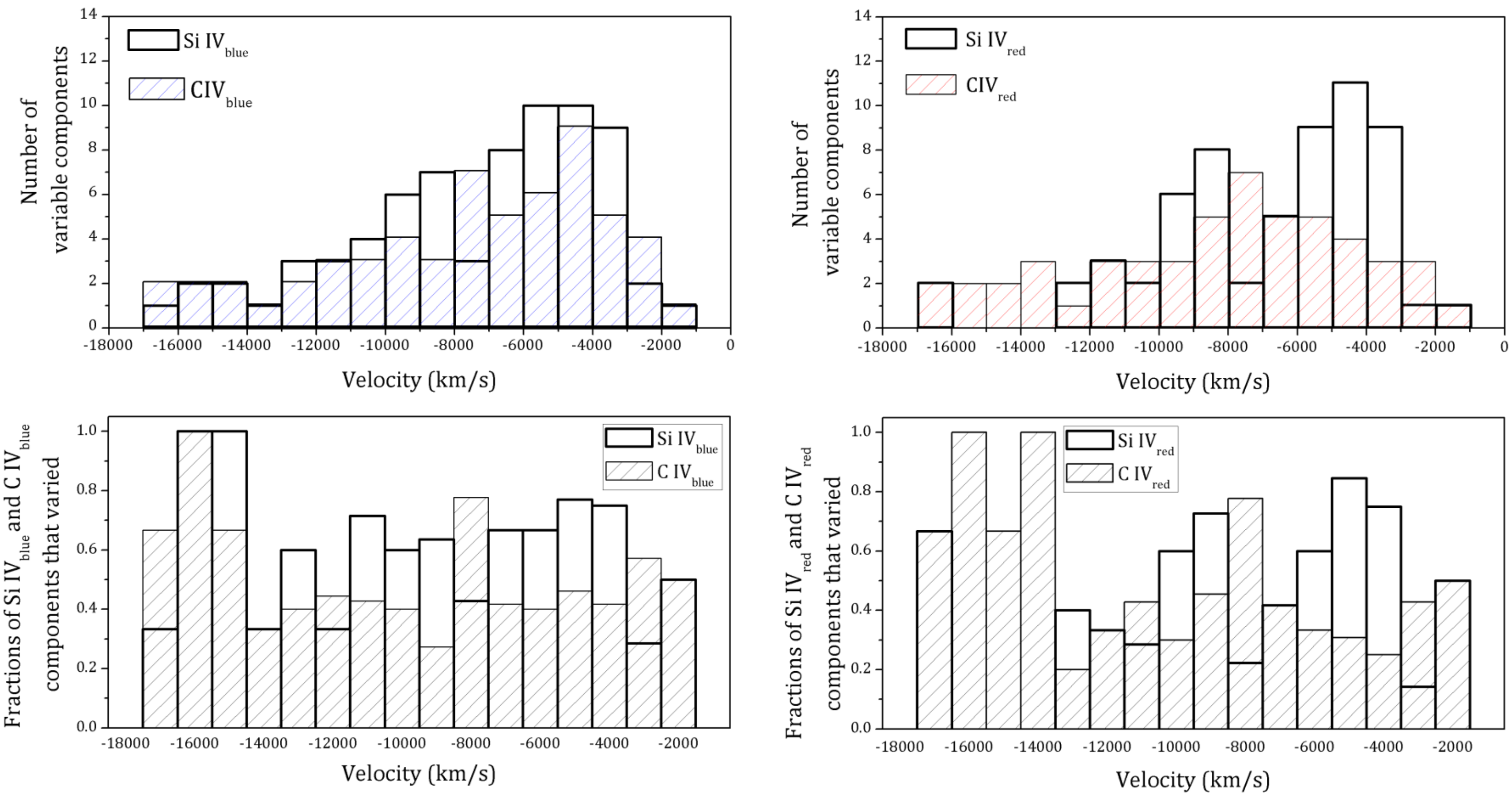
Black line: number of observed components in each velocity bin.
Dashed line: number of variable components in each velocity bin

Fraction of variable components (number of variable components divided by the number of observed components)

Figure 6

Upper panel: Comparison between the number of variable Si IV_{blue} and C IV_{blue} components (left) and of $SiIV_{red}$ and CIV_{red} components (right).

Lower panel: Comparisons between the fractions of variable Si IV_{blue} and C IV_{blue} components (left) and $SiIV_{red}$ and CIV_{red} components (right)



There might be a weak tendency for more variability in Si iv and C IV at higher velocities, the trend is not statistically significant.

Our comparisons show that over matching velocities, Si IV components have higher incidence of variability than C IV components.

The difference is probably related to different line strengths. In particular Si IV components are generally weaker than C IV components at corresponding velocities, and weaker lines tend to be more variable (Capellupo et al. 2011).

Indeed, over corresponding velocities, Si IV components are, in the majority of cases, weaker than C IV components as shown in Fig. 7.

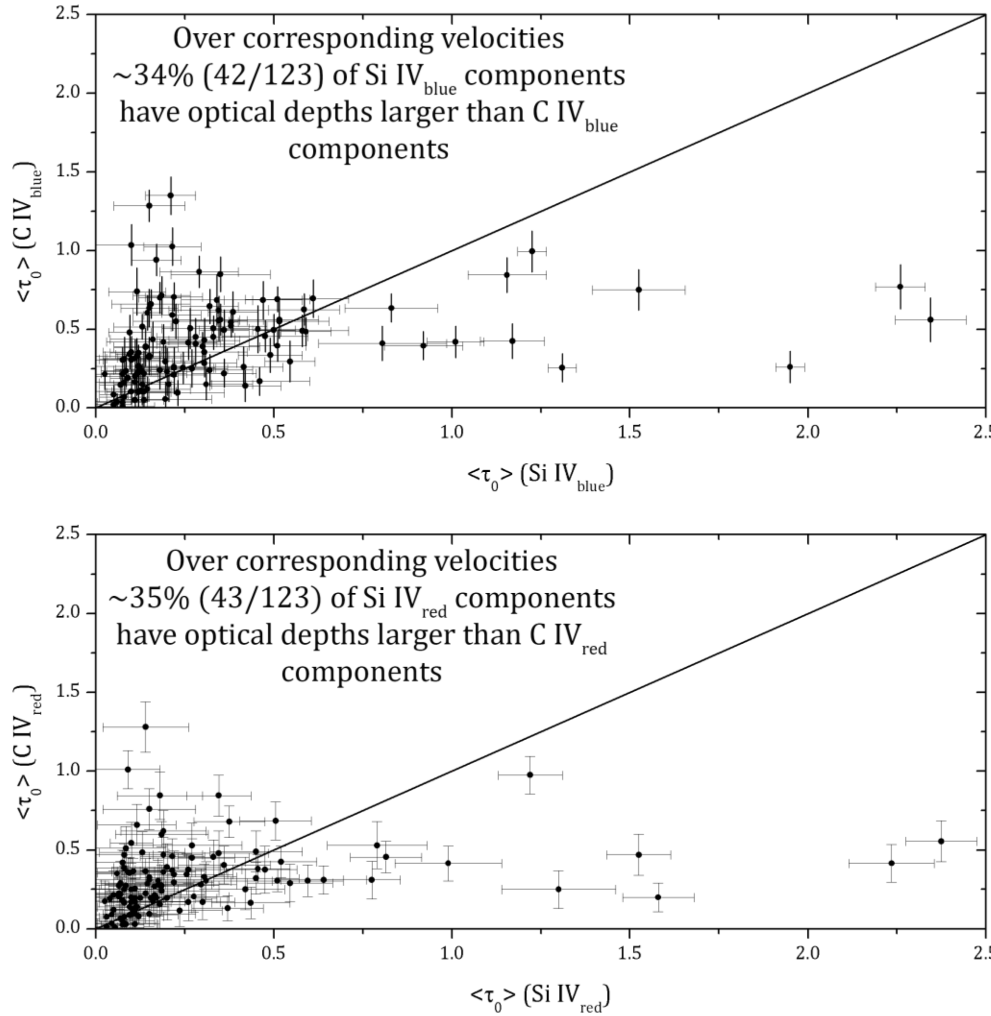


Figure 7.

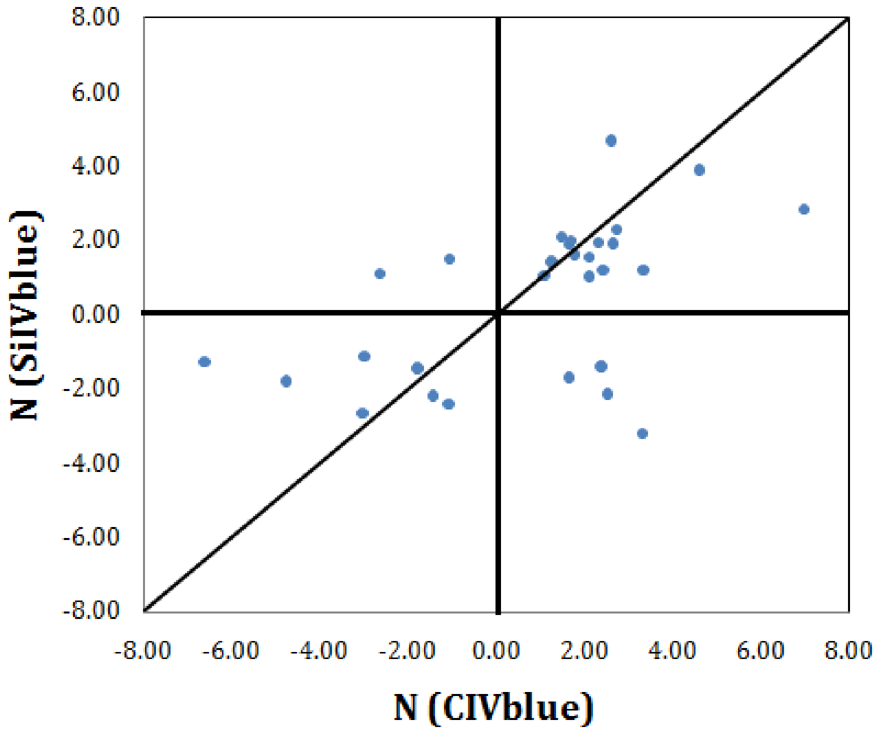
Upper panel: Optical depth of CIVb components versus Si IVb components

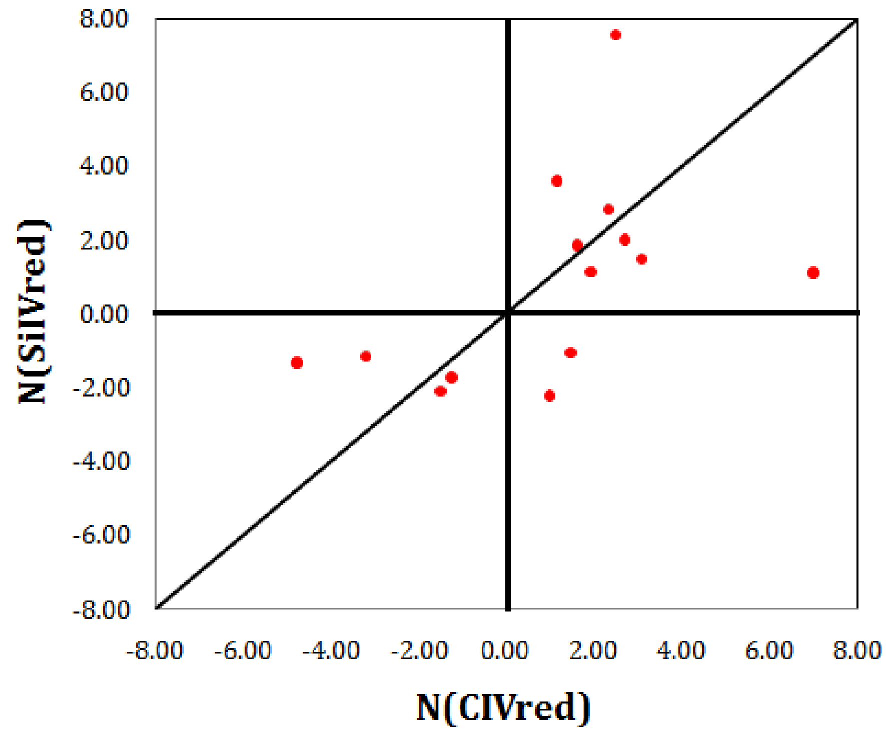
Lower panel: Optical depth of C IVr components versus Si IVr components

5. C IV versus Si IV variability

- If C IV and Si IV have the same covering fraction then C IV should be just as likely to vary as Si IV, which is contradicted by our results.

- Further, if the covering fraction was the same, then the change in strength in the two lines should be the same, which is contradicted by our results in the following figure.





- In the majority of cases, in the same quasar, at velocities where both Si IV and C IV varied, the changes occur in the same sense (both strengthen or weaken-coordinated variability) but the changes in strength are not the same. There are only 6 components (6 out of 38 ~ 16%) which do not follow this pattern. This fact points towards different covering fractions between C IV and Si IV.

- We observe in the same Quasars, Si IV components that vary without variable C IV components at the same velocity and vise versa.

  (From 70 Si IV_{blue} variable components and 54 C IV_{blue} variable components, 30 are variable over matching velocities.

  From 45 Si IV_{red} variable components and 45 CIV_{red} variable components only 15 are variable over matching velocities.)

- According to many researchers [Barlow & Sargent (1997); Hamann et al. (1997, 2001); Ganguly et al. (1999); Hamann & Sabra (2004); Gabel et al. (2005, 2006); Arav et al. (2008)], **clouds can have different covering fractions in C IV and Si IV. Thus, Si IV may trace a different area of the outflowing gas clouds than CIV.**

- If Si IV is tracing a smaller area of the gas cloud than C IV and this cloud is moving across our line-of-sight, then Si IV absorption would generally be more variable (in agreement with our results). Furthermore, if the covering fractions are different for each ion, then the change in covering fraction, as well as the change in strength of the absorption lines, for each ion can also differ. A smaller covering fraction in Si IV would be consistent with the results of Figure 7 which shows that Si IV lines are generally weaker than C IV lines.

6. **BAL variability occurs in only individual components of the BAL trough. This fits naturally in a scenario where movements of individual clouds, or substructures in the flow, are causing changes in covering fractions in the absorption lines (consistent with Lundgren et al. 2007, Gibson et al. (2008) , Capellupo et al. 2011, 2012).**

   In general, changes in ionization would result in more global changes in a BAL troughs rather than changes in individual components of the trough.

7. **In 8 out of 10 BALQSOs, within the same trough, individual components strengthen while others weaken. This can be explained in a moving cloud scenario, as it is possible for clouds at different velocities to enter/leave our line of sight at different times. In general, a change in ionization should cause more global changes, rather than changes in small, discrete velocity intervals.**

8. On the other hand, we observe cases in which within the same trough all components become weaker or stronger (coordinated variability). This cannot be explained in a cloud scenario as the movements of clouds at different velocities corresponding to different spatial locations, would have to be coordinated which seems unlikely.

   However according to Misawa et al. (2007) when substructures in the outflow vary in concert we cannot rule out the covering fraction explanation although coordinated changes favor changes in ionization.

9. We observe C IV and Si IV doublets in which the blue component strengthens while the red component weakens (or vise versa). If continuum changes were the driver of BAL variability we would expect both the blue and the red component to vary in unison.

10. We find no correlation between continuum variability and BAL variations. By running a Spearman correlation test we do not find any strong piece of evidence correlating the continuum variations ($\Delta f(\lambda_{1500)}$) with the variation of the EWs of Si IV and C IV BAL troughs.

To conclude,

- the cloud interpretation is a more realistic scenario for the origin of BALs
- transverse motions of clouds are the dominant driver of BAL variability

Thank you very much!