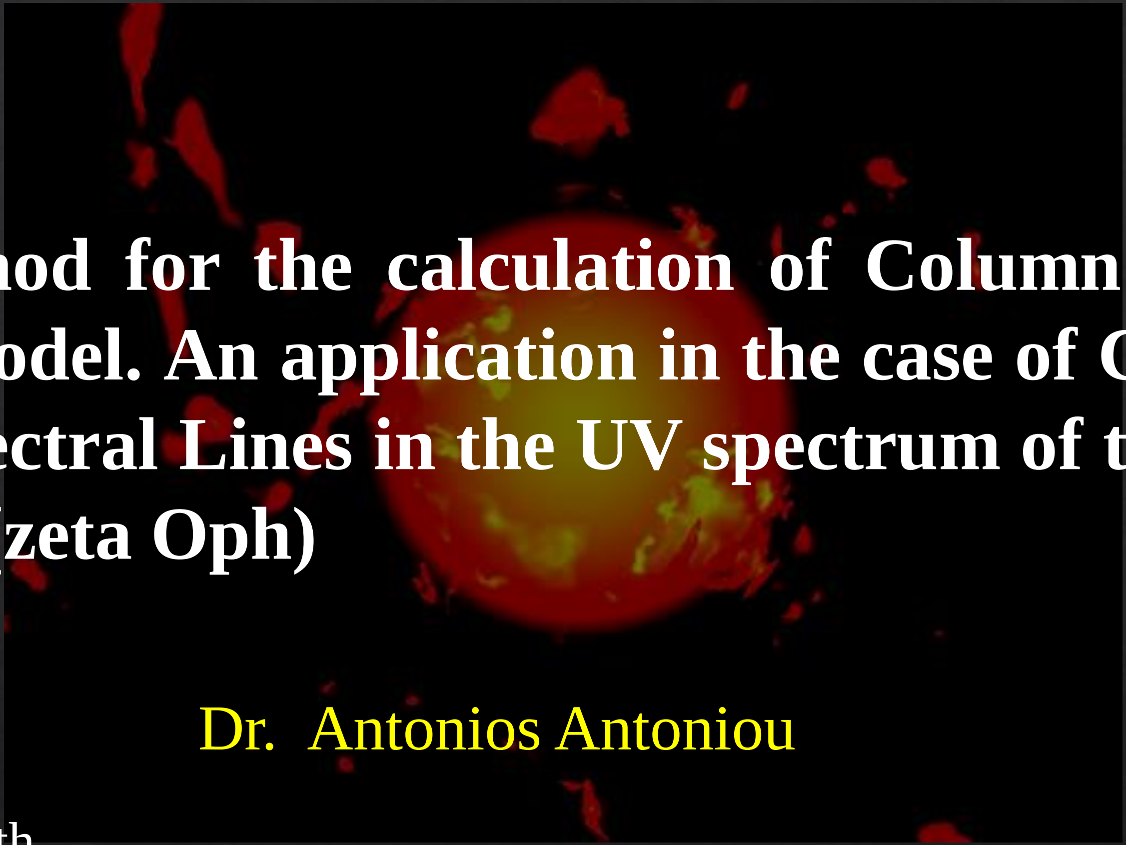

A new method for the calculation of Column Densities using GR model. An application in the case of C IV, N IV and N V Spectral Lines in the UV spectrum of the O-Star HD 149757 (zeta Oph)

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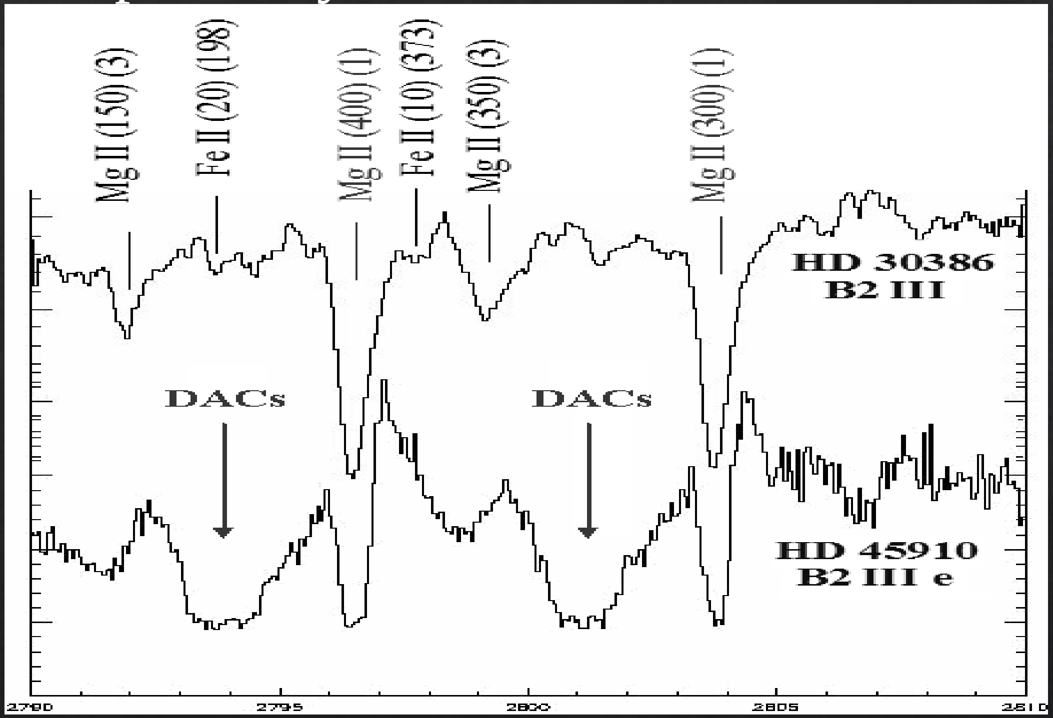
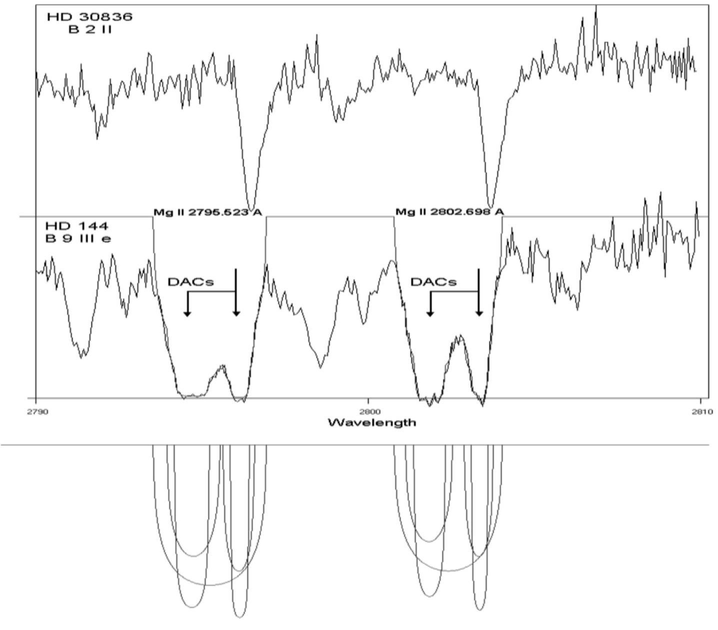
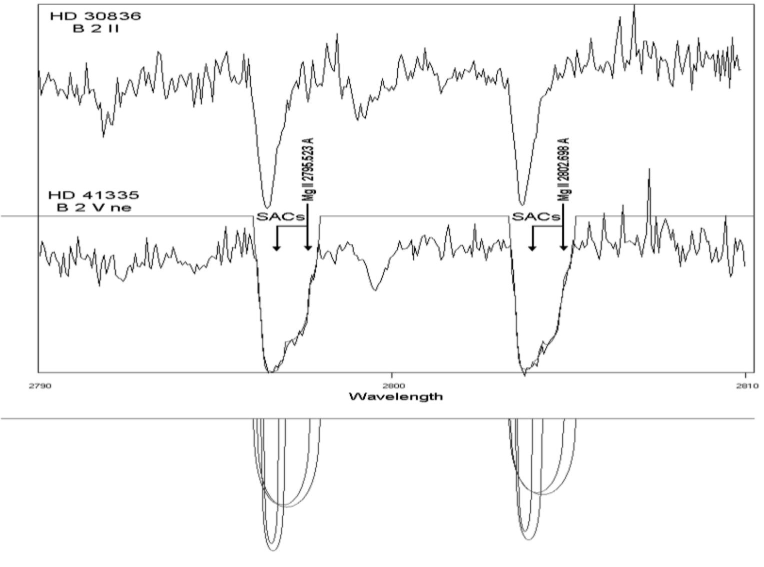
Hot Emission Stars (O and B stars, Teff ≥10,000 K) and ***Quasars*** (BALQSOs) exhibit ***absorption components*** blueshifted with respect to the correpsonding emission lines. These components are called ***Discrete Absorption Components (DACs)*** and ***Broad Absorption Lines (BALs) (*)***, respectively.



(*) 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 Δλ, 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) (**).**





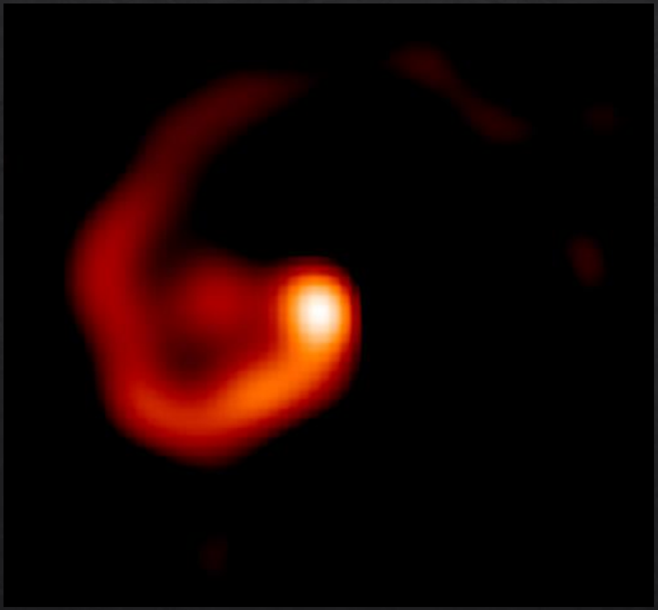
(*) Danezis 1983, 1987, Danezis et al. 1991, 2003, Lyratzi & Danezis 2004.

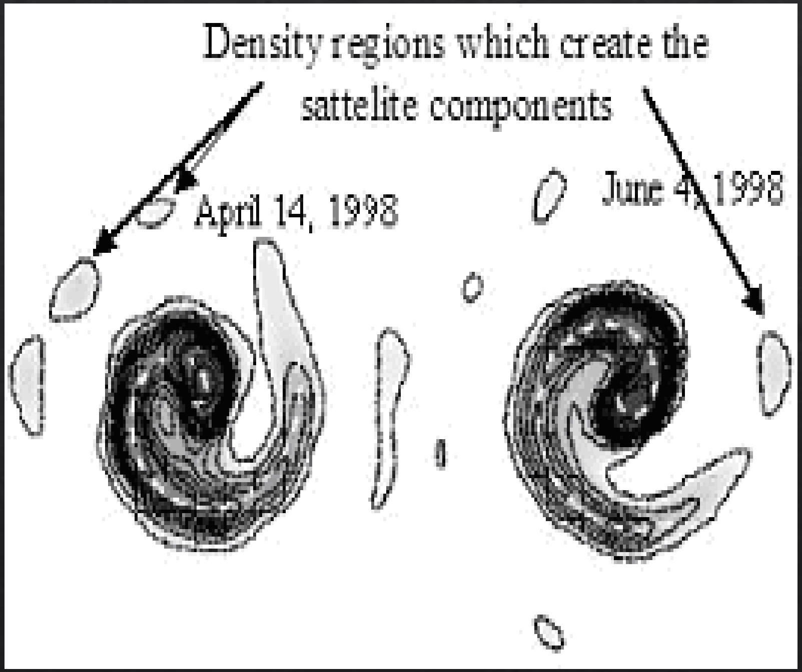
*(**) Danezis et al. 2003, 2007a, Lyratzi & Danezis 2004, Lyratzi et al. 2007a*

The origin of DACs and SACs

(How are DACs or SACs created)

Recent theoretical and observational evidence, indicate that winds of Hot Emission Stars and Quasars are far from being smooth and homogeneous but are rather unstable and clumpy.

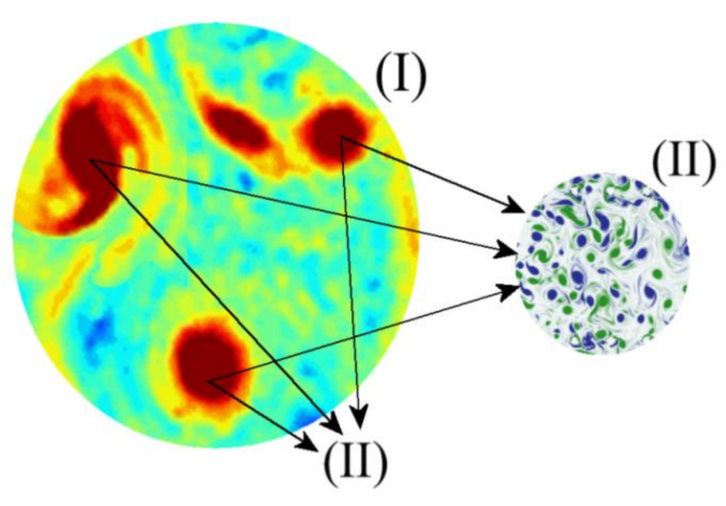




Wolf-Rayet star (WR 104), 8000 ly, O-star, Keck Telescope

The origin of DACs and SACs
(How are DACs or SACs created)

The main idea behind this scenario is that winds of all Hot Emission Stars and Quasars 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)***



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

Some points about our research…

We develop ***a new method for calculating column densities*** of ionic transitions exhibited in the spectra of various astronomical objects. The method is based on the GR model (*) and the A.S.T.A. (**) software that we have developed for analyzing broad and complex absorption and emission profiles of astronomical objects like hot stars and BAL quasars. As the model is able to decompose broad absorption and emission profiles to the uniquely determined number of components they consist of, ***we can measure not only the column density (N_ion) of the entire profile but the column density of each absorption component.*** Apart from column densities the model provides the radial (Vrad) and rotational (Vrot) velocities, optical depths at line centers ($\tau 0$), FWHMs and EWs of individual absorption components.

(*) Danezis et al. PASJ, 59, (827–834), 2007.
Lyratzi et al. PASJ, 59, (357–371), 2007
Antoniou et al. ASR, 54, (1308-1318), 2015

(**) Tzimeas et al., Astronomy and Computing 26, (14–34), 2019

Our research and its main goal

In this presentation:

1. **We present *this new method for calculating the column density.***

2. **We analyze the *broad absorption troughs of C IV, N IV and N V* of the *O-star HD149754 (ζ Oph)*, to the uniquely determined number of components they consist of.**

3. In order to apply ***our Column Density method***, we utilize ***multi-epoch spectra of the above mentioned troughs, obtained 13 years apart,*** in order to probe the ***variability of each absorption component's column density*** i.e. the variations of the column density of each absorbing system in the line of sight. ***Time variability of absorption components of DACs can lead to useful insights concerning the clumpy structure of the wind. That is the main goal of our research.***

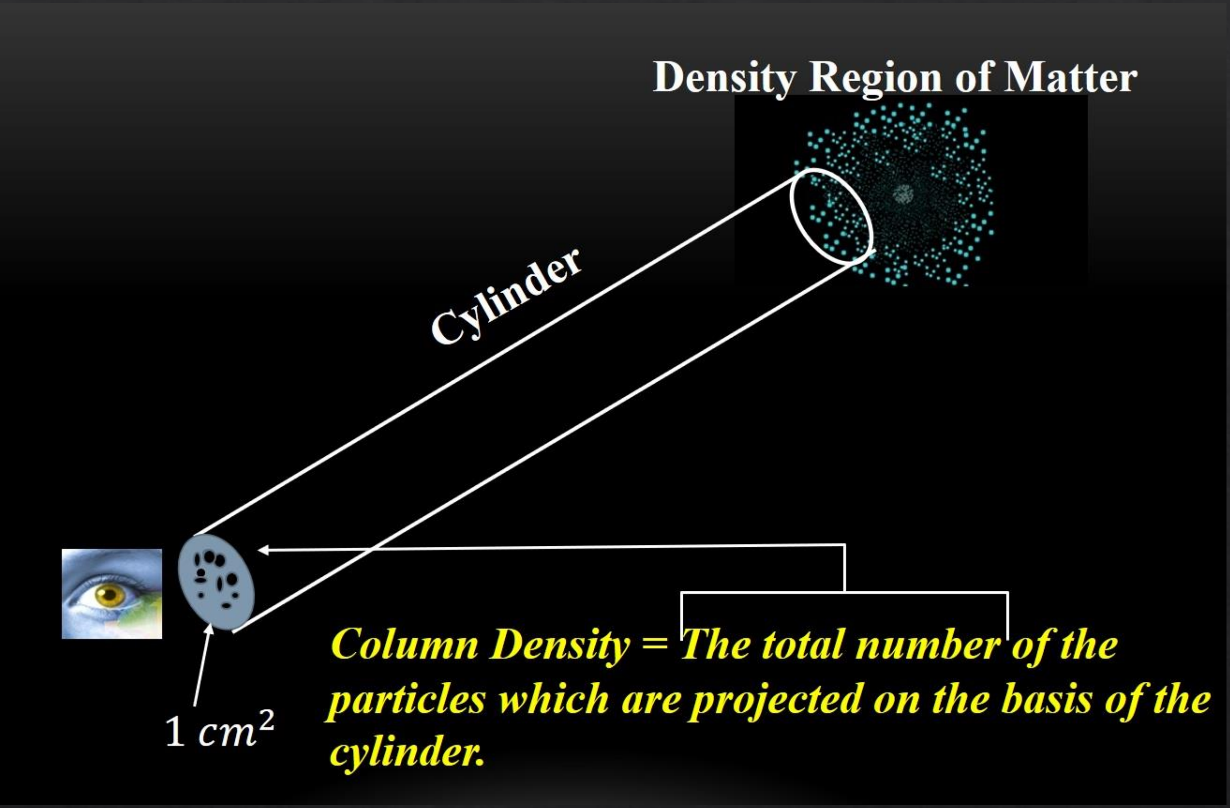
Why do we focus on the Column Density?

The column density is a crucial parameter because:

- It allows the investigation of the ***internal structure of clouds that produce the DAC/BAL components.*** Column density is a measure ***of the amount of intervening matter between an observer and the object*** being observed and is representative of the projected density of the clouds that produce DACs/BALs along a specific line of sight.

- In additional, the ***time scale-variations*** of the components' column densities can provide ***useful insights on the relative number of absorbers of each absorbing cloud in the line of sight.***

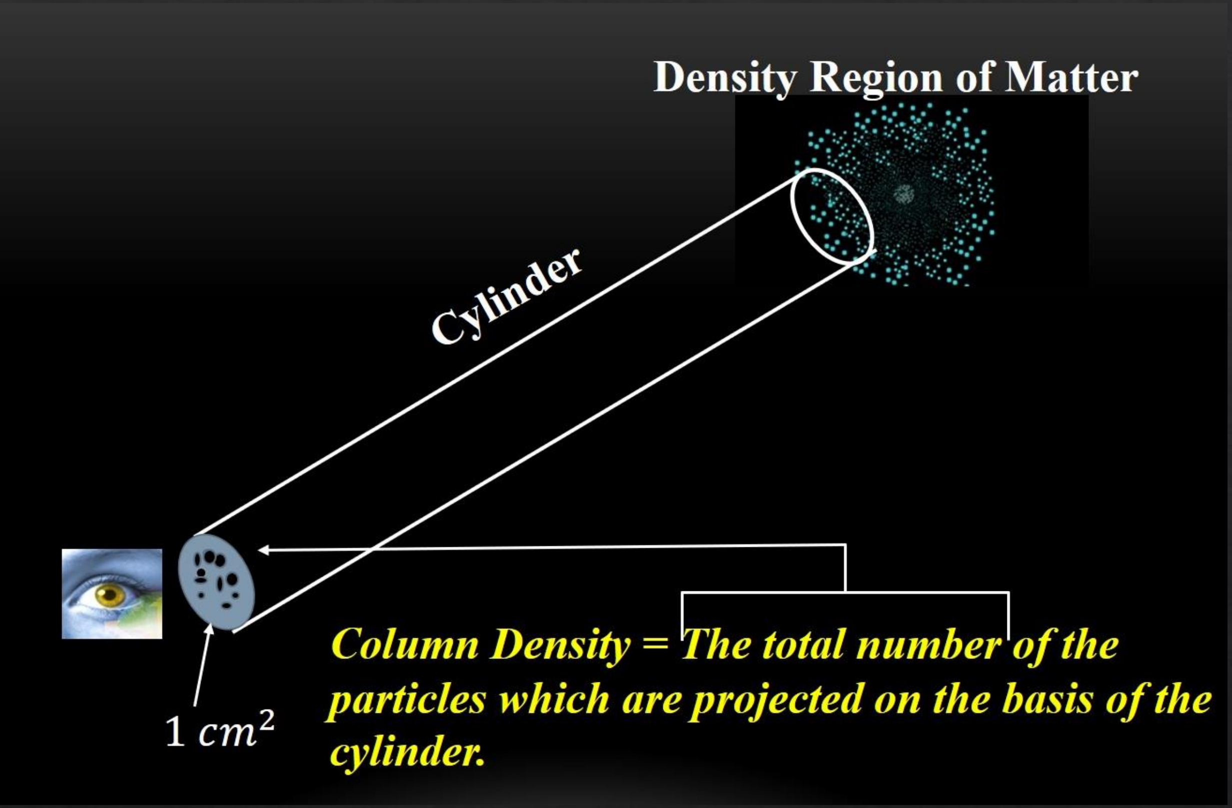
A Definition of the Column Density



Column Density = The total number of the particles which are projected on the basis of the cylinder.

With the term ***“column density”*** we mean the following: Let’s assume a cylinder which has a base of one cm^2. We assume that this cylinder extends from the observer to a density region of matter.

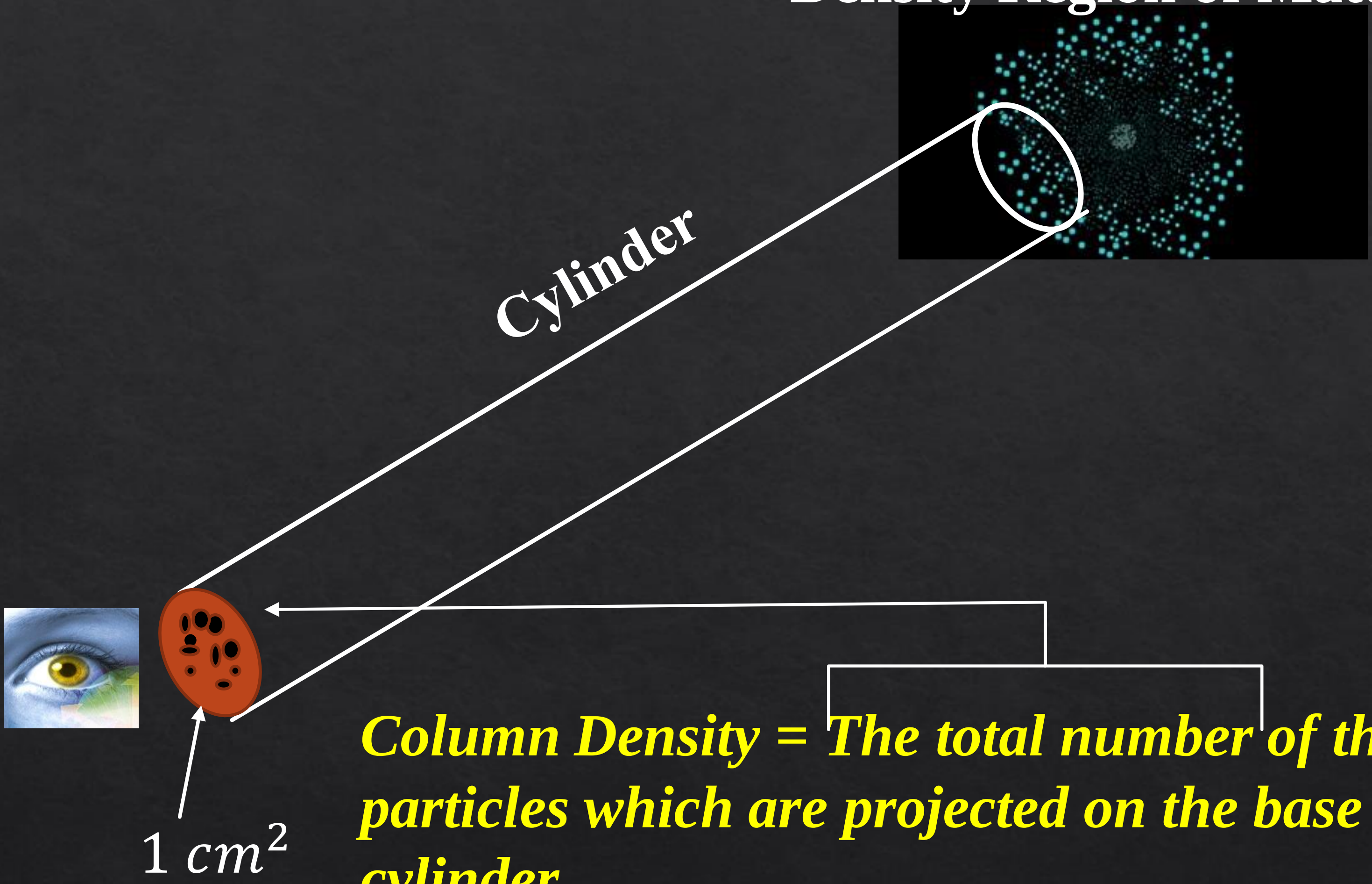
A Definition of the Column Density



Column Density = The total number of the particles which are projected on the basis of the cylinder.

We call ***“column density” of this density region the total number of the particles which are projected on the base of the cylinder.*** Obviously, we measure the column density in particles/ cm^2, or in cm^{-2}

Density Region of Matter



Column Density = The total number of the particles which are projected on the base of the cylinder.

A New Method of Column Density's Calculation

We can calculate the column density as following: Let's start from the definition of ***the optical depth:***

$$\tau = \int_{0}^{s} k\rho ds$$

where:

τ: is the optical depth (no units),
k: is the absorption coefficient ($\text{cm}^2{}_{/}\text{gr}$),
ρ: is the density of the absorbing region (gr/cm^3),
s: is the geometrical depth (cm)

Column Density's Calculation…

In the model we set $k = L\Omega$ so $\tau = \int_0^s L\Omega\rho ds$

where L is the distribution function of the absorption coefficient k and has no units, $\Omega = 1$ and has the units of k $(\Omega = 1\, cm^2/gr)$

Danezis et al. PASJ, 2007. Lyratzi et al. PASJ, 2007

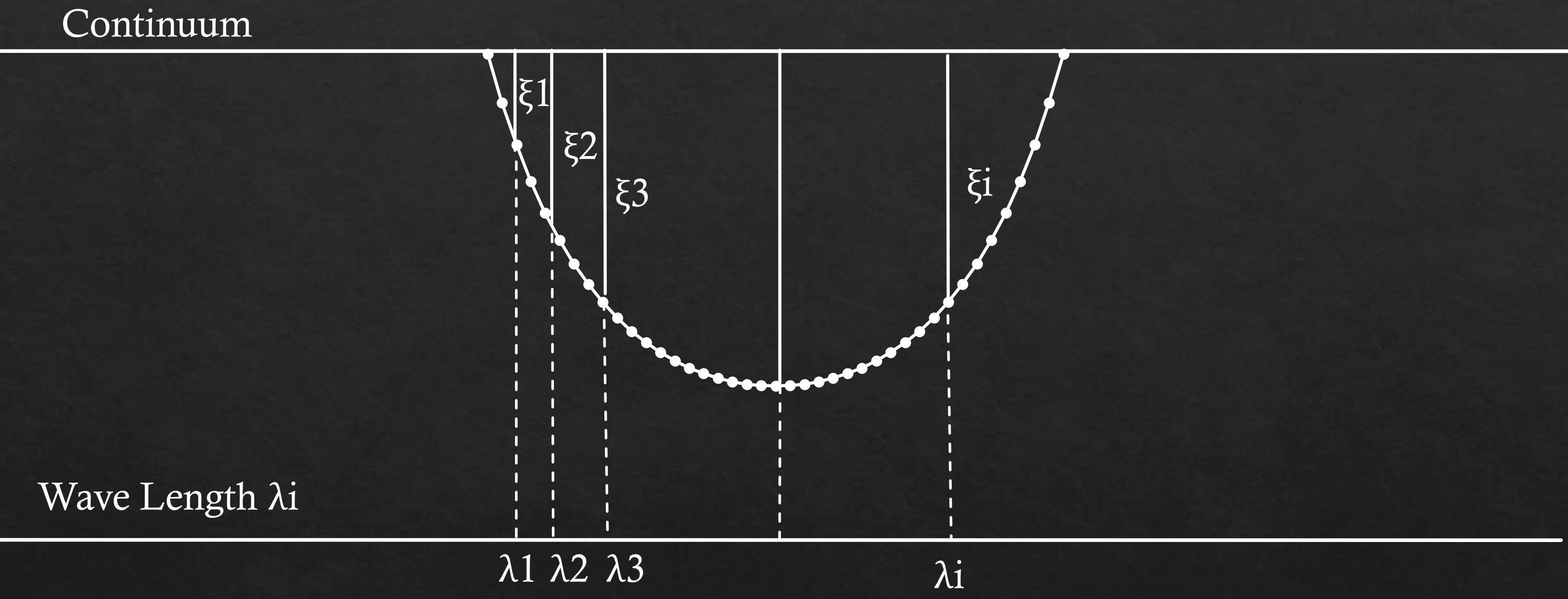
We consider that for the moment of the observation and for a specific ion, k is constant, so k (and thus L and Ω) may come out of the integral. So:

$$\tau = L\int_0^s \Omega\rho ds$$

We set $\xi = \int_0^s \Omega\rho ds$ and τ becomes $\tau = L\xi$

Column Density's Calculation…

a) Absorption Lines



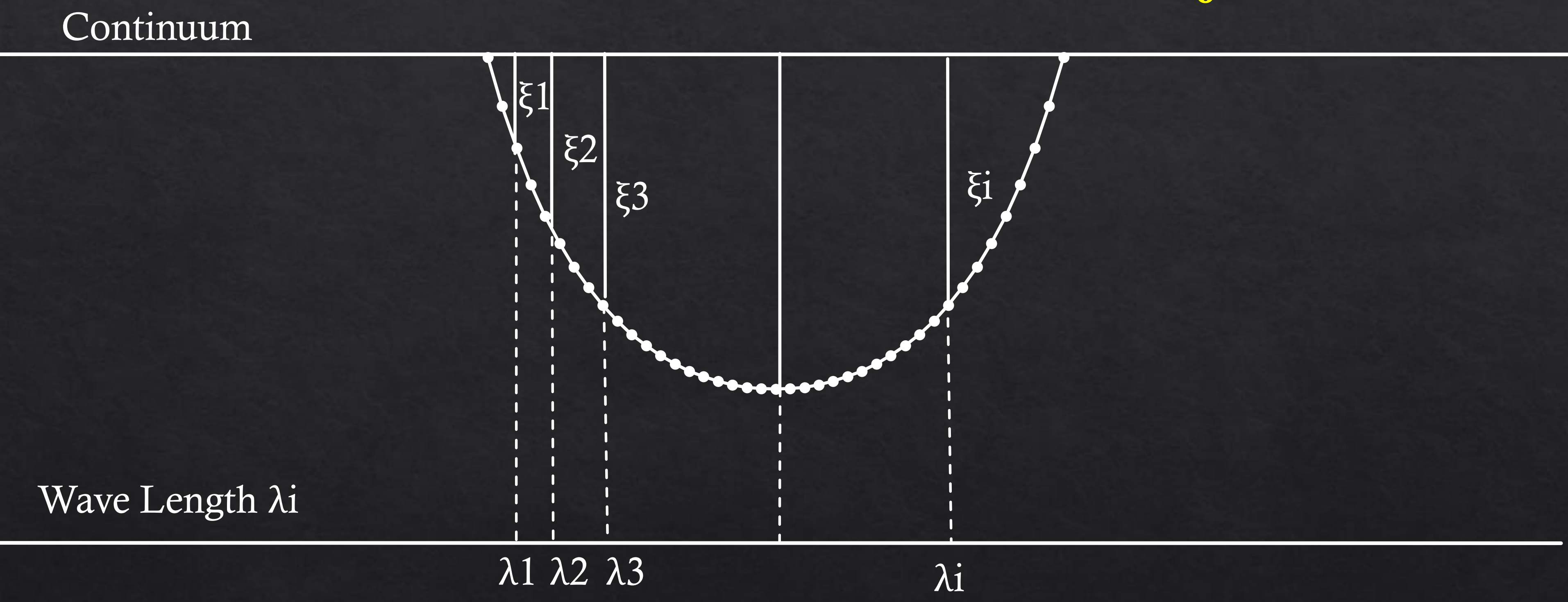
For every one ***ξ_i along the spectral line*** we have:

$$\xi_i = \int_0^s \Omega \rho ds \Rightarrow \xi_i = \Omega \int_0^s \rho ds \Rightarrow \frac{\xi_i}{\Omega} = \int_0^s \rho ds$$

Column Density's Calculation…

a) Absorption Lines

We set $$\boldsymbol{\sigma_i = \frac{\xi_i}{\Omega} = \int_0^s \rho ds}$$



As $\Omega = 1\text{cm}^2/\text{gr}$

contributes only to the units, σ_i takes the value of ξ_i. For each of wave length λ_i along the spectral line, we extract a ***σ_i* from each *ξ_i***.

Column Density's Calculation…

a) Absorption Lines

If we add the values of all σ_i along the spectral line then we have

$$\sigma = \sum_i \sigma_i \qquad (\text{in gr/cm}^2)$$

which is the ***surface density*** of the absorbing matter, which creates the spectral line.

If we divide σ with the atomic weight of the ion which creates the spectral line, we extract ***the number density of the absorbers***, meaning the number of the absorbers per square centimetre (cm^{-2})

$$n = \frac{\sigma}{AW}$$

It is well known, **that each absorber absorbs the specific amount of the energy needed for the transition which creates the specific line.**

Column Density's Calculation…

a) Absorption Lines

So: the factor ***(n ·AW) gr*** of the ions which create the observed absorption line correspond to a ***value of energy E***, which is calculated by our model.

The factor ***(1 · AW) gr*** of the ions corresponds ***to the energy E_i*** that each absorber needs for the transition and is known for each ion.

Thus,

$$\frac{n \cdot AW}{1 \cdot AW} = \frac{E}{E_i} \Rightarrow n = \frac{E}{E_i}$$

This means that the expression $n = \sigma / AW$ (in cm^{-2})

is ***arithmetically equal*** with the $n = E/E_i$.

Column Density’s Calculation…

a) Absorption Lines

In other words

$$n = \frac{E}{E_i} \text{ in units } \frac{\sigma}{AW}, \text{which are in } cm^{-2}$$

This is exactly ***the column density of the Absorption Line (or one of the Absorption Components*** which create the whole Absorption Line)

General Comment: n=σ/AW indicates that this n, which has units particles per square centimeter, cm^{-2}, is equal arithmetically with E/Eı. This means that the Atomic Weight is only used as argument and it is not necessary for the Column Density’s calculation.

Column Density’s Calculation…

b) Emission Lines

In the case of emission lines we have to take into account not only ξ_e, but also the ***source function S***, as both of these parameters contribute to the height of the emission lines. So in this case we have:

$$S\xi_e = \frac{j}{k}\int_0^s \Omega\rho_e ds$$

where: j is the emission coefficient $\left(\frac{\text{erg}}{\text{gr s rad Å}}\right)$

k :is the absorption coefficient (cm^2/gr)

ρ_e :is the density of the emitting region (gr/cm^3)

s :is the geometrical depth (cm).

Column Density's Calculation…

b) Emission Lines

We set $\boldsymbol{k = L\Omega}$

where L is the distribution function of the absorption coefficient k and has no units,

$\Omega = 1$ and has the units of k $\left(\Omega_e = 1\,\frac{\mathrm{erg}}{\mathrm{gr\ s\ rad\ Å}}\right)$

And $\mathrm{j} = \mathrm{L_e\Omega_e}$

where L_e is the distribution function of the emission coefficient j and has no units, $\Omega_e = 1$ and has the units of j

$$\left(\Omega_e = 1\,\frac{\mathrm{erg}}{\mathrm{gr\ s\ rad\ Å}}\right)$$

Column Density's Calculation…

b) Emission Lines

As we did before, in the case of the absorption lines, we may consider that Ω may come out of the integral.

So:

$$S\xi_e = \frac{j}{k}\int_0^s \Omega\rho_e ds = \frac{L_e\Omega_e}{L\Omega}\int_0^s \Omega\rho_e ds = \frac{L_e\Omega_e}{L\Omega}\Omega\int_0^s \rho_e ds = \frac{L_e\Omega_e}{L}\int_0^s \rho_e ds$$

As in the model we use the same distribution for the absorption and for the emission, $(L_e = L)$.

So:

$$S\xi_e = \Omega_e\int_0^s \rho_e ds \Rightarrow \frac{S\xi_e}{\Omega_e} = \int_0^s \rho_e ds$$

Column Density's Calculation…

b) Emission Lines

We set $\sigma_e = \dfrac{S\xi_e}{\Omega_e} = \int_0^s \rho_e ds$. As $\Omega_\mathrm{e} = 1 \dfrac{\mathrm{erg}}{\mathrm{gr\ s\ rad\ Å}}$

contributes only to the units, σ_e takes the value of $S\xi_e$.

For each λ_i along the spectral line, we extract a σ_i from each $S\xi_e$. The program we use calculates the ξ_e for the centre of the line and the S. This means that from this ξe and S we can measure the respective σ_i.

If we add the values of all σ_i along the spectral line then we have (in gr/cm^2)

$$\sigma = \sum_i \sigma_i$$

which is the surface density of the absorbing matter, which creates the spectral line.

Column Density's Calculation…

b) Emission Lines

If we divide σ with the atomic weight of the ion which creates the spectral line, we extract the number density of the emitters, meaning the number of the emitters per square centimetre (cm^{-2})

$$n = \frac{\sigma}{AW}$$

It is well known, that each emitter emits the specific amount of the energy needed for the transition which creates the specific line.

So, the: $n \bullet AW\ gr$

of the ions which create the observed absorption line correspond to a value of energy E, which is calculated by our model.

Column Density's Calculation…

b) Emission Lines

The $1 \bullet AW\ gr$

of the ions corresponds to the energy E_i that each emitter needs for the transition and is known for each ion.

Thus, $$\frac{n \cdot AW}{1 \cdot AW} = \frac{E}{E_i} \Rightarrow n = \frac{E}{E_i}$$

This means that the expression $$n = \frac{\sigma}{AW}$$

(in cm^{-2}) is ***arithmetically equal with the*** $$n = \frac{E}{E_i}$$

Column Density’s Calculation…

b) Emission Lines

In other words $n = \frac{E}{E_i}$ in units $\frac{\sigma}{AW}$, which are in cm^{-2}

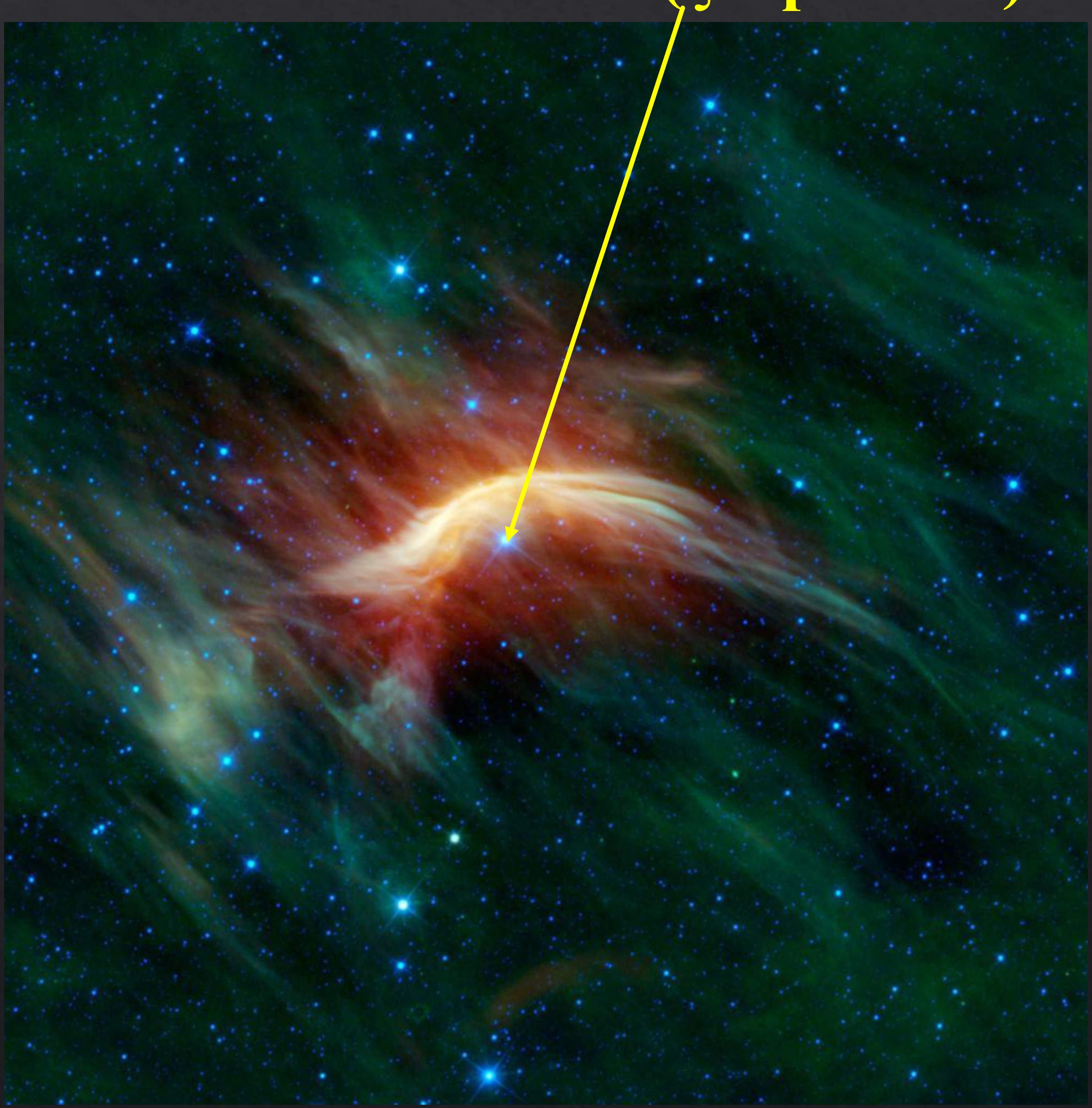
This is exactly **the column density of the Emission Line (or one of the Emission Components** which create the whole Absorption Line)

An application in the case of ***C IV, N IV and N V Spectral Lines*** **in the spectrum of the O-Star** ***HD 149757 (ζ Oph)***

Using GR model and A.S.T.A. software , we analyse the broad ***absorption troughs of C IV, N IV and N V,*** of the ***O-star HD149754 (ζ Oph),*** to the uniquely determined number of components they consist of.

Applying ***the before mentioned method for calculating the Column Density***, we utilize ***multi-epoch spectra, obtained 13 years apart,*** in order to probe the ***variability of each absorption component's column density*** i.e. the variations of the column density of each absorbing system in the line of sight.

The O-star HD 149757 (ζ Ophiuchi)



Basic stellar properties of HD 149757 (ζ Ophiuchi)

Spectral type	O9V(e)	Conti (1973)
m_V	2.56	Hoffleit (1964)
B-V	+0.02	Hoffleit (1964)
Angular diameter	5.1±0.5 milliarsrec	Brown & Davis. (1974)
$(R_*/R8)$	9.6±1.7	Morton (1976)
T_{eff}	31910±2040 34100	Code & Bless (1974) Underhill et al. (1979)
M_*	25±5	Morton (1976)
logg	3.9±0.2 cgs	Morton (1976)
Vsini	390 km/s 351 km/s 400 km/s 348 km/s	Hutchings & Stoeckley (1977) Conti & Ebbets (1977) Herrero (1993) Penny (1996)
Distance d	155 pc	Howarth & Reid. (1993)
Mass loss rate	$(1.3\pm0.1)x10^{-7}\ M_0\ yr^{-1}$	Howarth (1990)
Radial velocity	-15 km/s (variable radial velocity)	Hoffleit (1991)

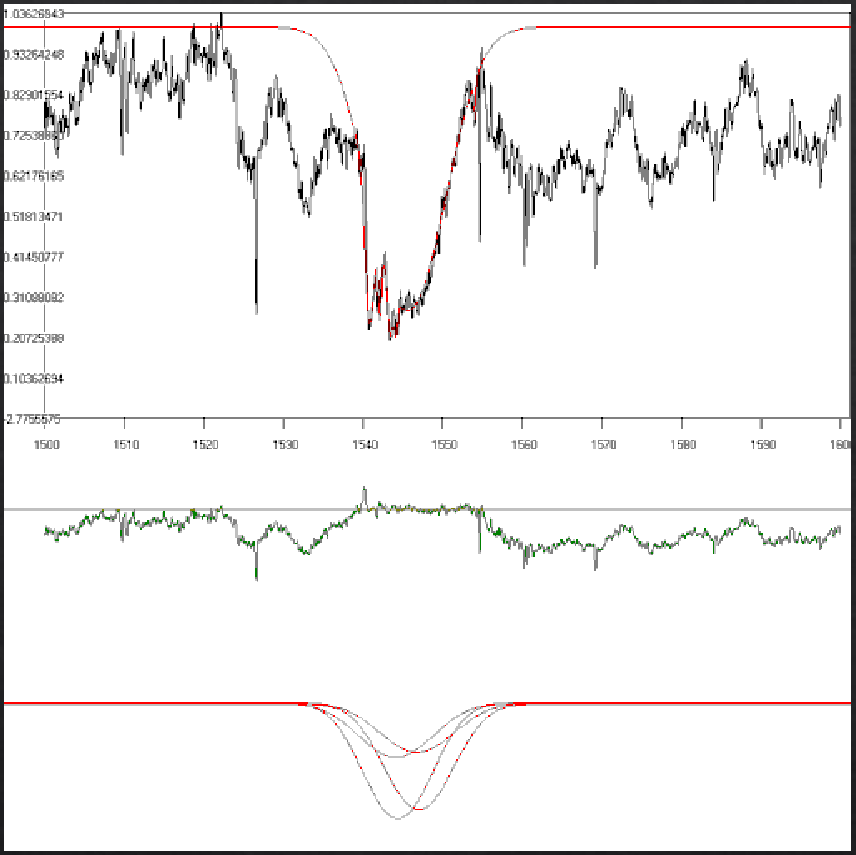
Observational data and reduction of the spectra

Our data are taken from the **satellite International Ultraviolet Explorer (IUE)** and are available in VILSPA Database (http://archive.stsci.edu/iue/search.php). For the far ultraviolet, the spectra were taken with the **Short Wavelength range Prime Camera (SWP).**

IUE- data of HD 149757 (ζ Ophiuchi)

Spectrum	Date
SWP05874	21/7/1979
SWP09123	26/5/1980
SWP14270	17/6/1981
SWP17584	4/8/1982
SWP21166	25/9/1983
SWP25461	16/3/1985
SWP33347	23/4/1988
SWP36080	24/4/1989
SWP38410	22/3/1990
SWP41190	26/3/1991
SWP45092	7/7/1992

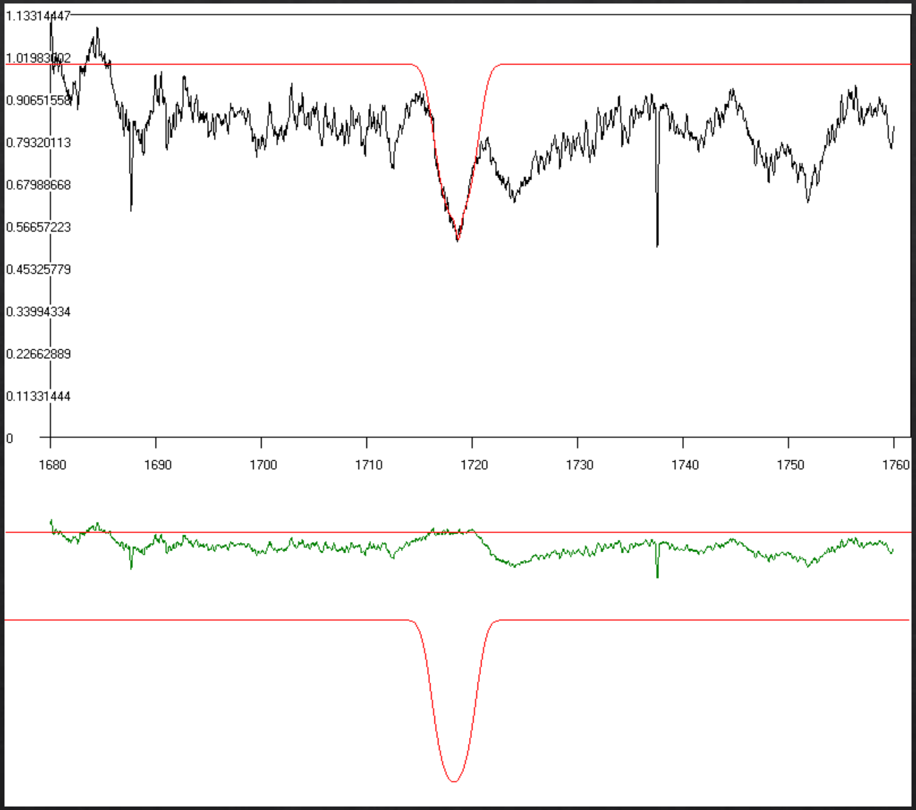
The C IV resonance lines



In this figure we present the ***C IV resonance lines and their best fit*** in in the spectrum SWP14270 of the star HD149757. The best fit has been obtained using ***two absorption components*** for the blue resonance line, as well as ***two absorption components*** for the red one.

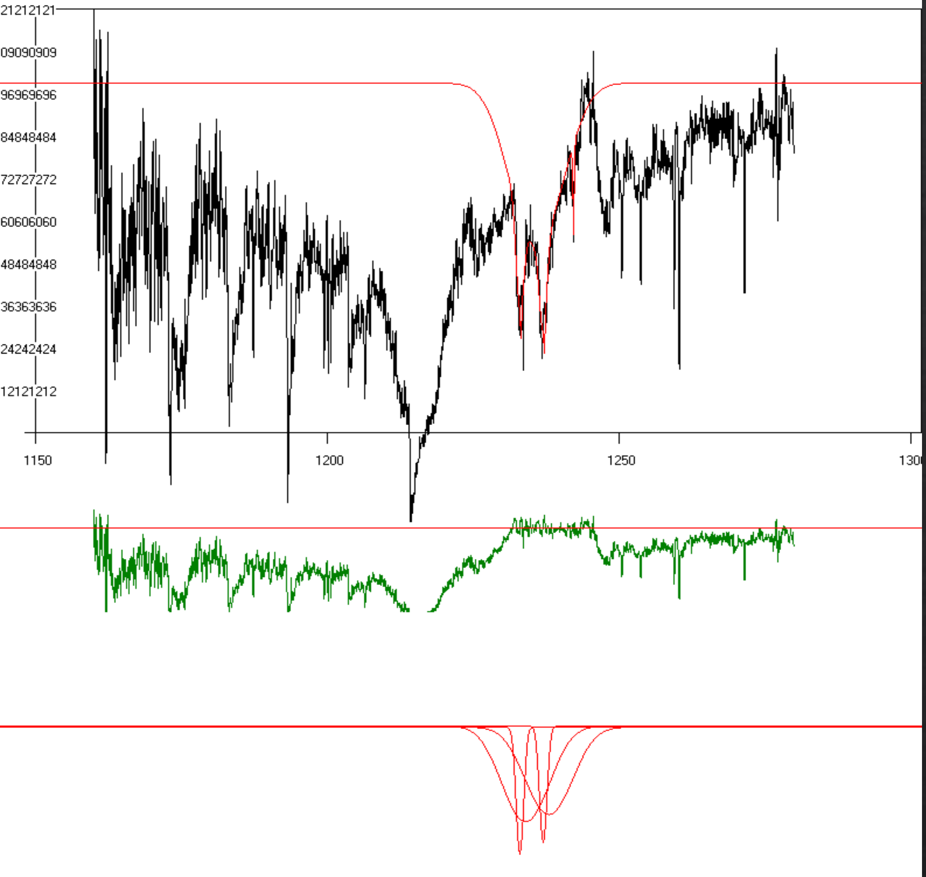
The graph bellow the fit indicates the differences between the observed spectrum and the fit. We present also the ***separated absorption components*** which the main resonance lines consist of.

The N IV spectral line



The best fit of the N IV spectral line with one component in the spectrum SWP21166 of the star HD 149757. The graph bellow the fit indicates the differences between the observed spectrum and the fit.

The N V resonance lines



Here one can see the ***N V resonance lines and their best fit*** in
in the spectrum SWP38410 of the star HD149757. The best fit has been obtained using ***two absorption components*** for the blue resonance line, as well as ***two absorption components*** for the red one.

The graph bellow the fit indicates the differences between the observed spectrum and the fit. We present also the ***separated absorption components*** which the main resonance lines consist of.

The Column Density's Values and variability

a) C IV resonance lines and their absorbing clouds

	Blue Resonance Line					Red Resonance Lines				
Year	**N1**	**N2**	**Δt**	**(ΔN1)%**	**(ΔN2)%**	**N1**	**N2**	**Δt**	**(ΔN1)%**	**(ΔN2)%**
1979	2.28	0.62	1979-1980	5%	32%	2.09	0.56	1979-1980	5%	26%
1980	2.39	0.82	1980-1981	-13%	29%	2.19	0.71	1980-1981	-14%	35%
1981	2.07	1.06	1981-1982	96%	-54%	1.89	0.96	1981-1982	106%	-51%
1982	4.07	0.48	1982-1983	-48%	19%	3.89	0.47	1982-1983	-50%	12%
1983	2.11	0.58	1983-1985	48%	91%	1.93	0.52	1983-1985	45%	73%
1985	3.12	1.10	1985-1988	31%	-45%	2.80	0.90	1985-1988	32%	-33%
1988	4.10	0.60	1988-1989	-47%	-2%	3.70	0.60	1988-1989	-46%	-9%
1989	2.17	0.59	1989-1990	-11%	45%	1.98	0.55	1989-1990	-12%	42%
1990	1.92	0.86	1990-1991	5%	22%	1.75	0.78	1990-1991	5%	22%
1991	2.02	1.05	1991-1992	16%	-28%	1.84	0.95	1991-1992	16%	-28%
1992	2.34	0.75				2.14	0.68			

Absolute Values and their Annual Percentage Variability of the ***Column Density*** ***N_i, i=1,2 (in 10^{10} cm^{-2})*** of the absorbing clouds which create the ***λ 1548.155 Å C IV (blue) and λ 1550.774 Å C IV (red) resonance lines.***

The Column Density's Values and variability

b) N IV spectral line and its one absorbing cloud

Year	N	Δt	ΔN%
1979	0.92	1979-1980	15%
1980	1.05	1980-1981	23%
1981	1.29	1981-1982	-8%
1982	1.19	1982-1983	-11%
1983	1.07	1983-1984	14%
1984	1.22	1984-1985	-8%
1985	1.12	1985-1986	20%
1986	1.35	1986-1987	6%
1987	1.43	1987-1988	-17%
1988	1.19	1988-1989	-18%
1989	0.98	1989-1990	11%
1990	1.09	1990-1991	11%
1991	1.21	1991-1992	-26%
1992	0.89		

Absolute Values and their Annual Percentage Variability of the ***Column Density N (in 10^{10} cm^{-2})*** of the absorbing clouds which create the ***λ 1718.8 Å N IV spectral line.***

The Column Density's Values and variability

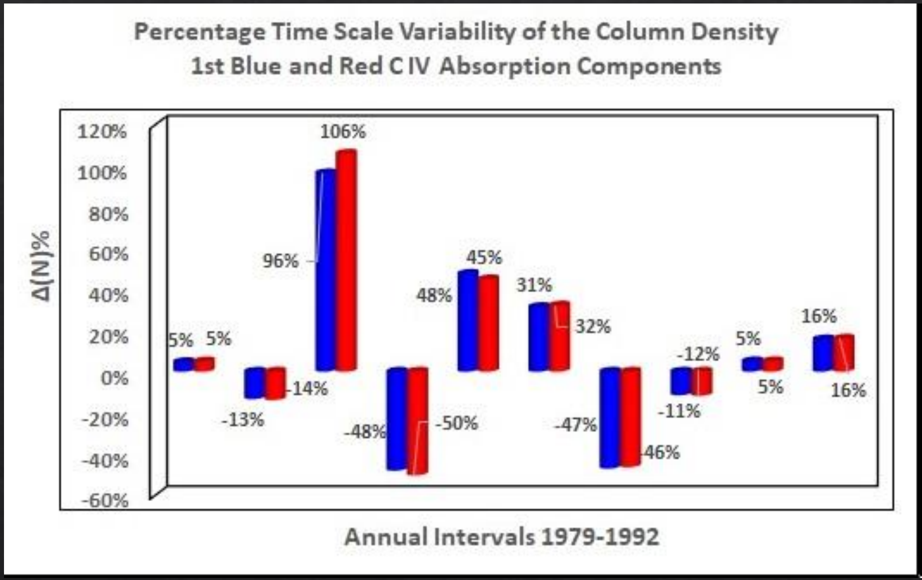
c) N V resonance lines and their absorbing clouds

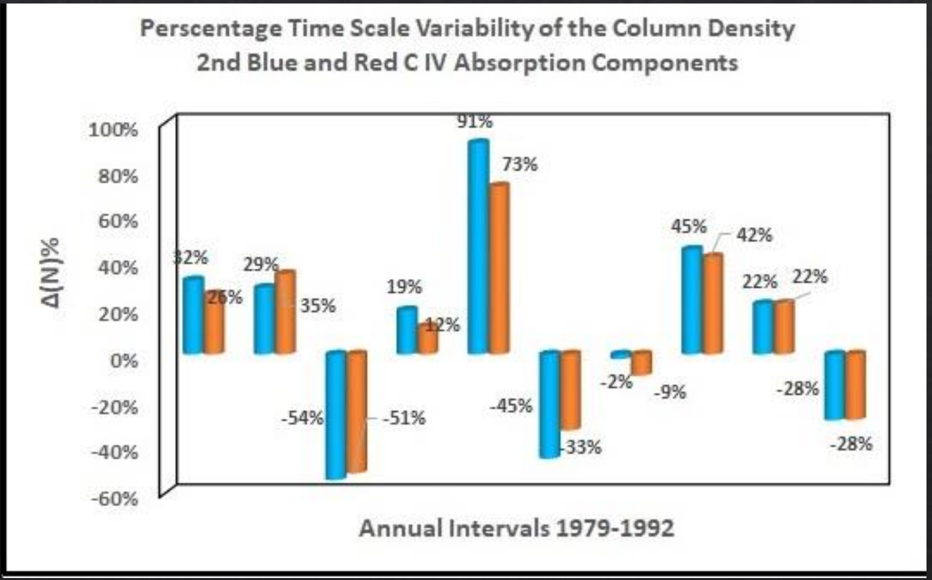
	Blue Resonance Lines		Red Resonance Lines						
Year	**N1**	**N2**	**N1**	**N2**	**Δt**	**(ΔN1)%**	**(ΔN1)%**	**(ΔN2)%**	**(ΔN2)%**
1979	0.99	0.21	0.90	0.19	1979-1980	7%	14%	15%	14%
1980	1.06	0.24	0.97	0.21	1980-1981	21%	47%	43%	47%
1981	1.30	0.34	1.17	0.32	1981-1982	-12%	-19%	-18%	-19%
1982	1.13	0.28	1.03	0.25	1982-1983	-6%	19%	36%	19%
1983	1.06	0.37	0.97	0.30	1983-1985	4%	-25%	-34%	-25%
1985	1.09	0.25	1.00	0.23	1985-1988	15%	15%	15%	15%
1988	1.26	0.28	1.15	0.26	1988-1989	-8%	-22%	-18%	-22%
1989	1.16	0.23	1.06	0.20	1989-1990	5%	17%	12%	17%
1990	1.22	0.26	1.12	0.24	1990-1991	-9%	-2%	-9%	-2%
1991	1.12	0.24	1.02	0.23	1991-1992	16%	21%	30%	21%
1992	1.29	0.31	1.18	0.28					

Absolute Values and their Annual Percentage Variability of the ***Column Density Ni, i=1,2 (in 10^{10} cm^{-2})*** of the absorbing clouds which create the **λ 1238.821 Å** ***N V (blue) and λ 1242.804 Å N V (red) resonance lines.***

The Column Density′s Percentage Variability

a) C IV resonance lines and their absorbing clouds

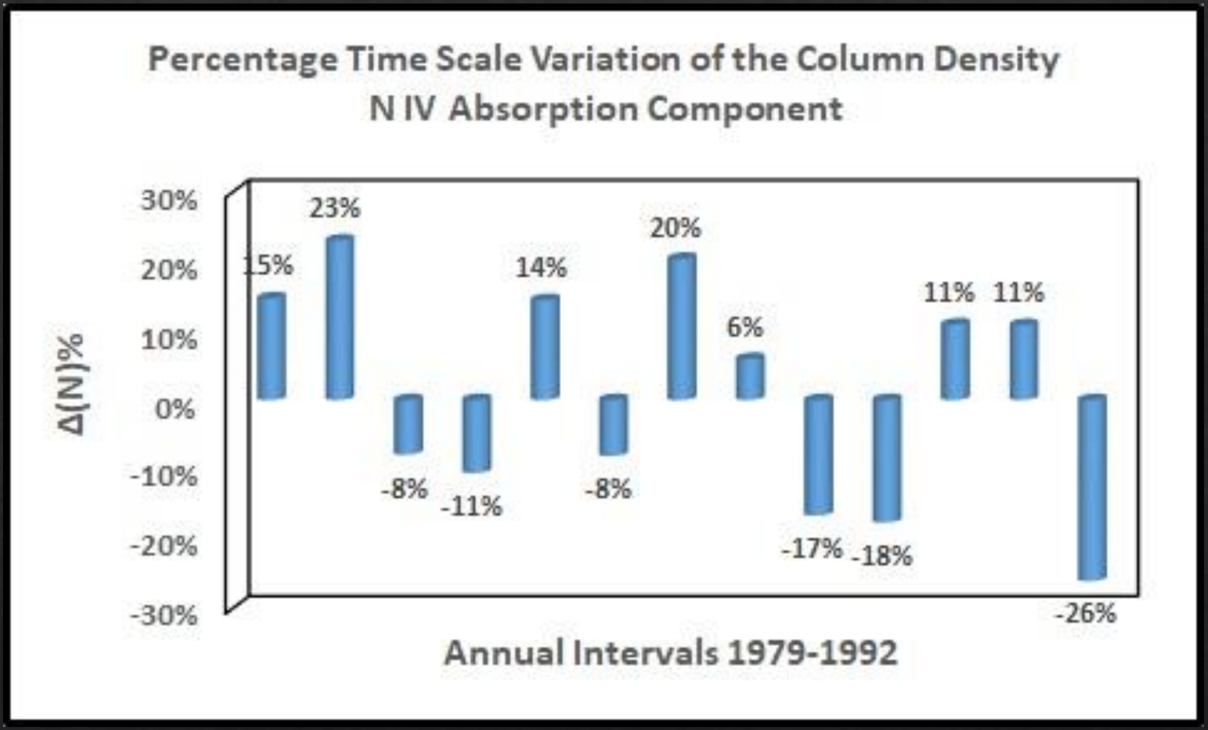




The ***percentage timescale variation*** of the ***Column Density Ni, i=1,2 (in 10^{10} cm^{-2})*** of the ***1st and 2nd blue and red absorption components*** which create the Spectral Profile of the ***C IV resonance lines.***

The Column Density′s Percentage Variability

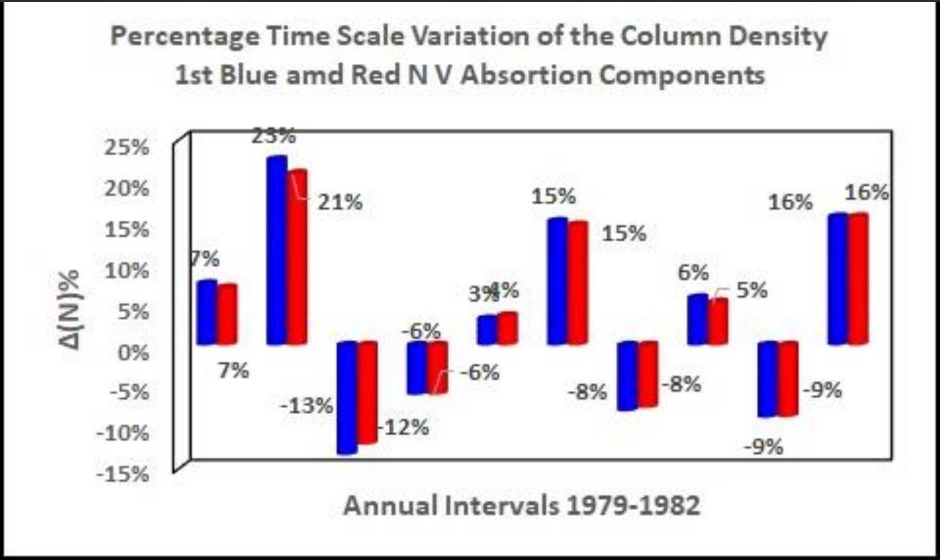
b) N IV spectral line

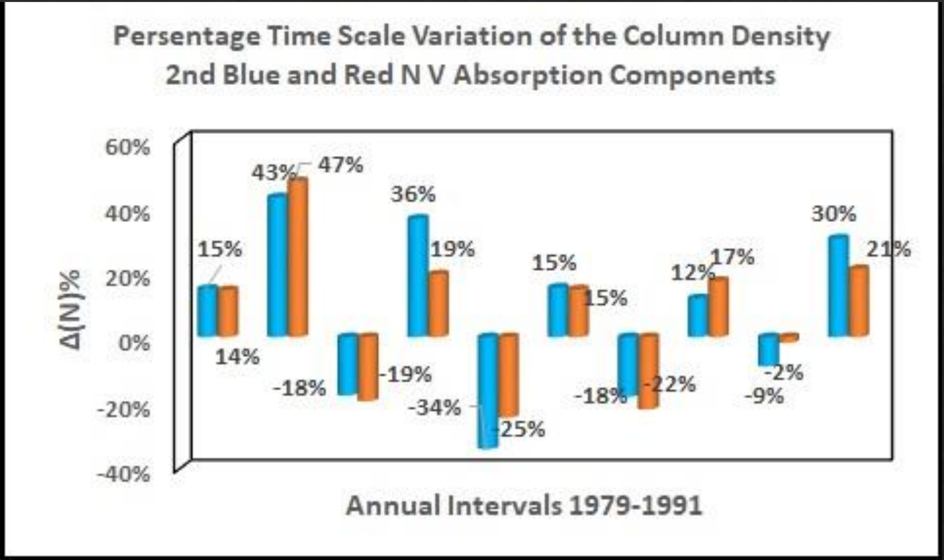


The ***percentage timescale variation*** of the ***Column Density N, (in 10^{10} cm^{-2})*** of the ***unique absorption component*** which create the Spectral Profile of the ***N IV spectral lines***

The Column Density′s Percentage Variability

c) N V resonance lines and their absorbing clouds





The ***percentage timescale variation*** of the ***Column Density Ni, i=1,2 (in 10^{10} cm^{-2})*** of the ***1st and 2nd blue and red absorption components*** which create the Spectral Profile of the ***N V resonance lines.***

Results and Discussion

Firstly (two general notes about the clumn density's calculation)

We presented ***a new method for the calculation of Column Density*** using the GR model. ***It is important to mention that:***

1. The column density is calculated by the most researchers considering that the observed spectral shape ***consists of only one absorption component.*** However, we consider that the observed spectral shape consists ***of a number of absorption components (DACs/SACs).*** This means that the calculated values of the column density ***is likely to be lower than the calculated values by other researchers.***

2. Comment ***(Howarth & Prinja, 1989. The Astrophysical Journal, 69, 527, p. 561)***

"The accuracy of the quoted column densities ***depends, of course, on the validity of the models used in the profile fits.*** Several of our assumptions in this regard are certainly in error ***(e.g., monotonie velocity law, steady state; Lucy 1983; Owocki, Castor, and Rybicki 1988).*** For example, Prinja, Howarth, and Henrichs, 1987 obtained two sets of very similar column densities for ξ Per using two rather different sets of assumptions for line formation. ***Nonetheless, the models are demonstrably deficient, so our N^n and N^p data are, strictly, parameters, not measurements***".

Results and Discussion

Secondly (The spectral line analysis)

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,*** as well as both of the ***N V resonance spectral lines***, consist ***of two independent and individual Satellite Absorption Components (SACs), while the N IV spectral line consists of one Absorption Component.***

Results and Discussion

Thirdly

We ***calculated observed variability*** in ***the Column Density*** in different time intervals. This variability was observed in the ***absorption C IV, N IV and N V*** spectral lines which create their ***whole spectral 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

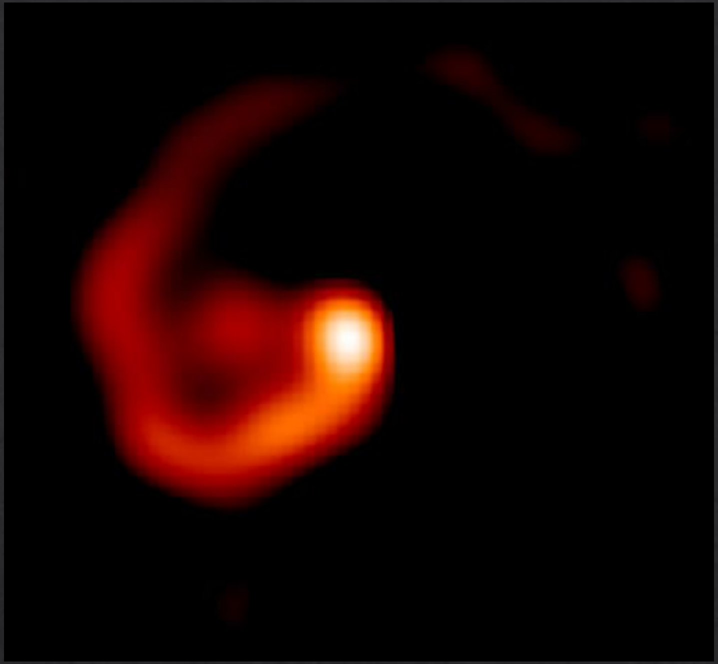
Answer to the basic question that was the goal of our study

All the above mentioned results lead us to note that the time scale variability of the Column Density compered to the variability of some other 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 were also confirmed in the case of the emission clouds forming the P-Cygni profile (***). This result is a third confirmation *(for the first and second see Antoniou et al., 2017, 2019)* of the "clumping" structure of the O- star HD 149757 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.

(***) Antoniou et al., 12th SCSLSA, Serbia 2019.



Thank you very much for your attention

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