A new approach for the structure of Ha regions in 120 Be-type stars

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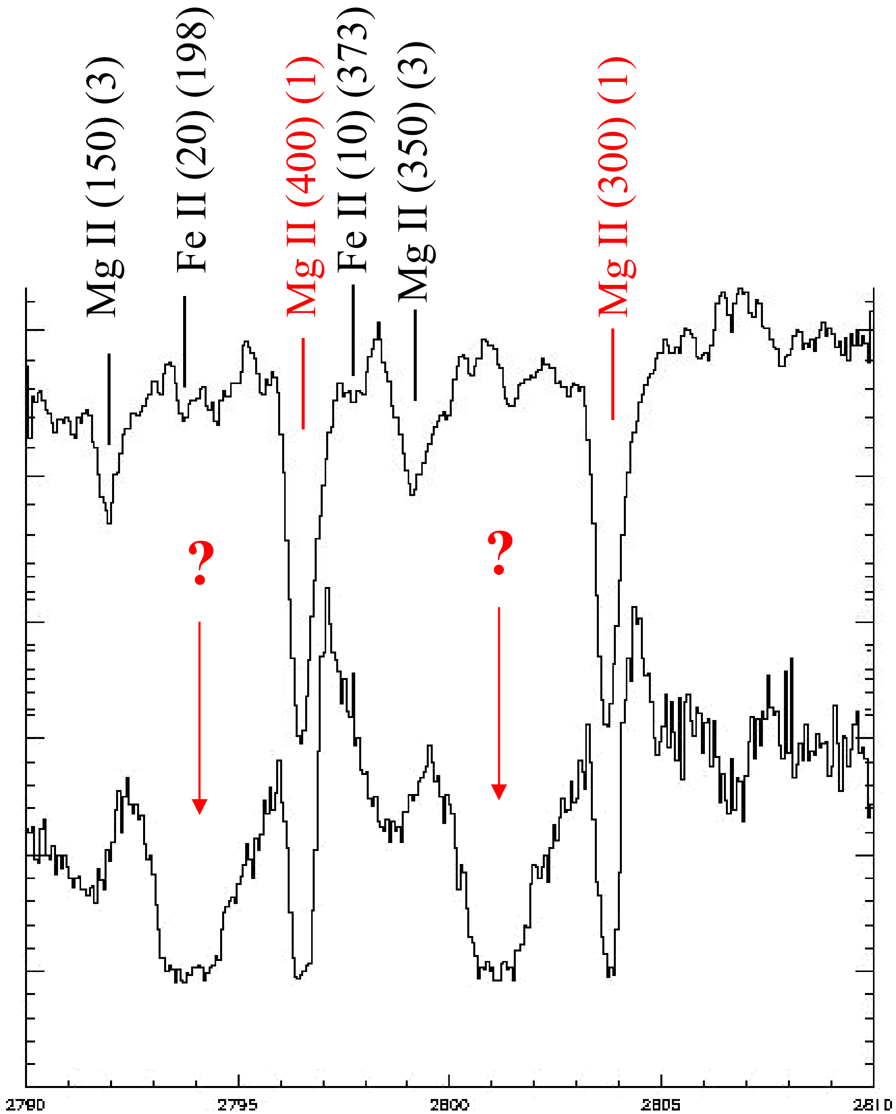
Observation of unknown spectral lines in the spectra of Oe and Be stars



Mg II λ 2795.523 (400) (1)
2802.698 (300) (1)

HD 30386 B2 III
LWR 09251

HD 45910 B2 III e
LWR 06234

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- **Peton (1974)** first pointed out, in the optical spectrum of the binary system AX Mon (HD 45910), the existence of a secondary component of the absorption line FeII λ 4233Å, which, depending on the phase, appeared in the violet or in the red side of the main spectral line. For this reason the secondary component was named “satellite component”.

- **Morgan et al. (1977)** studied the MgII resonance lines of γCas and ζTau and detected “significant absorption features” shortward of each resonance absorption which they attributed to “additional absorption within the stars’ extended atmosphere”.

- **Marlborough et al. (1978)** pointed out that the UV spectra of Be stars are very complex and contain many shell absorption lines which usually have velocity shifts.

- **Lamers et al. (1982)** observed satellite components superimposed on the wide P Cygni profile of the UV resonance lines of the OeIIf star HD 175754 and suggested that they may be the result of ionization gradients in an otherwise spherically symmetric and time-steady wind.

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- **Danezis (1984, 1986) and Danezis et al. (1991)** studied the UV spectrum of the binary system AX Mon and noted that the absorption lines of many ionization potential ions, are accompanied by two strong absorption components. This means that the regions where these spectral lines are created are not continuous, but they are formed by a number of independent density layers of matter.

- **Sahade et al. (1984) and Sahade & Brandi (1985)** also detected the existence of satellite components in the UV spectrum of AX Mon.

- **Hutsemekers (1985)** observed satellite components in the UV spectrum of another Be star, HD 50138.

- **Bates & Halliwell (1986)**, naming the satellite components "**Discrete Absorption Components" (DACs**), constructed a model of ejection of gas parcels from above the star's photosphere, accelerated by radiation pressure.

- **Laskarides et al. (1992a)** observed one more satellite component in the spectral lines of ions with low ionization potential in the UV spectrum of AX Mon, in the red side of the main lines. This fact indicates contraction of the outer layers of the gaseous envelope.

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Satellite Components

Such lines have been detected by many researchers, who have named them Satellite Components (Peton 1973, Lamers et al. 1982, Sahade et al. 1984, Sahade & Brandi 1985, Hutsemékers 1985, Danezis 1984,1987, Danezis et al. 1991, 1995, 1997a, 1997b, Theodossiou et al. 1993, 1997, Laskarides et al. 1992, 1993, Stathopoulou et al. 1995, 1997) or Discrete Absorption Components (Bates & Halliwell 1986, Prinja 1988, 1992, Willis et al. 1989, Bates & Gilheany 1990, Gilheany 1990, Kaper et al. 1990, Waldron et al. 1992, 1994, Henrichs et al. 1994, Telting et al. 1993, Telting & Kaper 1994, Cranmer & Owocki 1996, Rivinious et al. 1997, Prinja et al. 1997, Fullerton et al. 1997, Kaper et al. 1996, 1997, 1999, Cranmer et al. 2000).

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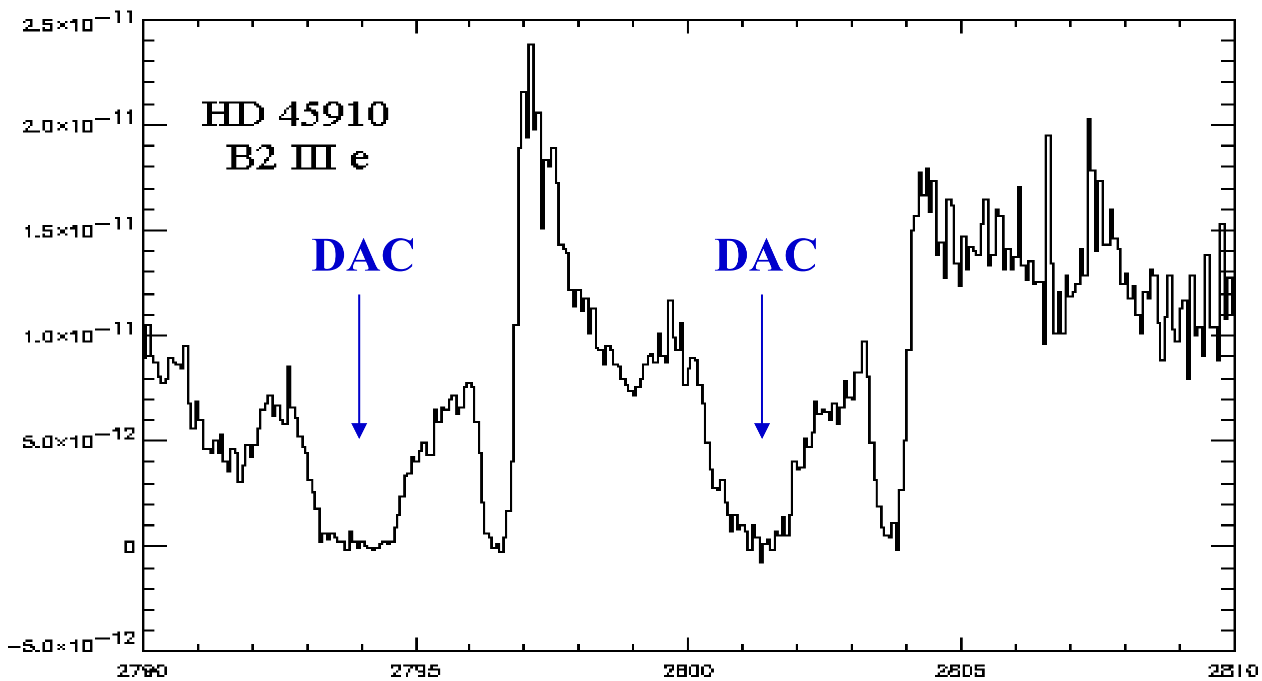
Definition of DACs - SACs

1. DACs, now, are not unknown absorption spectral lines, but **spectral lines of the same ion and the same wavelength as a main spectral line, shifted at different Δλ,** as they are created from different density regions which rotate and move radially with different velocities. The DACs are discrete lines, easily observed, in the spectra of some Be stars of luminosity class III.



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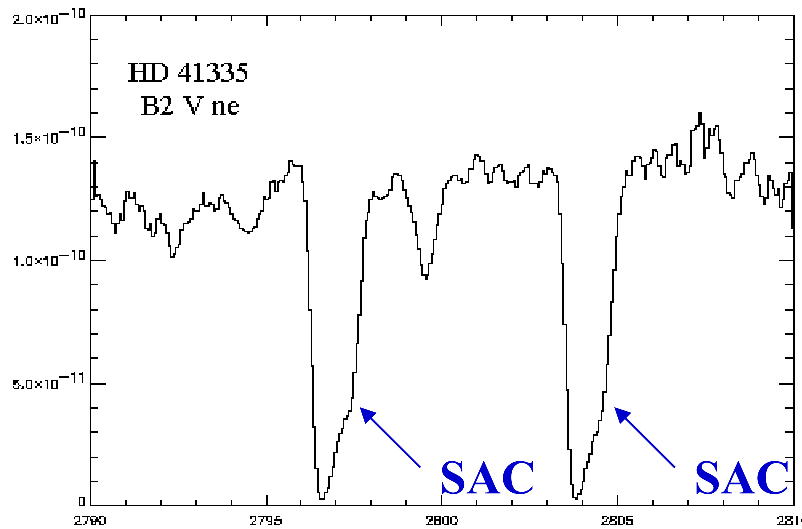
Definition of DACs - SACs

2. If the regions that create such lines rotate quickly and move radially slowly, the produced lines are quite broadened and little shifted. So, they may not be discrete absorption spectral lines, but blended among themselves. In such a case, they are not observable, but we can detect them through the analysis of the profile. As Peton (1974) first pointed out, these components appear as "satellites" in the violet or in the red side of a main spectral line, as a function of the time or the phase, in the case of a binary system.

For these two reasons and in order to include all these components, either they are discreet of not, to a unique name, we prefer to name them **Satellite Absorption Components (SACs)** and not Discrete Absorption Components (DACs).



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Mechanisms responsible for the SACs′ creation

- Mechanisms allowing the existence of structures which cover all or a significant part of the stellar disk, such as **shells, blobs or puffs** (Underhill 1975, Henrichs 1984, Underhill & Fahey 1984, Bates & Halliwell 1986, Grady et al. 1987, Lamers et al. 1988, Waldron et al. 1992, Cranmer & Owocki 1996, Rivinious et al. 1997, Kaper et al. 1996, 1997, 1999, Markova 2000).
- Interaction of fast and slow wind components, Corrotation Interaction Regions (CIRs), structures due to magnetic fields or spiral streams as a result of the star's rotation (Underhill & Fahey 1984, Mullan 1984a,b 1986, Prinja & Howarth 1988, Cranmer & Owocki 1996, Fullerton et al. 1997, Kaper et al. 1996, 1997, 1999, Cranmer et al. 2000).

Though we do not know yet the mechanism responsible for the formation of such structures, it is positive that the SACs result from **independent high density regions** in the stars' environment. These regions are formed by the specific ions which create a specific spectral line.

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MODEL

Danezis et al. (2003) constructed a mathematical model, in order to study the atmospheric regions that give rise to SACs.

Fundamental Hypotheses

- The atmospherical region where a specific line is created is not continuous, but it is composed of a number of successive independent absorbing density regions, a number of emission regions and an external general absorption region.
- The angular velocity of rotation is constant.
- None of the phenomena is relativistic.
- The shift of the center of the line from the laboratory wavelength is only due to the radial motion.

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MODEL

This model is simple, aiming to describe the regions where the spectral lines which present SACs are created.

- We use this model, as, even if it is simple, it is the only one which is able to reproduce accurately the peculiar and complex line's profiles which present SACs.
- We have not included variation with time, as our purpose is to describe the structure of the regions where the SACs are created at the specific moment when a spectrum is taken and not the construction of a time-dependent function of the line's profile. In order to study the time-variation of the calculated physical parameters we should study many spectra of the same star, taken at different moments.
- With this model **we study the atmospherical region of a specific ion which creates a specific spectral line**. As our purpose is to study the variations of some parameters of the same regions, we do not need to include the atomic parameters in the used model, as in such a case the atomic parameters remain constant.

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MODEL

By solving the equations of radiation transfer through a complex structure as the one described, we conclude to a function for the line's profile, able to give the best fit for the main spectral line and its Satellite Absorption Components in the same time. Such a best fit, through the function of the line's profile, enables us to calculate some parameters (rotational and radial velocities, FWHM, optical depth) of the independent layers of matter, which form the main spectral line and its satellite absorption components.

$$\boxed{I_\lambda = \left[I_{\lambda 0} \prod_i e^{-x_i} + \sum_j S_{\lambda ej}\left(1 - e^{-x_j}\right) \right] e^{-x_g}}$$

where:

- **$I_{\lambda 0}$:** the initial radiation intensity,
- **$S_{\lambda ej}$:** the source function, which, at the moment when the spectrum is taken, is constant
- e^{-x} : the appropriate distribution function (Gauss, Lorentz, Voigt, Rotation)

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Rotation distribution function

We considered that:

• the density regions, where the SACs or DACs are created, present spherical symmetry

• the main reason of the spectral lines' broadening is the rotation of the density regions which create them

and we calculated the rotation distribution function $e^{-L\xi}$, where:

$$L(\lambda)=\begin{cases}\sqrt{1-\cos^2\theta_0}\,, \text{if } \cos\theta_0=\dfrac{-\lambda_0+\sqrt{\lambda_0^2+4\Delta\lambda_{rotation}^2}}{2\Delta\lambda_{rotation} z_0}<1\\[2ex] 0\,, \quad \text{if } \cos\theta_0=\dfrac{-\lambda_0+\sqrt{\lambda_0^2+4\Delta\lambda_{rotation}^2}}{2\Delta\lambda_{rotation} z_0}\geq 1\end{cases}$$

where:

λ_0 is the observed wavelength of the center of the spectral line,

$\Delta\lambda_{rotation}$ is the broadening of the spectral line and

$z_0=\dfrac{\Delta\lambda_{rotation}}{\lambda_{lab}}=\dfrac{V_{rotation}}{c}$, where λ_{lab} is the laboratory wavelength of the spectral line and

ξ is the optical depth for each λ_i along the spectral line

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Distribution functions

In case we do not want to consider certain geometry, but only some physical parameters, we may replace the Rotation distribution function with a classical distribution function (Gauss, Lorentz, Voigt).

Gauss: The lines' broadening is mainly due to the ions' random motion.

Lorentz: The lines' broadening is mainly due to the collisional effects among the ions.

Voigt: The lines' broadening is mainly due to the ions' random motion, as well as the collisional effects among the ions, which, in an environment of high pressure and temperature, result to the broadening of the produced spectral lines (synthesis of a Gaussian and a Lorentzian distribution).

Geometry

The calculation of I_λ does not depend on the geometry of the absorbing or emitting independent density regions of matter. The decision on the geometry is essential for the calculation of the Rotation distribution function $e^{-L\xi}$. In order to decide on the appropriate geometry, we took into consideration the following important facts:

- The spectral line's profile is reproduced in the best way when we consider 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, in which case spherical symmetry is justified, or at a greater distance from the star, where the spherical symmetry can not be justified.

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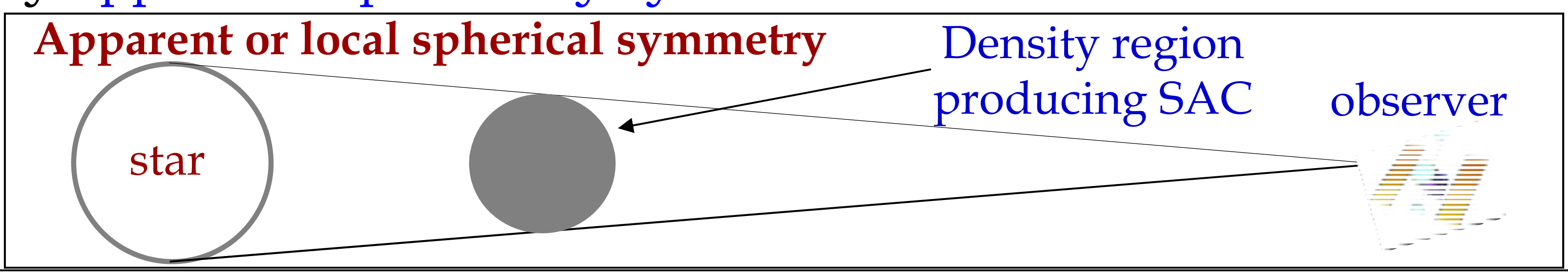
Geometry

1. <u>Independent density regions of matter that lie</u> <u>close to the star</u>: We consider the existence of a classical spherical symmetry

2. <u>Independent density regions of matter that lie</u> <u>at a greater distance from the photosphere</u>: We consider the existence of independent density regions such as **blobs**, which cover all or a substantial fraction of the stellar disk. These regions, do not present spherical symmetry around the star, but they may present local spherical symmetry and they form spectral lines' profiles which are identical with those deriving from a spherically symmetric structure. So, even if the density regions are not spherically symmetric, through their effects on the lines' profiles, they appear as spherically symmetric structures to the observer.



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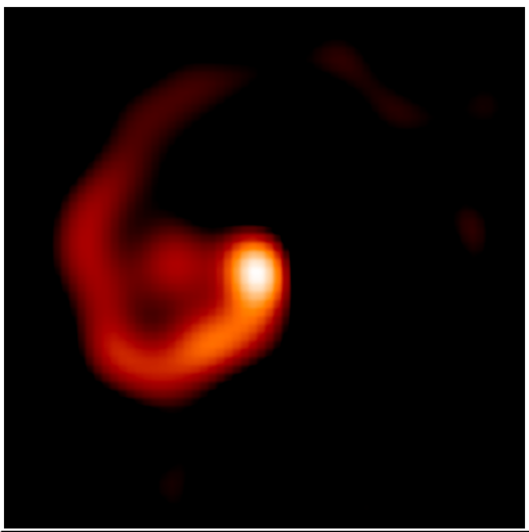
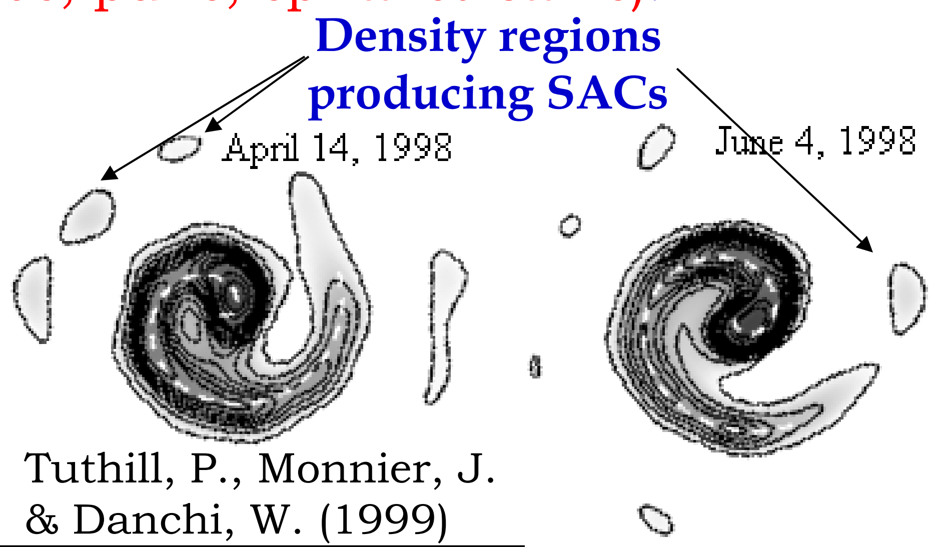
Geometry

2. The star ejects mass with a specific radial velocity. The stream of matter is twisted, forming density regions such as corotating interaction regions (CIRs), structures due to magnetic fields or spiral streams as a result of the star's rotation (Underhill & Fahey 1984, Mullan 1984a,b 1986, Prinja & Howarth 1988, Cranmer & Owocki 1996, Fullerton et al. 1997, Kaper et al. 1996, 1997, 1999, Cranmer et al. 2000)). This means that hydrodynamic and magnetic forces take effect as centripetal forces, resulting to the outward moving matter twisting and moving around the star. Some parts of these streams cut off and form the observed high density regions (shells, blobs, puffs, spiral streams).





Tuthill, P., Monnier, J. & Danchi, W. (1999)

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Criteria

The function e^{-x} reproduces the spectral line's profile formed by the i density region (the profile of one component). For each trio of the parameters V_{roti}, V_{expi} and $\xi_{i,}$ we have a different profile. This results to the existence of only one trio able to give the best fit of the i component. In order to accept as best fit of the observed spectral line, what is given by the trios (V_{expi}, V_{roti}, ξ_i) of all the calculated SACs, we must adhere to all the physical criteria and techniques, such as:

- It is necessary to have the superposition of the spectral region we study with the same region of a classical star of the same spectral type and luminosity class, in order to identify the existence of spectral lines that blend with the studied ones and the existence of SACs .
- The resonance lines, as well as those that form in regions that are close to each other (small difference in ionization potential), must have the same number of SACs and the same values for V_{exp} and V_{rot}. Besides, in the cases of resonance lines and of lines of the same ion and the same multiplet, the ratio of the values of ξ must be the same as the ratio of the respective intensities.
- The final criterion to accept or reject a best fit is that the calculated values of the physical parameters should not go against the classical physical theory.

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Application of the model to the Hα line of 120 Be stars
Data

In our study we use the stellar spectrographs which were taken by Andrillat & Fehrenbach (1982) and Andrillat (1983) (resolution 5,5 and 27 Å) with the telescope of 152 cm in the Observatory of Haute Provence.

We applied the model on the Ha line 6562.817 Å in the spectra of 120 Be stars of all the spectral subtypes and luminosity classes.

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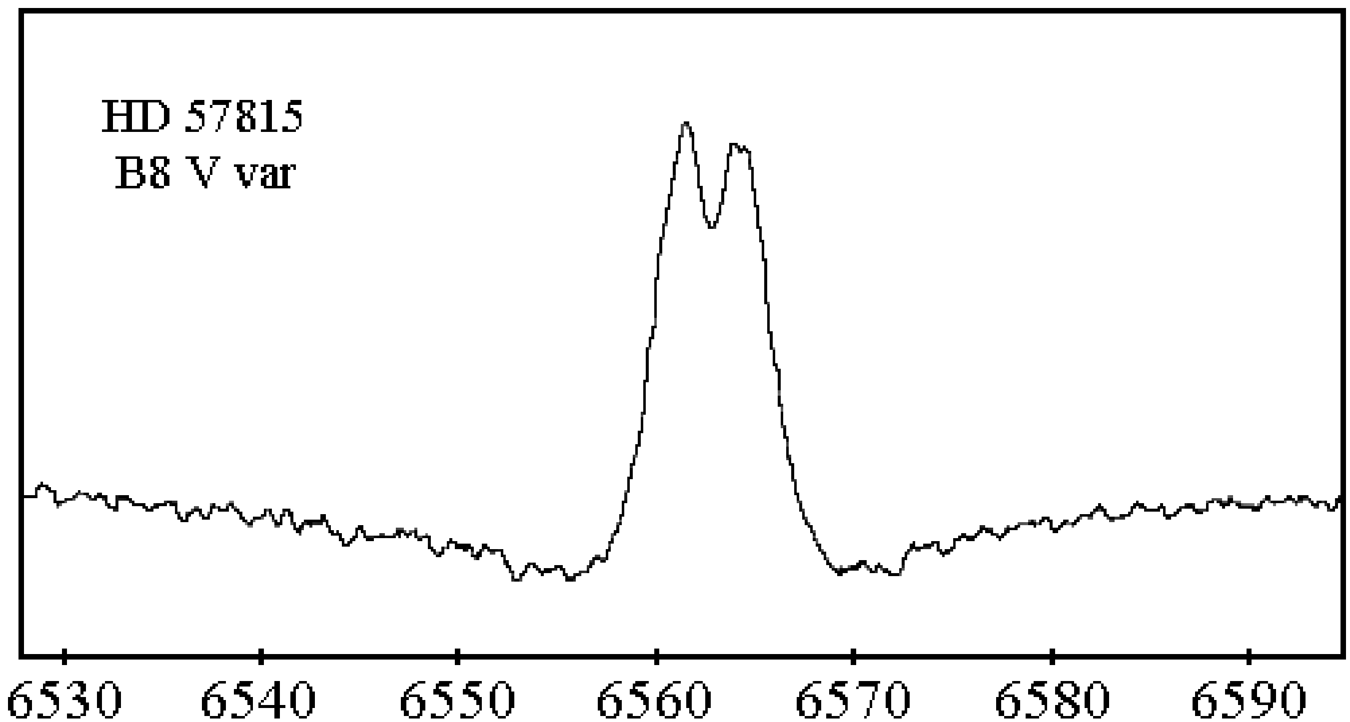
Study of the Hα line

In most of the Be stellar spectra the Ha line presents peculiar and complex profiles. Usually the Ha line's profile consists of:

- a very broad absorption component (created in the chromosphere)
- an emission component (created in the cool extended envelope)
- a narrow absorption component (created in the cool extended envelope).



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Study of the Hα line

We applied the proposed model in order to reproduce these complex profiles. We tried to fit the observed profiles by applying all the classical distribution functions (Gauss, Lorentz, Voigt, Rotation).

We concluded that the best fit is accomplished when we fit:

- the very broad absorption component with Rotation distribution

(the broad absorption line is composed by one to five components)

- the emission component with Voigt distribution

(in 7 of the 120 stars there exist two emission components)

- the narrow absorption component with Gauss distribution.

The most important point is that the best fit is not a graphical composition of the distributions for each component, but it is the result of the final function of the model where the appropriate distribution function is applied in the place of the exponential e^{-x}

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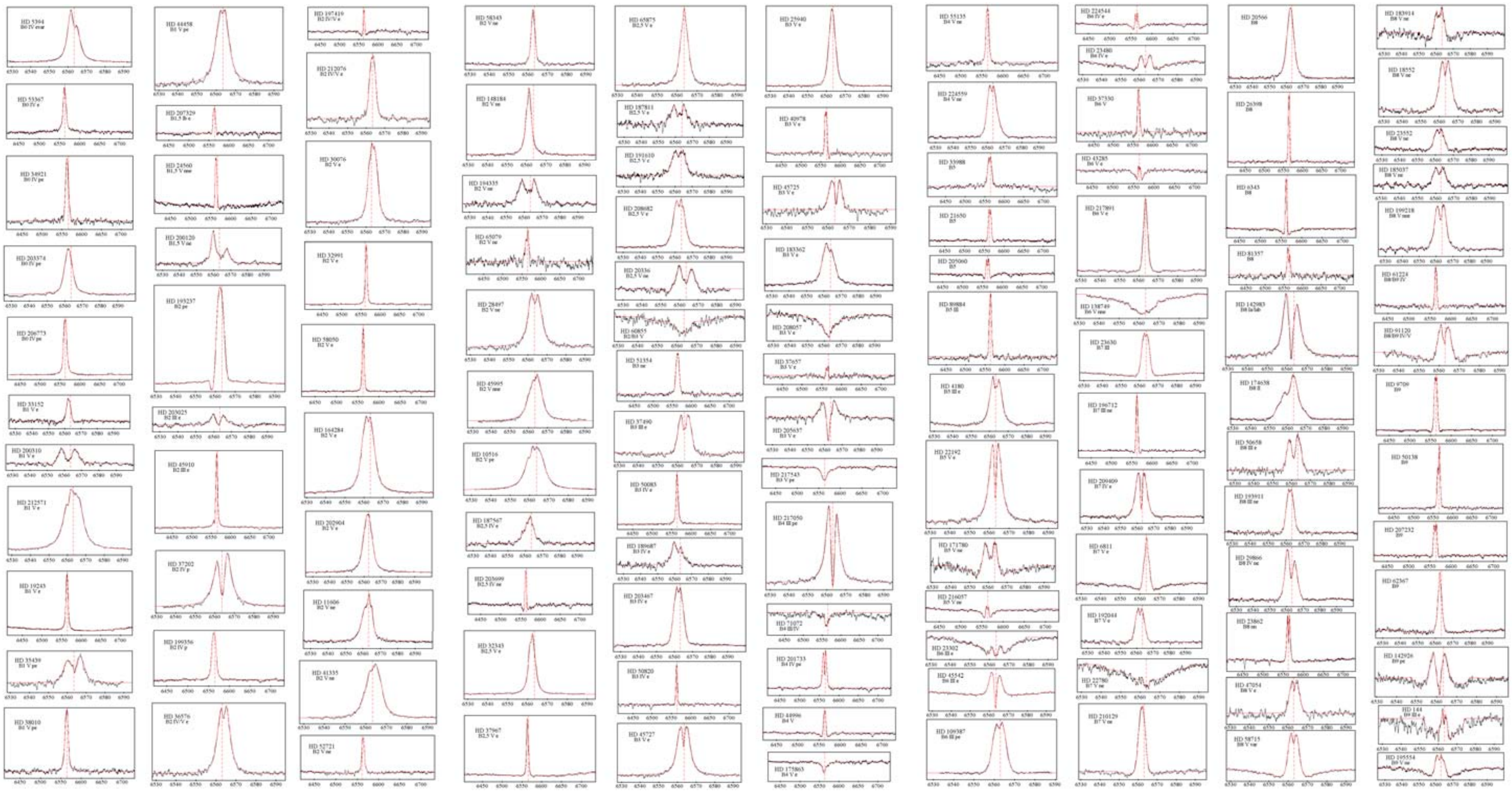
Study of the Hα line



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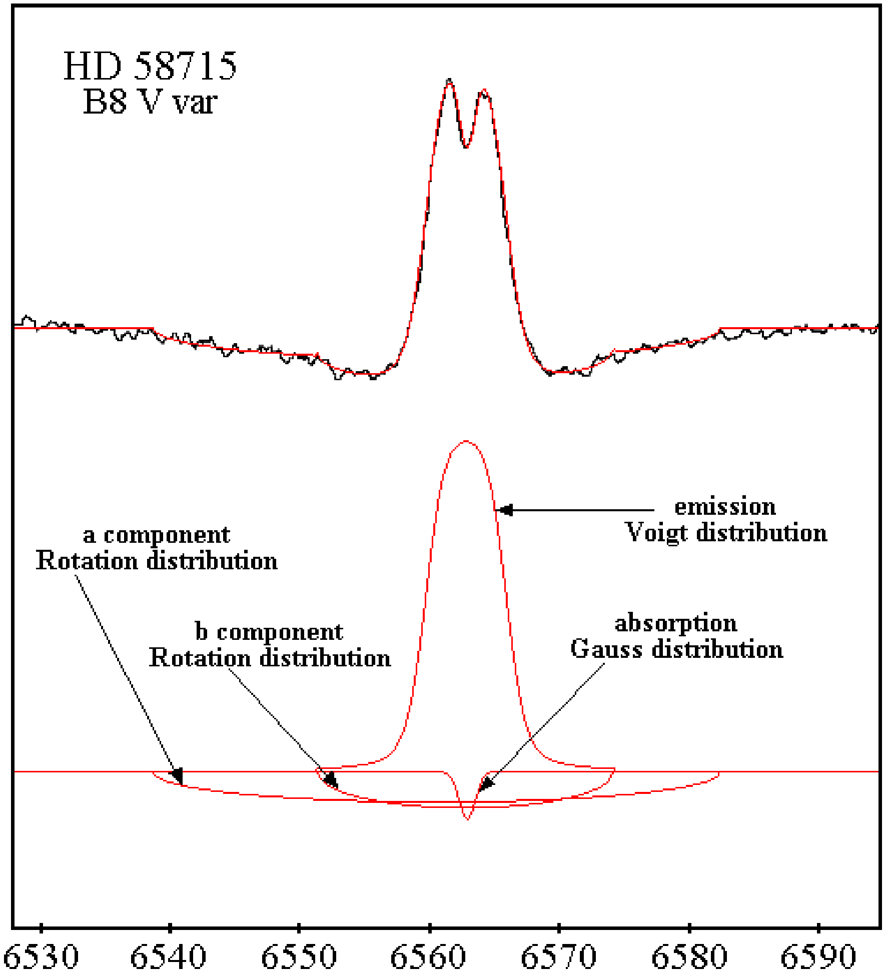

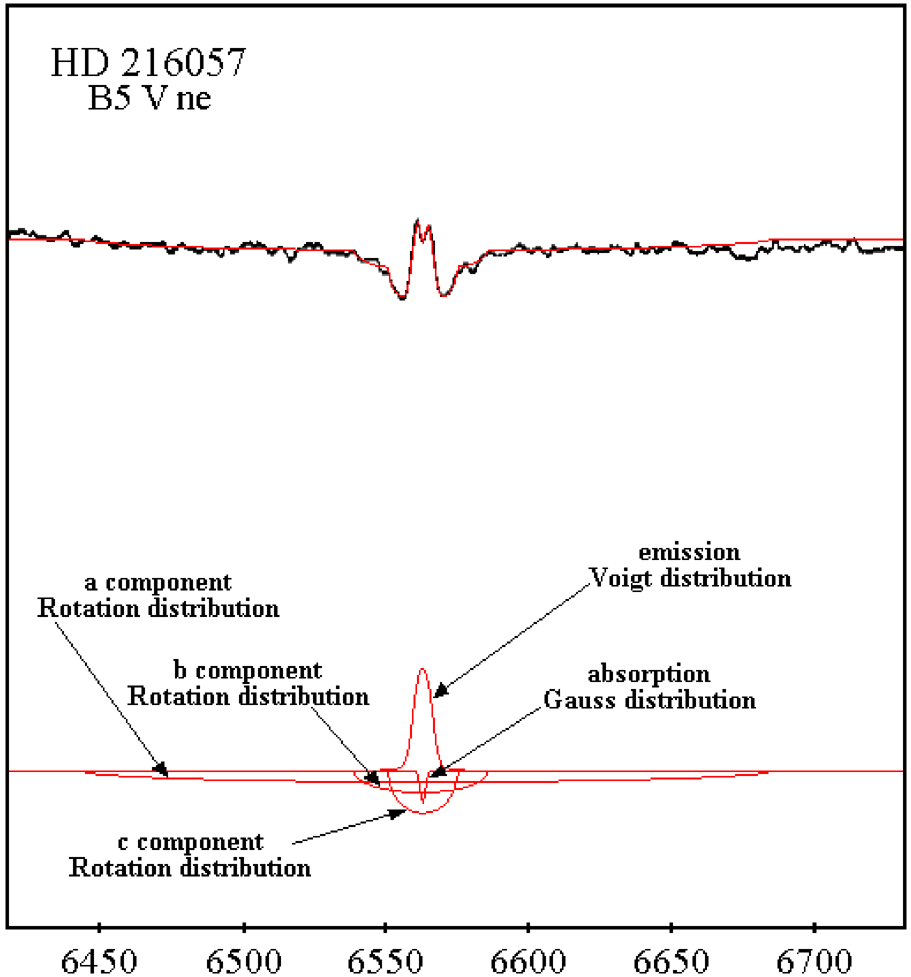

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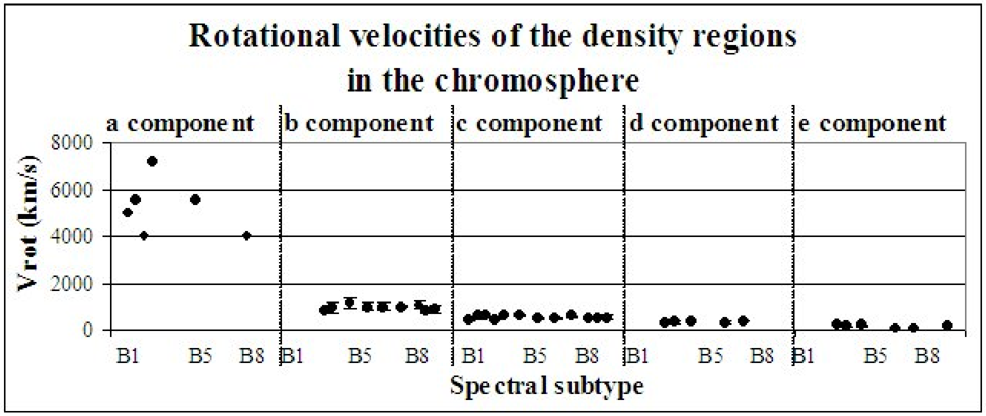
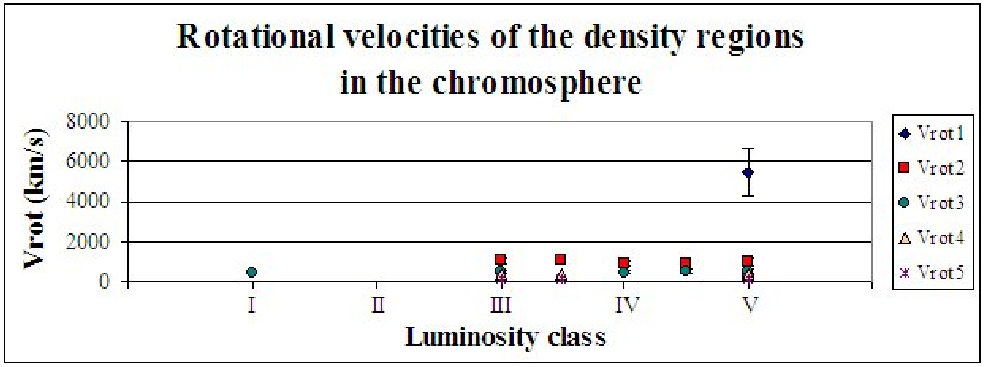
Study of the Hα line (chromosphere)

Mean values of the rotational velocities, as a function of the spectral subtype and the luminosity class, of the five density regions in the chromosphere. The rotational velocity of each density region is 5200±1192 km/s, 990±170 km/s, 536±68 km/s, 352±37 km/s and 152±46 km/s. **The five density regions do not appear in all the studied stars.**

The dispersion around the mean value dicreases from the first to the fifth desity region. The very broad absorption components appear only in the spectra of dwarfs. The observed dispersion is probably due to the different rotational axis inclination, of the regions which create the SACs.





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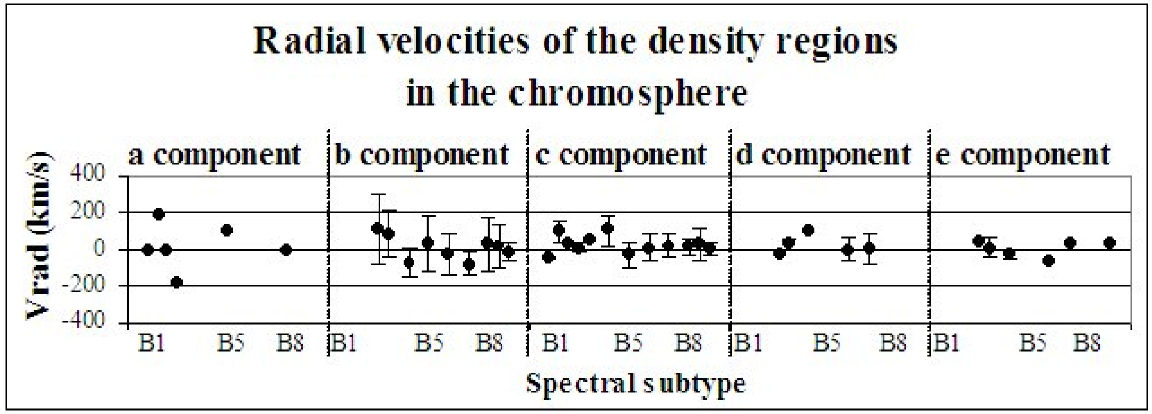
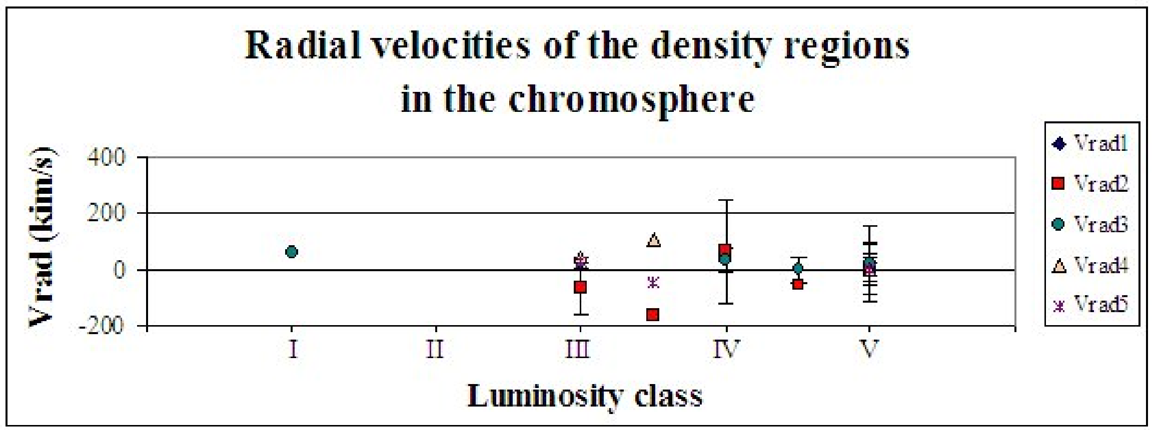
Study of the Hα line (chromosphere)

Mean values of the radial velocities, as a function of the spectral subtype and the luminosity class, of the five density regions in the chromosfphere. The radial velocity of each density region is 15±121 km/s, 7±123 km/s, 19±62 km/s, 15±60 km/s and -2±42 km/s.





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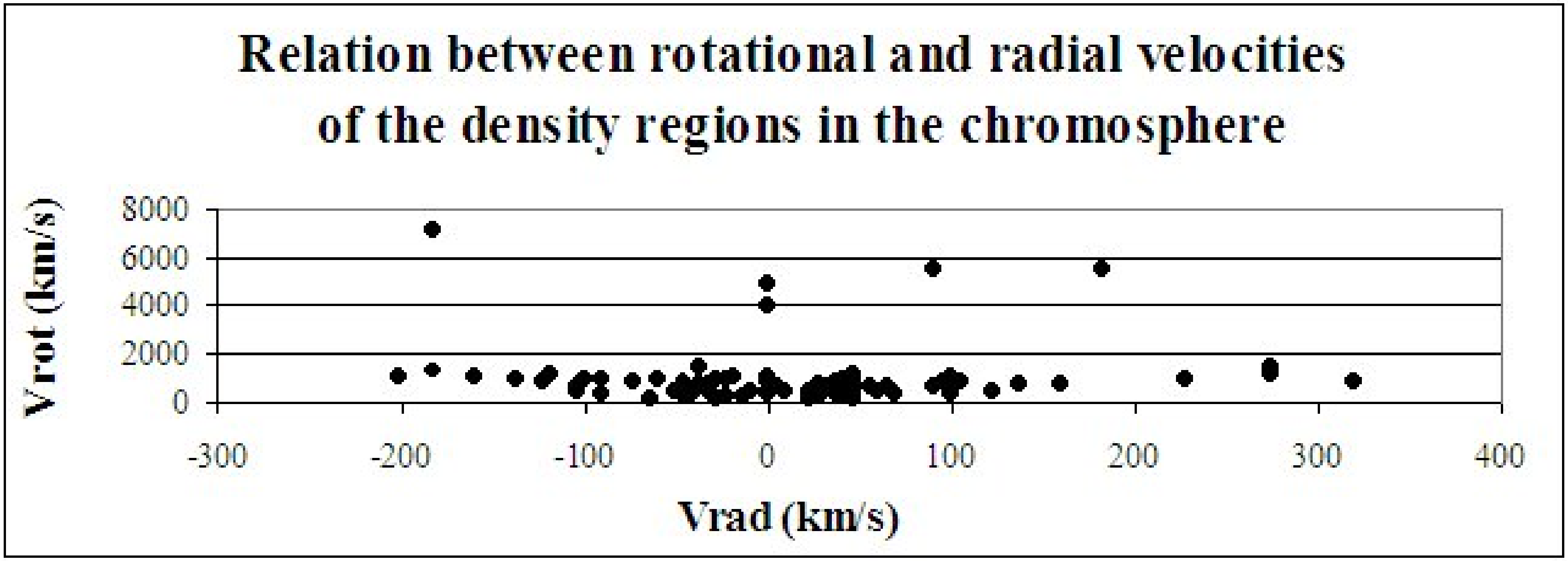
Study of the Hα line (chromosphere)



Rotational velocities of the five density regions in the chromosphere, as a function of the respective radial velocities.

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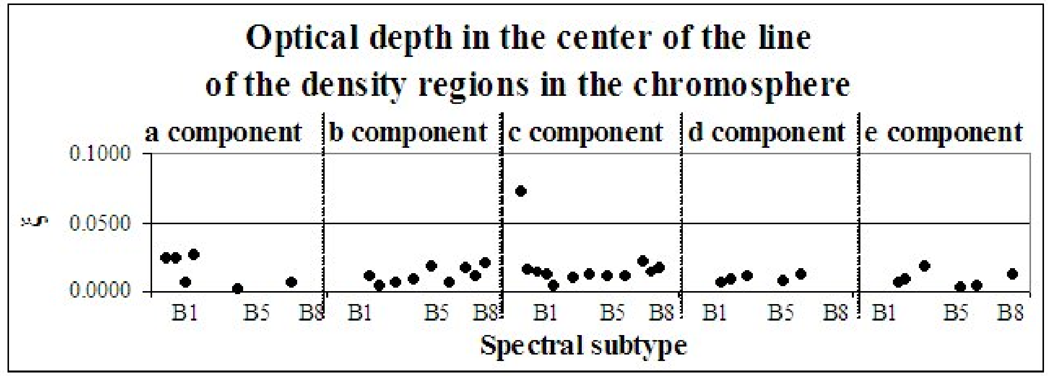
Study of the Hα line (chromosphere)

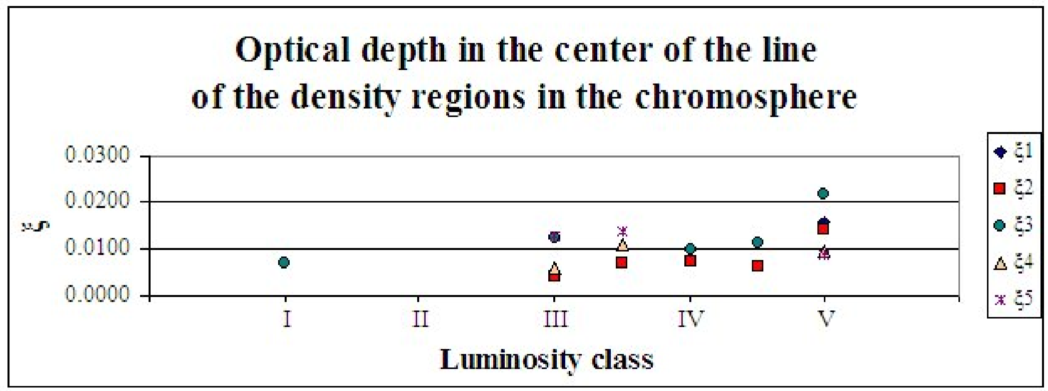
Mean values of the optical depth ξ for the five density regions in the chromosphere, as a function of the spectral subtype and the luminosity class.

The optical depth in the center of the spectral line (ξ), for the five density regions is between the values:

a) 0.0020 and 0.0255,
b) 0.0033 and 0.0964
c) 0.0029 and 0.1296
d) 0.0024 and 0.0196 and
e) 0.0025 and 0.0230.

The optical depth increases from the supergiants towards the dwarfs.





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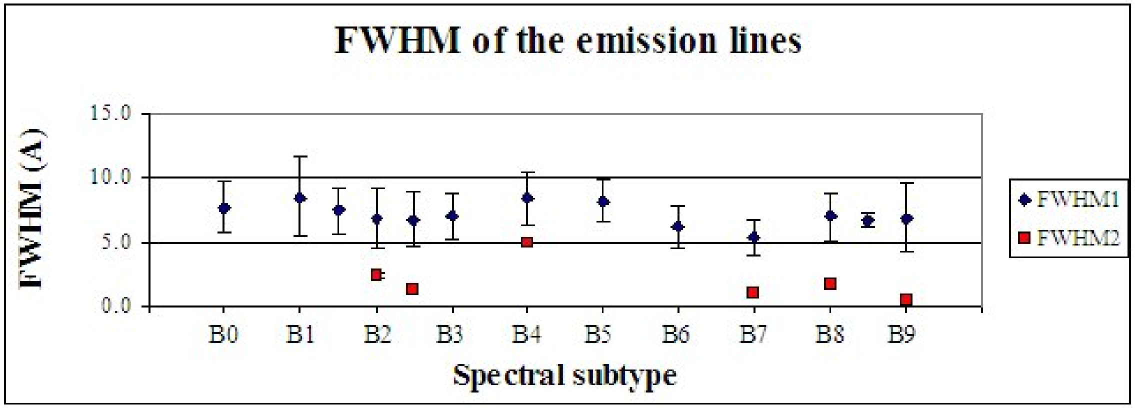
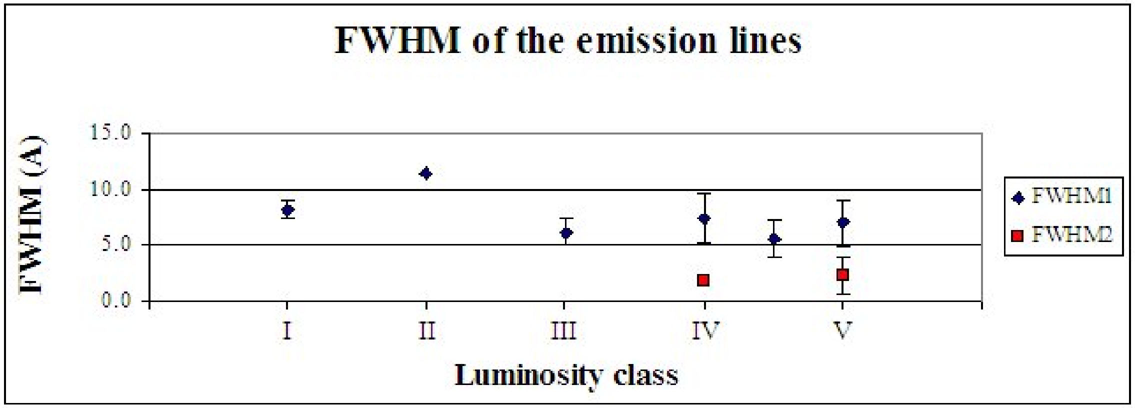
Study of the Hα line (cool extended envelope) (emission components)

Mean values of the FWHM of the emission components, as a function of the spectral subtype and the luminosity class.

The main emission component presents a fluctuation of the FWHM around the value of 7.1 Å. For the second emission component (when it appears) the fluctuation of FWHM is around the value of 2.0 Å.

The FWHM decreases from the supergiants towards the dwarfs.





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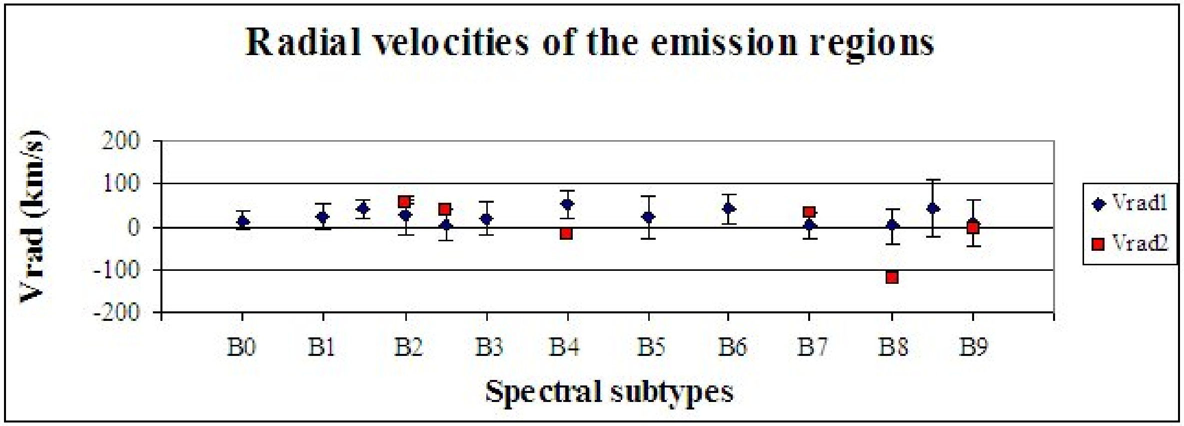
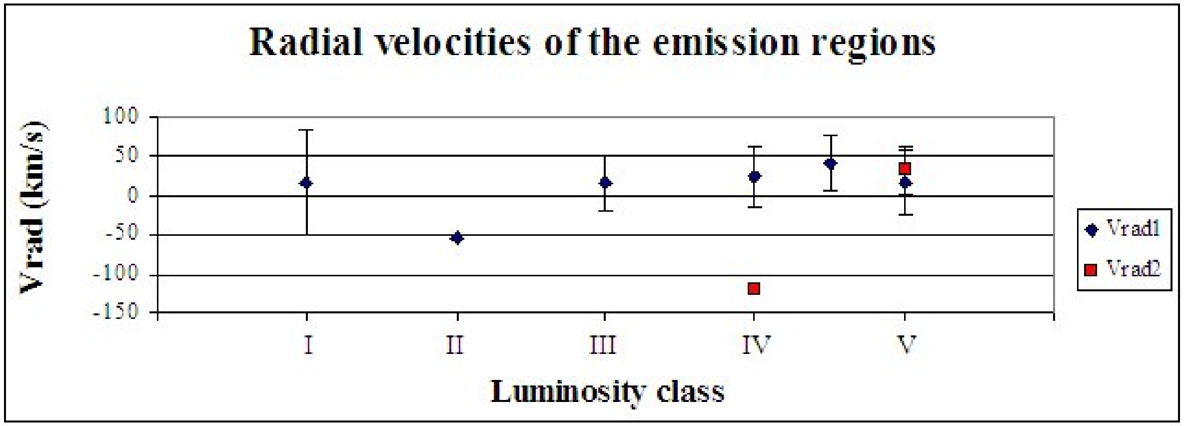
Study of the Hα line (cool extended envelope) (emission components)

Mean values of the radial velocities of the emission components as a function of the spectral subtype and the luminosity class. The radial velocity of the two emission regions presents a fluctuation around the value of 20 km/s.





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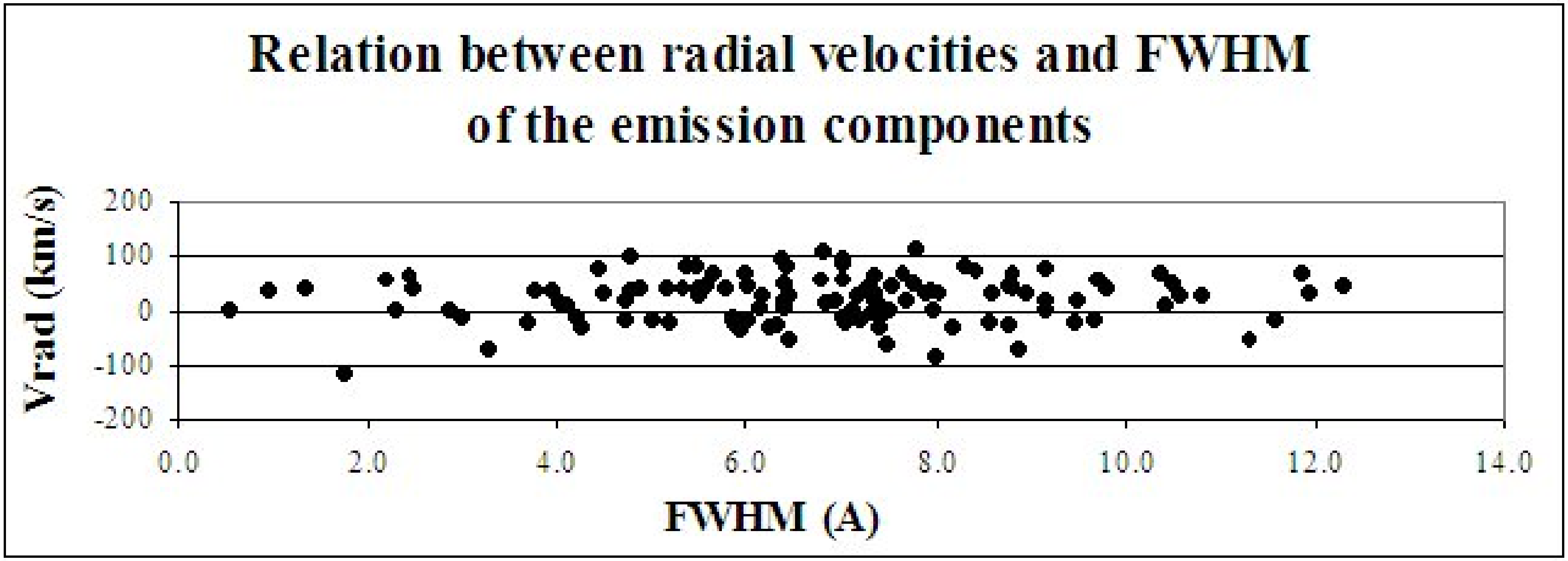
Study of the Hα line (cool extended envelope) (emission components)



Radial velocities of the emission regions, as a function of the respective values of the FWHM.

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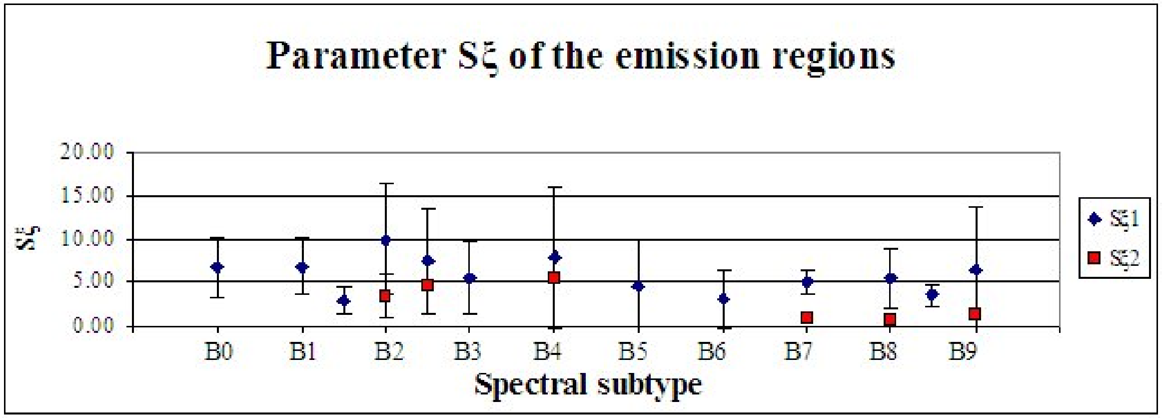
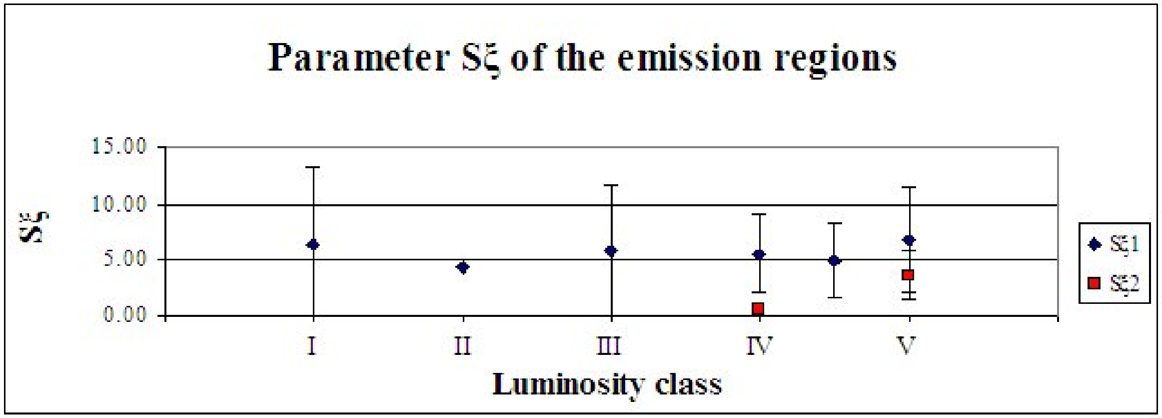
Study of the Hα line (cool extended envelope) (emission components)

Mean values of the parameter Sξ for the emission regions, as a function of the spectral subtype and the luminosity class.

The value of the parameter Sξ of the two emission regions is between the values:

a) 0.63 and 21.54 and
b) 0.64 and 5.60.





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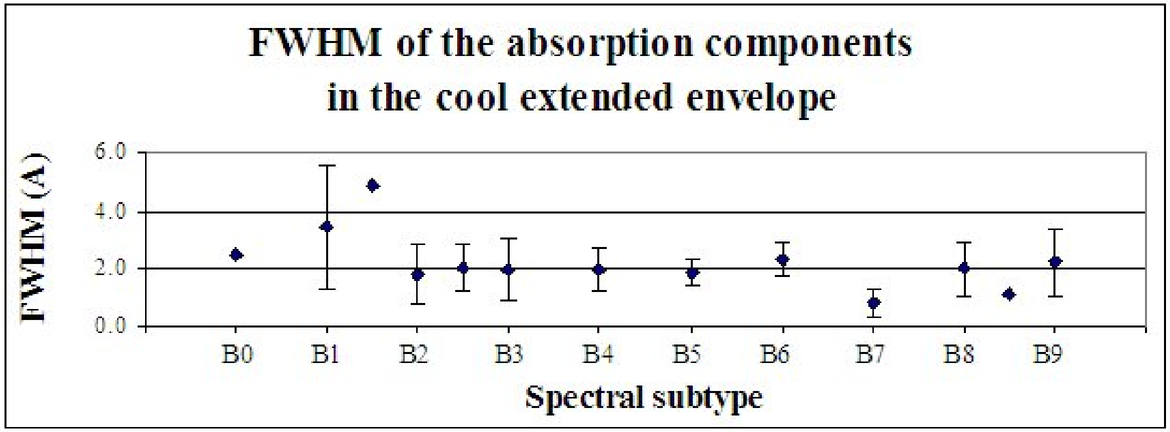
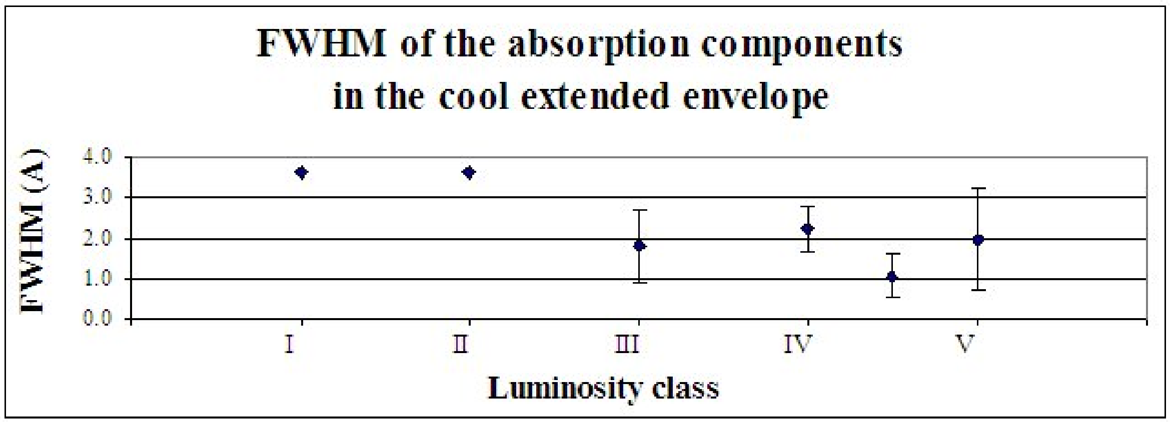
Study of the Hα line (cool extended envelope) (narrow absorption components)

Mean values of the FWHM of the absorption components, as a function of the spectral subtype and the luminosity class.

The FWHM fluctuates around the value of 2.0 Å.



The FWHM decreases from the supergiants towards the dwarfs.



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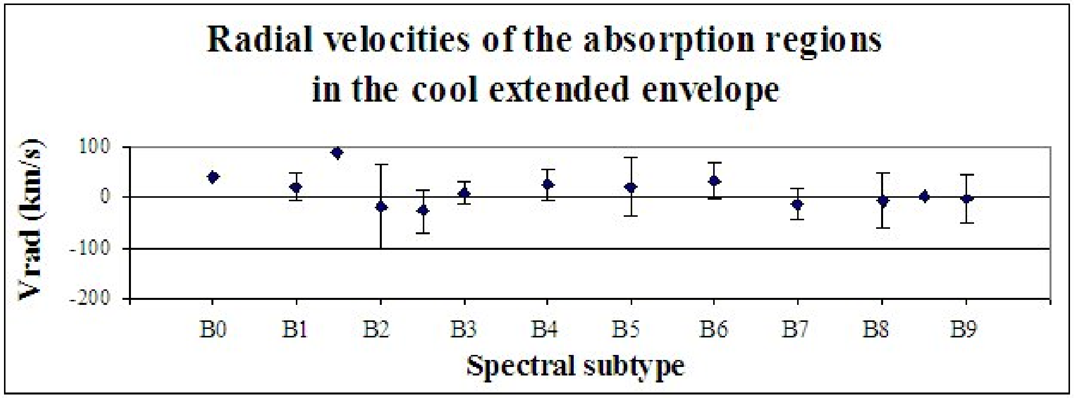
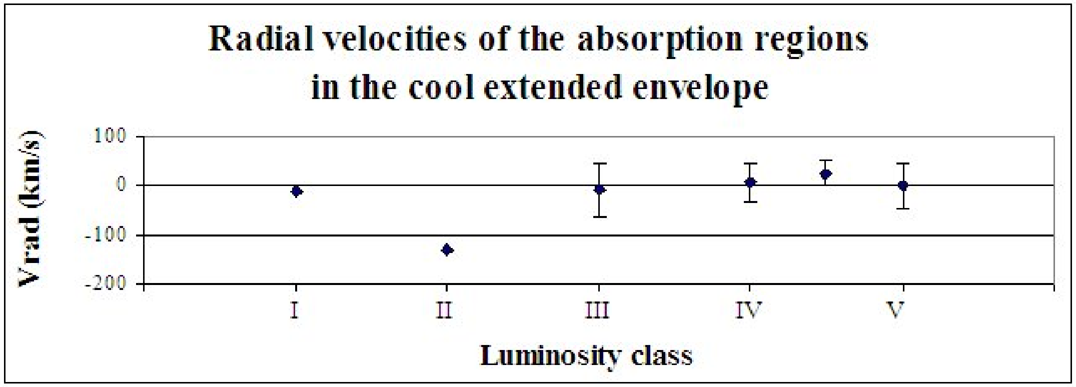
Study of the Hα line (cool extended envelope) (narrow absorption components)

Mean values of the radial velocity of the absorption components which is created in the cool extended envelope, as a function of the spectral subtype and the luminosity class.
The radial velocity fluctuates around the value of 0 km/s.





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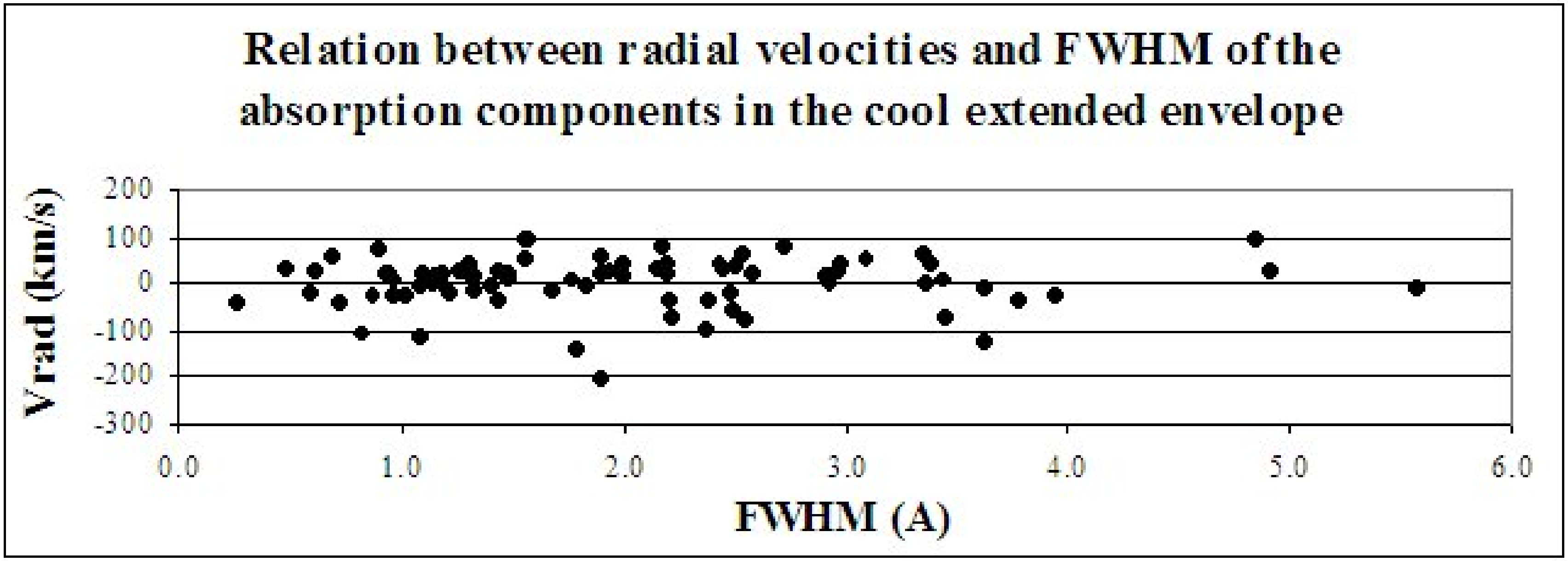
Study of the Hα line (cool extended envelope) (narrow absorption components)



Radial velocities of the absorption region, as a function of the respective values of the FWHM.

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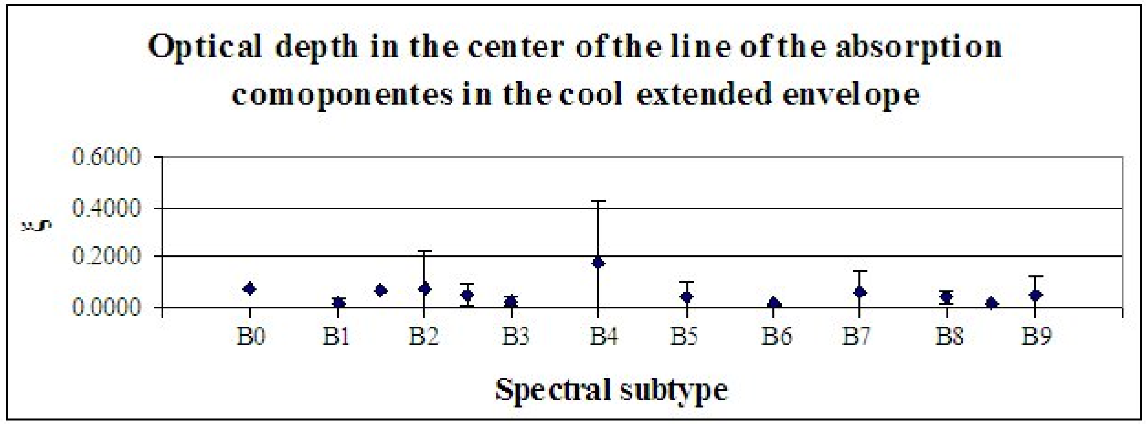
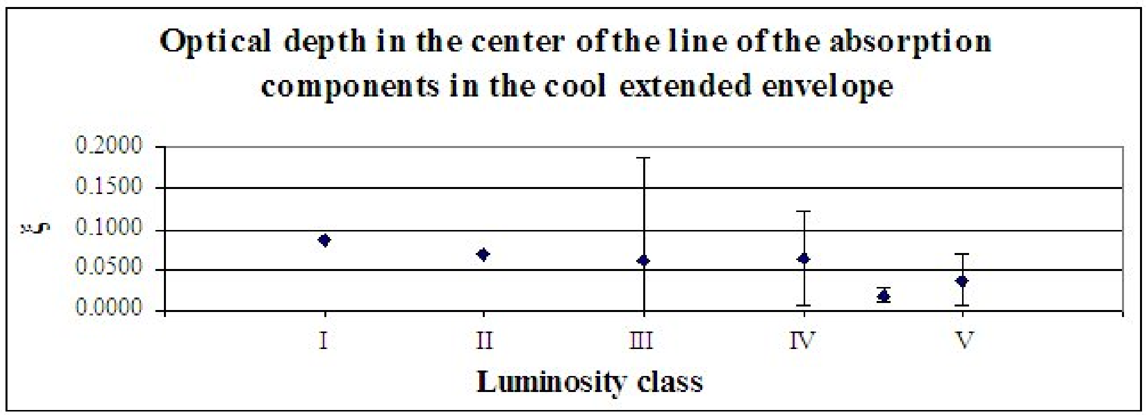
Study of the Hα line (cool extended envelope) (narrow absorption components)

Mean values of the optical depth in the center of the line (ξ) of the absorption component, which is created in the cool extended envelope, as a function of the spectral subtype and the luminosity class.

The optical depth in the center of the line (ξ) is between the values 0.0039 and 0.6250.



The optical depth decreases from the supergiants towards the dwarfs.



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Conclusions

1. The proposed line function $I_\lambda = \left[I_{\lambda 0}\prod_i e^{-x_i} + \sum_j S_{\lambda ej}\left(1-e^{-x_j}\right)\right] e^{-x_g}$ is able to reproduce accurately the complex Hα profiles of all the 120 studied Be-type stars. This means that the regions where the Ha line is created are not continuous, but they consist of successive independent density regions.

In the place of the exponential e^{-x}, which gives the profile of each component, we apply the appropriate distribution function. The choice of the appropriate distribution function depends on the physical conditions of the regions which create the SACs. The most important point is that, in any case, the proposed line function remains the same. The important advantage of this method is that we are able to accomplish the best fit of the observed spectral lines, by applying a line function, to which we conclude after the solution of the radiation transfer equations, through a complex atmospherical structure, and not by a graphical composition of mathematical distribution functions with no physical meaning.

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Conclusions

2. The existence of SACs is a general phenomenon in the spectra of Be-type stars.

3. The absorption regions of the Hα line, lie in two different atmospherical regions: one in the chromosphere and one in the cool extended envelope.

Chromospheric absorption regions: one to five successive, independent density regions. Each region creates one Satellite Absorption Component (SAC).

Cool extended envelope: density regions which create the emission components and the narrow absorption components.

The profiles of the studied Hα lines appear to be peculiar and complex, as they do not present only one spectral line, but a number of SACs, which are created in independent density regions. **All the studied stars do not present the same number of independent density regions**.

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Thank you!!!