Timescale variation of the components that form the C IV and Si IV P-Cygni Profiles in the UV spectrum of the O-star HD 93521

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In collaboration with

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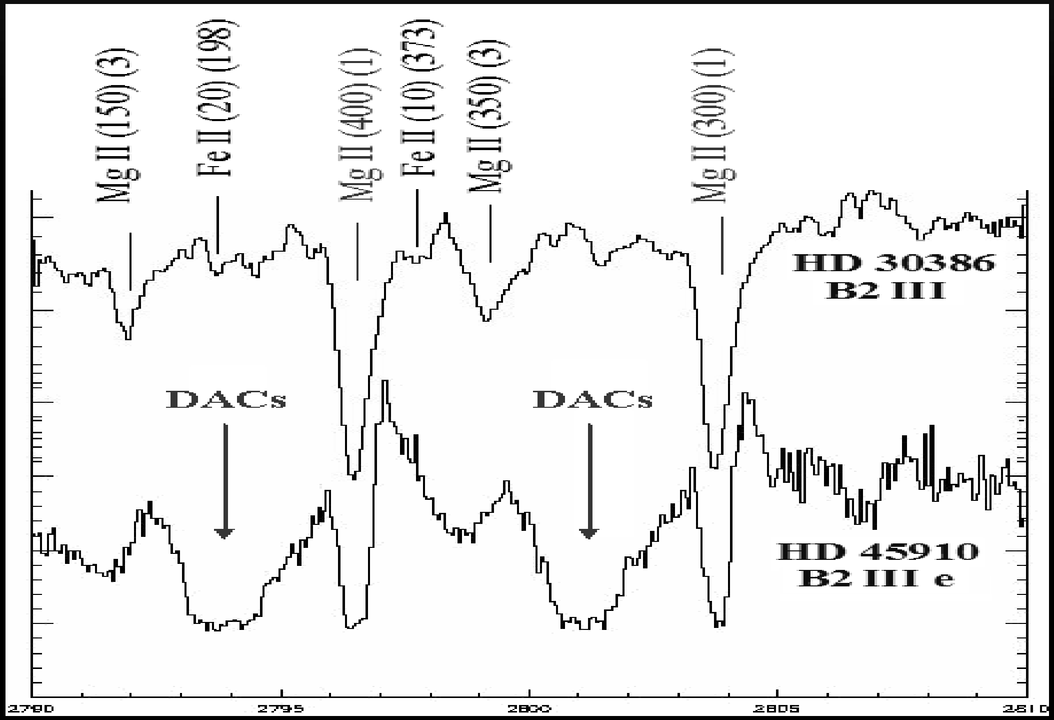
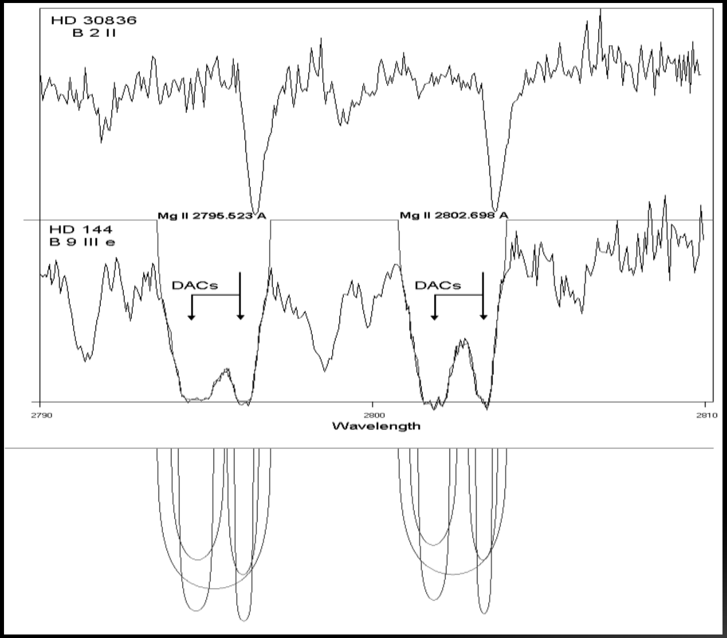
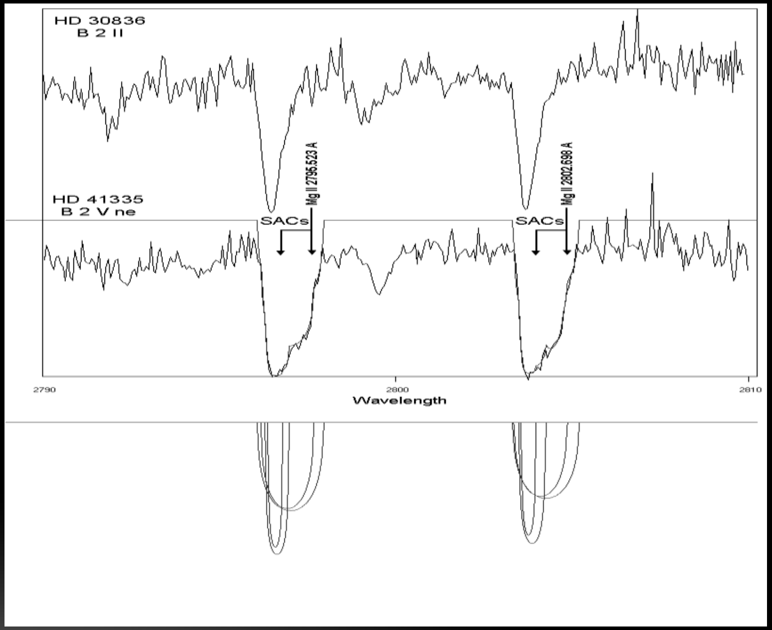
Studding the Hot Emission Stars (O and B stars, T_{eff} ≥10,000 K) we can sometimes detect independent absorption components blueshifted from the corresponding emission lines. We call these absorption spectral lines, **Discrete Absorption Components (DACs) (*)**



(*) Underhill 1975, Henrichs 1984, Underhill & Fahey 1984, Bates & Halliwell 1986, Grady et al. 1987, Lamers et al. 1988, Waldron et al. 1992, 1994, Cranmer & Owocki 1996, Rivinius et al. 1997, Kaper et al. 1996, 1997, 1999, Markova 2000, Cranmer et al. 2000, Danezis, E. et al. 1987, Danezis et al. 2003,

However, DACs are spectral lines of the same ion and the same wavelength as the main spectral line, shifted at different $\Delta\lambda$, as they are created in different density regions which rotate and move radially with different velocities (*). Furthermore, DACs have very complex profiles that we can not theoretically reproduce with a known distribution, such as Gaussian, Voigt, or Lorenzian. In order to explain this complex line profiles we proposed the phenomenon **of SACs (Satellite Absorption Components) (**).**

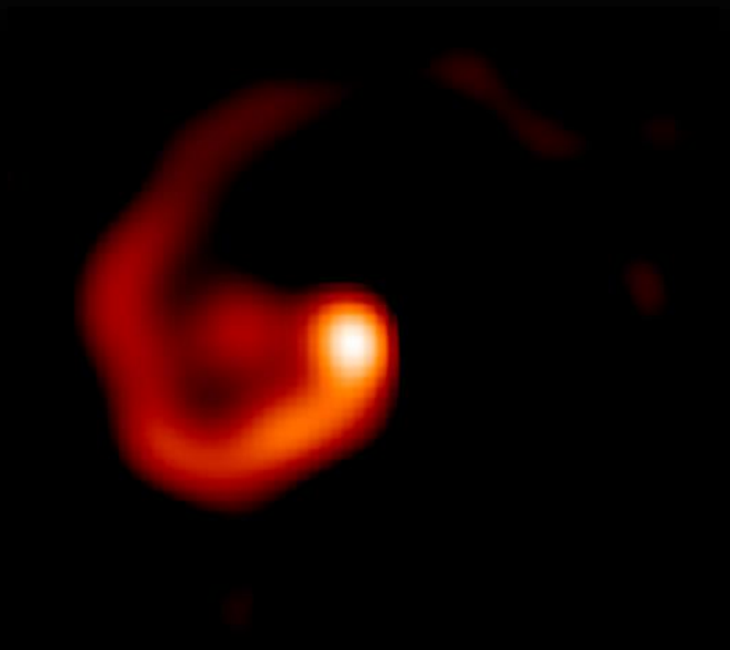


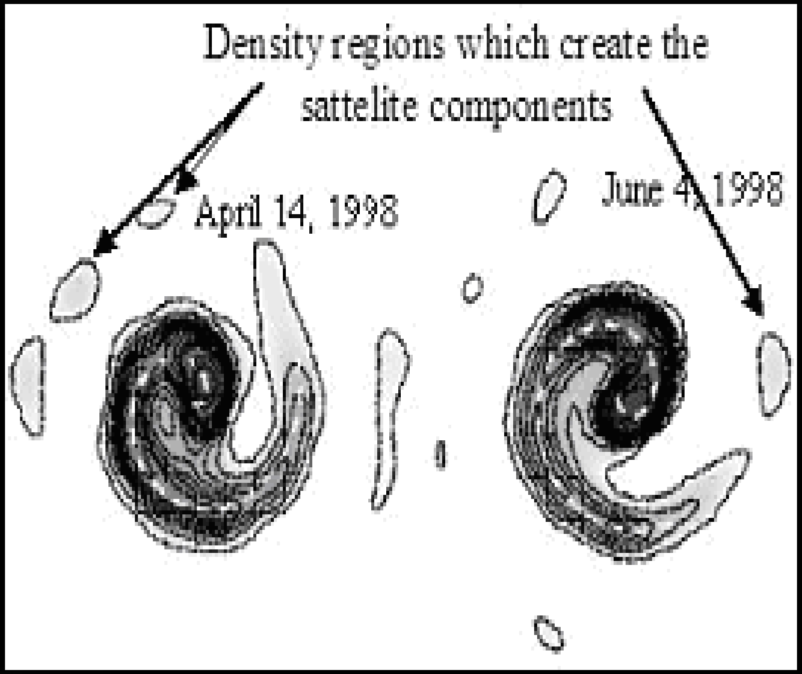


(*) Danezis 1983, 1987, Danezis et al. 1991, 2003, Lyratzi & Danezis 2004.

*(**) Danezis et al. 2003, 2007a, Lyratzi & Danezis 2004, Lyratzi et al. 2007a*

According to this phenomenon, a DAC is not a single absorption line, **but a synthesis of classical absorption components of the same spectral line of an ion (SACs).** These spectral components are created in **independent density regions** inside the violent stellar wind surrounding Hot Emission Stars (*)

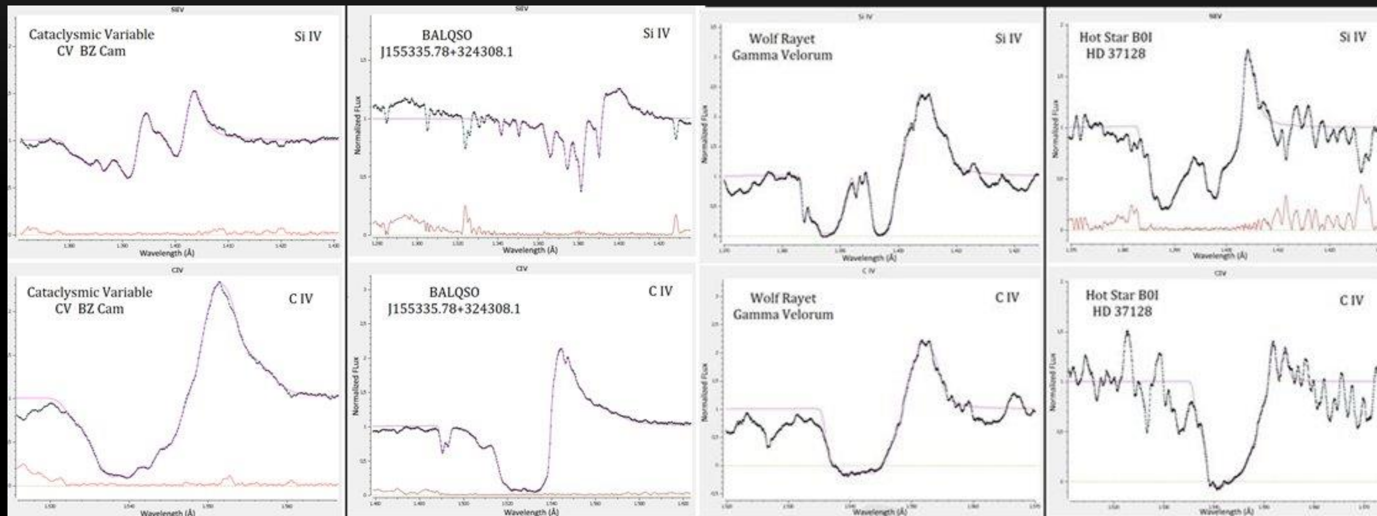


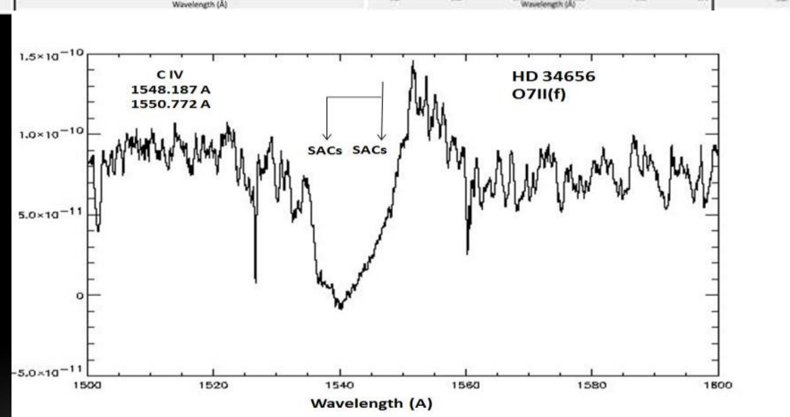


Wolf-Rayet star (WR 104), 8000 ly, O-star, Keck Telescope

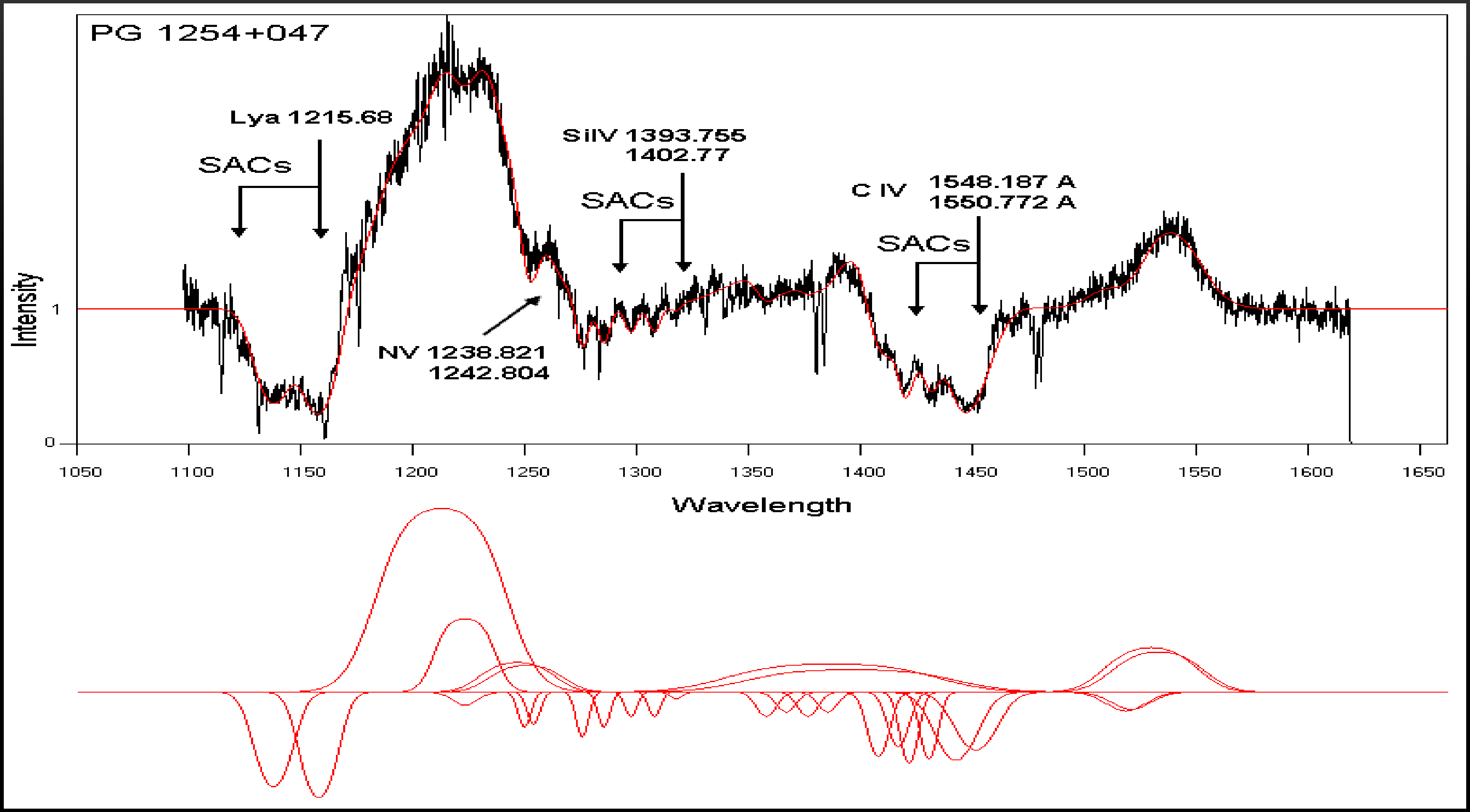
(*) e.g. Danezis et al. 2007, Lyratzi et al. 2007, Antoniou et al. 2015

DACs and SACs phenomena, are also observed, in the case of other type of astronomical objects such as **Wolf Rayet stars, Cataclysmic Variables and Quasars (*).**





(*) Stathopoulos et al. 2016, Stathopoulos et al. 2017 , Stathopoulos et al. MNRAS, 2019, Danezis et. al. 2005, ~~Proga et al. 2000~~



In this figures we can see the SACs phenomenon in the spectrum of the AGN PG 1254+047

(Stathopoulos et. al. 2016, Stathopoulos et. al. 2017, Stathopoulos et al., MNRAS 2019).

In the tomorrow session our Research Group's Members **Dr. Evagelia Lyratzi** and **Dimitrios Stathopoulos** will present a part of their research about the DACs and SACs phenomena in the above mentioned type of **Stars and Quasars.**

Wednesday, June 5, 2019

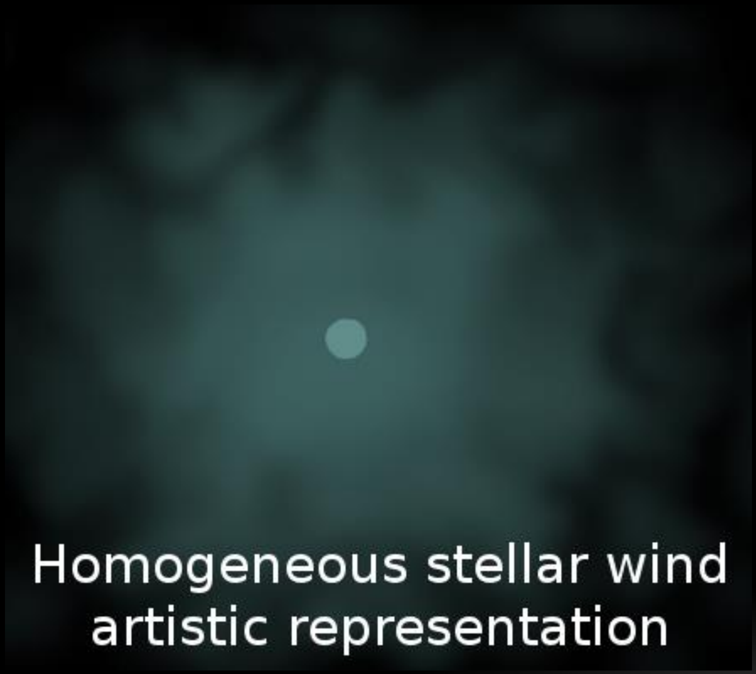
12:20 - 12:40 Evangelia Lyratzi:
Variability of Si IV and C IV broad absorption and emission lines of Wolf-Rayet stars, cataclysmic variables, hot emission stars and quasars using GR model and ASTA software

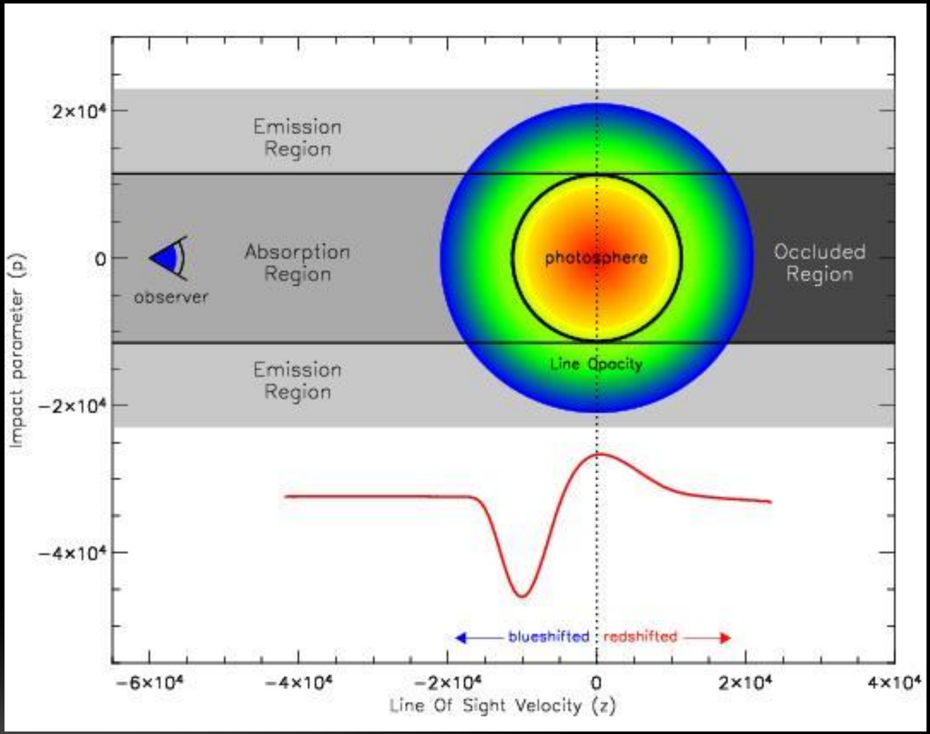
12:40 - 13:00 Dimitrios Stathopoulos
Multicomponent nature of Lya, N V, Si IV, C IV BALs of J131912.39+534720.

The origin of DACs/SACs. **The two models**

From smooth and homogeneous wind models to «clumping» structure

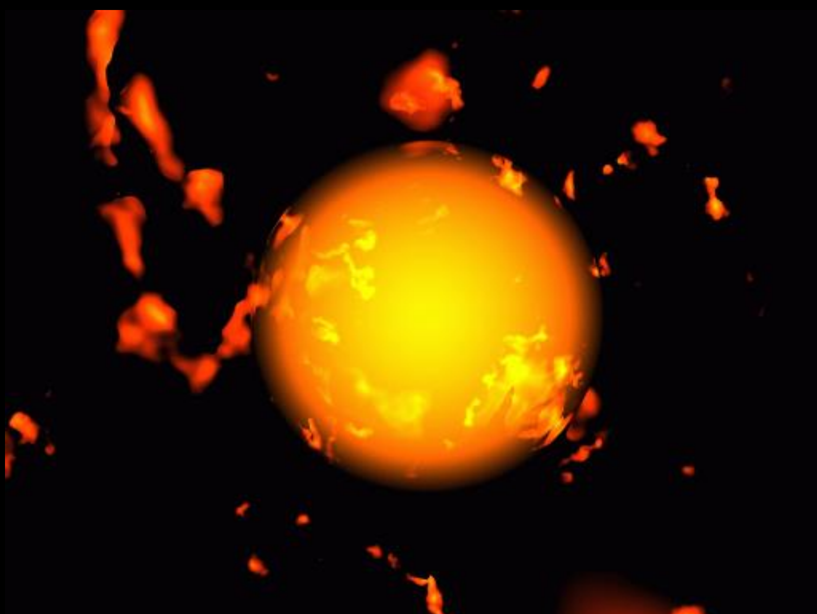
1. ***Smooth and homogeneous Wind:*** *The so-called standard model of hot star winds (*) assumes that the wind is stationary, smooth and homogeneous (e.g. no shocks or clumps), spherically symmetric and driven by radiation pressure acting on resonance lines.*

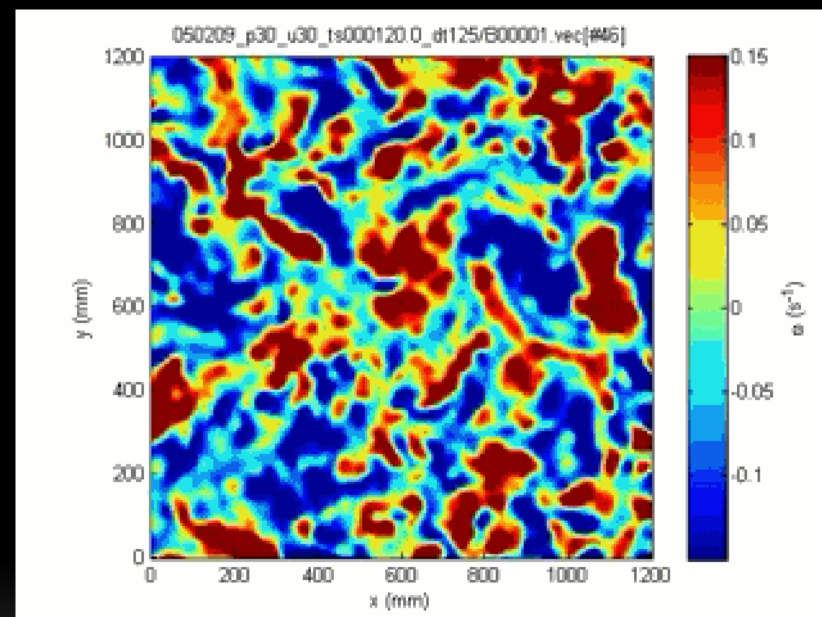


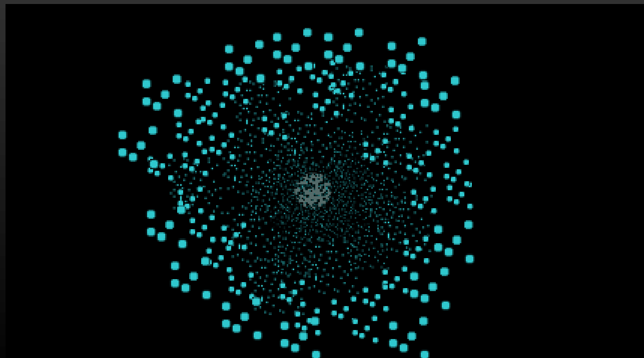


(*) Lucy & Solomon 1970; Castor, Abbott & Klein 1975; Friend & Castor 1983; Abbott & Lucy 1985; Friend & Abbott 1986; Pauldrach, Puls & Kudritzki 1986; Puls 1987; Lucy & Abbott 1993

2. Clumpy wind model: *Recent theoretical and observational evidence indicate that hot star winds are far from being smooth and homogeneous but are rather unstable and clumpy. The main idea behind this scenario is that all hot star winds are pervaded by some type of radiative instability which produces density enhancements in the wind called clumps (see conference proceedings "Clumping in hot star winds" Potsdam 2003 and Pragati et al. 2019, MNRAS, 483, 4)*







Schematic representation of a clumpy wind structure

Homogeneous stellar wind artistic representation

A&A 541, A37 (2012)

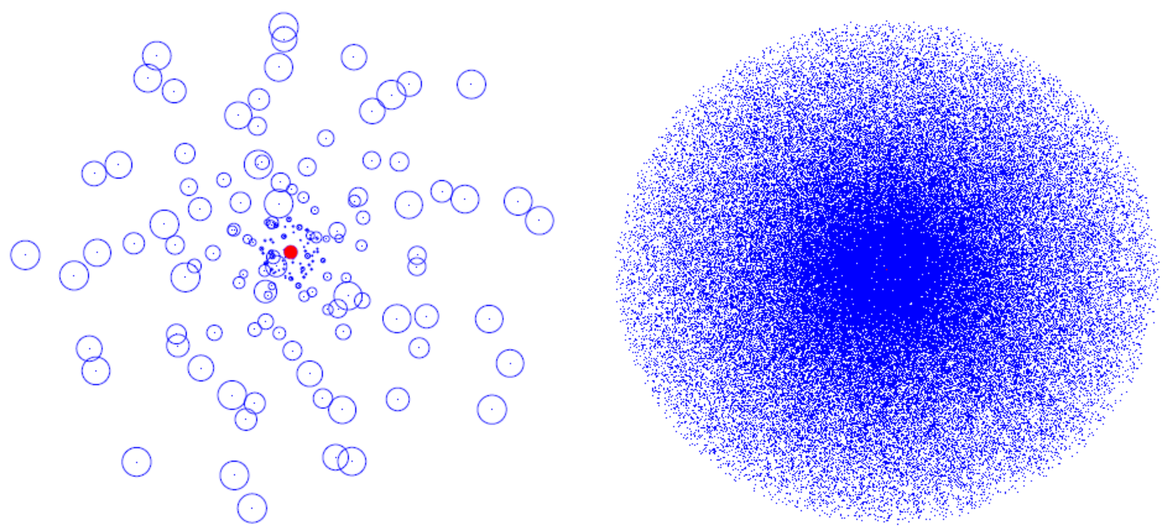


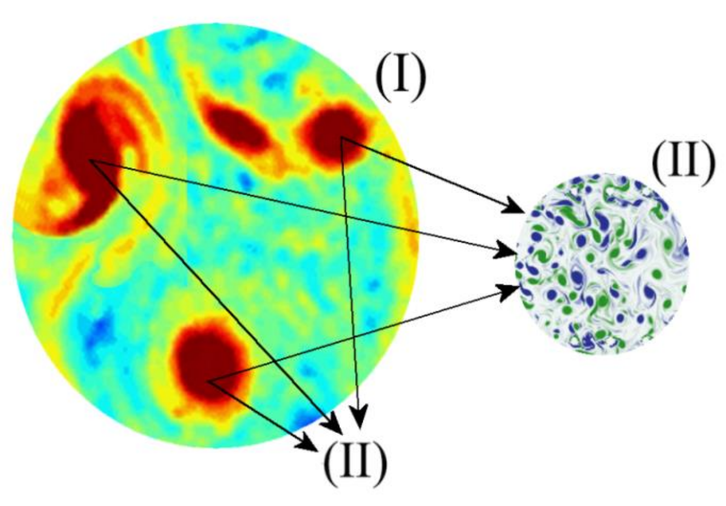
Fig. 2. Two-dimensional projection of an example of a realisation of our stochastic 3D wind model. *Left*: clumps (blue circles) with the different size distributed around the star (red filled circle). *Right*: distribution of the clumps; the filled red sphere at the center represents the star, while the blue dots represent the positions of the clump centers.

Surlan et al. 2012, A&A 541, A37

Our theoretical ad hoc proposed models for DAC/SAC Regions (*)

3. Independent and individual clouds: All the above lead us to the conclusion that **in the inner regions** of the stellar atmosphere (from the photosphere to the first regions of the disk) of the stars that present DACs or SACs, **the plasma is ejected violently** and it does not have the form of smooth stellar wind, for as long as the phenomenon lasts.

During the phenomenon, in the regions where the DACs or SACs are created, the majority of plasma is distributed in the density regions of spherical symmetry around the star or around their own centers.

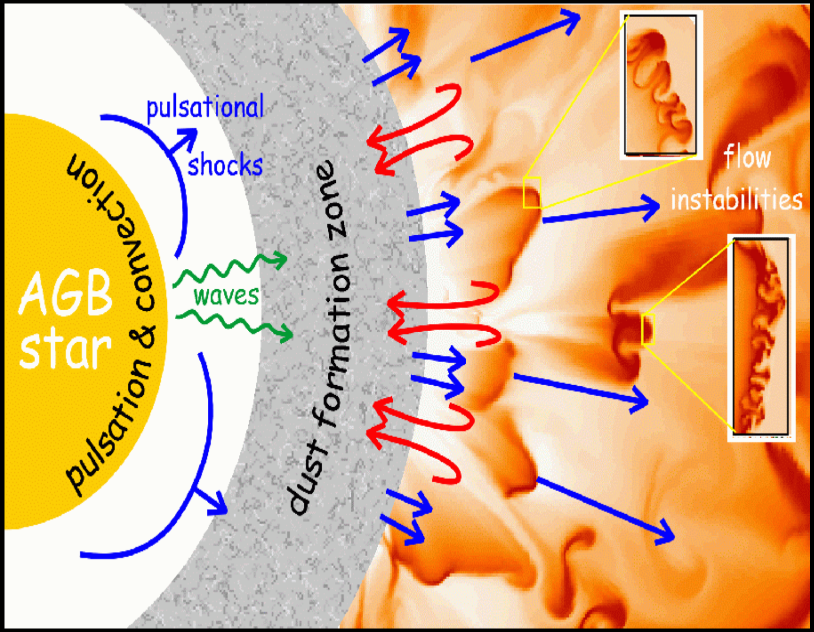


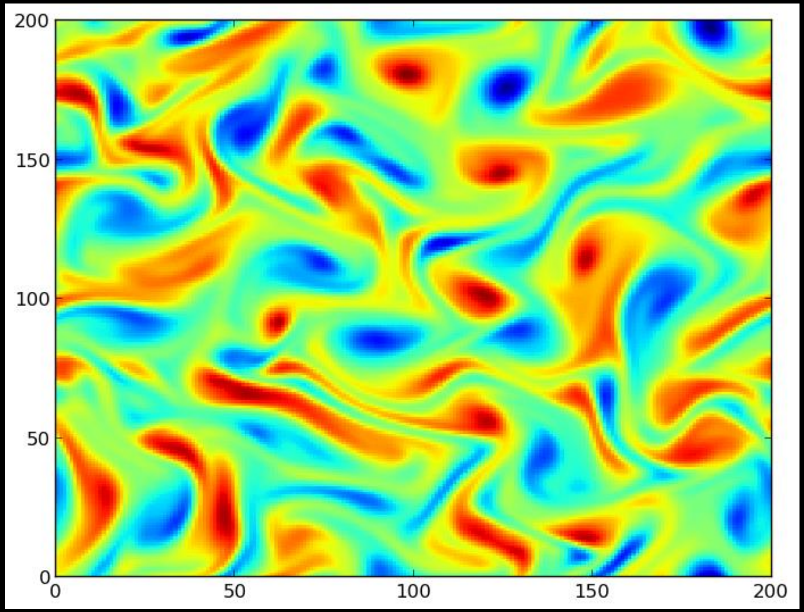
Density regions (I) that form the Discrete Absorption Components (DACs) and SAC regions (II) that form the DACs regions (I).

(*) Stathopoulos, D., Danezis, E., Lyratzi, E., Antoniou, A.; Tzimeas: Multicomponent Analysis of the UV Si IV and C IV Broad Absorption Troughs in BALQSO Spectra: The Examples of J01225 + 1339 and J02287 + 0002D. 2015, JApA, 36, 495

Stathopoulos, D., Danezis, E. Lyratzi, E., Antoniou, A., Tzimeas, D. "On Si IV and C IV broad absorption line variability in the UV spectra of 10 BALQSOs", MNRAS, 2019, 486, 894

…Independent and individual clouds: These density regions were created as a result of the violent mass ejection during the period of the emission phenomenon (i.g. in Be and Oe stars). The ejected matter takes the form of stellar wind as it goes away from the **turbulent medium** of the inner atmospheric layers of hot emission stars.





(*) Stathopoulos, D., Danezis, E., Lyratzi, E., Antoniou, A.; Tzimeas: Multicomponent Analysis of the UV Si IV and C IV Broad Absorption Troughs in BALQSO Spectra: The Examples of J01225 + 1339 and J02287 + 0002D. 2015, JApA, 36, 495

Stathopoulos, D., Danezis, E. Lyratzi, E., Antoniou, A., Tzimeas, D. "On Si IV and C IV broad absorption line variability in the UV spectra of 10 BALQSOs", MNRAS, 2019, 486, 894

All the above give rise to some questions:

1. Can DACs be simulated and analyzed taking into account their complex structure and large widths?
2. How can Si IV and C IV DACs be analyzed?
3. Accepting the point of view that DACs are the synthesis of a series of spectral line components, is there a way to study not only the whole profile but the profiles of each individual component (line function of each individual absorber in the line of sight)?
4. Which is the interpolation polynomial that describes the whole DAC profile?
5. In the case of multiple DAC which is the interpolation polynomial that describes the whole absorbing region?
6. Can the two members of the resonance doublets (f. e Si IV and C IV) be studied independently? Until now the resonance doublets (f. e C IV and Si IV) are considered one spectral line.

In order to answer in this set of questions we use **GR model (*)** which incorporates all the previously mentioned characteristics

(*) Danezis, E., Nikolaidis, D. , Lyratzi, E., Antoniou, A. Popovic, L.C., Dimitrijevic, M., PASJ, 2007

Our past work *"Timescale variation of the **absorption** components that form the C IV and Si IV DACs in the UV spectrum of the O-star HD 93521" (*)* gave us, according to the calculated timescale variation, a strong evidence for the existence of individual clouds which create the whole DAC absorption troughs.

It is already known that in a **P-Cygni Profile** the absorption is blended with the emission. After our above mentioned study and the calculated variability, **we extend our research studding the emission components which create the whole C IV and Si IV P-Cygni Profile.**

*(*) **Antoniou et al. 11th SCSLCA, Šabac, Serbia, August 21-25, 2017***

The main target of our work

Why is variability important?

By analysing DACs to the individual components they consist of we are able to study the variability of the physical parameters, of each individual absorbing region (cloud, clump) in the line of sight. Time variability of absorption components of DACs can lead to useful insights concerning the clumpy structure of the wind.

This work is a part of a larger study of our Research Team, aiming to **analyse the P-Cygni Profiles, using GR model (*) and ASTA software (**),** in the UV spectra of a large sample of hot stars in order to reach to general conclusions.

(*) Danezis, E., Nikolaidis, D. , Lyratzi, E., Antoniou, A. Popovic, L.C., Dimitrijevic, M., PASJ, 2007

(**) Tzimeas, D., Danezis, E., Stathopoulos, D., Lyratzi, E., and Antoniou, A. "Some important notes on ASTA software: A new method of analysis of simple and complex emission and absorption spectral lines", Astronomy and Computing, 2019

Our research

We analyze the **C IV (λλ 1548.155, 1550.774 Å) and Si IV (λλ 1393.755, 1402.77 Å) emission and absorption** lines in the **O-star HD 93521,** in four different periods in a time interval of 16 years, **to the individual components (SACs) they consists of.**

Name	Date
SWP 05621	25 June 1979
SWP 34788	20 November 1988
SWP 50360	24 March 1993
SWP 54037	3 April 1995

Our research

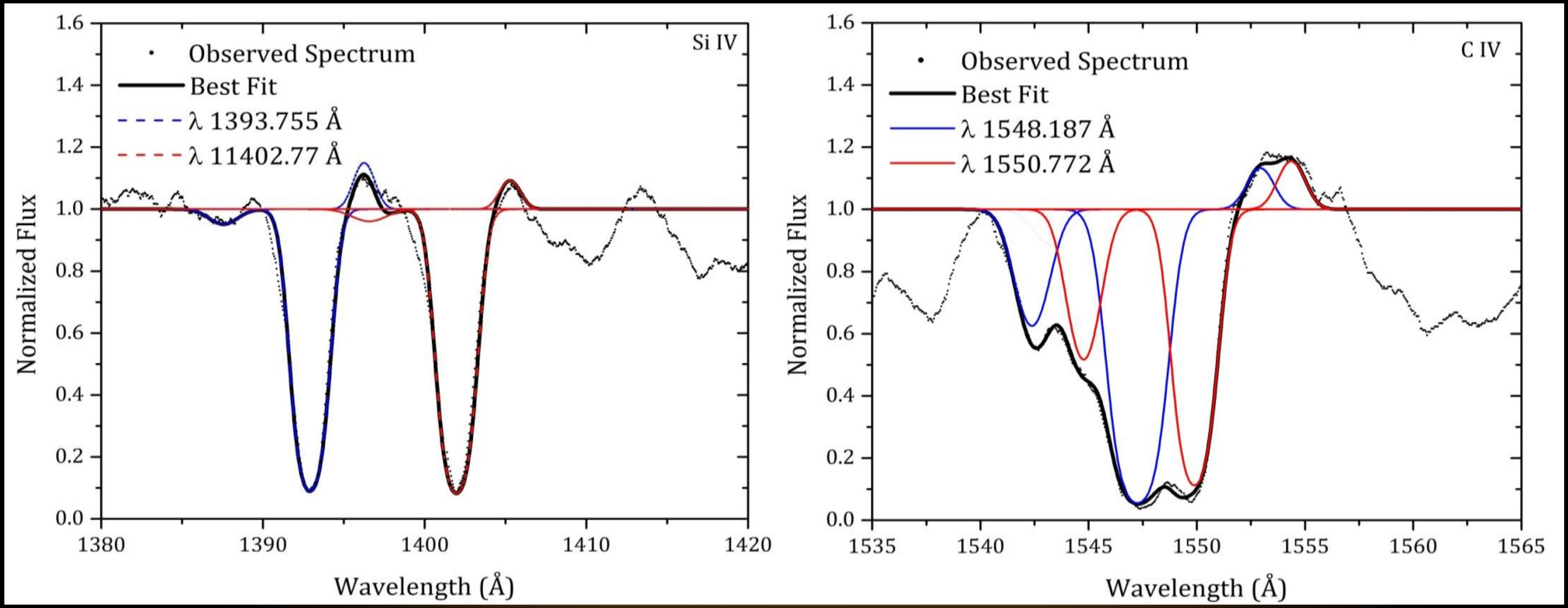
Table 1: The physical parameters of the star HD 93521

Physical Parameter	Value	Reference
Luminocity (L)	104.9 Lo	Howarth & Prinja (1989)
Distance (d)	1.5 kps	Edgar & Savage (1992)
	1.4 kpc	Hobbs et al. (1982)
	2 kpc	Howarth et al. (2001)
Colour Index (B-V)	-0.28	Guetter (1974)
Colour Index (U-B)	-1.09	Guetter (1974)
Spectral Type	O9.5V	Hobbs et al. (1982)
Magnitute (V)	7.04	Guetter (1974)
	7.03	Tobin (1984)
Terminal Velocity (V∞)	400 – 2000 km/s	Howarth &Reid (1993)
Rotational Velocity (Vsini)	400±20 km/s	Conti & Ebbets (1977)
		Lennon et al. (1991)
Radial Velocity(Vrad)	-11 km/s	Garmany et al. (1980)
	-16 km/s	Barnstedt et al. (2000)
Effective Temparature (Teff)	33500±1500	Lennon et al. (1991)
	31200	Hack & Yilmaz (1977)
	34500	Prinjia & Howarth (1986)
logg (cm/sec2)	3.8±0.2	Lennon et al. (1991)
	3.4	Hack & Yilmaz (1977)
Radius (R/Ro)	8	Prinjia & Howarth (1986)
Mass (M/Mo)	24	Prinjia & Howarth (1986)
Bolometric (Mbol)	-7.4	Prinjia & Howarth (1986)
Escape Velocity (Vesc)	1036 km/s	Howarth & Prinja (1989)

Our research

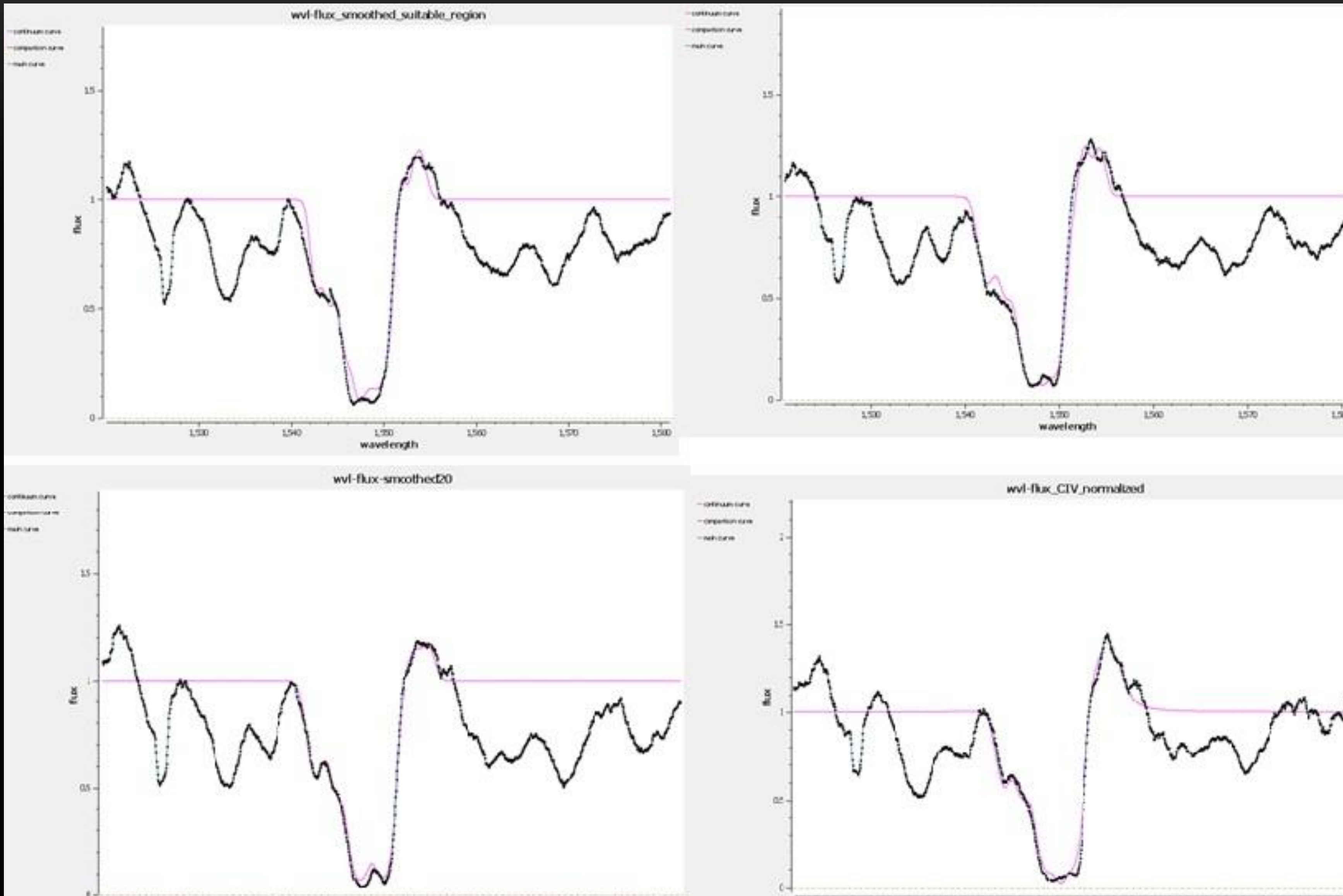
By measuring the **Radial Velocities, FWHMs, Optical Depths (at lines centers), Column Densities and *Equivalent Widths*** of each individual emission and absorption component we probe the physical conditions, kinematics and time variability of each individual **emitting/absorbing** cloud in the line of sight.

The best fit process

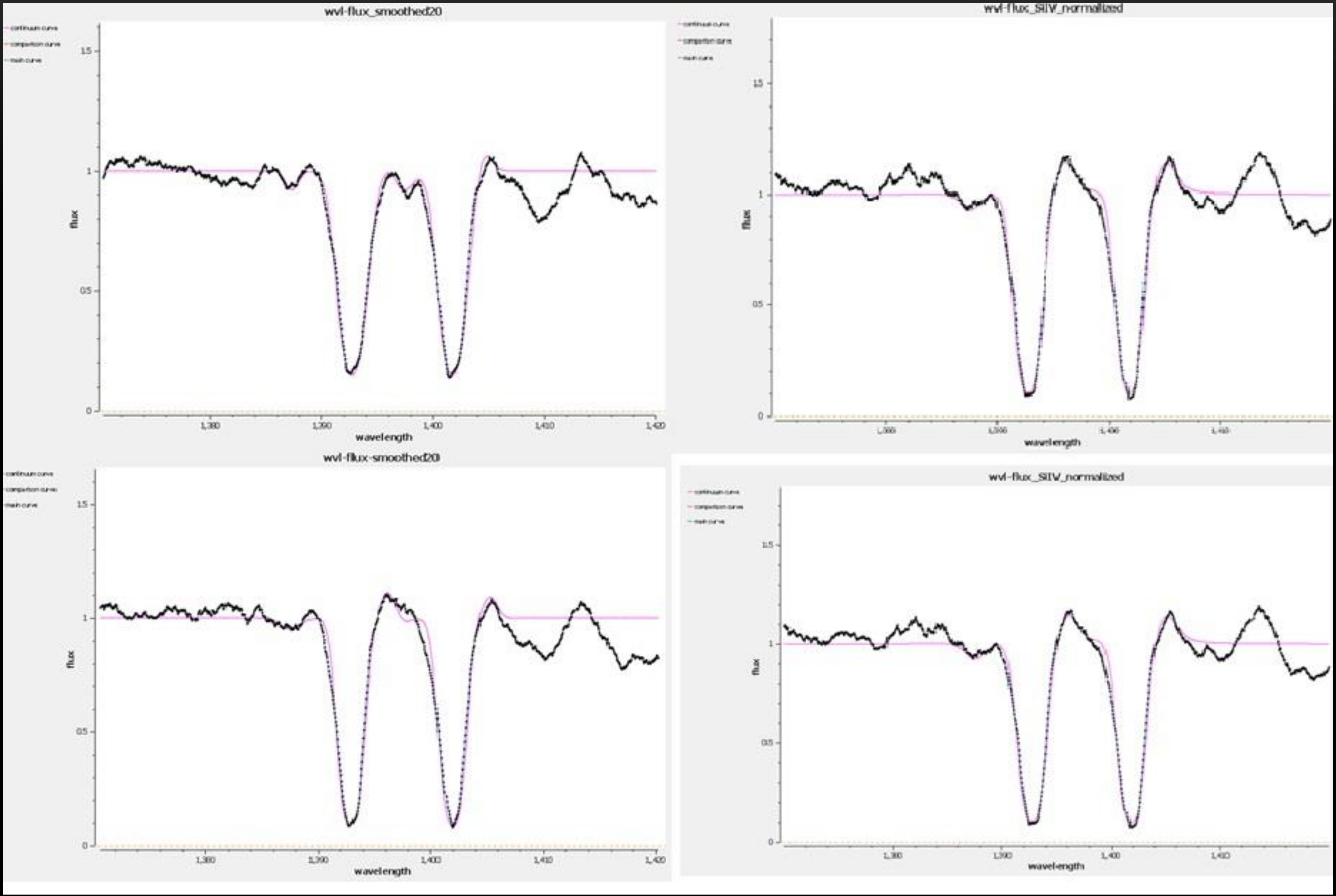


In this figure one can see the C IV and Si IV doublet of the HD 93521 and its best fit.

C IV P-Cygni Profiles and their best fit in four different dates



Si IV P-Cygni Profiles and their best fit in four different dates



Tables with the calculated parameters in four different dates

C IV region

Table 2: Radial velocity (Vrad) in km/s, FWHM in A, optical depth at line center (τ) and Column Density (CD in cm^-2) of the absorption and emission components of the blue (b) and the red (r) lines of the C IV P-Cygni Profile for four different dates

Date	Component	Vrad (b)	τ(b)	FWHM (b)	CD (b)	Vrad (r)	τ(r)	FWHM (r)	CD (r)
25 June 1979	Absorption	-226	2.1	2.53	1.40E+09	-276	2	2.02	2.84E+09
	Emission	678	0.36	1.18	3.22E+08	193	0.28	1.65	3.46E+08
20 November 1988	Absorption	-242	2.42	2.83	2.09E+09	-232	2	2.56	1.81E+09
	Emission	872	0.3	1.28	2.56E+08	677	0.25	1.41	3.07E+08
24 March 1993	Absorption	-184	2.6	2.87	2.16E+09	-174	2.2	2.65	1.65E+09
	Emission	920	0.15	1.41	1.67E+08	696	0.1	1.51	1.97E+08
3 April 1995	Absorption 1	-252	2.62	2.83	2.09E+09	-232	2.42	2.68	1.99E+09
	Emission	872	0.3	2.33	3.12E+08	677	0.28	2.56	3.56E+08

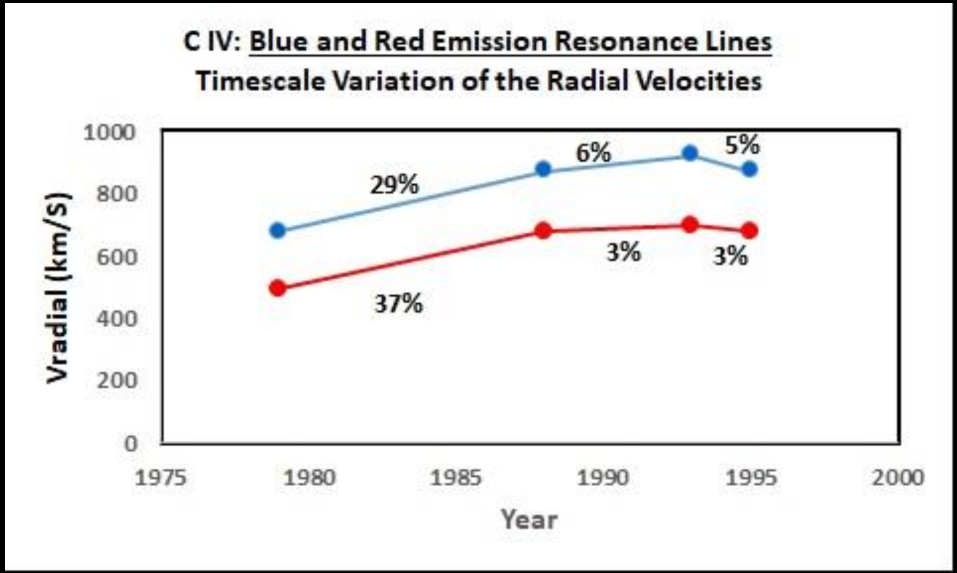
Si IV region

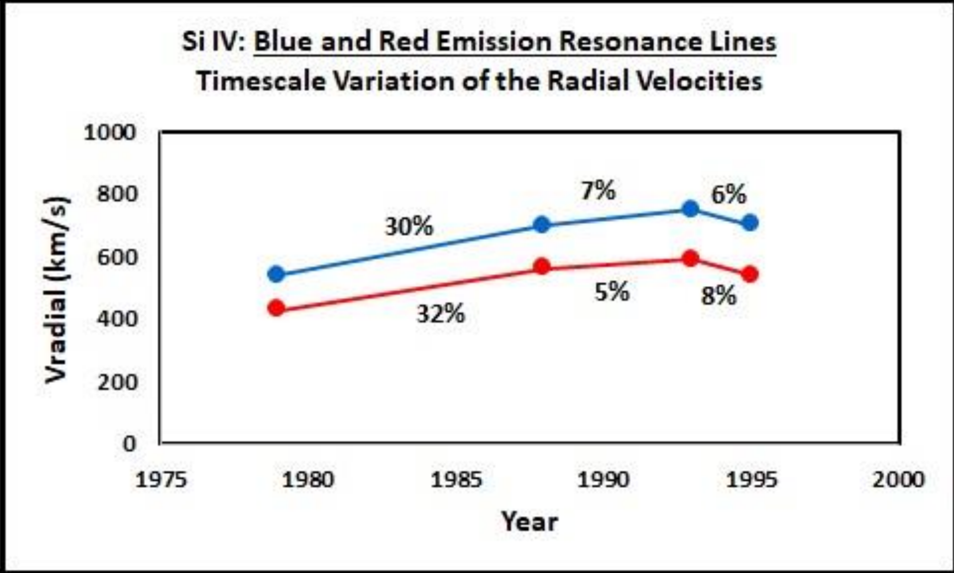
Table 3: Radial velocity (Vrad) in km/s, FWHM in A, optical depth at line center (τ) and Column Density (CD in cm^-2) of the absorption and the emission components of the blue (b) and the red (r) lines of the Si IV P-Cygni Profile for four different dates

Date	Component	Vrad (b)	τ(b)	FWHM (b)	CD (b)	Vrad (r)	τ(r)	FWHM (r)	CD (red)
25 June 1979	Absorption	-215	1.9	3.09	1.32E+09	-214	1.9	2.24	1.27E+09
	Emission	538	0.5	1.41	4.70E+07	428	0.2	1.48	5.54E+07
20 November 1988	Absorption	-248	2	2.73	1.18E+09	-235	2.2	1.88	1.16E+09
	Emission	699	0.5	1.53	1.72E+08	563	0.25	1.59	7.15E+07
24 March 1993	Absorption	-183	2.42	2.63	1.20E+09	-171	2.5	2.72	1.25E+09
	Emission	750	0.5	1.81	1.19E+08	590	0.4	1.81	7.26E+07
3 April 1995	Absorption	-213	2.49	2.95	1.34E+09	-192	2.6	2.88	1.31E+09
	Emission	702	0.5	2.39	3.34E+08	540	0.4	2.44	2.09E+08

Radial Velocities

In the this figure we show **the timescale variation of the Radial Velocities** of the **blue and red emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines. We see also the **percentage variability of them**. In the first time interval we calculated a significant variability in both of the regions. In the other time intervals, the variability is in the statistical error range.

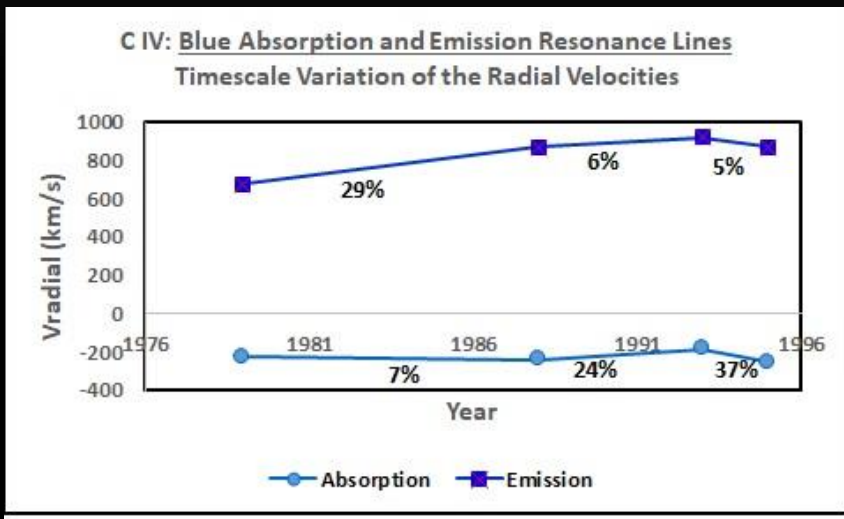


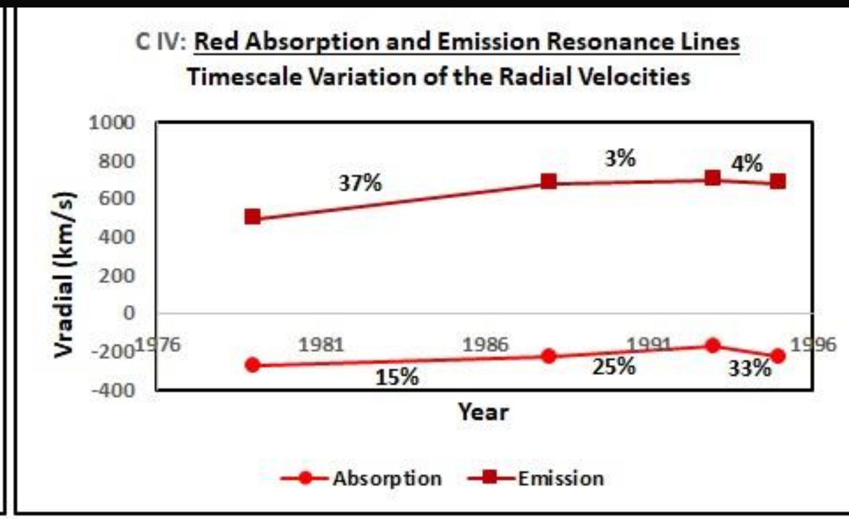


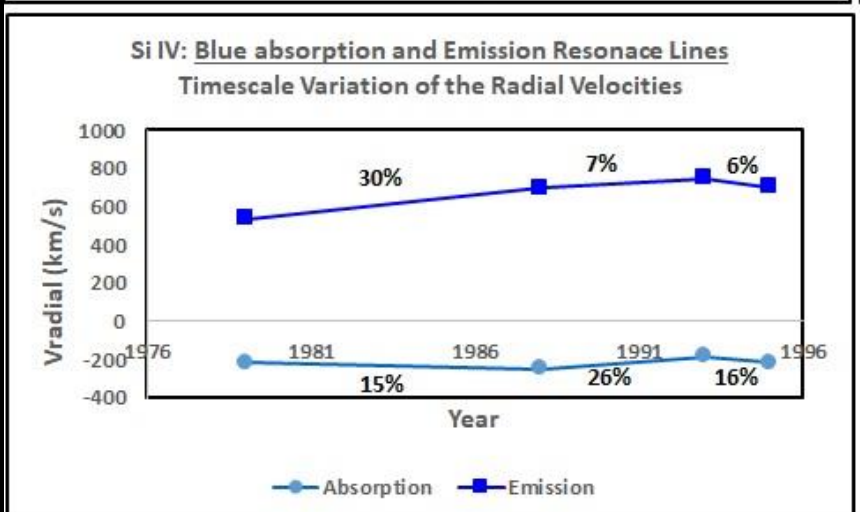
It is very important to note that **in both regions** the variation of the radial velocities of the clouds, which create the emission C IV and Si IV spectral lines, **have exactly the same variability.** This is expected because the C IV and Si IV ions are **created almost under the same physical conditions.**

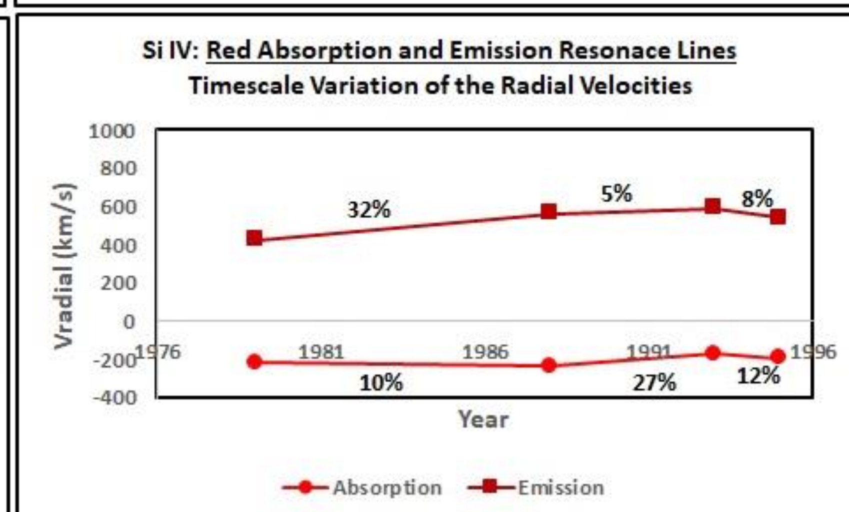
Radial Velocities (Absorption vs Emission)

Here we present **the timescale variation of the Radial Velocities** of the **blue and red absorption and emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines. We note that the emitting clouds' radial velocities have in each case positive values. **The radial velocities' percentage variability of the emission clouds as well of the absorption clouds is comparable.**



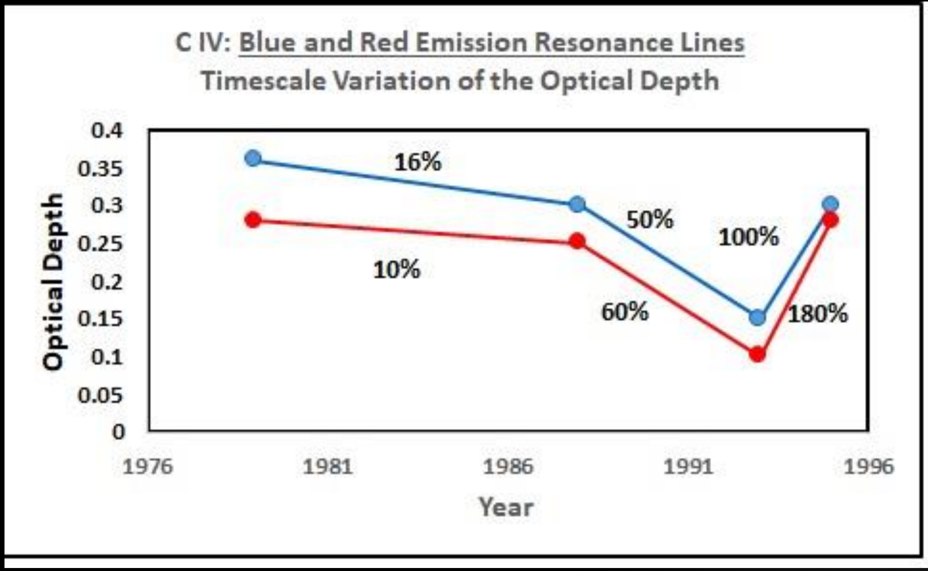


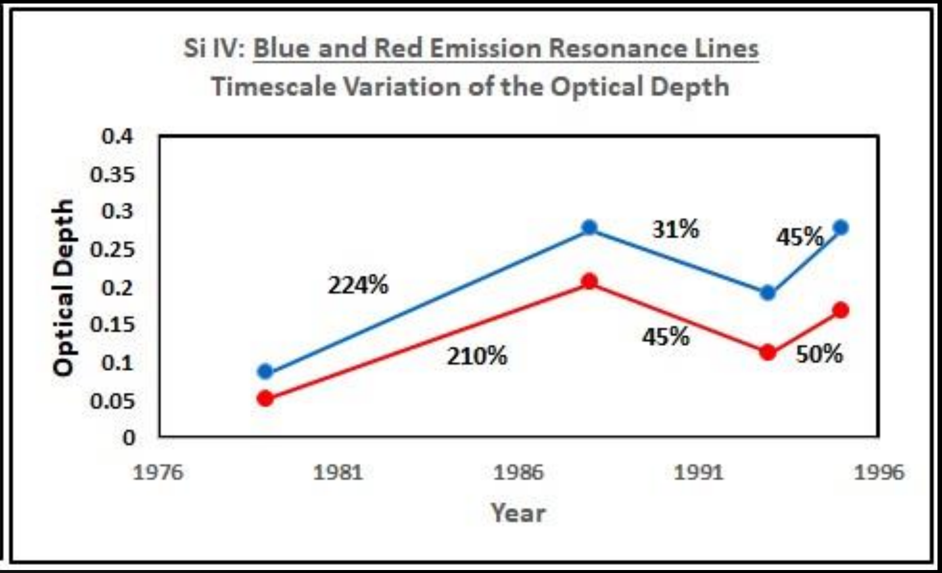




Optical Depths

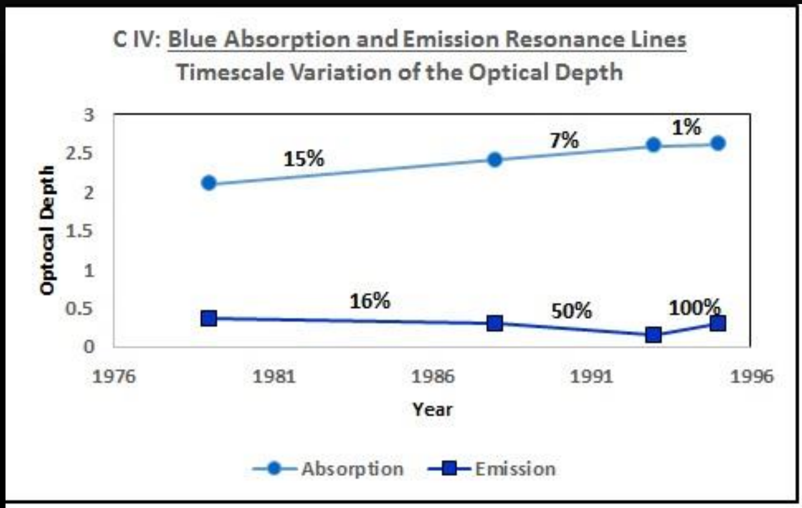
Here we have **the timescale variation of the Optical Depths at the center** of the **blue and red emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines. We see also the **percentage variability of them.** We note that in the **first time interval (1979-1987) the optical depths present a different way of variability.** The values of them are decreasing in the C IV region and increasing in Si IV region

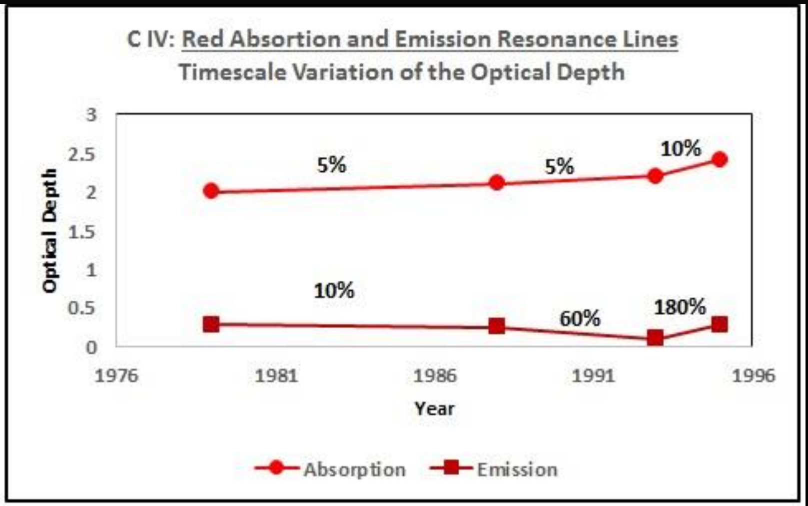


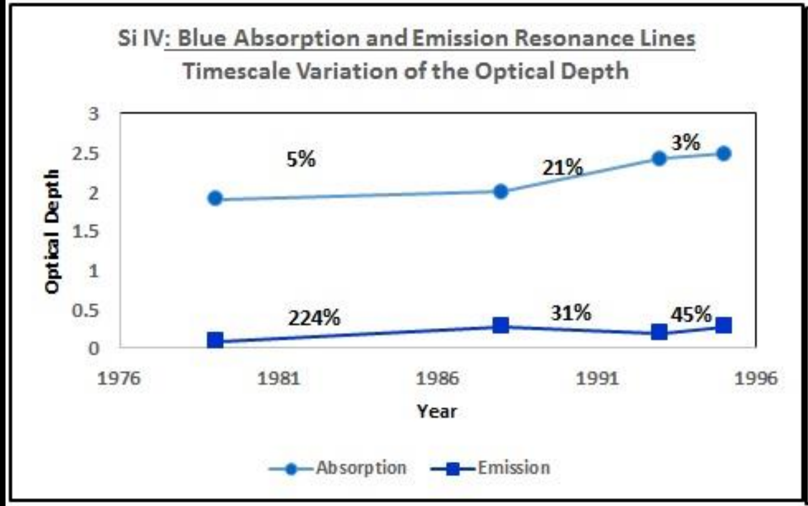


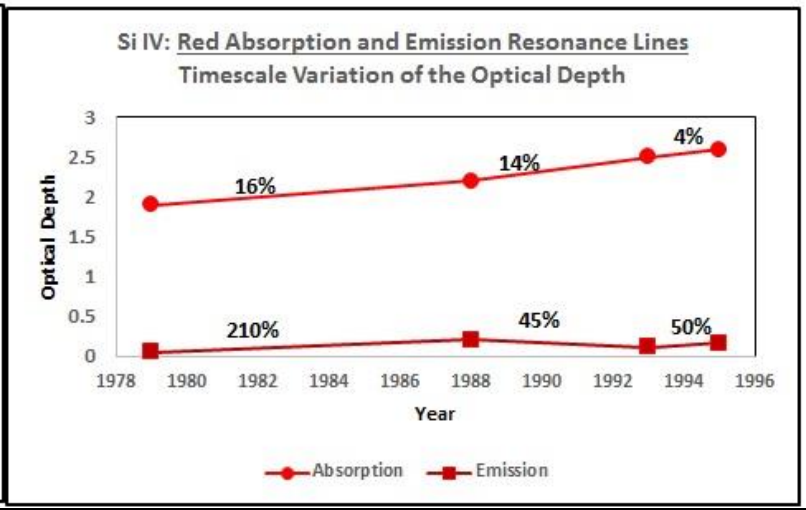
Optical Depth (Absorption vs Emission)

In the following figures we show the **timescale variation of the Optical Depths** of the **blue and red absorption and emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines.



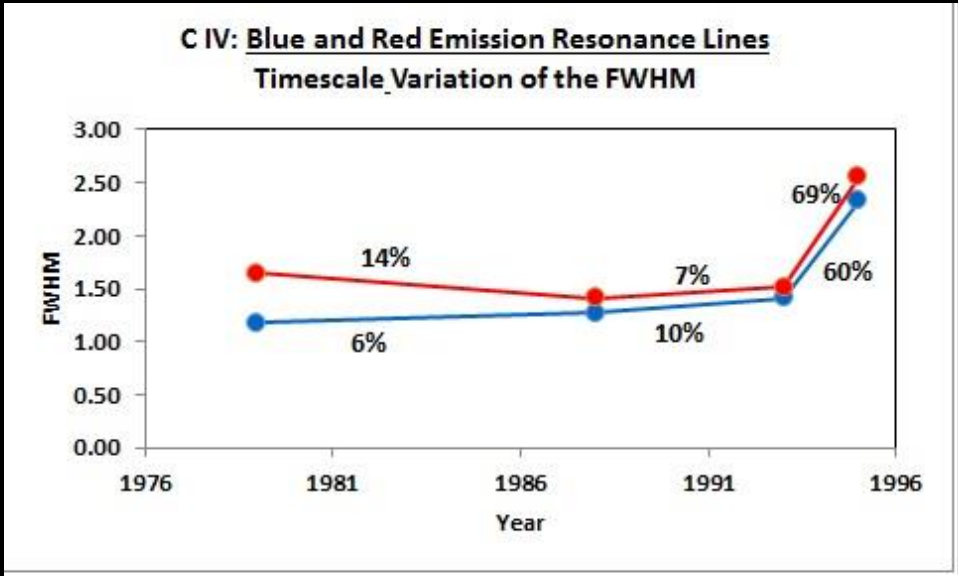


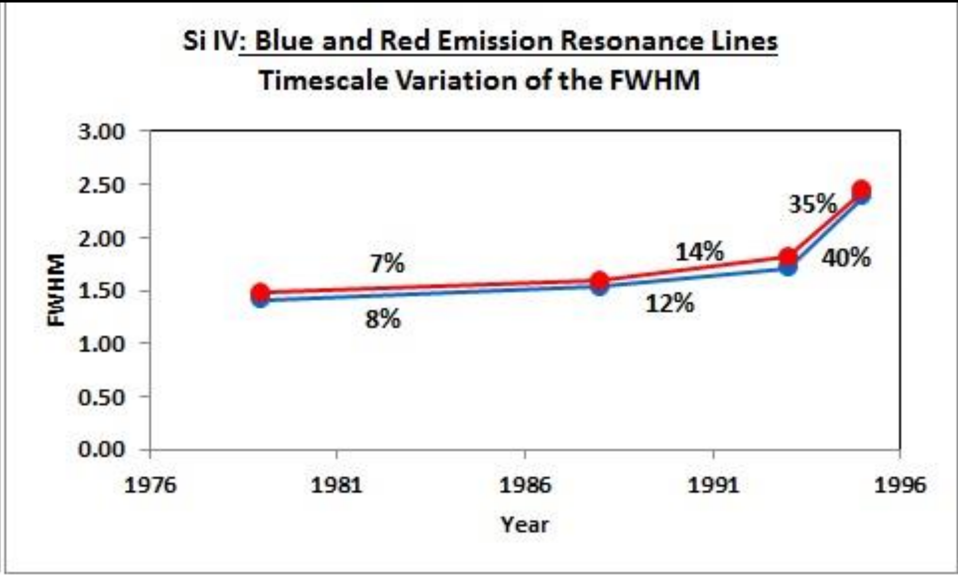




The Full Width at Half Maximum (FWHM)

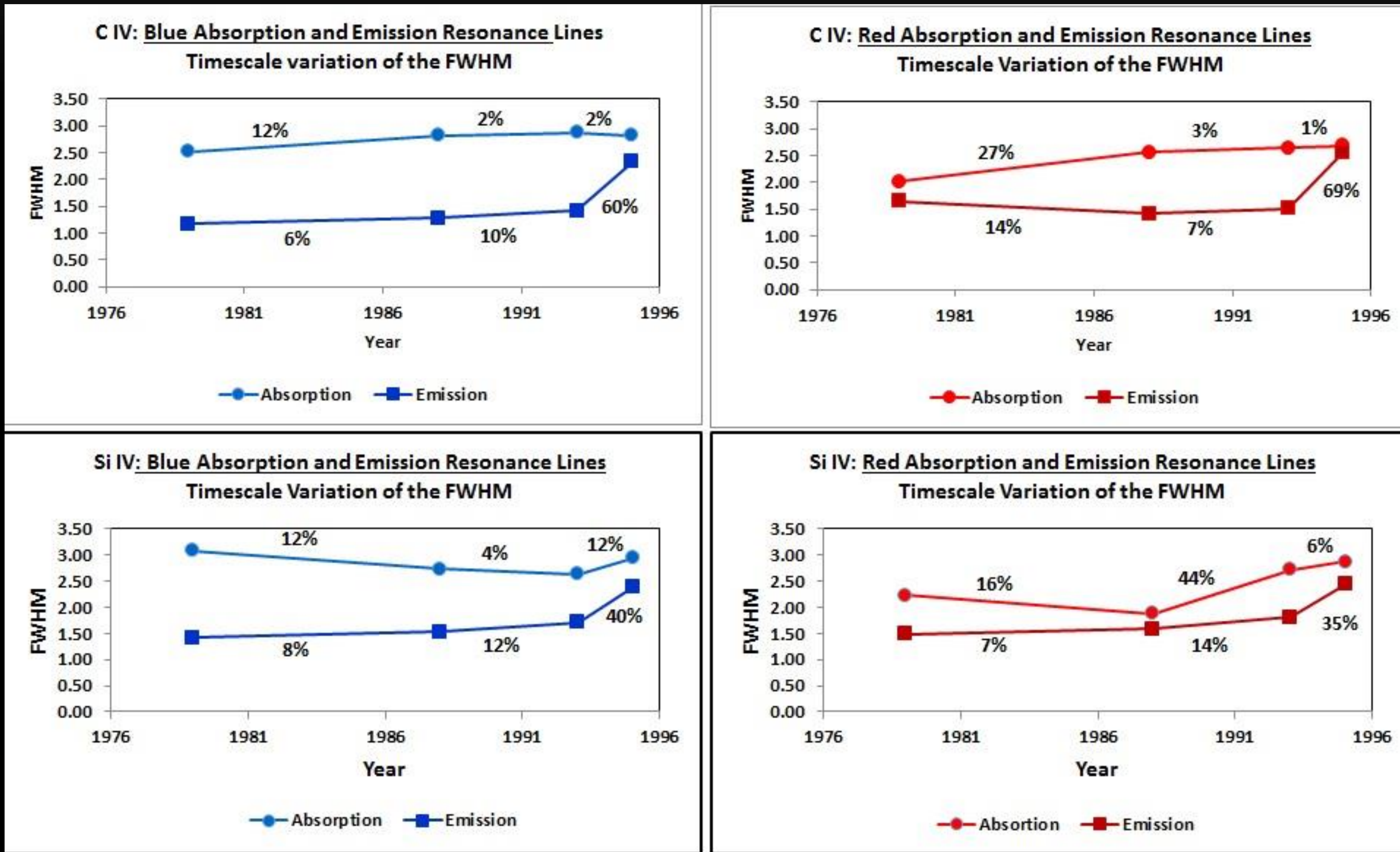
In this figure we present **the timescale variation of the FWHM** of the **blue and red emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines. It is important to mention **the same behavior of the variability in both of the regions.**





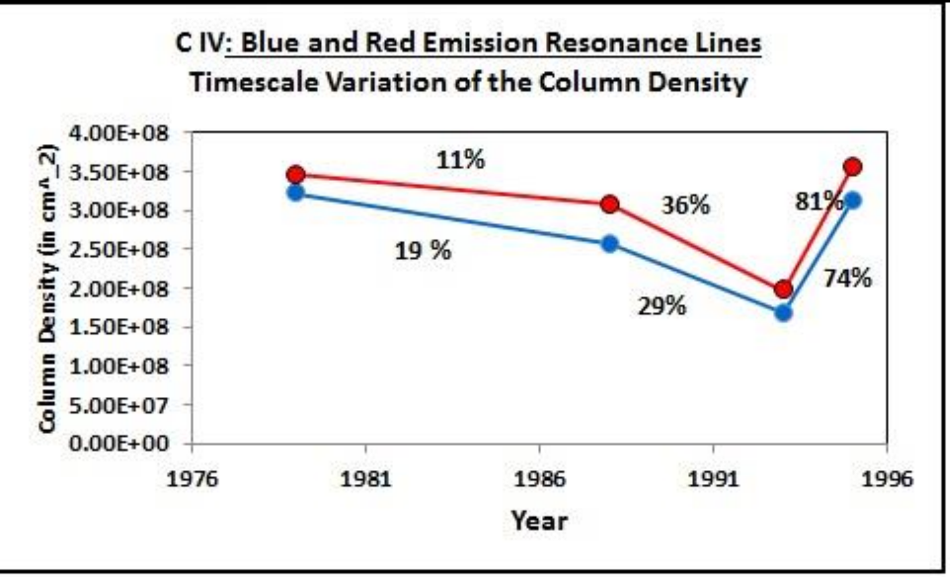
FWHM (Absorption vs Emission)

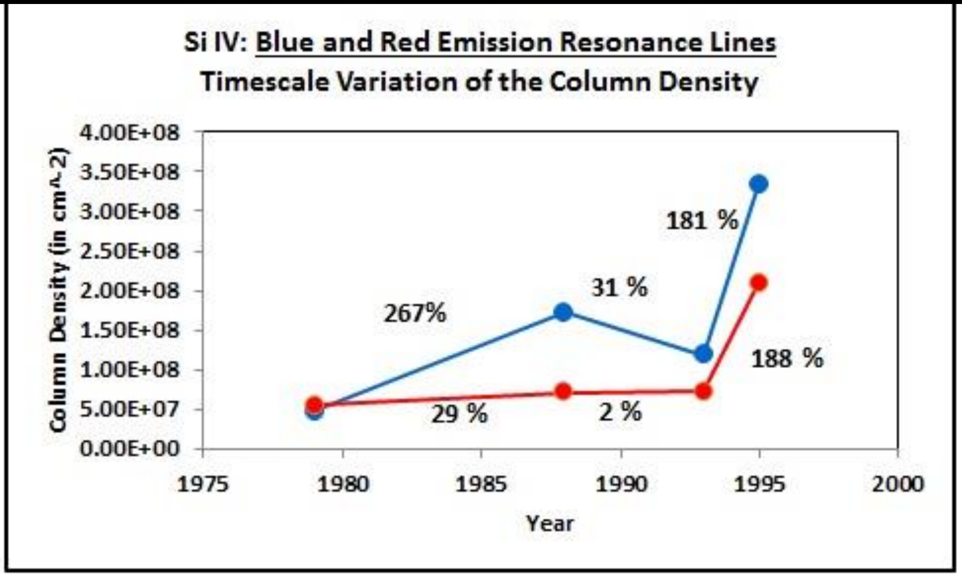
Here we present the **the timescale variation of the FWHM** of the **blue and red absorption and emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines.



The Column Density (CD)

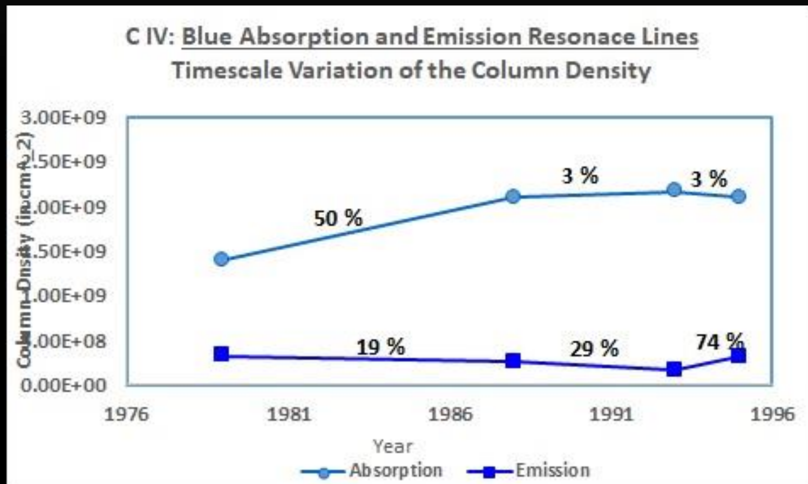
Finally, we present **the timescale variation of the Column Density (in cm^_2)** of the **blue and red emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines. **Remarkable is the variability of the Column Density in the Si IV region.**

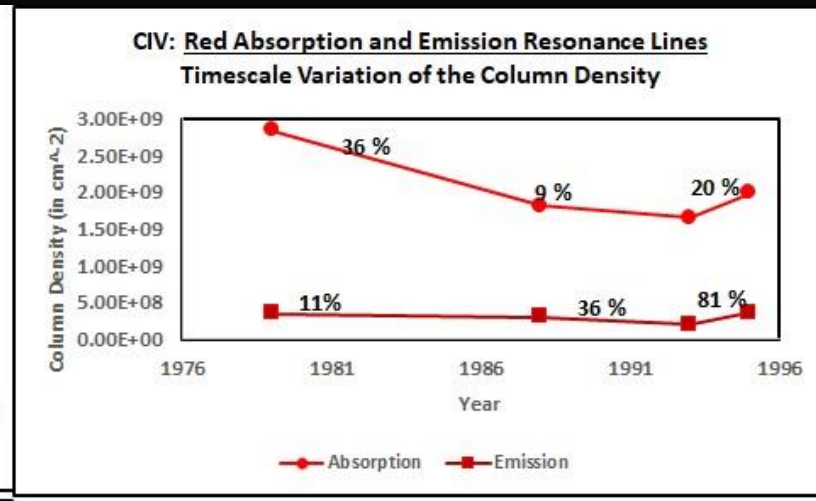


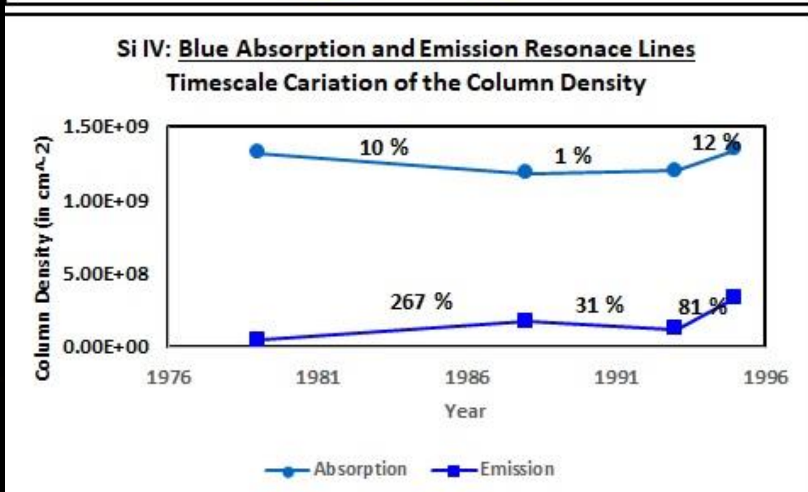


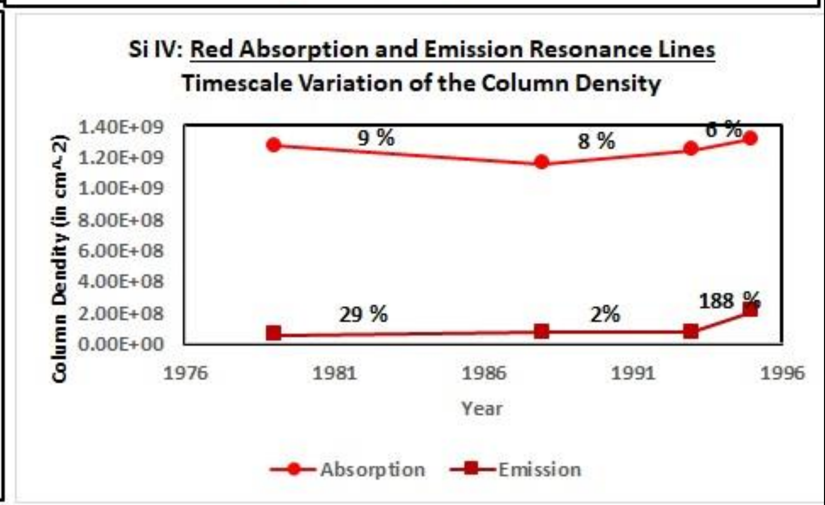
Column Density (Absorption vs Emission)

And here we see **the timescale variation of the Column Density** of the **blue and red absorption and emission components** which create the **P-Cygni Profile** of the C IV and Si IV resonance lines.









Results and Discussion

***A first note*:**

Due to **the strict criteria (*Stathopoulos et al. 2015*)** we apply during the fitting process, we are able not only to distinguish the individual components that compose the final profile but also calculate the values of the physical parameters of each individual component. Thus we are able to compare **individual components between different epochs and investigate the variability of individual structures in the outflow.**

According to these criteria, we detected that both of the C IV resonance spectral lines, as well as both of the Si IV resonance spectral lines, consist **of two independent and individual Satellite Absorption and Emission Components (SACs).**

Results and Discussion

1. We calculated **a variability of the radial velocities in different time intervals.** This variability was observed in the **absorption as well as in emission** C IV and Si IV spectral lines which create the **P-Cygni Profile.** This fact is **an evidence of the existence of clouds** inside the stellar wind in the areas which these spectral lines are created. **This means** that independent variability of radial velocities, apart from a strong evidence of the existence of clouds, **is also one of the causes of the variability of the DACs spectral shapes.**

2. As in the case of the radial velocities, we **calculated variability** in the **Optical Depth and the Column Density** in different time intervals too. This variability was observed in the **absorption as well as in emission** C IV and Si IV spectral lines which create the **P-Cygni Profile.** This fact is possibly caused by **the changes in the ionizing state of the outflowing gas.** Ionization changes can have result in **changes in the column densities of absorbing ions.** (*)

(*) ***Stathopoulos et al., MNRAS, 2019***

Results and Discussion

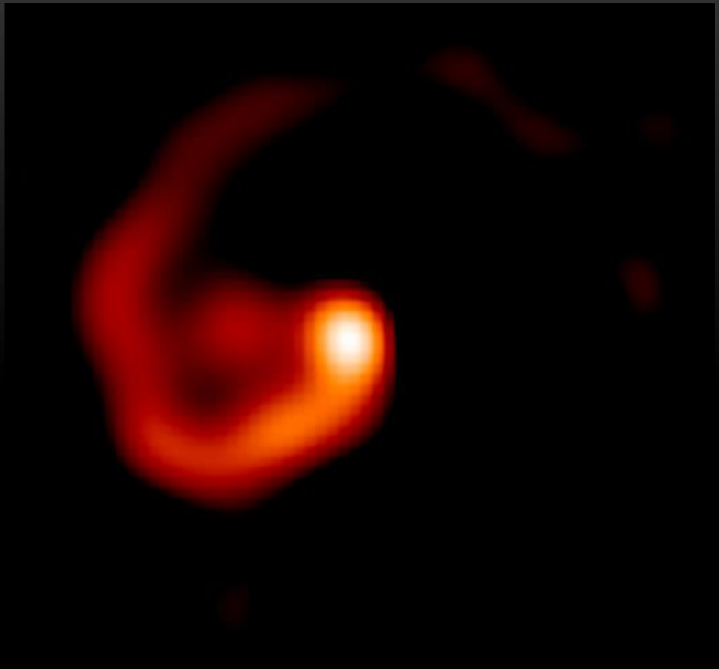
3. The best fit of the emission spectral lines **is obtained by the Voigt (Gauss+Lorentz) distribution.** This means that the line broadening is caused by the **radial motions of the ions** as well as by **the strong pressure** in the C IV and Si IV regions.

Answer to the basic question that was the goal of our study

All the above mentioned results lead us to note that the time scale variability of some parameters, such, e.g., the radial velocities or optical depth at the center of the absorption components gives us an additional strong evidence for the existence of the individual clouds which create the whole DAC absorption troughs (*) (**). **These changes are now confirmed and in the case of the emission clouds forming the P-Cygni profile. This result is a second confirmation *(for the first one see Antoniou et al., 2017)* of the "clumping" structure of the Oe star HD 93521 environment.**

*(*) **Henrichs, 1984; Prinja & Howarth, 1986; Prinja et al., 1987; Henrichs et al., 1988 Prinja, 1990; Balona, 1992; Fullerton et al., 1996***

*(**) **Antoniou et al., 11th SCSLSA, Serbia 2017.***



Thank you very much for your attention

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