The peculiar absorption and emission phenomena from stars to quasars

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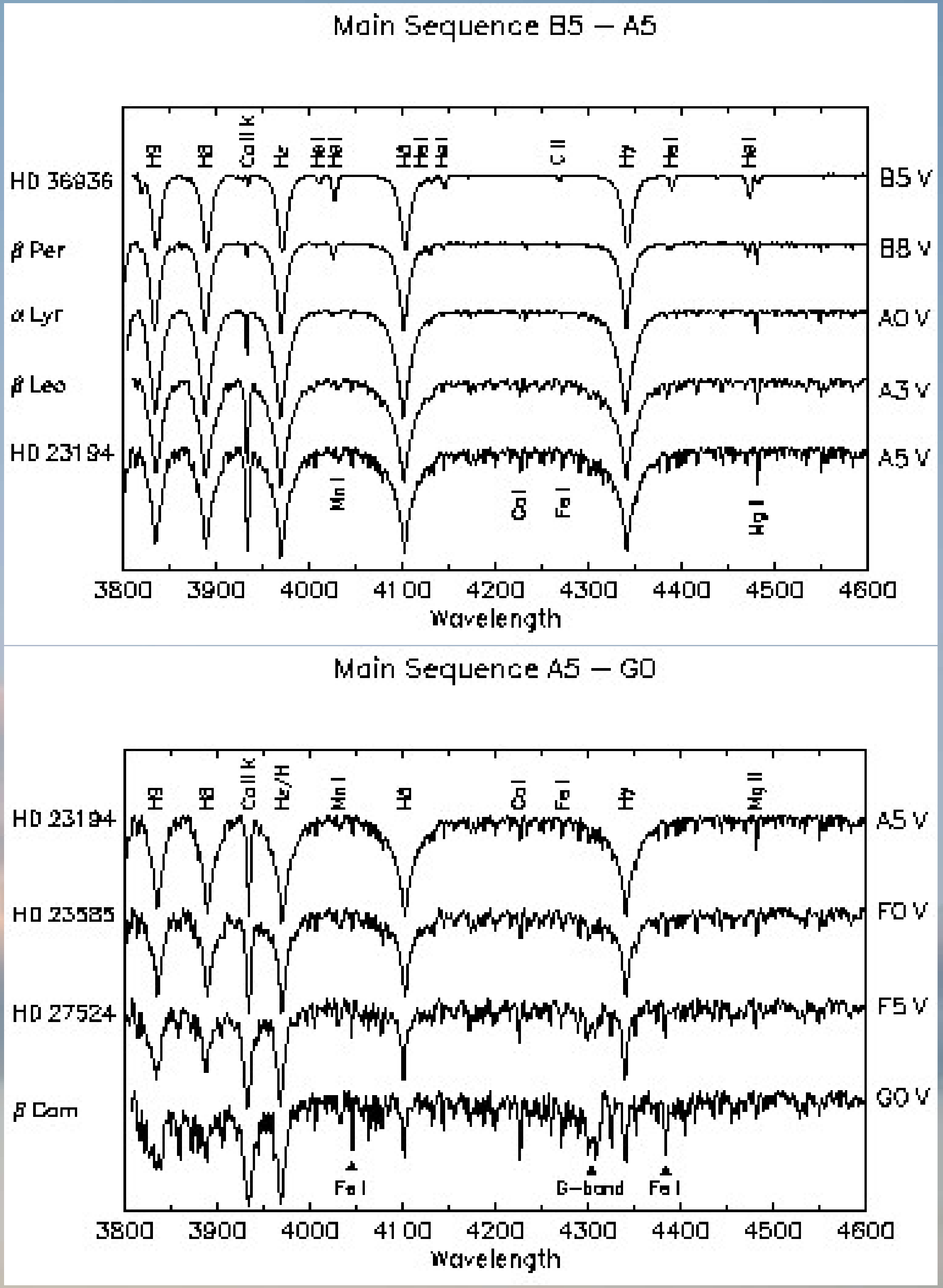
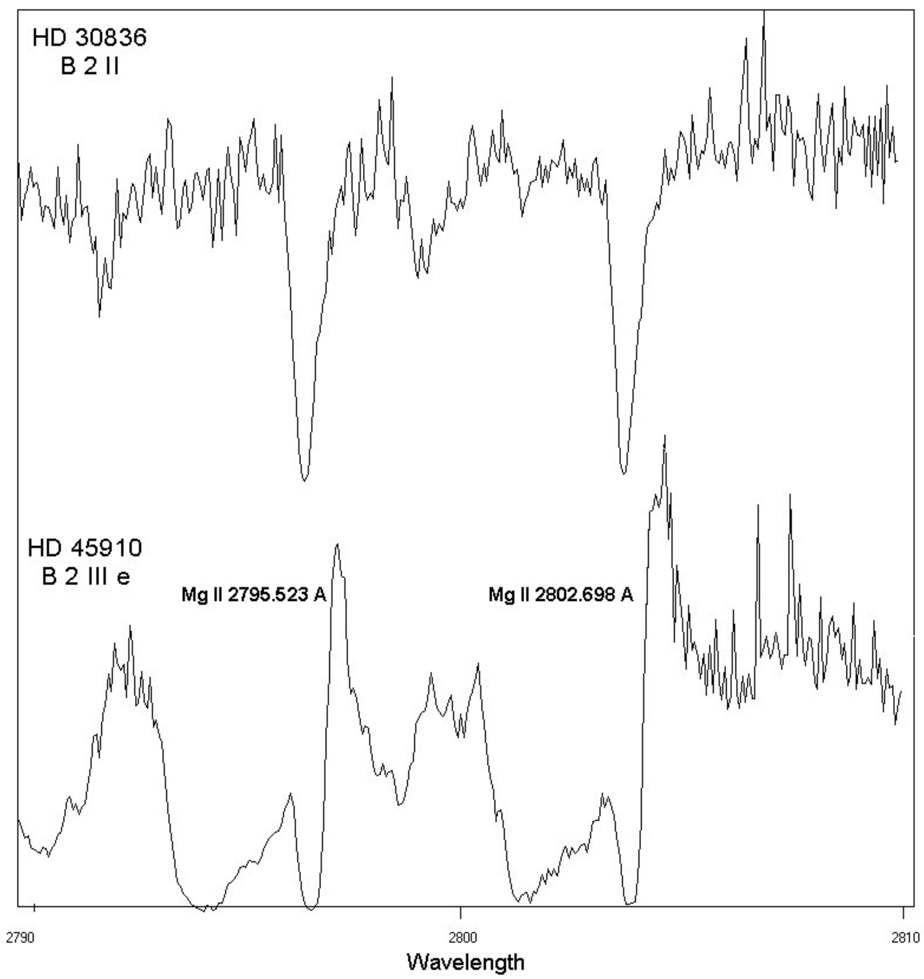
The spectral lines in astrophysical objects

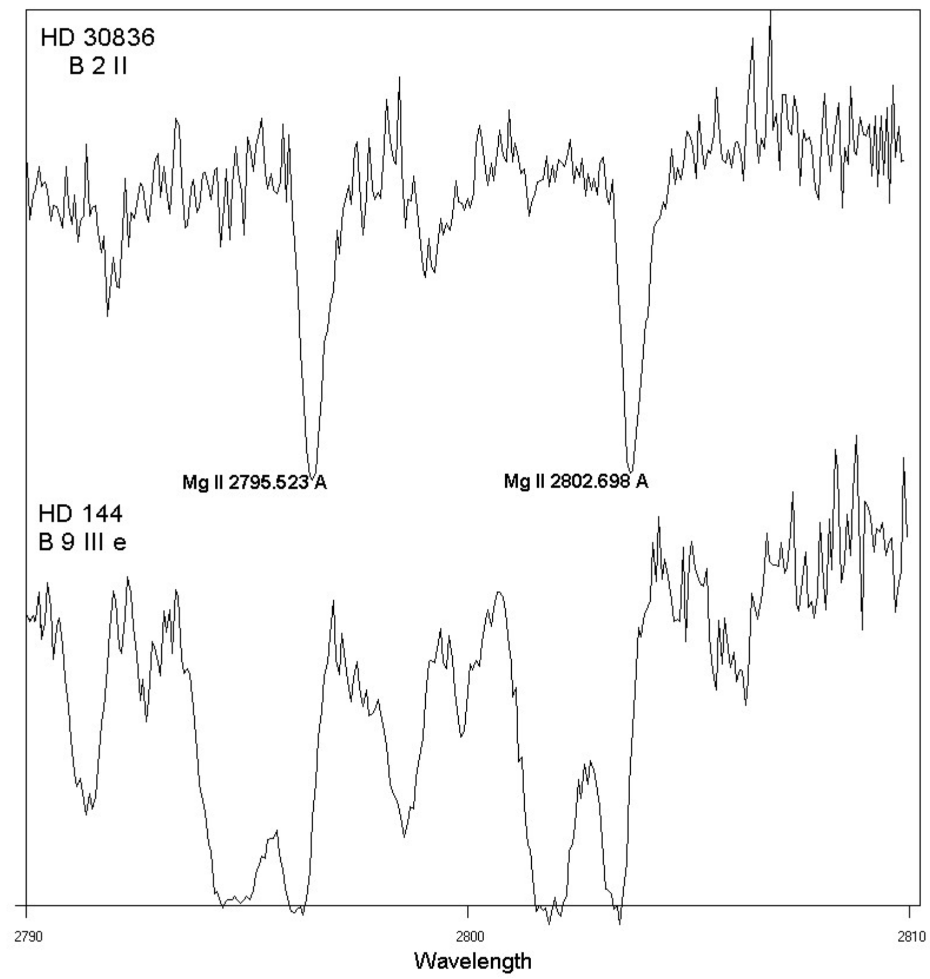
It is well known that the absorption spectral lines that we can detect in the spectra of normal stars are an important factor to study many physical parameters of stellar atmospheres.

In these figures we can see two groups of classical stellar spectra of different spectral subtypes that present normal spectral absorption lines.

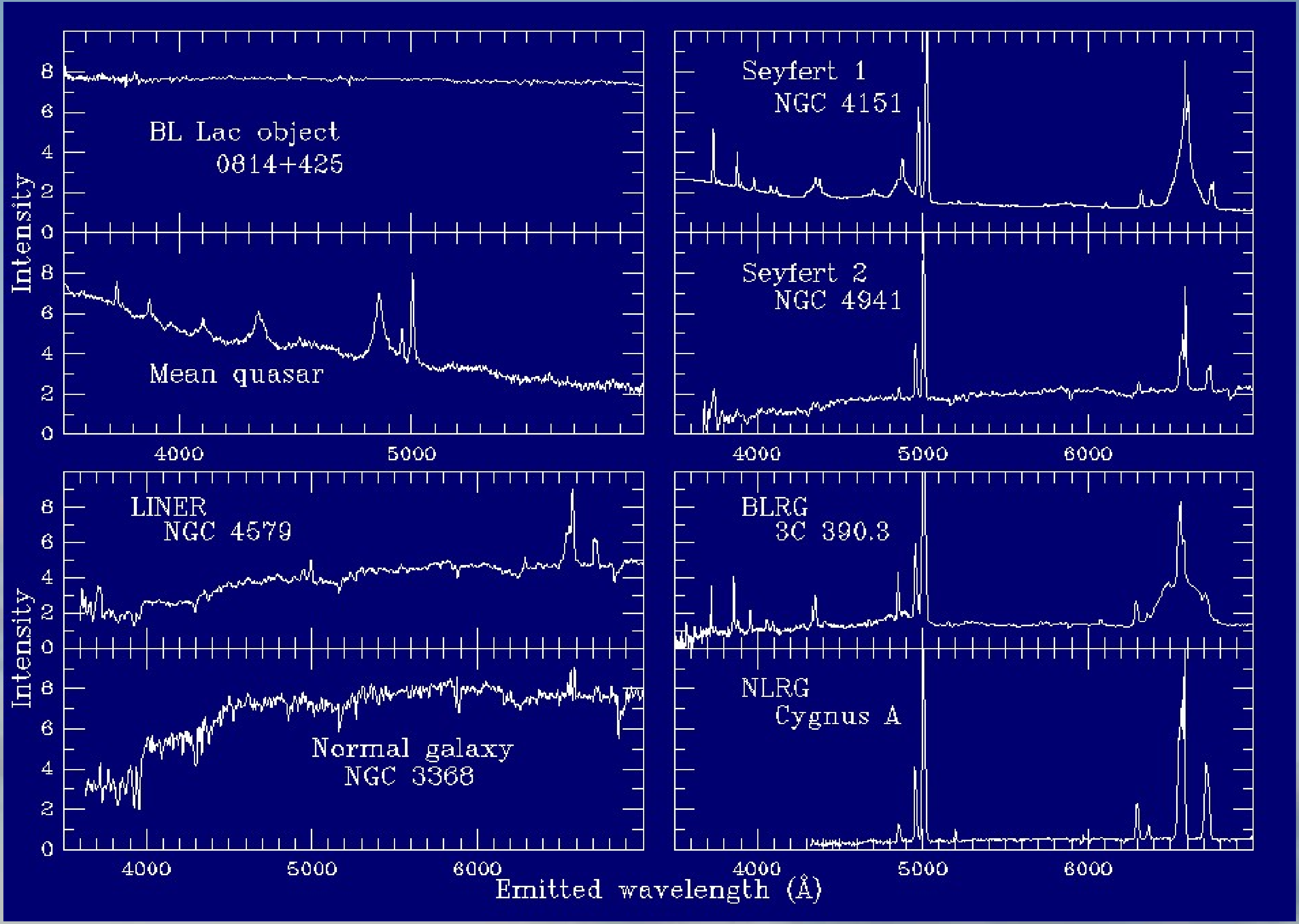


However Hot Emission Stars (Oe and Be stars) present peculiar profiles





In these figures we can see the comparison of Mg II resonance lines between the spectrum of a normal B star and the spectra of two active Be stars that present complex and peculiar spectral lines. In the first figure we observe a combination of an emission and some absorption components (P Cygni).

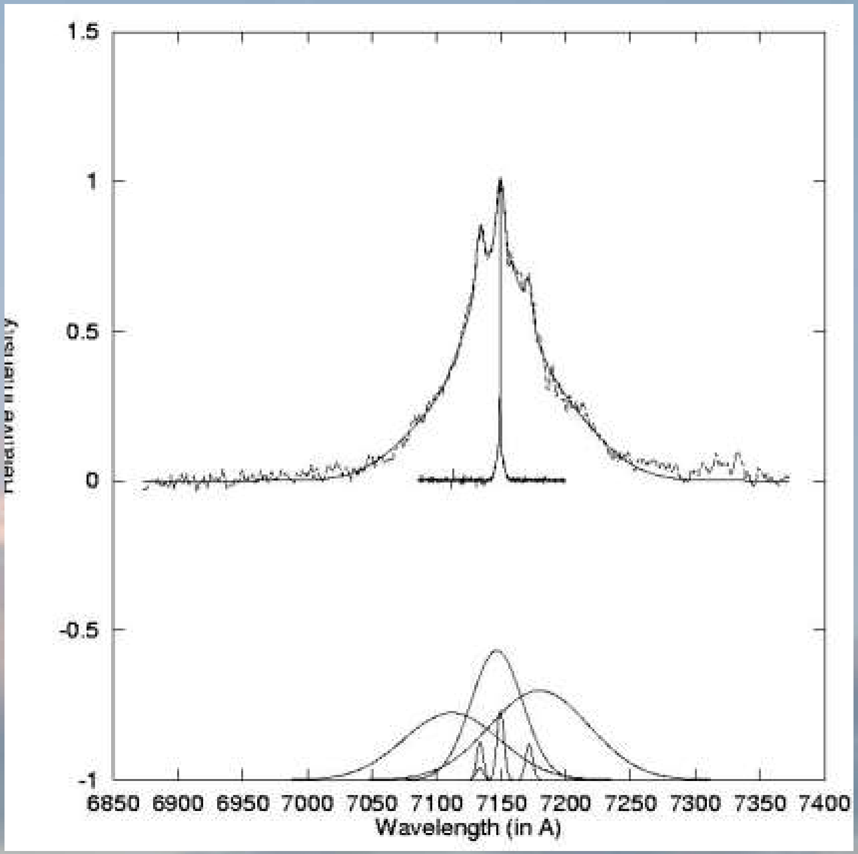


Normal galaxies present spectra without emission lines, as normal stars.
In contrary AGNs present emission lines (Hα, Hβ) like Hot Emission Stars (Oe and Be).

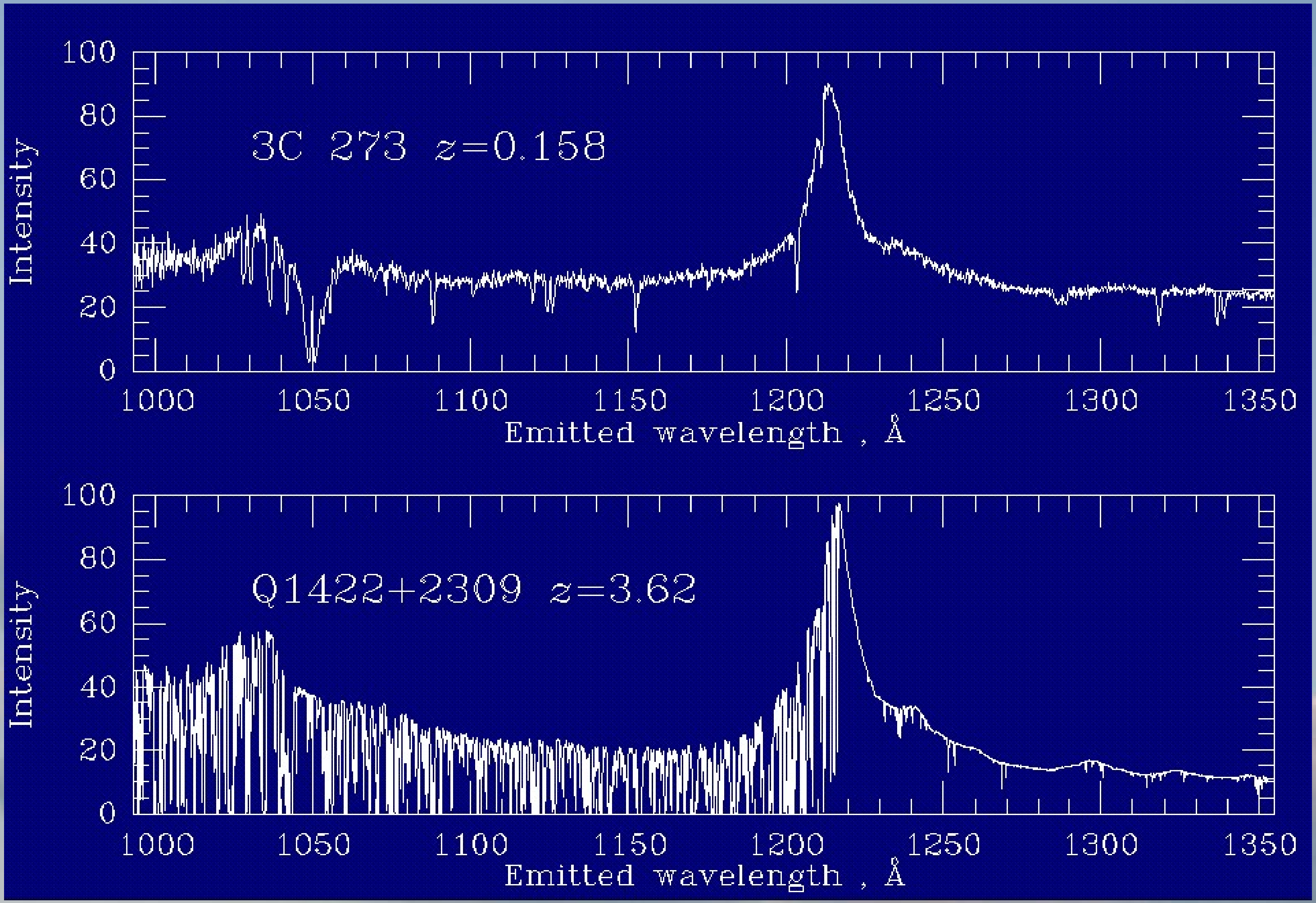
Our Problems

The spectral lines of Hot Emission Stars and AGNs may be very broad and satellite lines may appear.

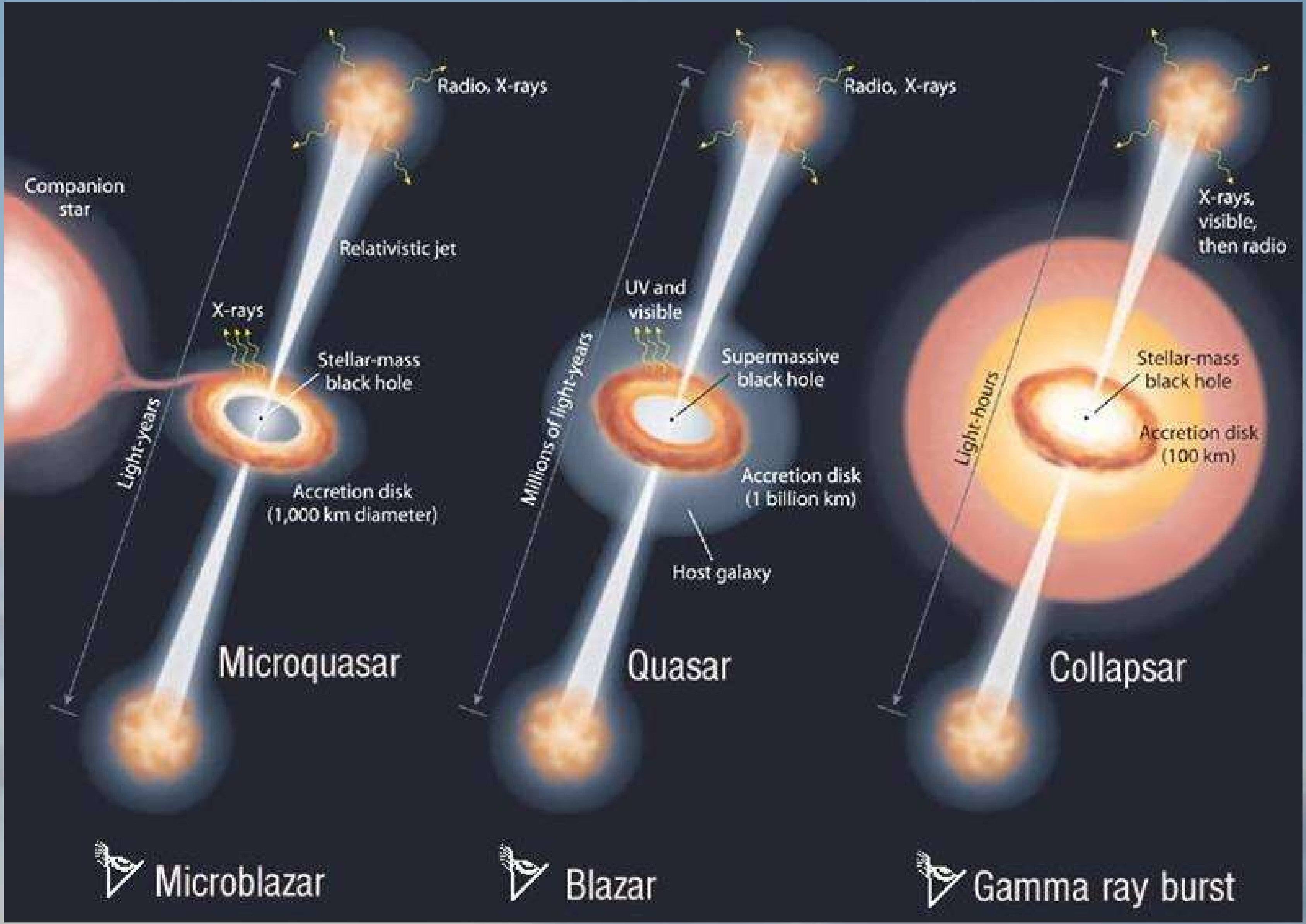
In this figure we present the comparison between the observed Ha line of an AGN (III Zw2) and the same line obtained from laboratory plasma. This spectral line is blended with two [NII] satellite lines. The line broadening is a kinematical effect (radial, rotational and random velocities) that arises from the geometry of the emitting region.



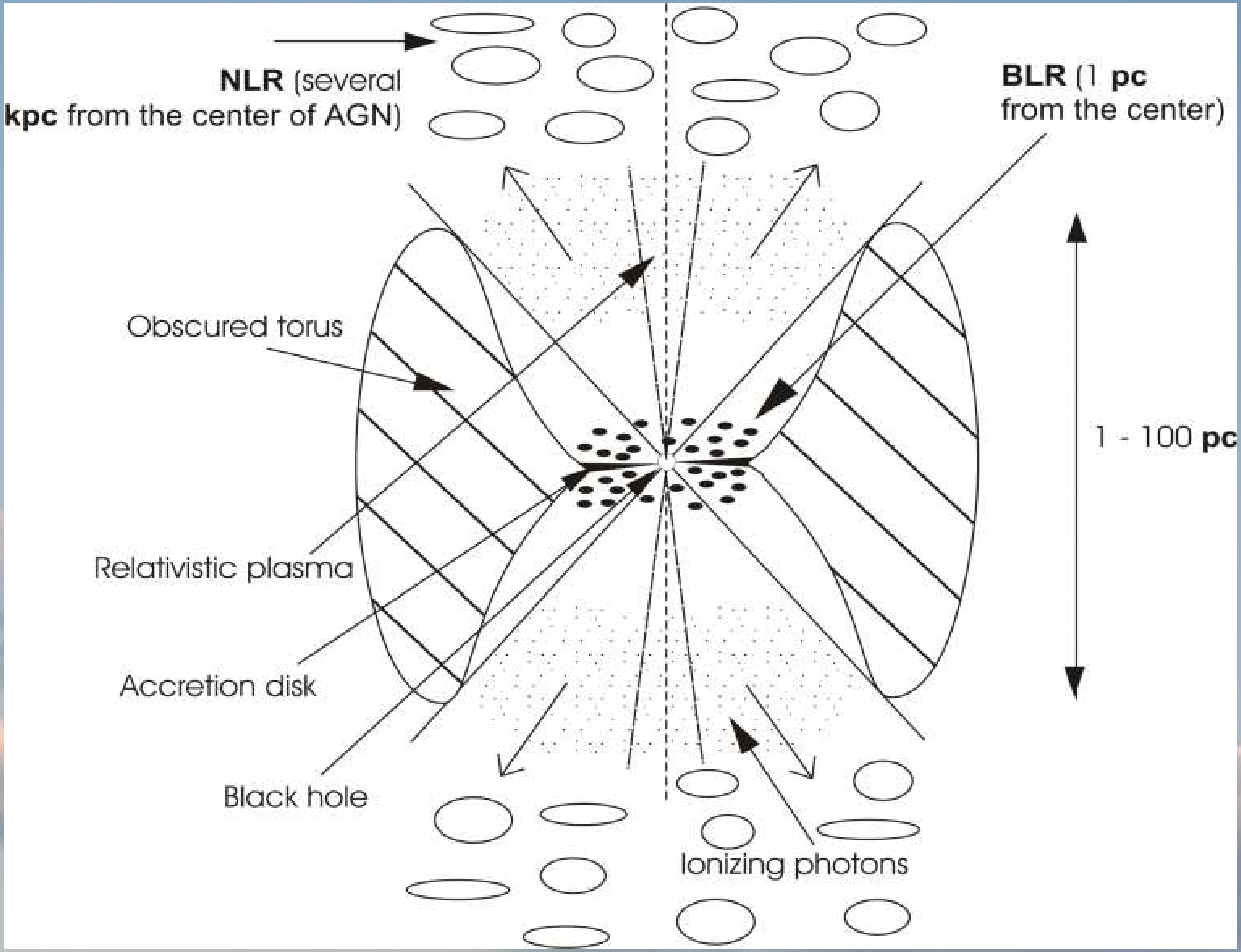
An answer for the origin of satellite lines is the matter that exists between the observer and the object.



In these figures we can see the absorption lines which are created in the heart of a quasar (up) in comparison with the absorption that can be constructed by matter located between an observer and the quasar (down).

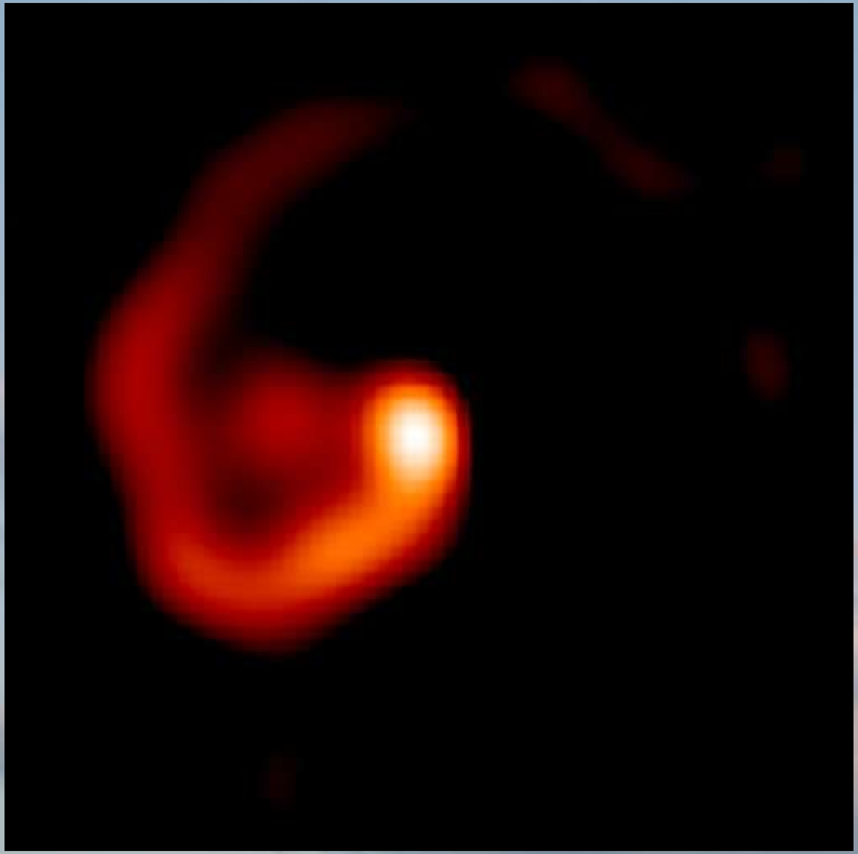


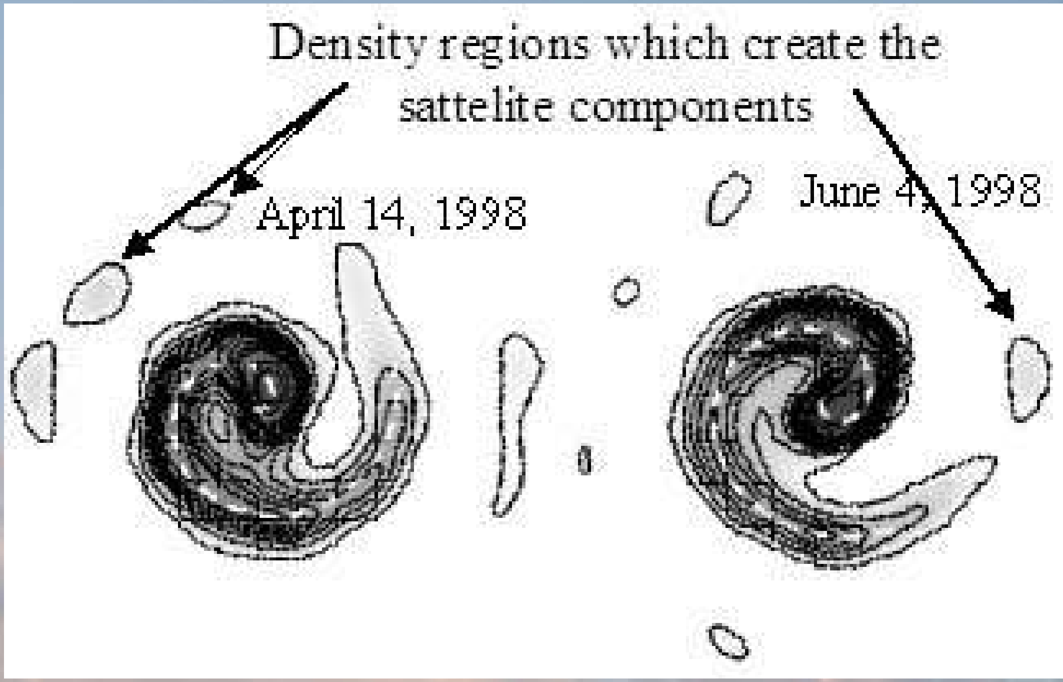
In this figure we present different types of objects, like microquasars, quasars and collapsars, that can show peculiar absorption/emission lines. We point out that the peculiar lines are always characteristic of the objects with very dynamical processes (jets, winds, etc.).



In the case of AGNs, accretion, wind (jets, ejection of matter etc.), BLR (Broad Line Regions) and NLR (Narrow Line Regions) are the density regions that construct peculiar profiles of the spectral lines.

Similar phenomena can be detected as an effect of the ejected plasma around peculiar stars.

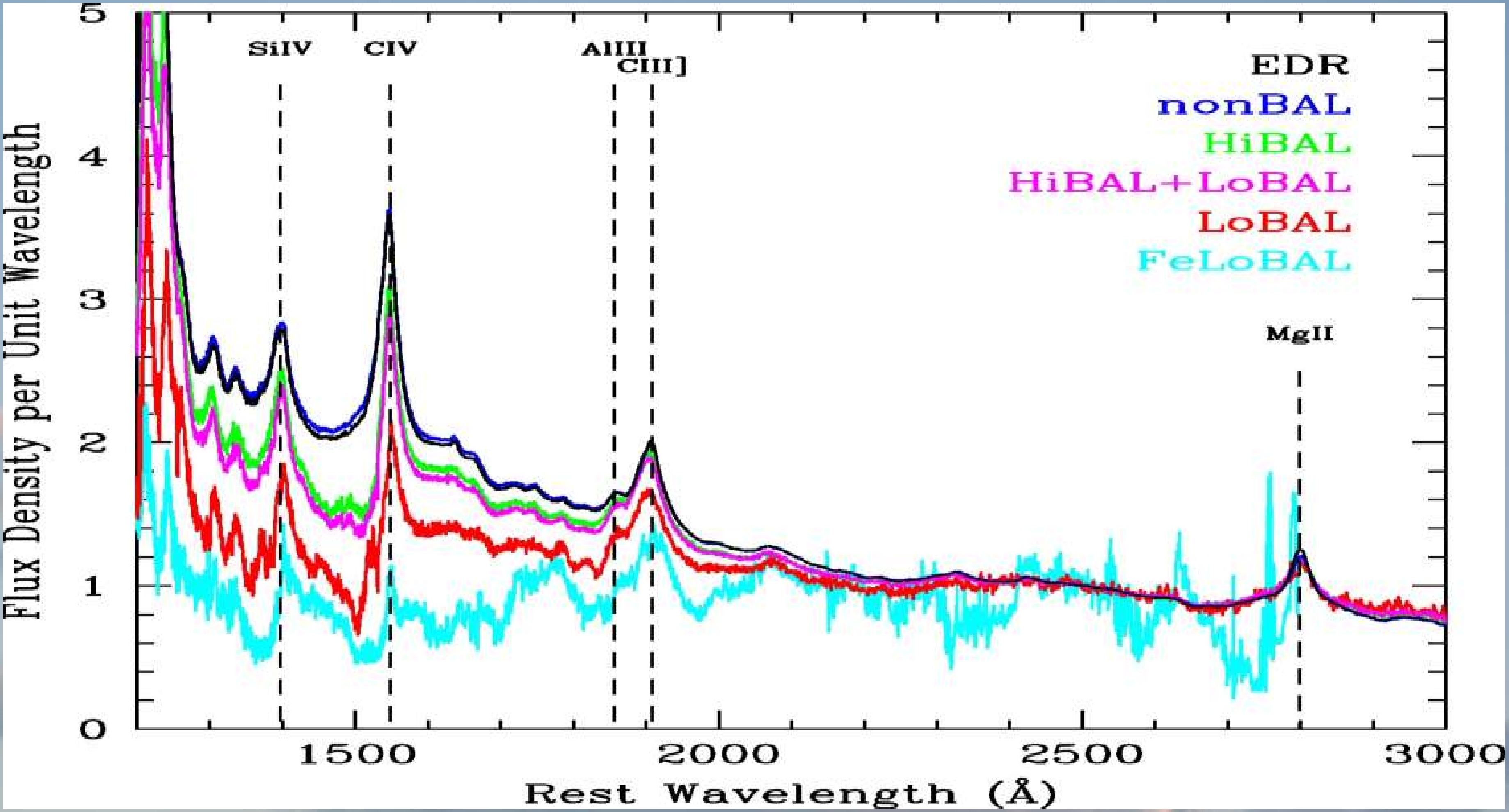




Around a Wolf-Rayet star (WR 104) we can detect density regions of matter quite away from the stellar object, able to produce peculiar profiles.

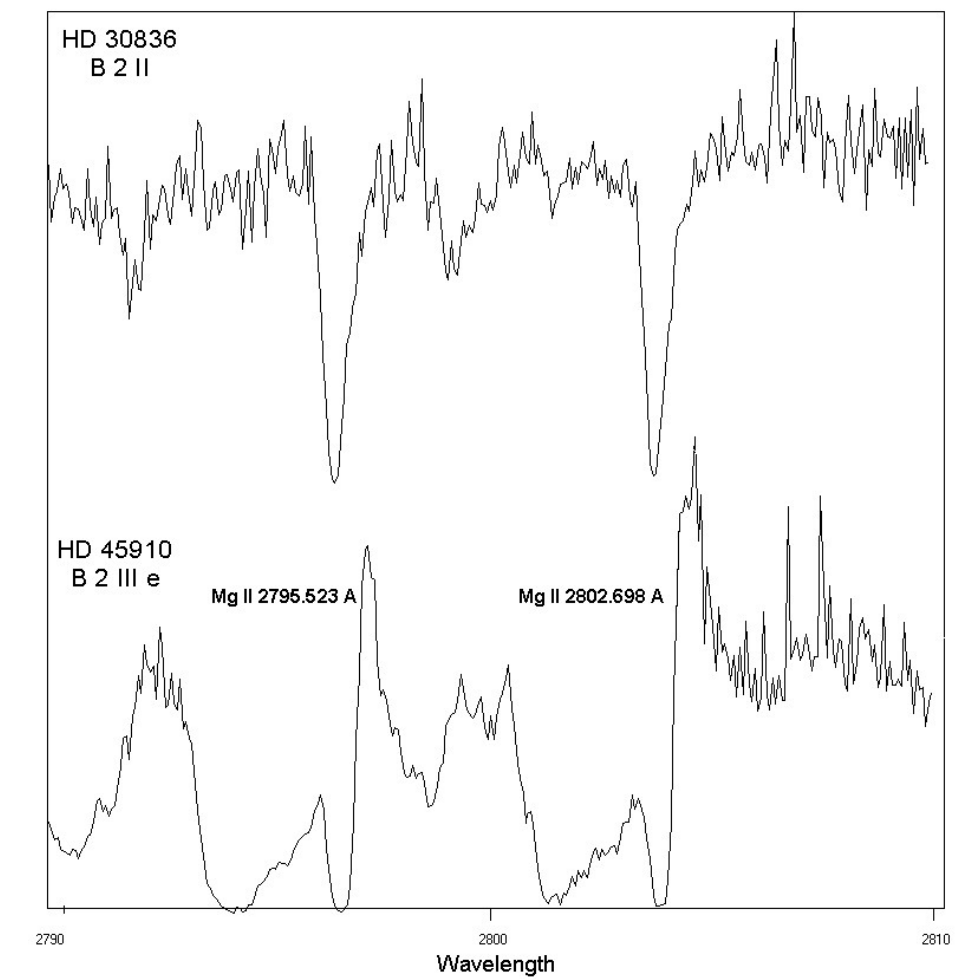
(This figure is taken by Tuthill, Monnier & Danchi (1999) with Keck Telescope.)

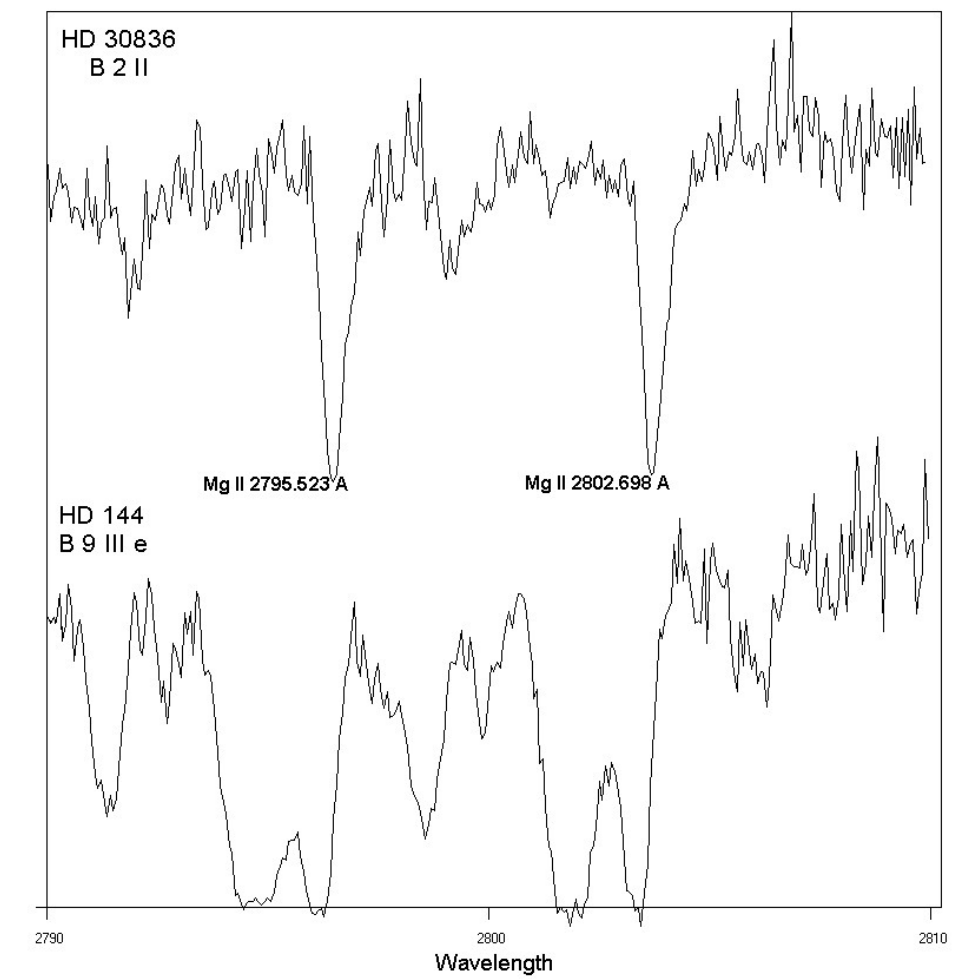
Peculiarity in AGN spectra



In this figure we present typical spectra of many types of AGNs in the UV spectral range (Reichard et al. 2003, AJ, 126, 2594). The combination of emission and, in some cases, absorption components produce peculiar profiles (P Cygni profiles).

Peculiarity in Hot Emission Stars' Spectra





As we can see, in the case of Hot Emission Stars we also may observe the same phenomenon. A combination of absorption and emission lines can construct peculiar profiles.

There are some models to reproduce such peculiar profiles.

1. ***Several Non-LTE models (very bad reproduction).***
2. ***Non-LTE specialized models (e.g. PHOENIX) having very complicated codes that may reproduce the peculiar profiles in some cases.***

In order to explain the peculiar profile that we observe in the spectra of hot emission stars and AGNs, our group proposed a simple new model to explain the structure of regions that produce these spectral lines (Danezis et al. 2003, 2005).

The proposed model

We point out that with the proposed model we can study and reproduce specific spectral lines. This means that we can study specific density regions in the plasma surrounding the studied object.

In order to construct a general model we need to study with the proposed model many density regions that produce spectral lines of different ionization potential, meaning different temperature and thus different distance from the studied object.

In order to explain simply our model, we need to explain two similar phenomena, the DACs and SACs phenomena, able to construct peculiar spectral line profiles in some Hot Emission Stars and AGNs.

The DACs phenomenon

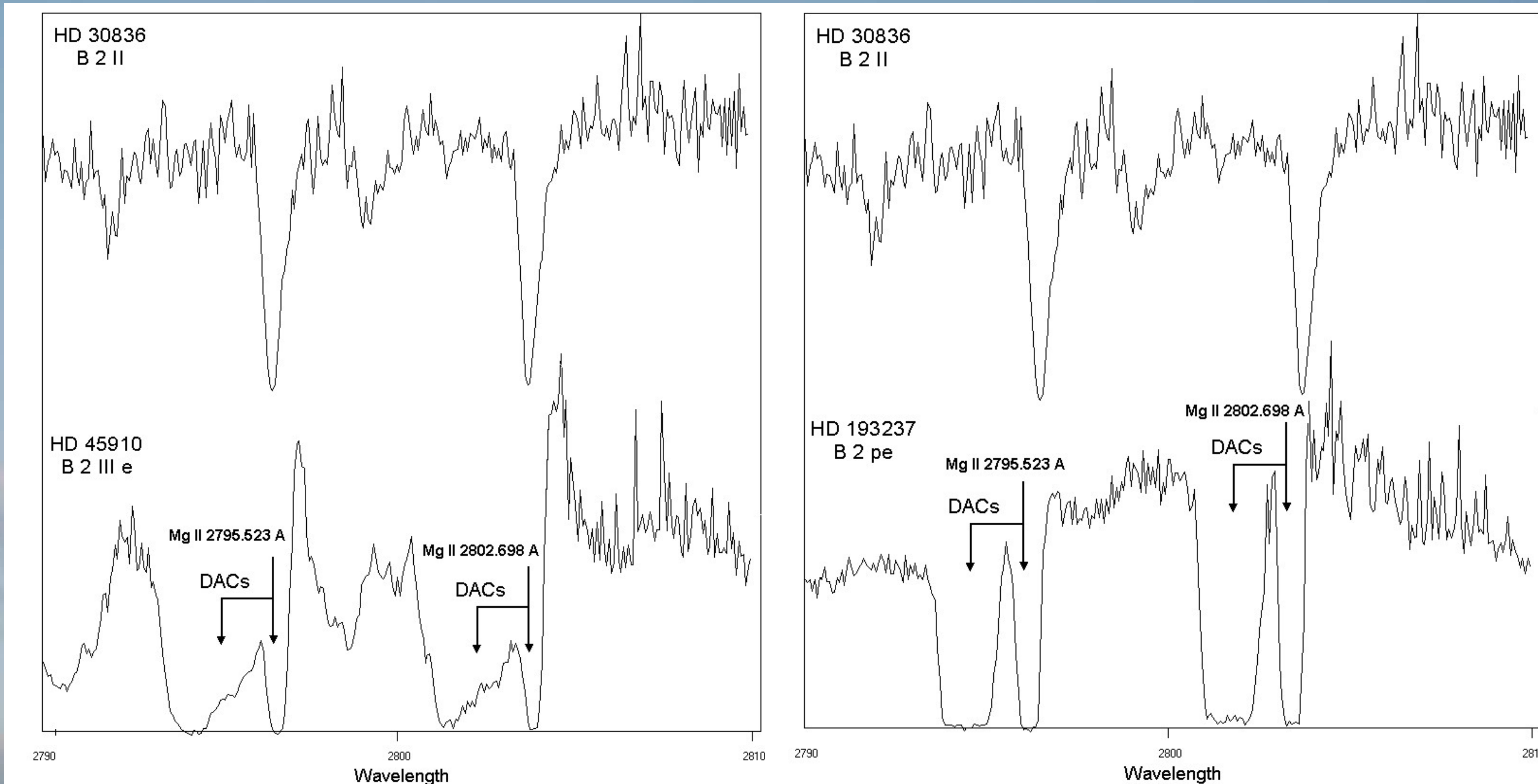
In a stellar atmosphere or disc that we can detect around hot emission stars, an absorption line can be produced in several regions that present the same temperature. From each one of these regions an absorption line arises.

The line profile of each one of these absorption components is a function of a group of physical parameters, as the radial, the rotational, the random velocities and the optical depth of the region that produces the specific components of the spectral line.

These spectral lines are named Discrete Absorption Components (DACs) when they are discrete (Bates, B. & Halliwell, D. R.: 1986, MNRAS, 223, 673).

DACs are discrete but not unknown absorption spectral lines. They are spectral lines of the same ion and the same wavelength as a main spectral line, shifted at different $\Delta\lambda$, as they are created in different density regions which rotate and move radially with different velocities (Danezis et al. 2003).

DACs are lines, easily observed, in the spectra of some Be stars, because the regions that give rise to such lines, rotate with low velocities and move radially with high velocities.

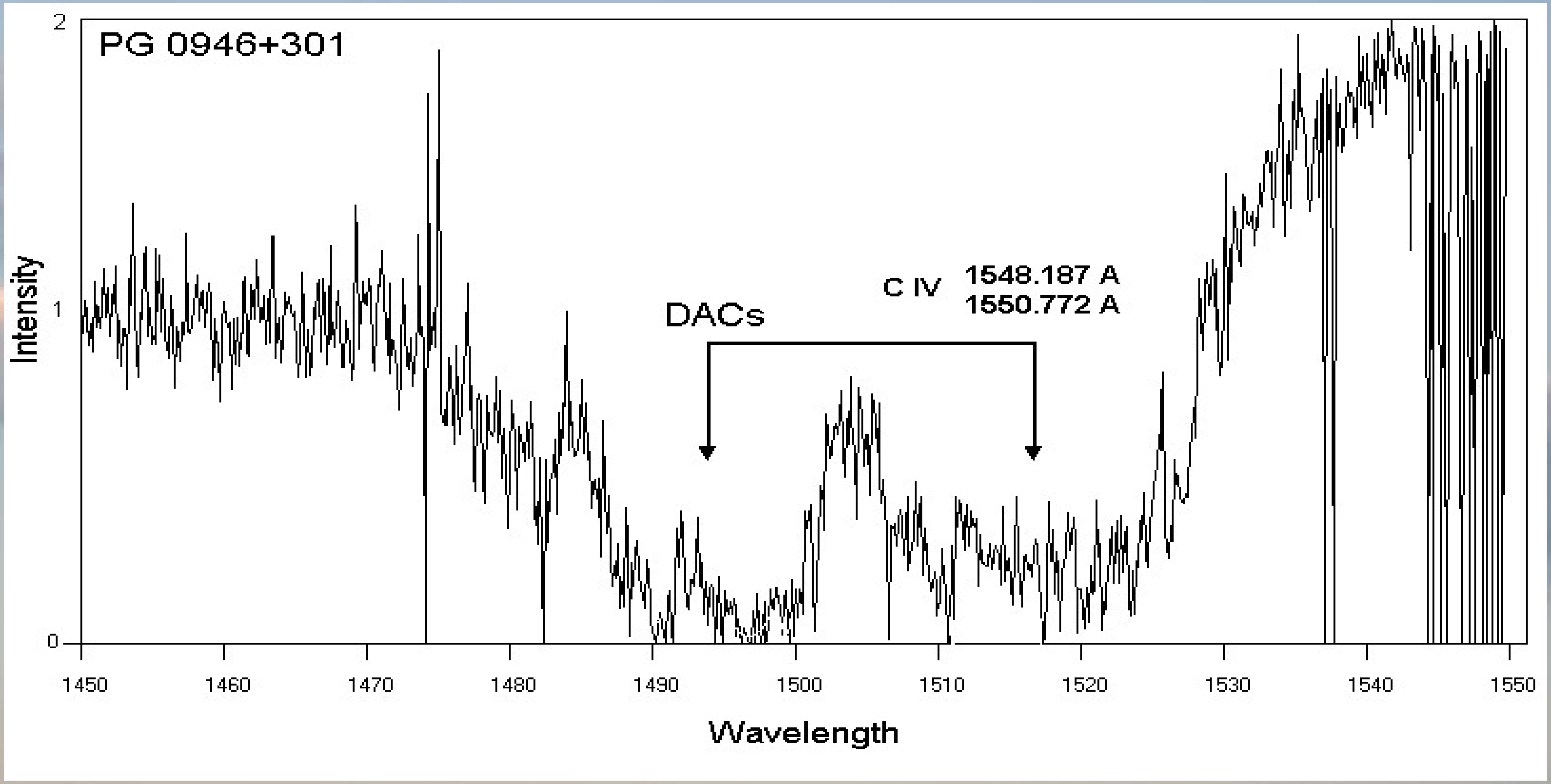


In these figures we can see the Mg II spectral lines of two Be stars that present DACs, in comparison with the Mg II lines of a classical B star. In these line profiles we can see the main spectral lines and at the left of each one of them a group of DACs.

It is very important to point out that we can detect the same phenomenon in the spectra of some AGNs

In this figure we can see the C IV UV doublet of an AGN (PG 0946+301).

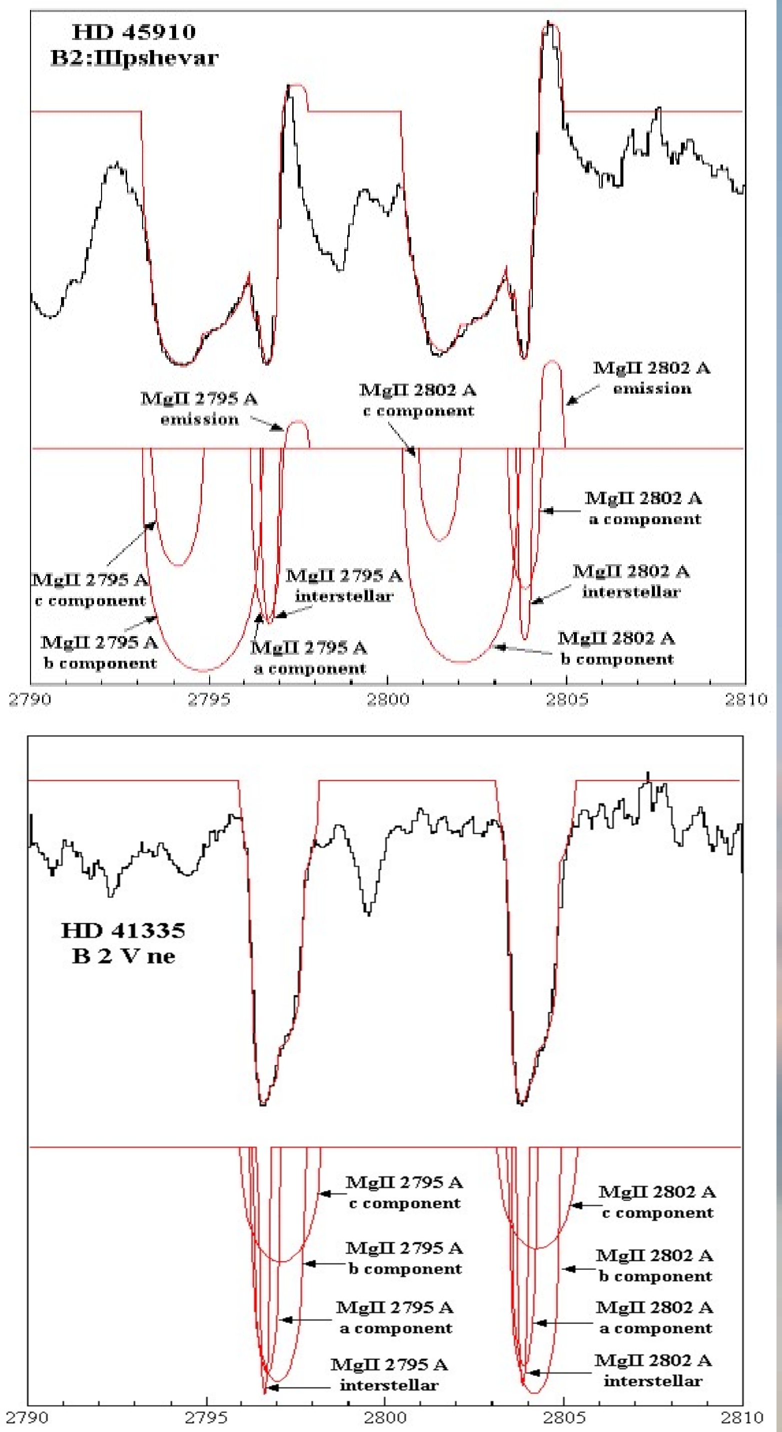
From the values of radial displacements and the ratio of the line intensities we can detect that the two observed C IV shapes indicate the presence of a DACs phenomenon similar with the DACs phenomenon that we can detect in the spectra of hot emission stars.



The SACs phenomenon

If the regions that give rise to such lines rotate with large velocities and move radially with small velocities, the produced lines have large widths and small shifts.

As a result they are blended among themselves as well as with the main spectral line and thus they are not discrete. In such a case the name Discrete Absorption Components is inappropriate and we use only the name Satellite Absorption Components (SACs) (Danezis et al. 2005).



In this figure it is clear that the Mg II line profiles of the star AX Mon (HD 45910), which presents DACs and the star HD 41335, which presents SACs are produced in the same way.

The only difference between them is that the components of HD 41335 are much less shifted and thus they are blended among themselves.

The black line presents the observed spectral line's profile and the red one the model's fit.

We also present all the components which contribute to the observed features, separately.

Calculation of the peculiar line shapes

In the case of SACs phenomenon we need to calculate the line function of the complex line profile.

Recently our group proposed a model in order to explain the complex structure of the density regions of hot emission stars and some AGNs, where the spectral lines that present SACs or DACs are created (Danezis et al. 2003, 2005).

The main hypothesis of this model is that the stellar envelope is composed of a number of successive independent absorbing density layers of matter, a number of emission regions and an external general absorption region.

By solving the radiation transfer equations through a complex structure, as the one described, we conclude to a function for the line profile, able to give the best fit for the main spectral line and its Satellite Components at the same time.

$$I_\lambda = \left[I_{\lambda 0} \prod_i e^{-\tau_{ai}} + \sum_j S_{\lambda ej} \left(1 - e^{-\tau_{ej}} \right) \right] e^{-\tau_g}$$

where:

$I_{\lambda 0}$ ***is the initial radiation intensity,***

$S_{\lambda ej}$ ***is the source function, which, at the moment when the spectrum is taken, is constant and***

τ ***is the optical depth in the center of the line's component shape.***

In the equation $I_\lambda = \left[I_{\lambda 0} \prod_i e^{-\tau_{ai}} + \sum_j S_{\lambda ej} \left(1 - e^{-\tau_{ej}}\right) \right] e^{-\tau_g}$

the functions $e^{-\tau_i}$, $S_{\lambda ej}\left(1 - e^{-\tau_{ej}}\right)$, $e^{-\tau_g}$

are the distribution functions of each satellite component and we can replace them with a known distribution function (Gauss, Lorentz, Voigt).

An important fact is that in the calculation of I_λ ***we can include different geometries (in the calculation of τ) of the absorbing or emitting independent density layers of matter.***

The decision on the geometry is essential for the calculation of the distribution function that we use for each component. This means that for different geometries we have different shapes for the spectral line profile, presenting the considered SACs.

In the case of rapidly rotating hot emission stars, it is very important to insert in the line function the rotational, the radial and the random velocities of the regions which produce the satellite components.

In this case we have to assume the geometry for the corresponding regions.

The spherical symmetry hypothesis

In order to assume the appropriate geometry we took into account the following important facts:

The spectral line profile is reproduced in the best way when we assume spherical symmetry for the independent density regions. Such symmetry has been proposed by many researchers (Lamers et al. 1982, Bates & Gilheany 1990, Gilheany et al. 1990, Waldron et al. 1992, Rivinius et al. 1997, Cidale 1998, Markova 2000).

However, the independent layers of matter, where a spectral line and its SACs are born, could lie either close to the star, as in the case of the photospheric components of the Hα line in Be stars (Andrillat & Fehrenbach 1982, Andrillat 1983), when spherical symmetry is justified, or at a larger distance from the star, where the spherical symmetry can not be justified.

These lead us to conclude that:

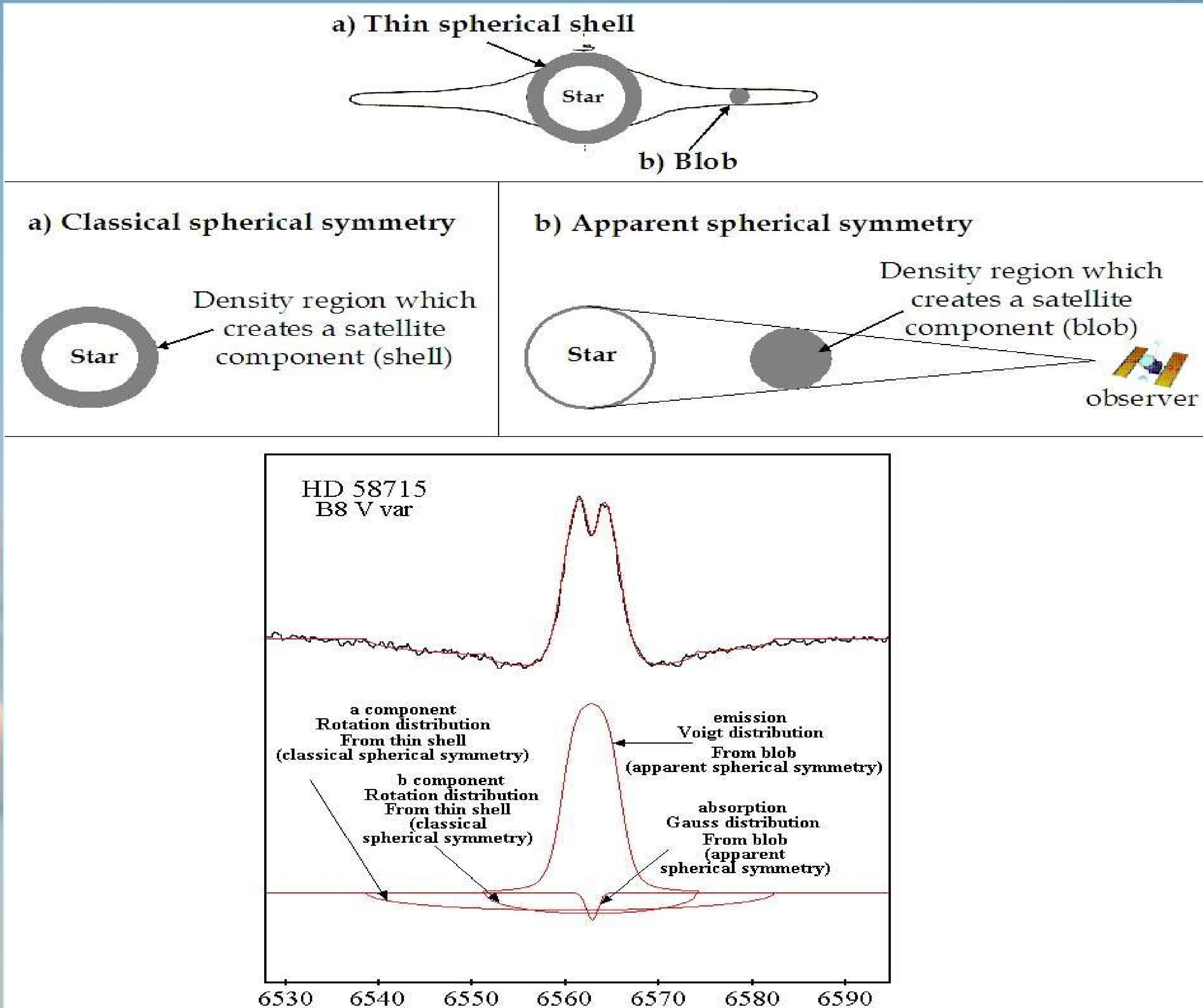
1. ***In the case of independent density layers of matter which lie close to the star we could suppose the existence of classical spherical symmetry around the star (Lamers et al. 1982, Bates & Gilheany 1990, Gilheany et al. 1990, Waldron et al. 1992, Rivinius et al. 1997, Cidale 1998, Markova 2000).***

2. *In the case of independent density layers of matter which lie at a larger distance from the photosphere, we could suppose the existence of independent density regions such as blobs, which could cover a significant part of the stellar disk and are outwards moving inhomogeneities, spiral streams or CIRs (Corotating Interaction Regions), which may result from non-radial pulsations, magnetic fields or the stellar rotation and are able to make structures that cover a substantial part of the stellar disk. (Cranmer & Owocki 1996, Rivinius et al. 1997, Fullerton et al. 1997, Cranmer et al. 2000, Markova 2000, Mullan 1984a,b, 1986, Prinja & Howarth 1988, Kaper et al. 1996, 1997, 1999)*

These regions, though they do not present spherical symmetry around the star, they form spectral line profiles which are identical with those deriving from a spherically symmetric structure.

In such a case, though the density regions are not spherically symmetric, through their effects on the line profiles, they appear as spherically symmetric structures to the observer.

The above mentioned ideas led us to suppose spherical symmetry (or apparent spherical symmetry) around the center of the density regions of matter, where the main spectral line as well as its SACs are born.



Density regions which create the observed SACs or DACs in the stellar spectra

The Final Line Function

So, in the case of spherical symmetry, the line function

$$I_\lambda = \left[I_{\lambda 0} \prod_i e^{-\tau_{ai}} + \sum_j S_{\lambda ej} \left(1 - e^{-\tau_{ej}} \right) \right] e^{-\tau_g}$$

takes the following form:

$$I_\lambda = \left[I_{\lambda 0} \prod_i \exp\{-L_i \xi_i\} + \sum_j S_{\lambda ej} \left(1 - \exp\{-L_{ej} \xi_{ej}\} \right) \right] \exp\{-L_g \xi_g\}$$

where:

$I_{\lambda 0}$: is the initial radiation intensity,

L_i, L_{ej}, L_g: are the distribution functions of the absorption coefficients $k_{\lambda i}$, $k_{\lambda ej}$, $k_{\lambda g}$,

ξ: is the optical depth in the centre of the spectral line,

$S_{\lambda ej}$: is the source function, that is constant during one observation.

Calculation of the distribution functions L

It is known that Be and Oe stars are rapid rotators. This means that we accept that a reason of the line broadening is the rotation of the regions that produce each satellite component. These rapidly rotating density regions may also present radial and random motions. For this reason we search an expression for the distribution function L of the spectral line components that has as parameters the rotational, the random and the radial velocities of the spherical region.

The distribution function (L) has the form:

$$L_{final}(\lambda) = \frac{1}{2\lambda_0 z} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \left[erf\left(\frac{\lambda - \lambda_0}{\sqrt{2}\sigma} + \frac{\lambda_0 z}{\sqrt{2}\sigma} \cos\theta \right) - erf\left(\frac{\lambda - \lambda_0}{\sqrt{2}\sigma} - \frac{\lambda_0 z}{\sqrt{2}\sigma} \cos\theta \right) \right] \cos\theta d\theta$$

where

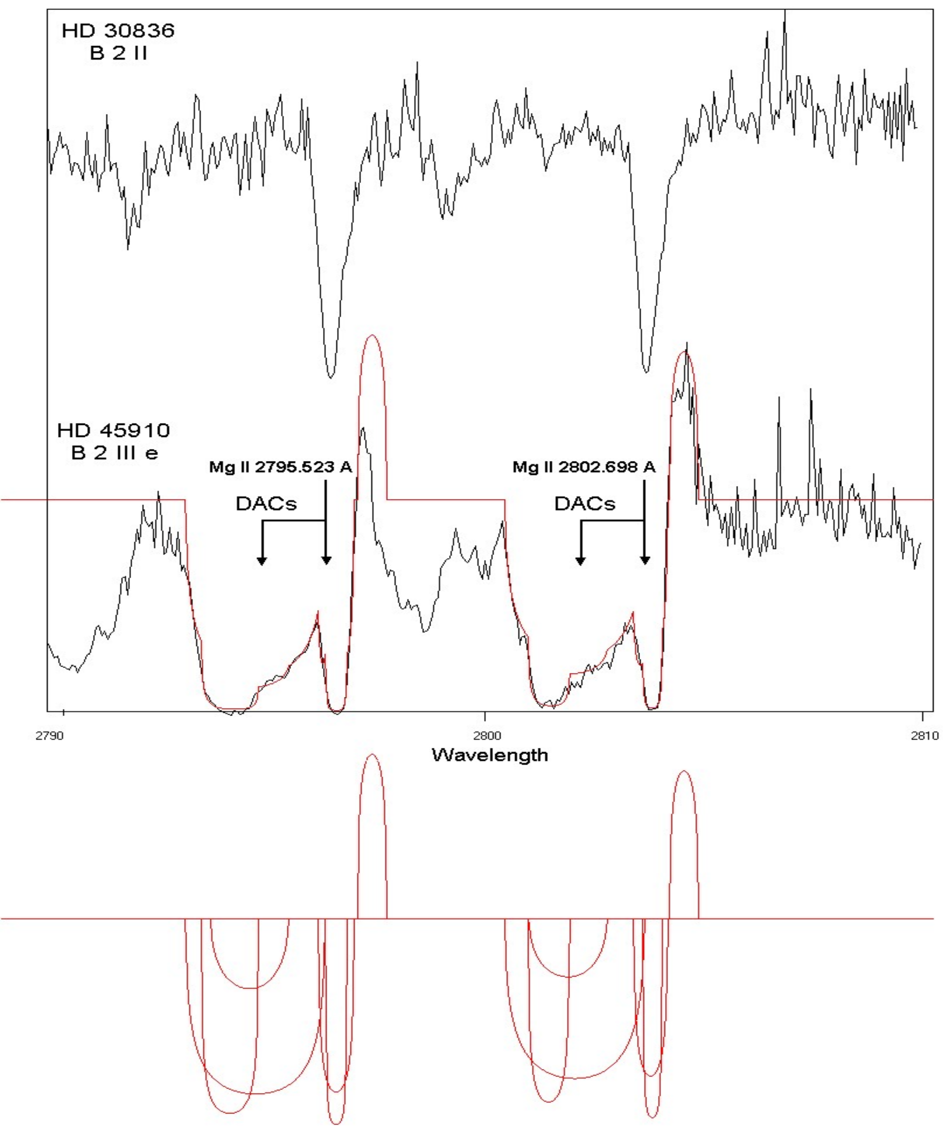
λ_0 is the observed wavelength of the center of the spectral line and $\lambda_0 = \lambda_{lab} + \Delta\lambda_{rad}$ where λ_{lab} is the laboratory wavelength and $\Delta\lambda_{rad}$ is the radial displacement,

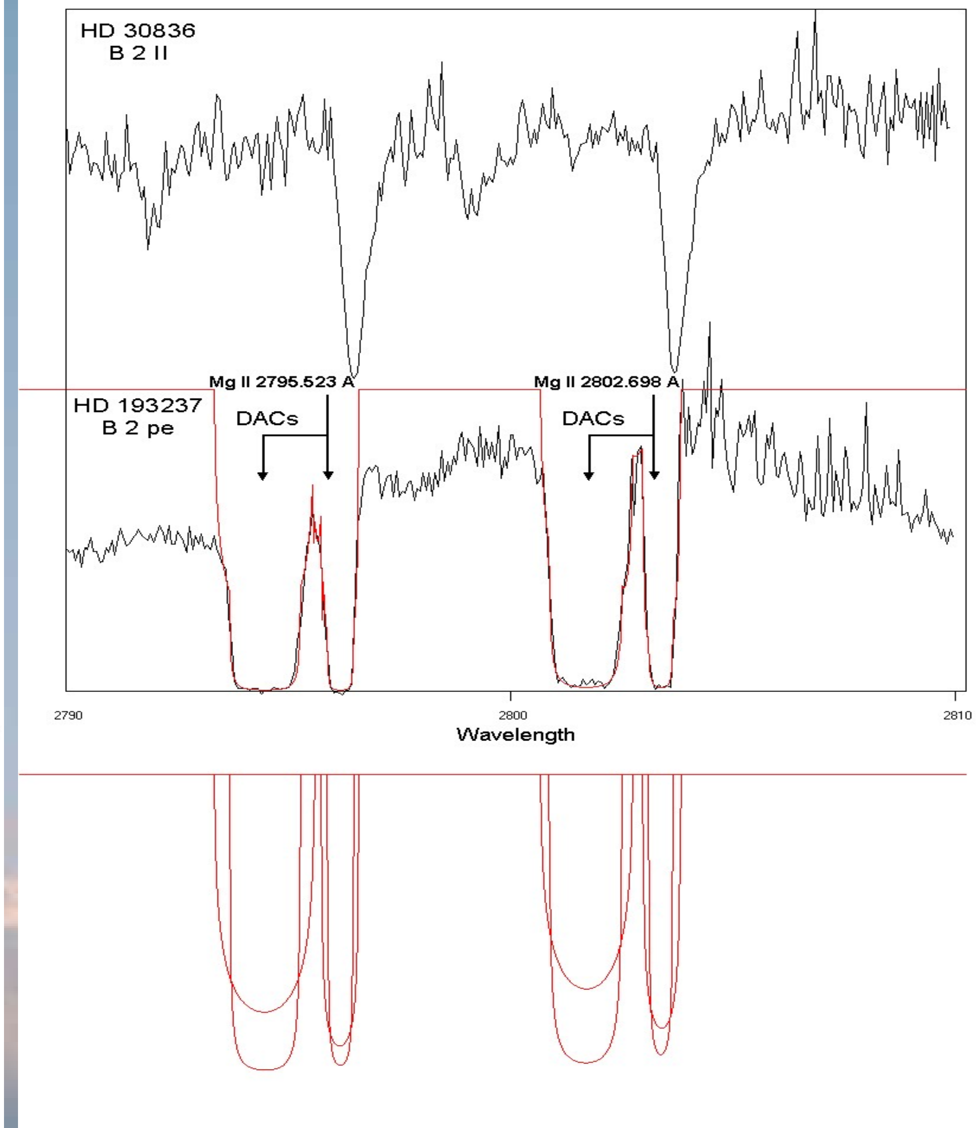
$z = \frac{V_{rot}}{c}$ ***and***

V_{rot} ***is the rotational velocity of the region which creates the spectral line.***

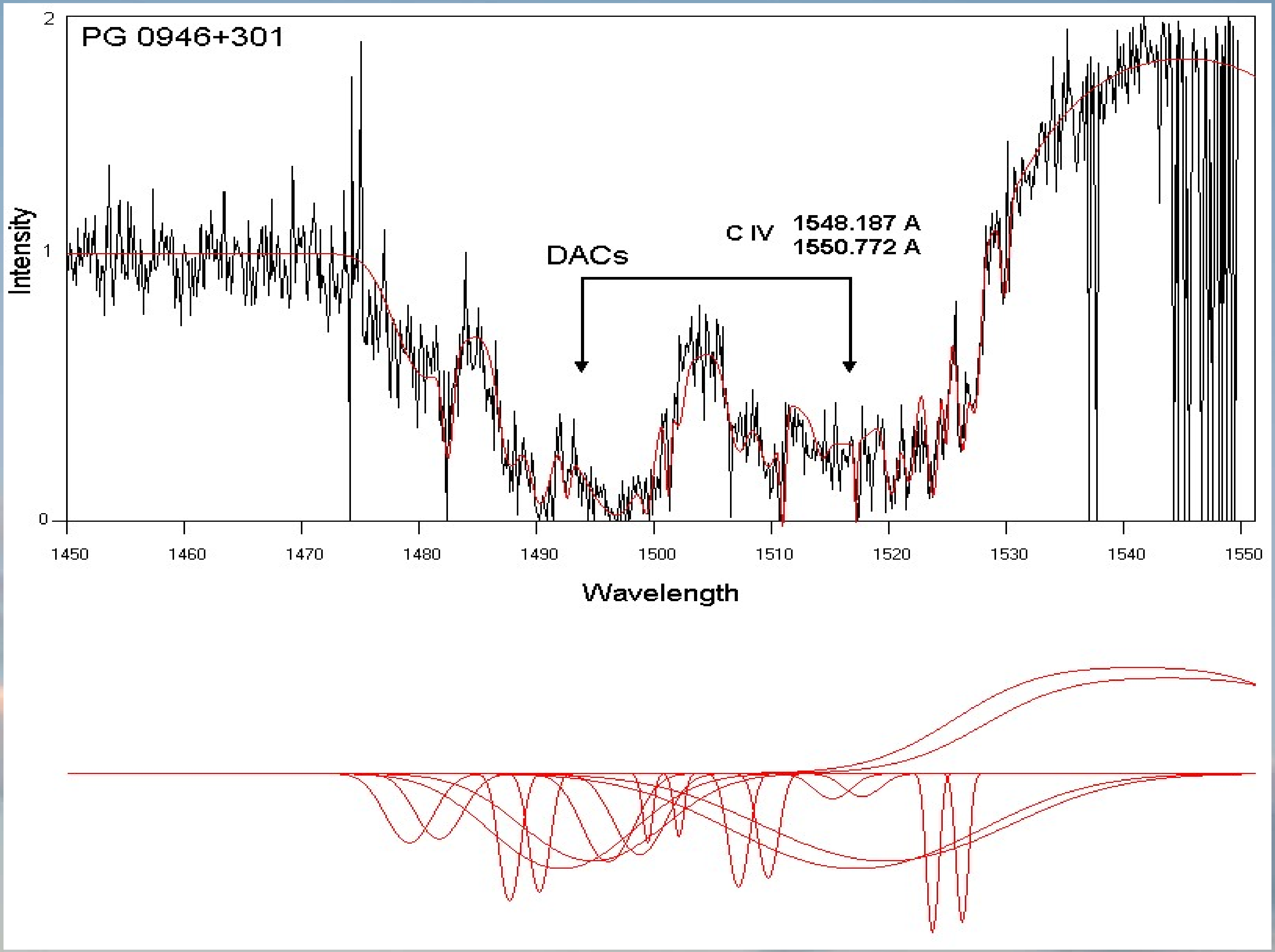
We use this distribution function $L_{final}(\lambda)$ in the line function $e^{-L\xi}$, when the line broadening is an effect of both the rotational velocity of the density region as well as the random velocities of the ions.

This means that now we have a new distribution function to fit every satellite component of a complex line profile that presents DACs or SACs. We name this function Gauss-Rotation distribution function (GR distribution function).

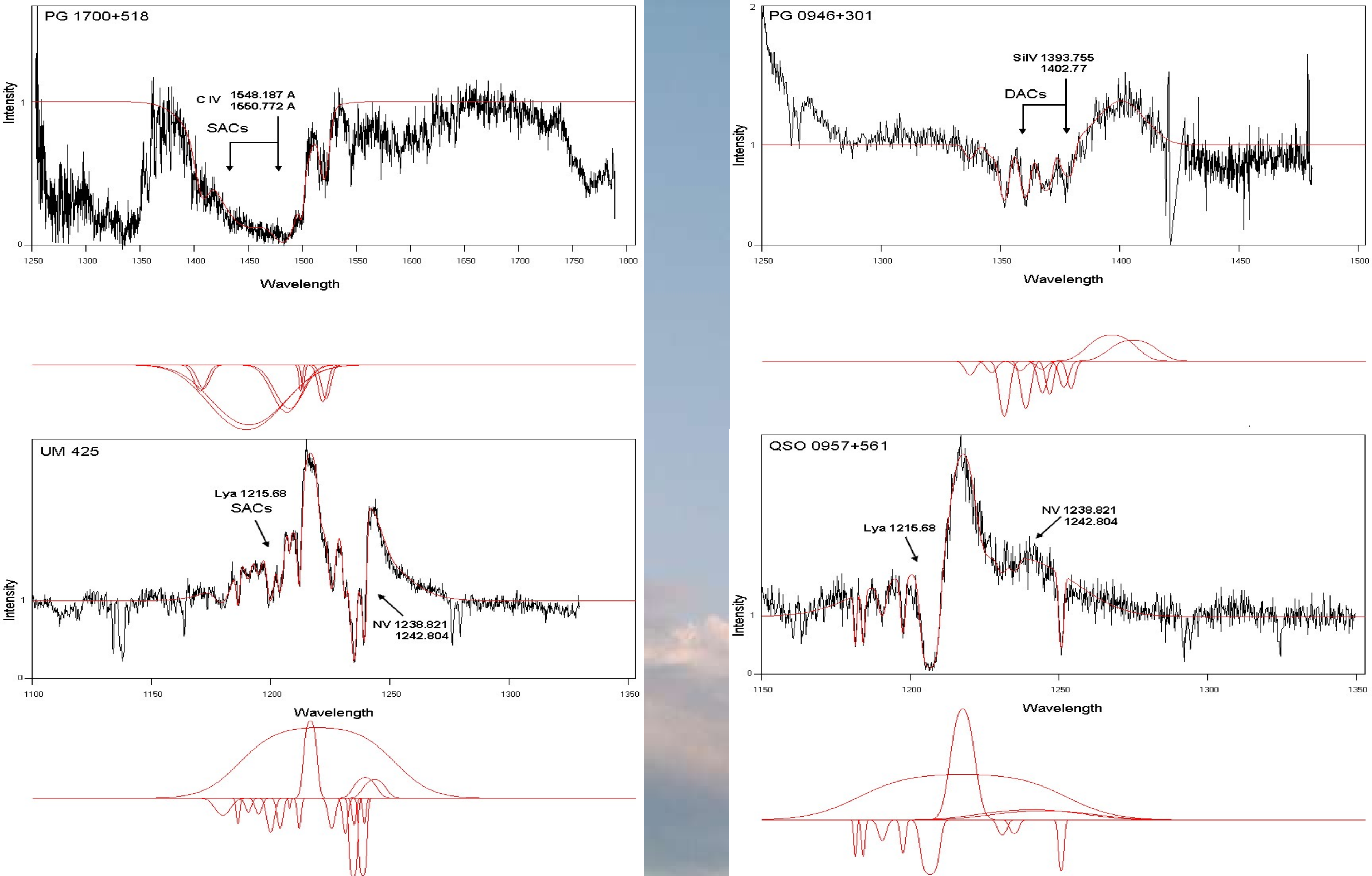




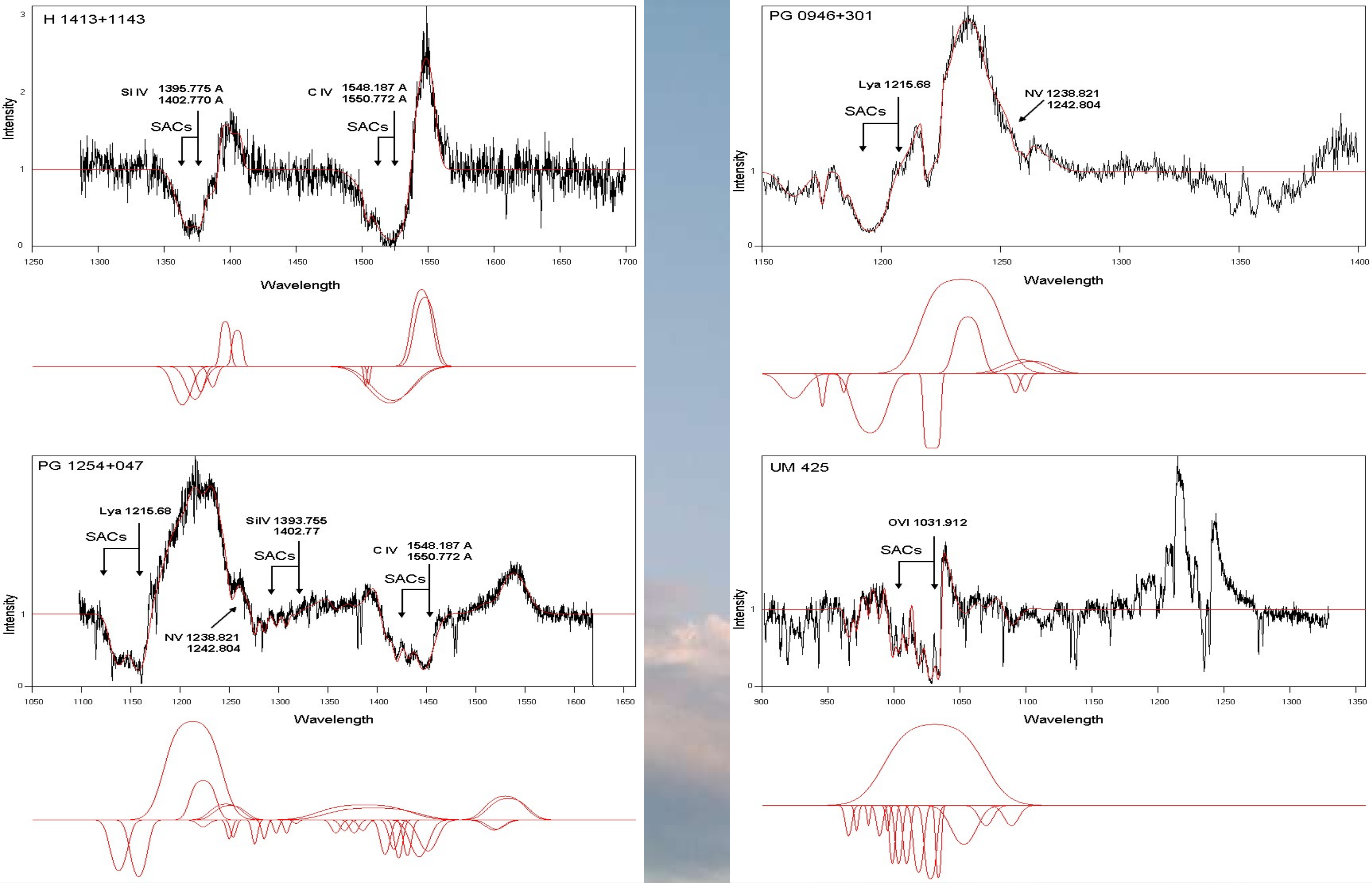
In these figures we can see the fitting of Mg II spectral lines of two Be stars that present DACs with the proposed model. We point out that we cannot explain and fit these spectral lines with another method.



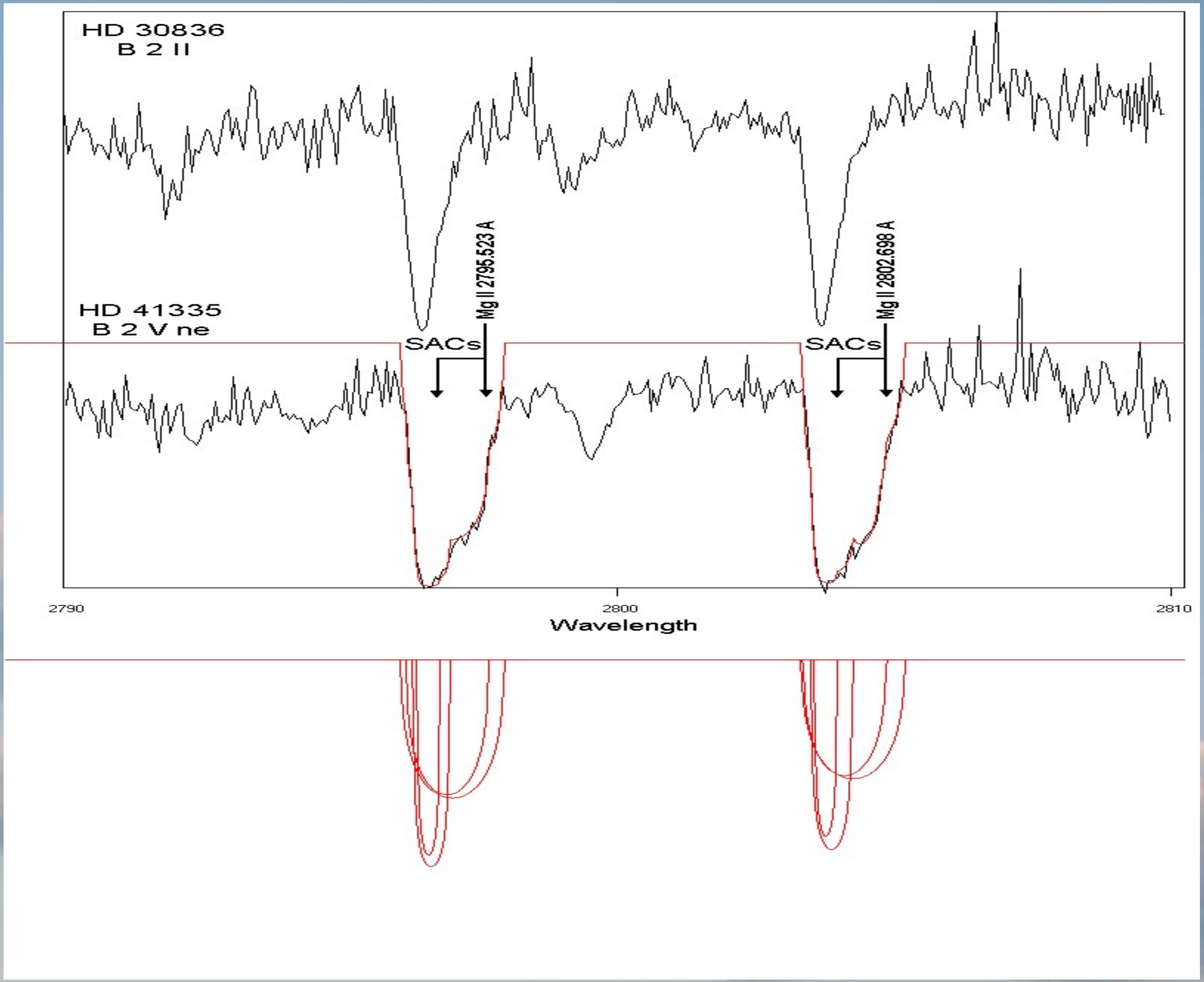
In this figure we can see the fitting of the C IV UV doublet of an AGN (PG 0946+301) that present DACs with the proposed model.



In these figures we can see the fitting of some AGN spectral lines that present SACs with the proposed model.



In these figures we can see the fitting of some AGN spectral lines that present SACs with the proposed model.



In this figure we can see the the fiting of Mg II spectral lines of a Be star that present SACs with the proposed model.

Discussion of the proposed model

In order to accept a fit of the complex spectral line as the best, we should apply all the physical criteria and techniques, such as the following:

1. It is necessary to check practically and theoretically the presence of blended lines that can deform the line shape as well as the existence of SACs.

2. The resonance lines as well as all the lines originating in a particular region should have the same number of SACs, depending on the structure of this region, without influence of ionization stage or ionization potential of emitters/absorbers. As a consequence, the respective SACs should have similar or same values of the radial and rotational velocities.

3. The ratio of the optical depths in the centre of two resonance lines has to be the same as the ratio of the respective relative intensities.

4. The proposed line function

$$I_\lambda = \left[I_{\lambda 0} \prod_i \exp\left\{-L_i \xi_i\right\} + \sum_j S_{\lambda ej} \left(1 - \exp\left\{-L_{ej} \xi_{ej}\right\}\right) \right] \exp\left\{-L_g \xi_g\right\}$$

can be used in the case that i=1 and j=1, meaning when we deal with simple, classical spectral lines. This means that we can calculate all the important physical parameters, such as the rotational, the radial and the random velocities, the optical depth and the column density, for all the simple and classic spectral lines in all the spectral ranges.

The F-Test

***A second step is to check the correct number of satellite components* that construct the whole line profile.**

At first we fit using the number of the components that give the best difference graph between the fit and the observed spectral line. Then we fit using one component less than in the previous fit.

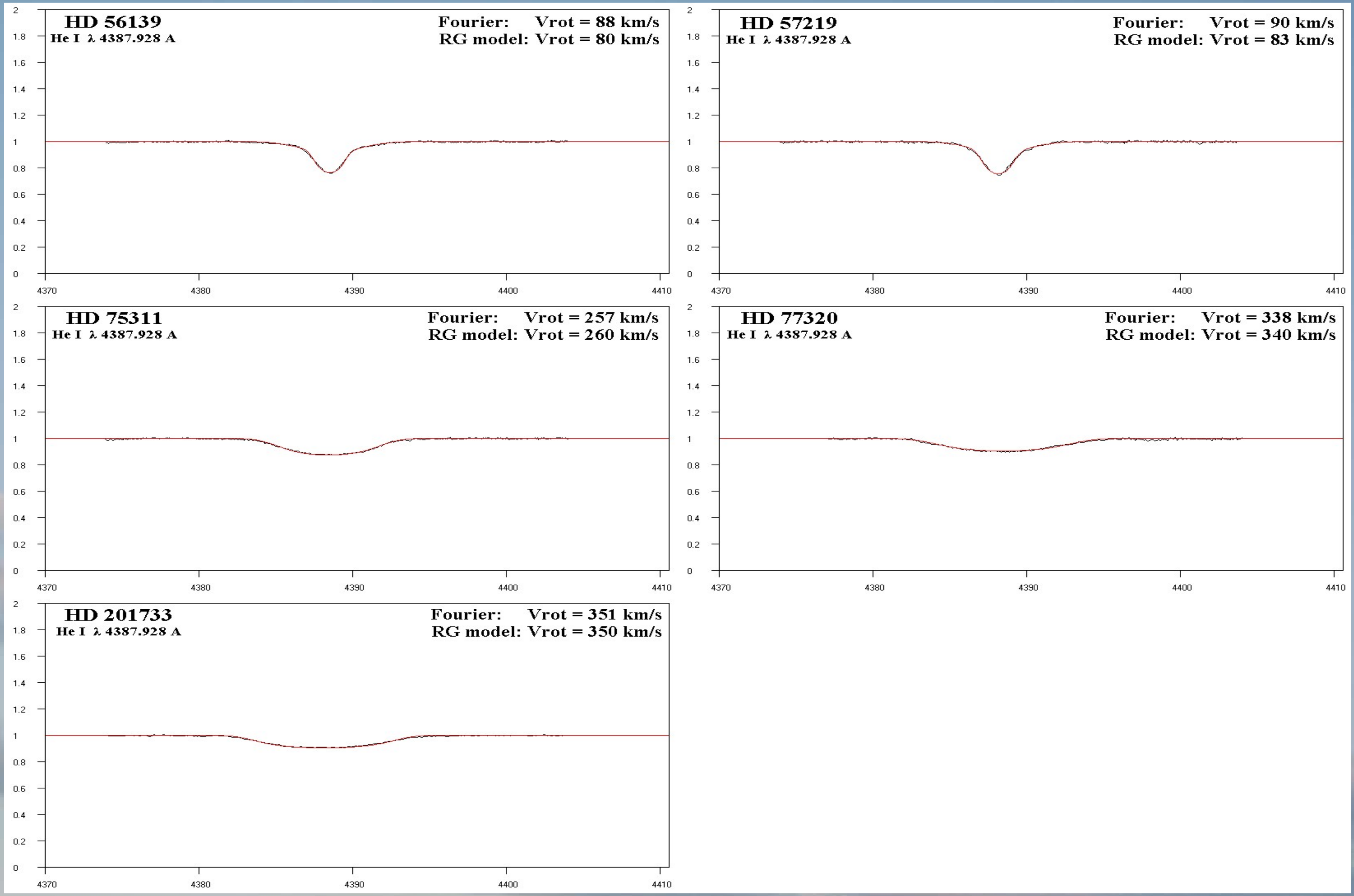
The F-test between them allows us to take the correct number of satellite components that construct in the best way the whole line profile.

Testing the model

Test 1. ***In order to check the spectral line function, we calculated the rotational velocity of an He I (λ 4387.928 Å) absorption line for five Be stars, using two methods, the classical Fourier analysis and our model.***

The rotational velocities that we calculate with both methods are almost the same.

We point out that with our model, apart from the rotational velocities, we can also calculate some other parameters as the standard Gaussian deviation (σ), the velocity of random motions of the ions, the radial velocities of the regions producing the studied spectral lines, the full width at half maximum (FWHM), the optical depth, the column density and the absorbed or emitted energy.



The five He I (λ 4387.928 Å) line fittings for the studied Be stars and the measured rotational velocities with both methods. The results are favorable for our model.

2. A second test ***for our model is to calculate the random velocities of the layers that produce the C IV satellite components of 20 Oe stars with different rotational velocities. The values of the random velocities do not depend on the inclination of the rotational axis. As the ionization potential of the regions that create the satellite components for all the studied stars is the same, we expect similar average values of the random velocities for each component for all the studied stars.***

The C IV test is based on the analysis of 20 Oe stellar spectra taken with the IUE – satellite

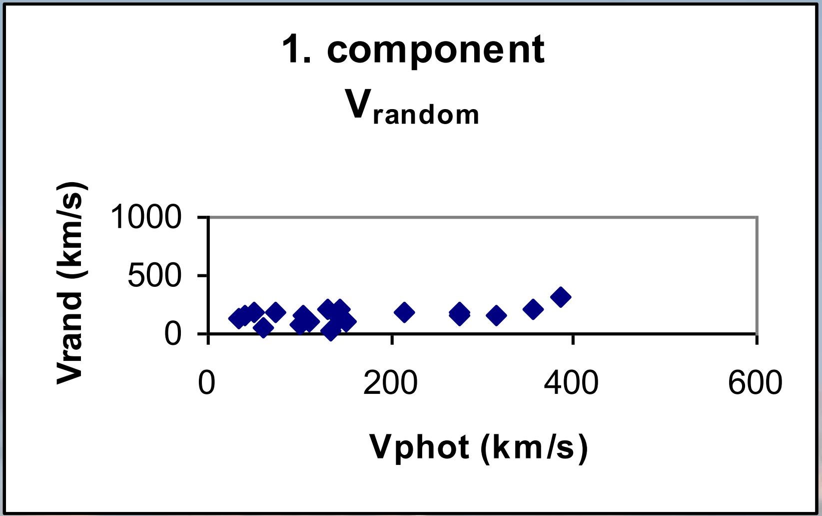
(IUE Database http://archive.stsci.edu/iue).

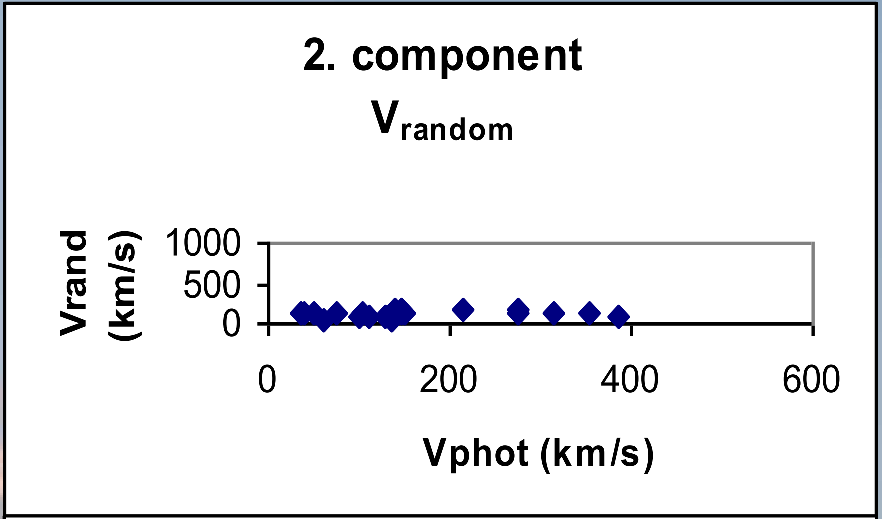
We examine the complex structure of the C IV resonance lines ***(λλ 1548.155 Å, 1550.774 Å). Our sample includes the subtypes O4 (one star), O6 (four stars), O7 (five stars), O8 (three stars) and O9 (seven stars). The values of the photospheric rotational velocities are taken from the catalogue of Wilson (1963).***

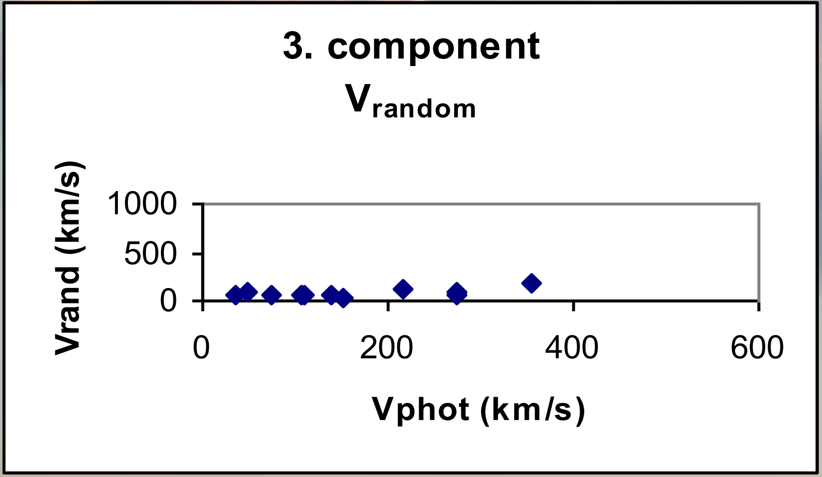
After the study of the C IV spectral lines we detected two components in 9 stars, three in 7 stars, four in 3 stars and five in 1 star.

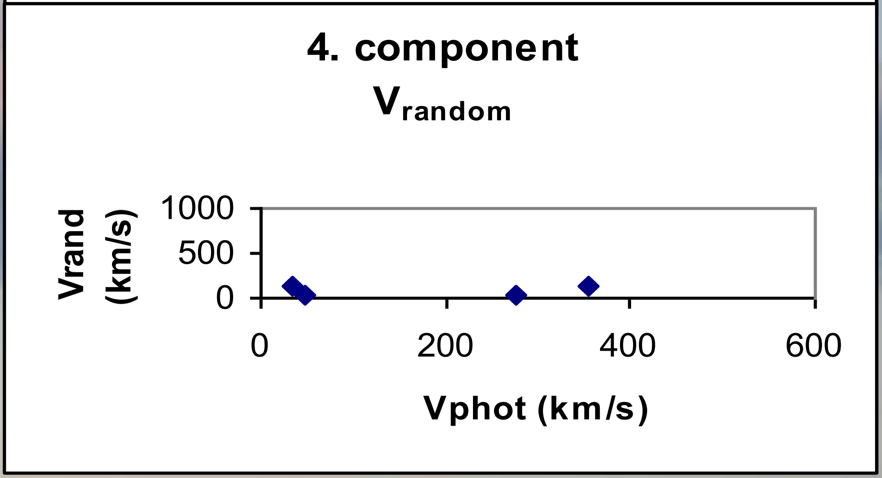
In these figures we present the relation between the random velocities and the photospheric rotational velocities of the studied stars.

The results are favourable for our model. The differences between the average values of the random velocities of the satellite components arise from the small variations of the temperature that exist in each one of the regions that produce the satellite components.







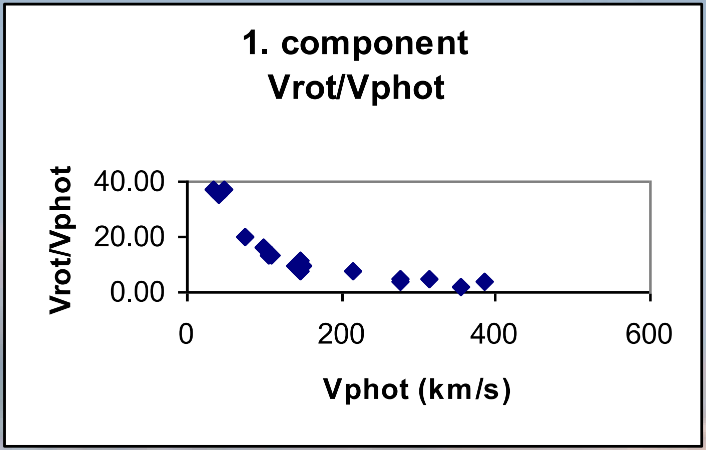


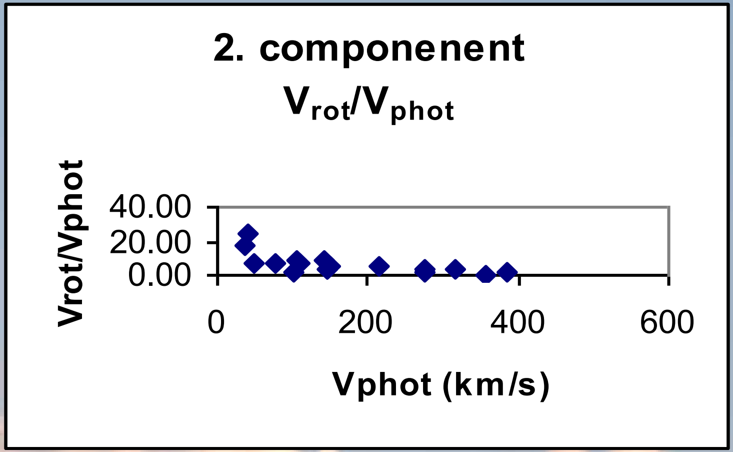
Applications of the model

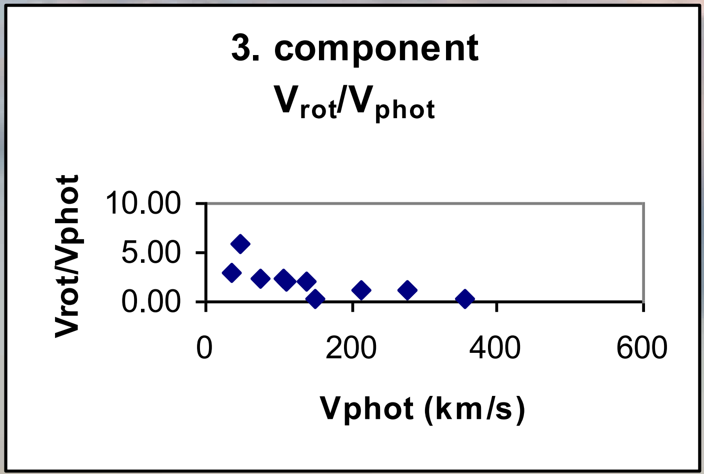
First application

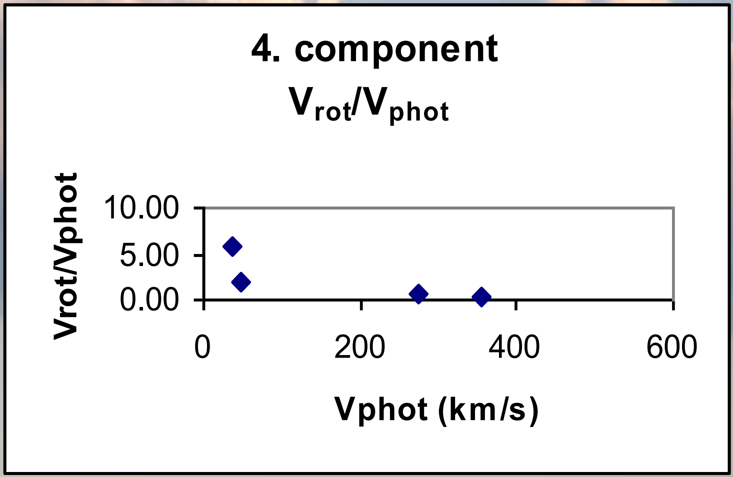
In this application we use the previously mentioned C IV IUE spectra. In the following figures we present the ratio Vrot/Vphot of the first, second, third and fourth detected component as a function of the photospheric rotational velocity (Vphot). This ratio indicates how much the rotational velocity of the specific C IV layer is higher than the apparent rotational velocity of the star.

For each component of the C IV doublet we can conclude that there exists a logarithmic relation between the ratio Vrot/Vphot and the photospheric rotational velocity (Vphot). The maximum ratio Vrot/Vphot varies from 40 for the first to 5 for the fourth component. A possible explanation of this situation is the inclination of the stellar axis.







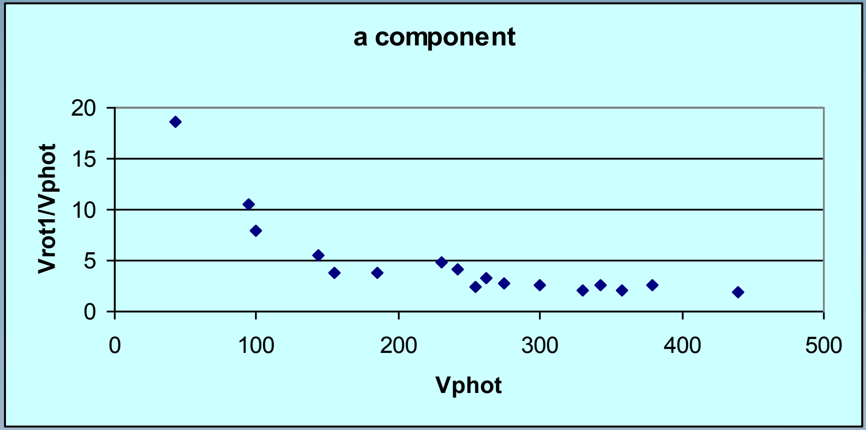


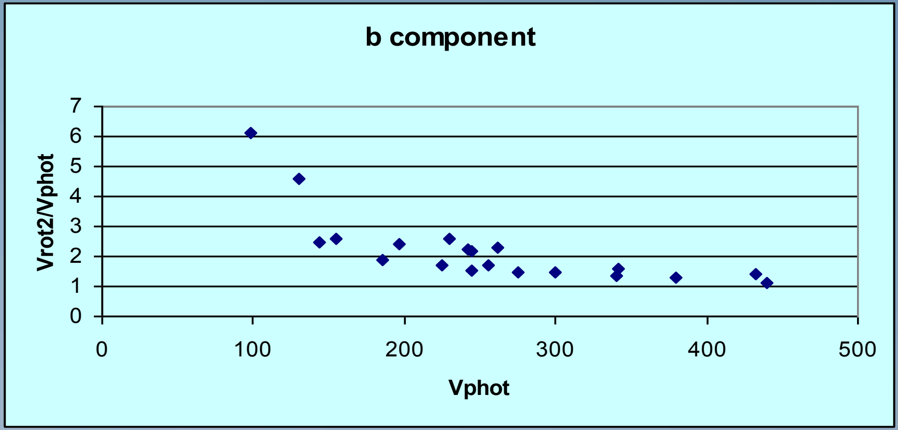
Second application

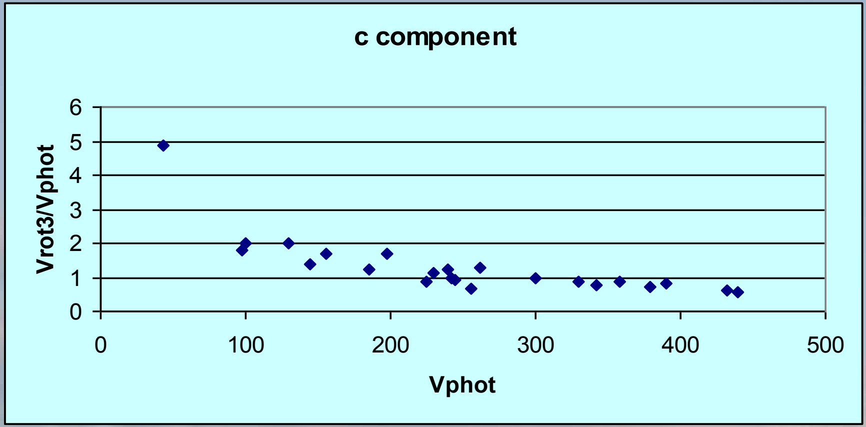
This study is based on the analysis of 27 Be stellar spectra taken with the IUE – satellite (IUE Database http://archive.stsci.edu/iue). We examine the complex structure of the Si IV UV resonance lines (λλ 1393.755 Å, 1402.77 Å). Our sample includes all the subtypes from B0 to B8.

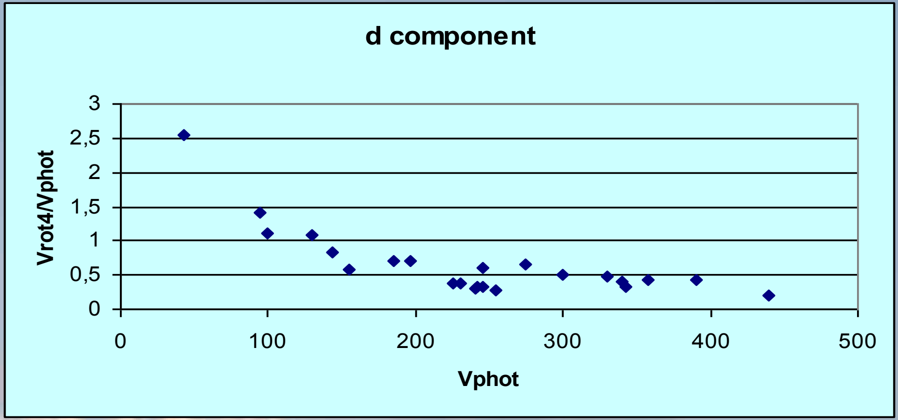
We found that the Si IV spectral lines consist of three components in 7 stars, four in 15 stars and five in 5 stars.

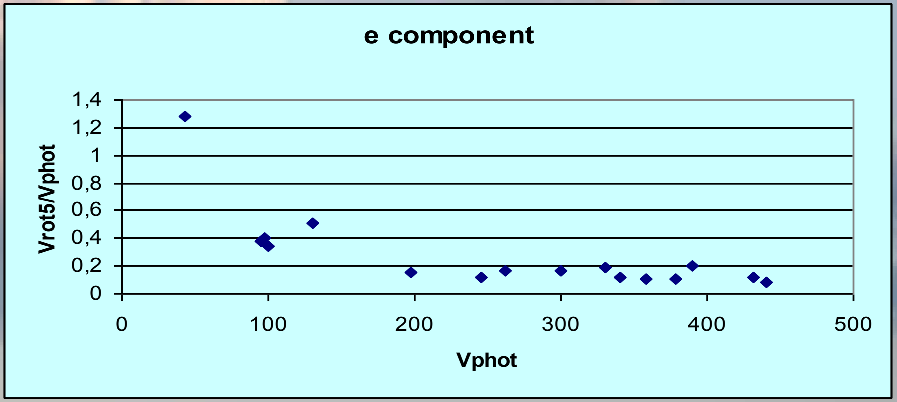
The ratio Vrot/Vphot of the first to fifth detected components as a function of the photospheric rotational velocity (Vphot) is presented in the following figures. In such a way we obtain an indication of how much the rotational velocity of the specific Si IV layer is higher than the apparent rotational velocity of the star.











As we can see, for the Si IV resonance lines of the studied Be stars we can detect the same logarithmic relation between the ratio V_{rot}/V_{phot} and the photospheric rotational velocity (V_{phot}) that we have detected for the C IV resonance lines of the studied Oe stars.

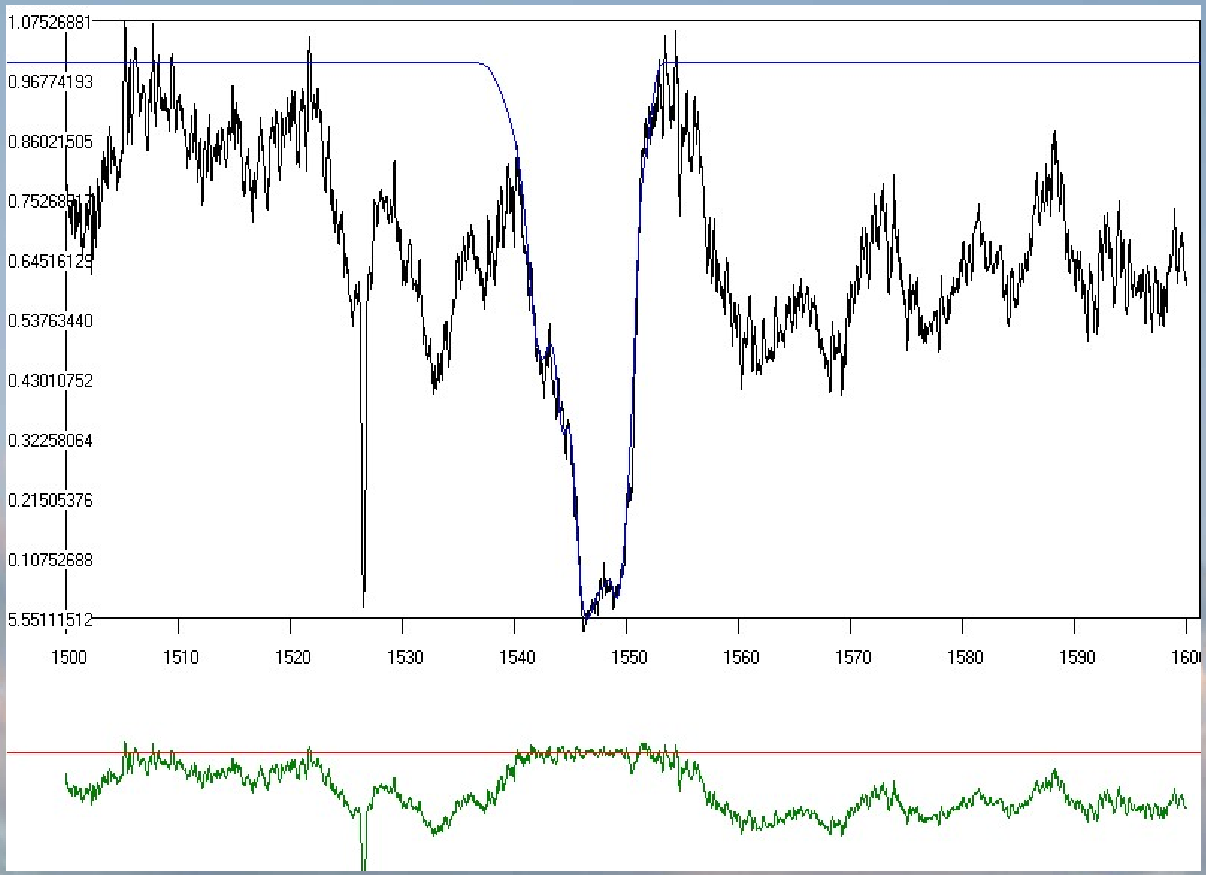
Third application.

Long term variability of the radial and rotational velocities

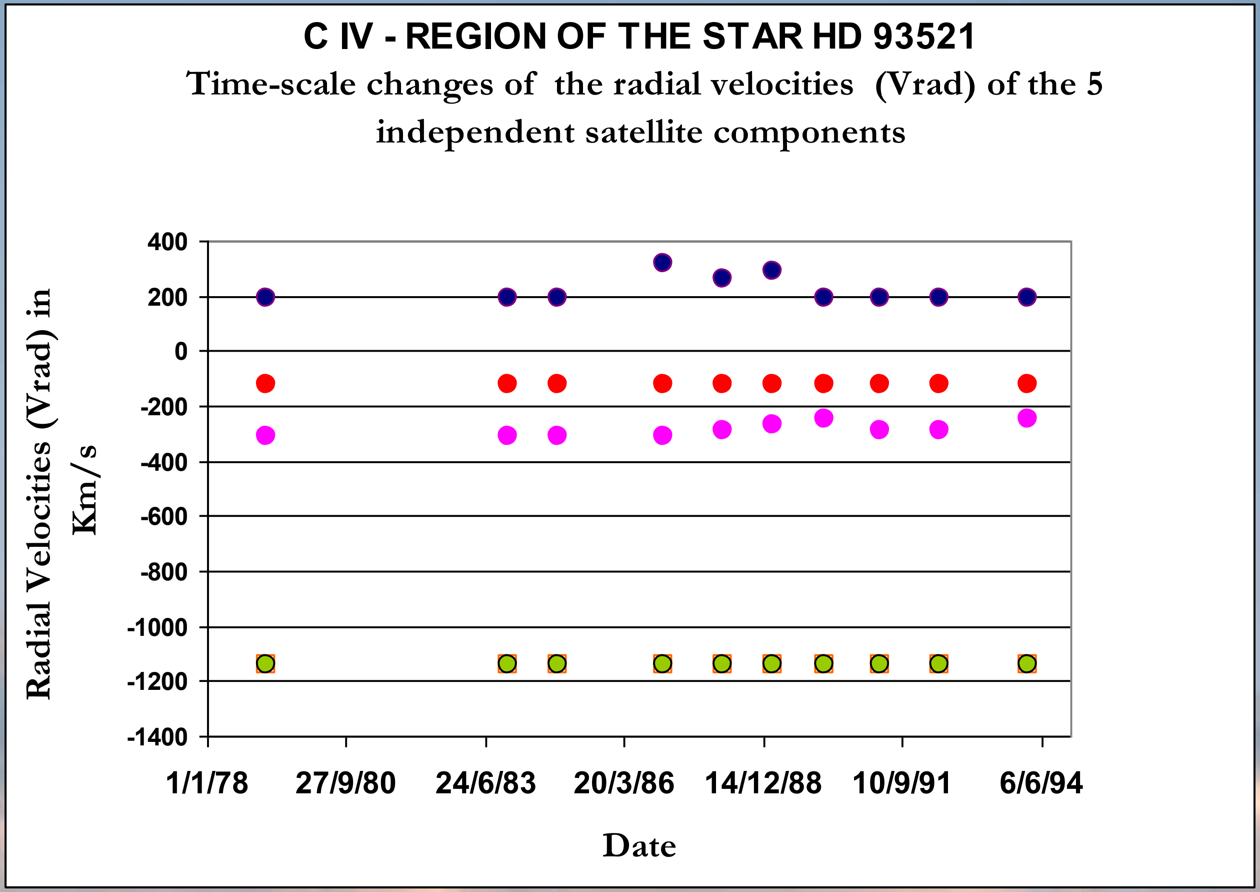
This study is based on eleven different spectra of HD 93521 (O 9.5 V) taken with the IUE satellite.

We study the structure of the UV resonance lines of C IV (λλ 1548.155 Å, 1550.774 Å).

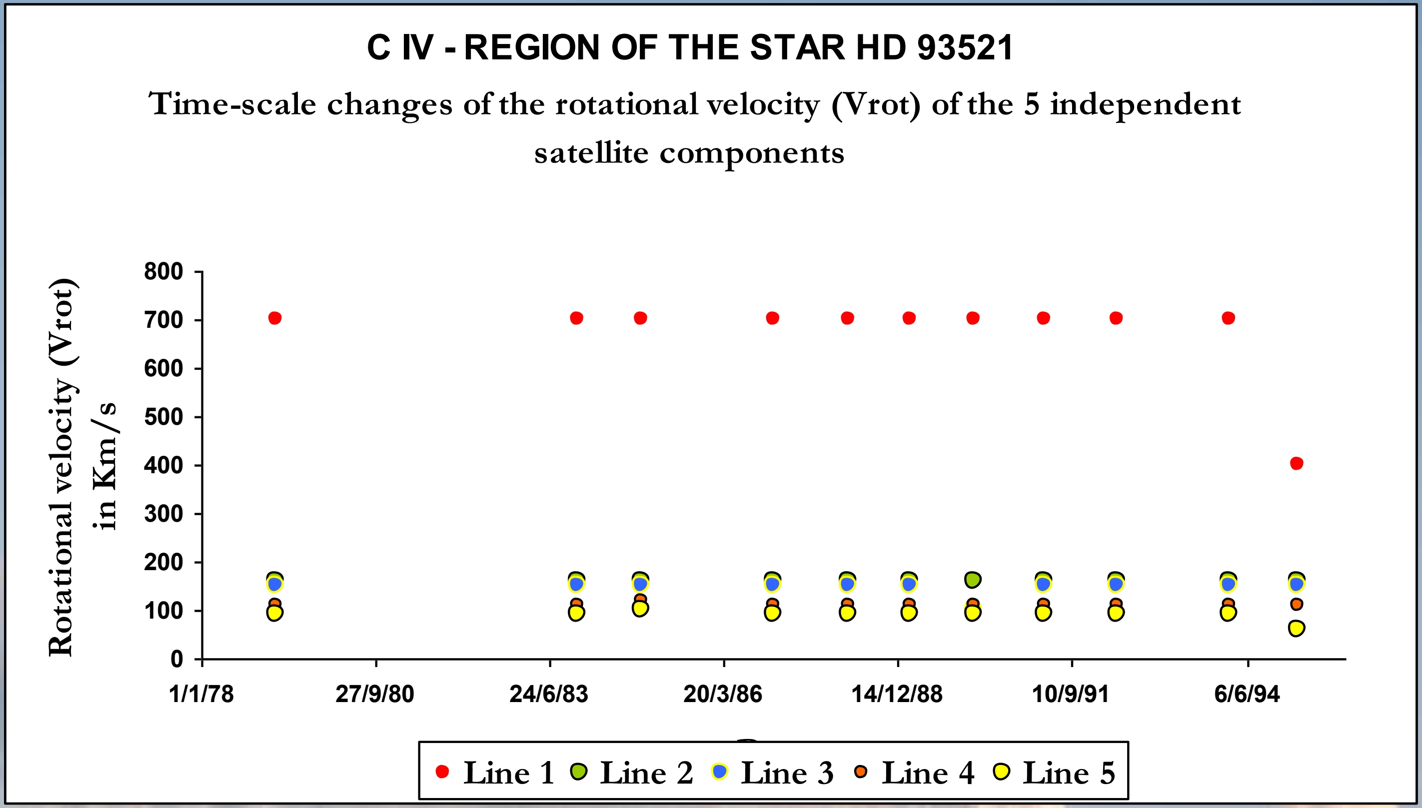
C IV doublet in the spectrum of the star HD 93521



In this figure we present the best fit of the C IV UV doublet. The green diagram presents the differences between the theoretical and the physical line shape.



Time scale variations of the <u>radial velocities</u> of the five independent density regions that produce the satellite components of the C IV doublet as a function of time. Small radial velocities' differences can be detected during the studied sixteen years period.



Time scale variations of the <u>rotational velocities</u> of the five independent density regions that produce the satellite components of the C IV doublet as a function of time. Small rotational velocities' differences can be detected for all the SACs during the studied sixteen years period.

Conclusions

1. ***The peculiar spectral lines in Hot Emission Stars and AGNs are caused mainly by accretion and/or ejection of matter from these objects.***
2. ***Spectral lines peculiarity could be explained by DACs and SACs phenomena, indicating the existence of layers of matter with different physical conditions.***
3. ***The results obtained confirm the assumptions of the proposed model.***

With GR model we can measure the radial and the rotational velocities of the density regions of matter that produce the spectral lines as well as the random velocities of the ions.

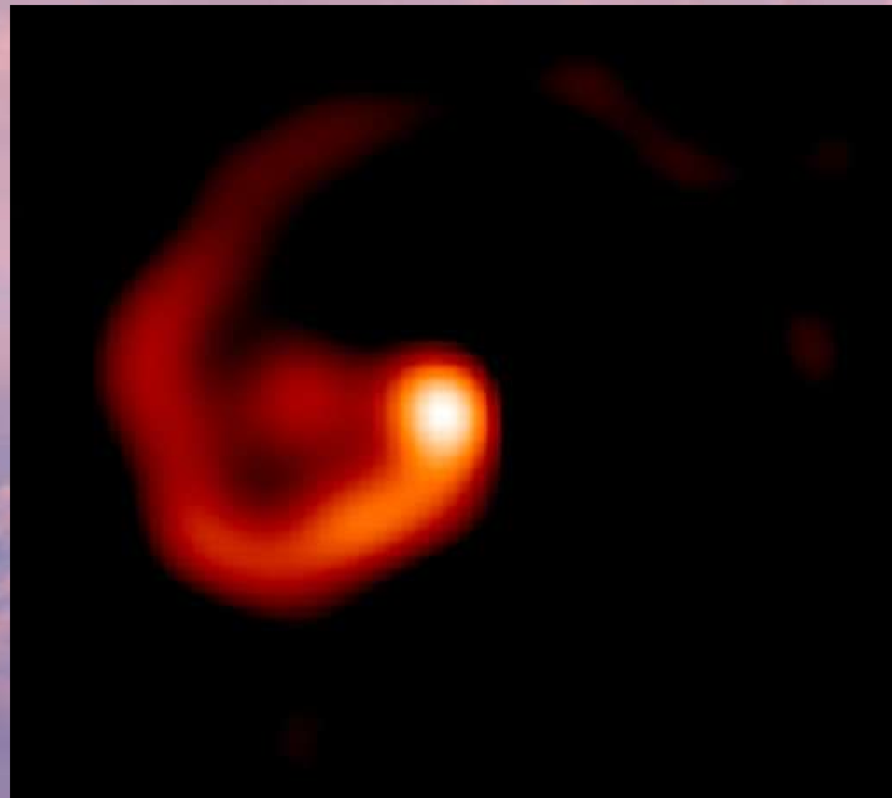
Additionally, we can measure the optical depth in the center of the spectral line, the column density and the absorbed or emitted energy for each one of the density regions.

But the main questions remain………

1. *What is the origin and the mechanism that permit the periodic ejection of mass from the equator of rapidly rotating Hot Emission Stars?*

2. *What is the origin and the mechanism responsible for the construction and the stability for long time of density regions in the ejected matter that produce the DACs and SACs phenomena?*

These great questions and many others that arise from the study of hot emission stars and AGNs with the proposed model, wait for future answers.



Thank you very much for your attention