SACs and DACs phenomena in the atmospheres of Hot Emission Stars

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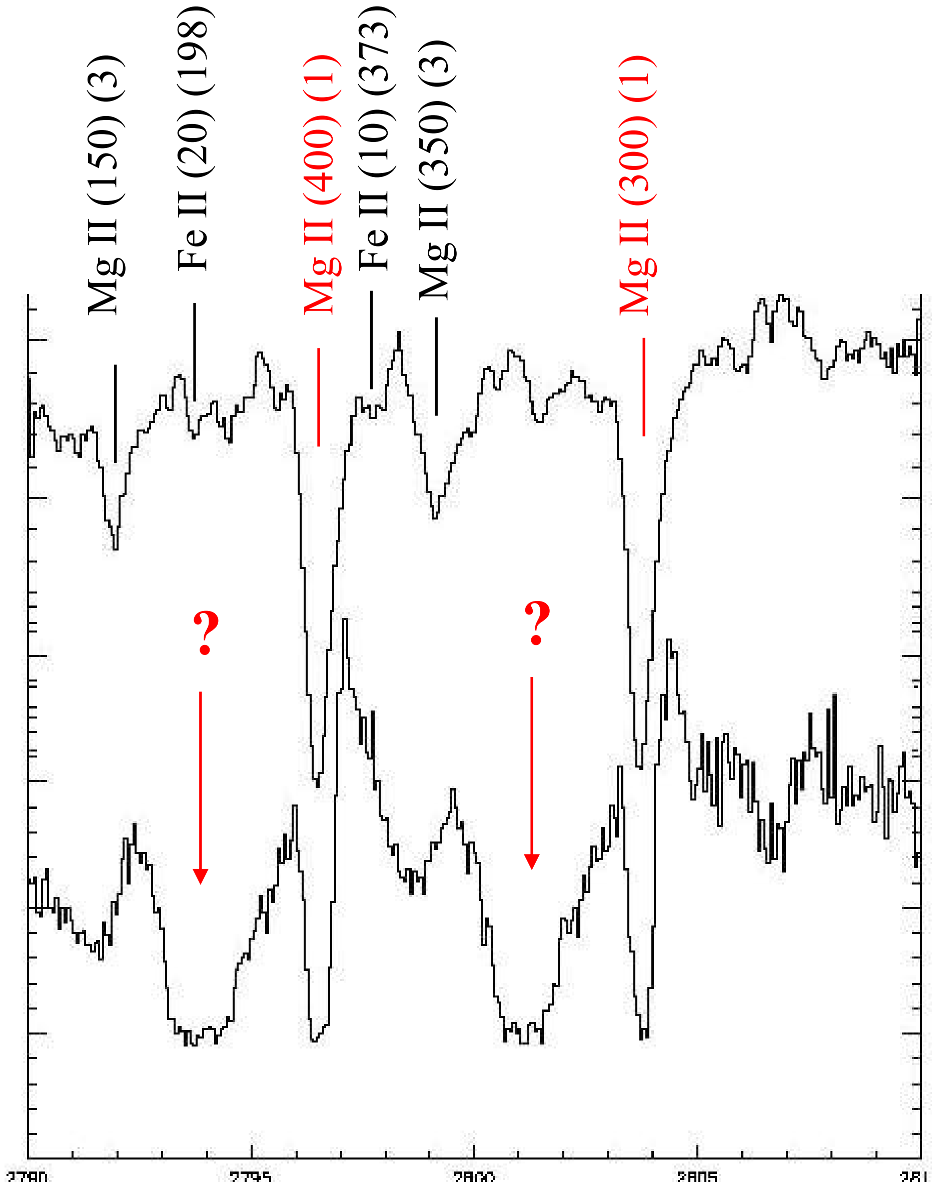
Observation of unknown spectral lines in the spectra of Oe and Be stars



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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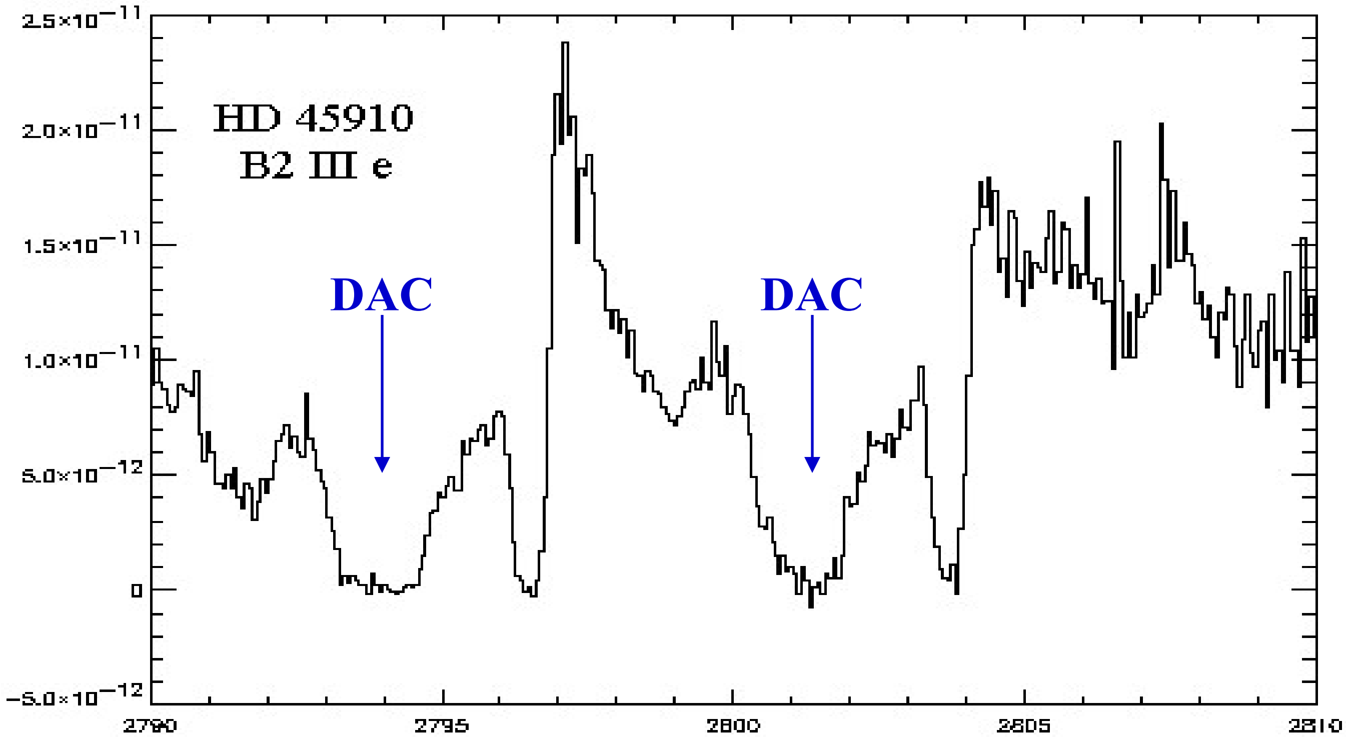
Definition of DACs - SACs

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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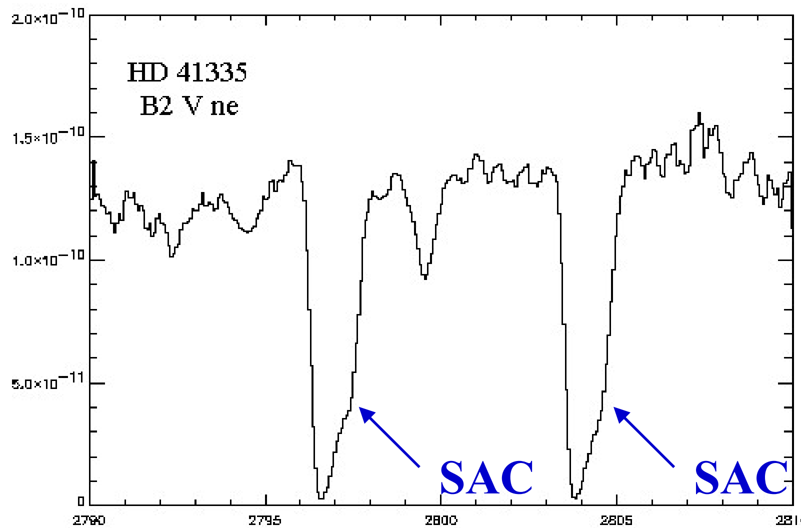
2. If the regions that create such lines rotate quickly and move radially slowly, the produced lines are quite broadened and little shifted. So, they may not be discrete absorption spectral lines, but blended among themselves. In such a case, they are not observable, but we can detect them through the 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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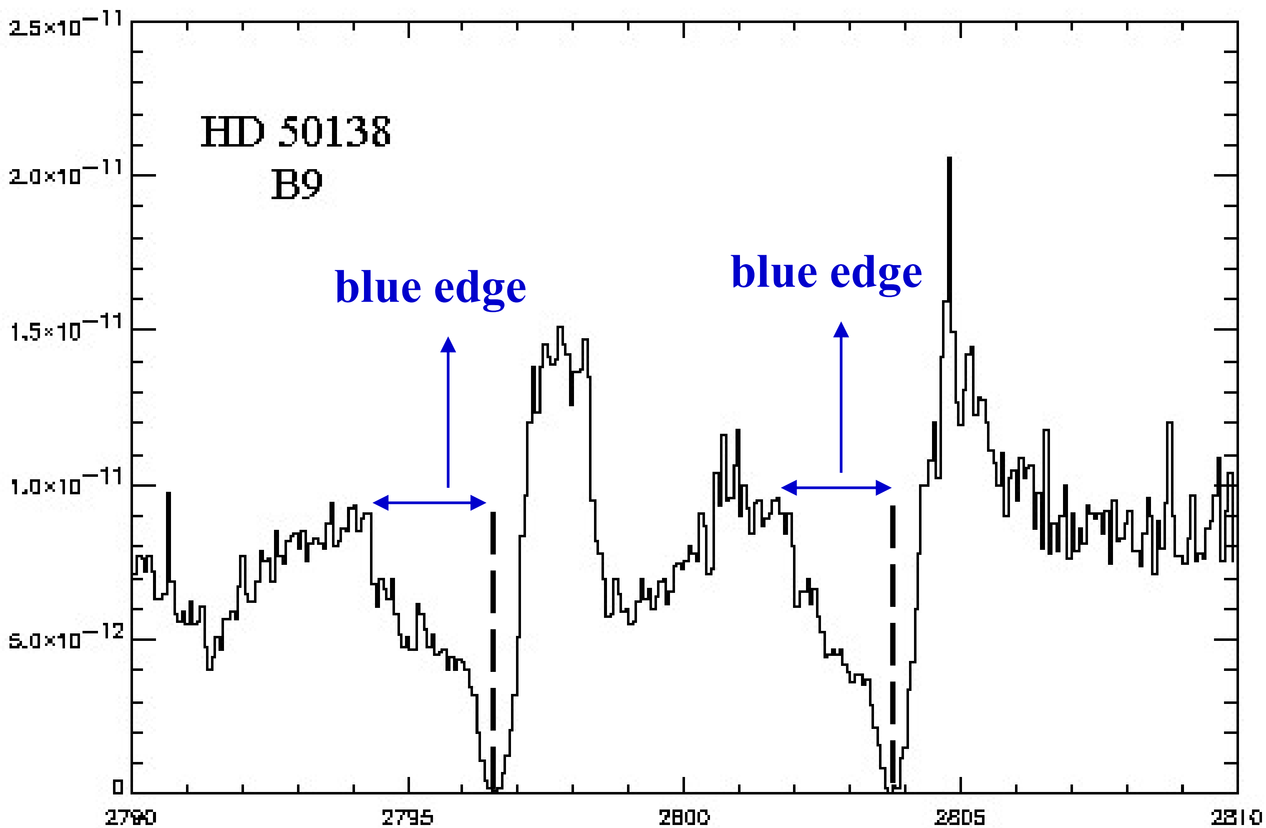
On the measurement of velocities

Until now, the equivalent width was calculated supposing that the whole absorption feature represents one absorption line. The rotational velocity was calculated by the width of the blue edge and the radial velocity was calculated by the line shift, supposing that the deepest point of the feature corresponds to the wavelength at which the absorption appears.



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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 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.
- The angular velocity of rotation is constant.
- None of the phenomena is relativistic.
- The only effect of a shell's expansion or contraction is a Doppler shift from the laboratory wavelengh.
- Thermal and natural broadening of the spectral lines are negligible. This means that the whole width of the line is measured as rotational velocity (V_{rot}).

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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 the rotational and radial velocities 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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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 of the independent layers of matter which form the main spectral line and its satellite absorption components, such as the apparent rotational and radial expansion/contraction velocities and an expression of the optical depth ξ.

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

where:

- $\mathbf{I_{\lambda 0}}$: the initial radiation intensity,
- $\mathbf{L_i}$, $\mathbf{L_{ej}}$, $\mathbf{L_g}$: are the distribution functions of the absorption coefficients $k_{\lambda i}$, $k_{\lambda e}$, $k_{\lambda g}$ respectively. Each L depends on the values of the rotational velocity as well as of the radial expansion/contraction velocity of the density shell, which forms the spectral line (V_{rot}, V_{exp}),
- $\xi = \int_0^s \Omega \rho ds$ is an expression of the optical depth τ, where Ω is an expression of k_λ and has the same units as k_λ,
- $\mathbf{S_{\lambda ej}}$: the source function, which, at the moment when the spectrum is taken, is constant

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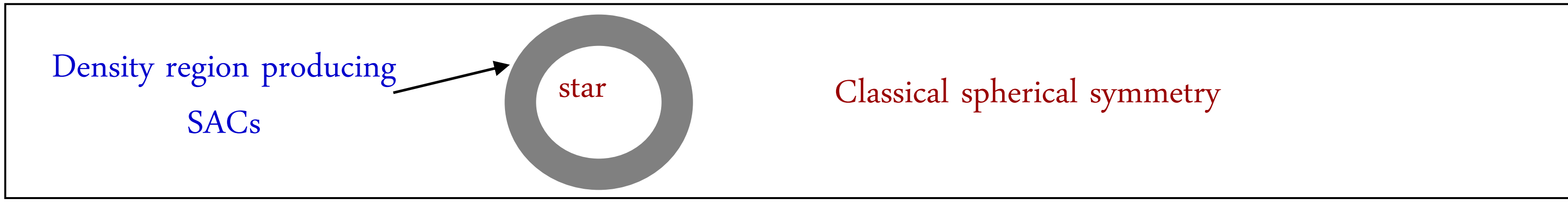
The calculation of I_λ does not depend on the geometry of the absorbing or emitting independent density regions of matter. The decision on the geometry is essential for the calculation of the distribution functions L_i. By deciding on a different geometry we conclude to a different analytical form of L_i, and thus to a different shape of the profile of the spectral line, which presents SACs.

In order to decide on the appropriate geometry we took into consideration the following important facts:

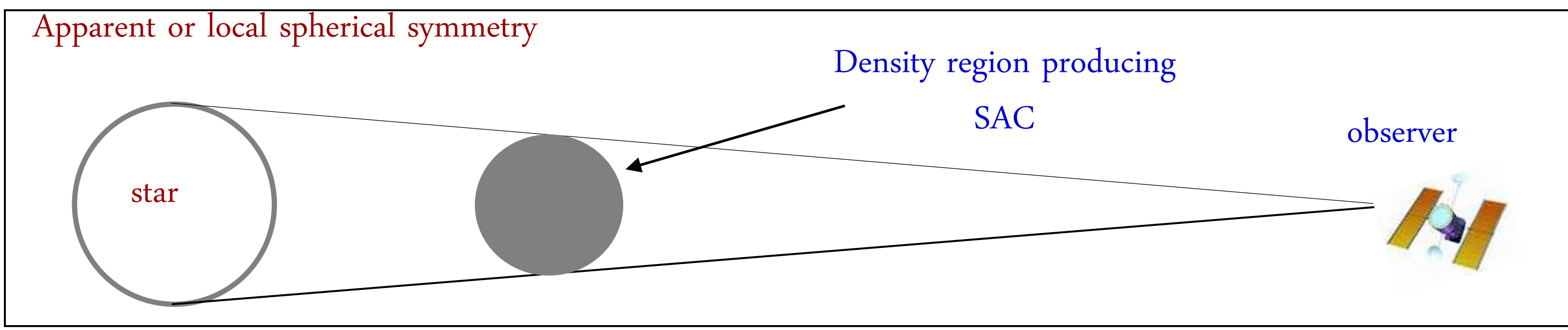
- The spectral line's profile is reproduced in the best way when we consider spherical symmetry for the independent density regions. Such symmetry has been proposed by many researchers (Lamers et al. 1982, Bates & Gilheany 1990, Gilheany et al. 1990, Waldron et al. 1992, Rivinius et al. 1997, Cidale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

Geometry

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



2. Independent density regions of matter that lie at a greater distance from the photosphere: 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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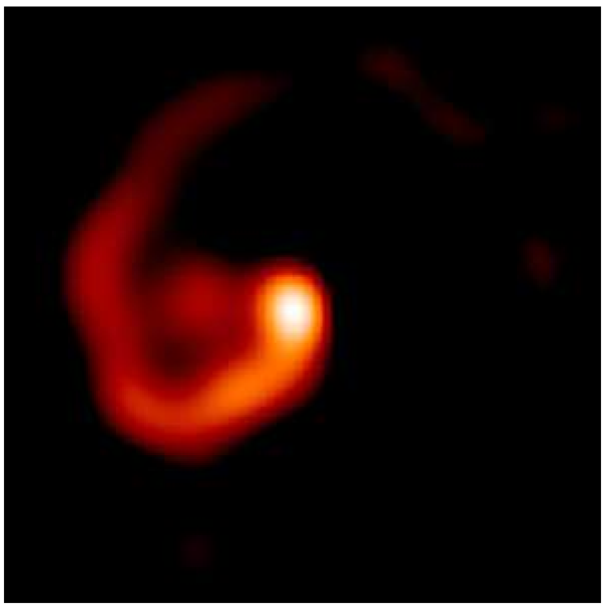
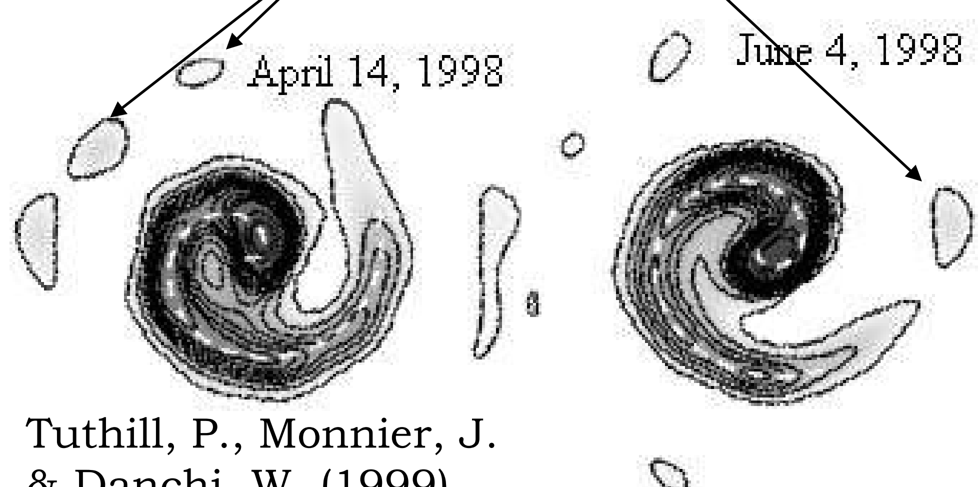
2. The star ejects mass with a specific radial velocity. The stream of matter is twisted, forming density regions such as corrotating interaction regions (CIRs), structures due to magnetic fields or spiral streams as a result of the star's rotation (Underhill & Fahey 1984, Mullan 1984a,b 1986, Prinja & 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).



Density regions producing SACs



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

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Criteria

The function $I_{\lambda i} = e^{-L_i \xi_i}$ 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 ξ_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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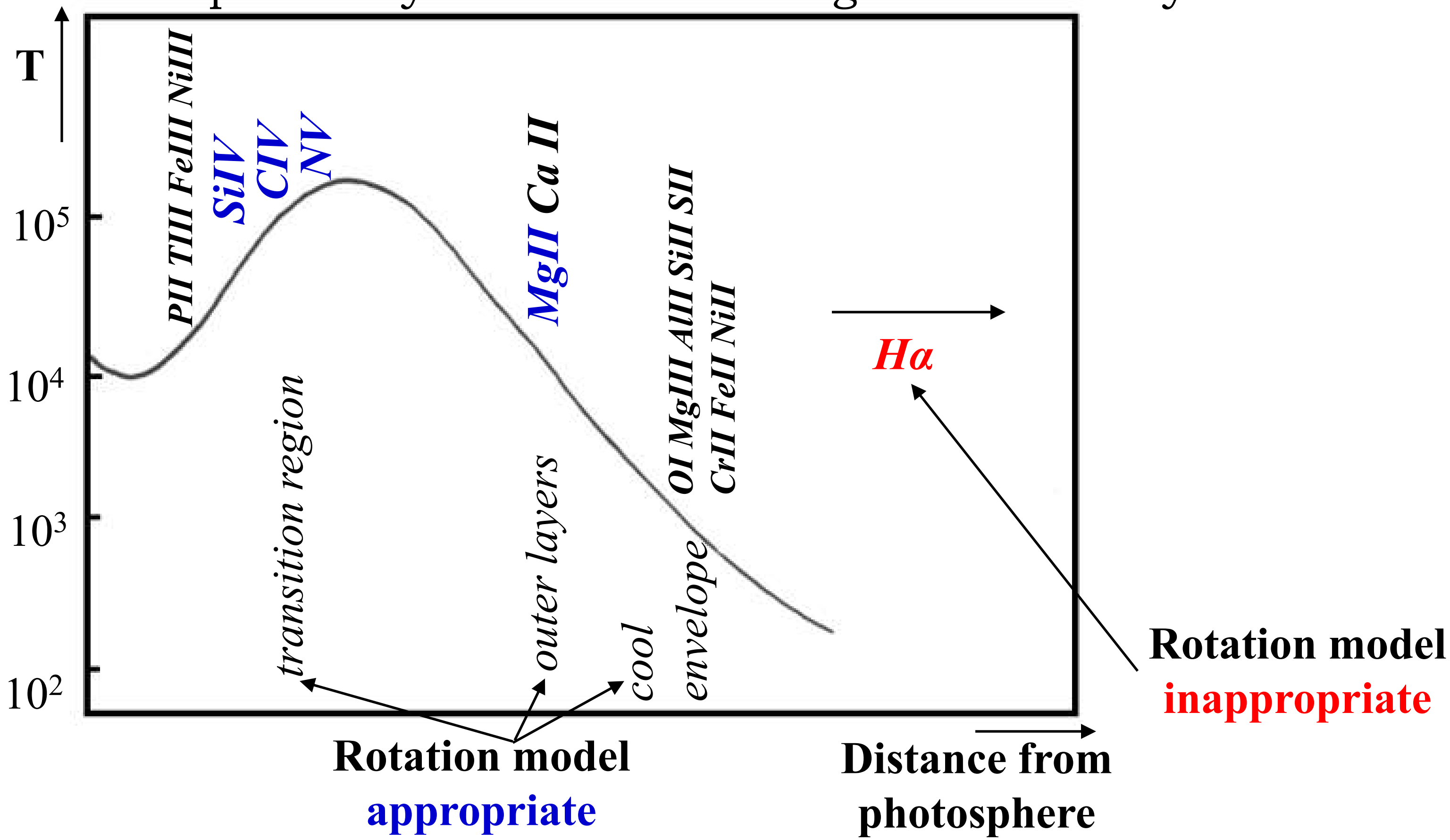
1. Till which distance from the star is the rotation model appropriate?
   Till which atmospheric layer does the model give satisfactory results?



2. We applied the model on a number of Oe and Be stars, in order to check whether such a rotation model may describe in a unique way all the lines that present SACs for all the hot stars.

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Applications - Data

In our study we use the stellar spectrographs which are available by the Villafranca Space Agency (Vilspa)* and have been taken with the International Ultraviolet Explorer (IUE). The stars' spectral types have been taken by the SIMBAD database (Centre de Données Astronomiques de Strasbourg (CDS), Strasbourg, France)**.

We studied:

1. the MgII resonance lines λλ 2795.523, 2802.698 Å in the spectra of 64 Be stars of all the spectral subtypes and luminosity classes
2. the SiIV resonance lines λλ 1393.755, 1402.77 Å in the spectra of 57 BeV stars of all the spectral subtypes
3. the rotational and radial velocities' variations with time of the post coronal regions in some Oe stars.

* http://archive.stsci.edu/cgi-bin/iue

** http://simbad.u-strasbg.fr/sim-fid.pl

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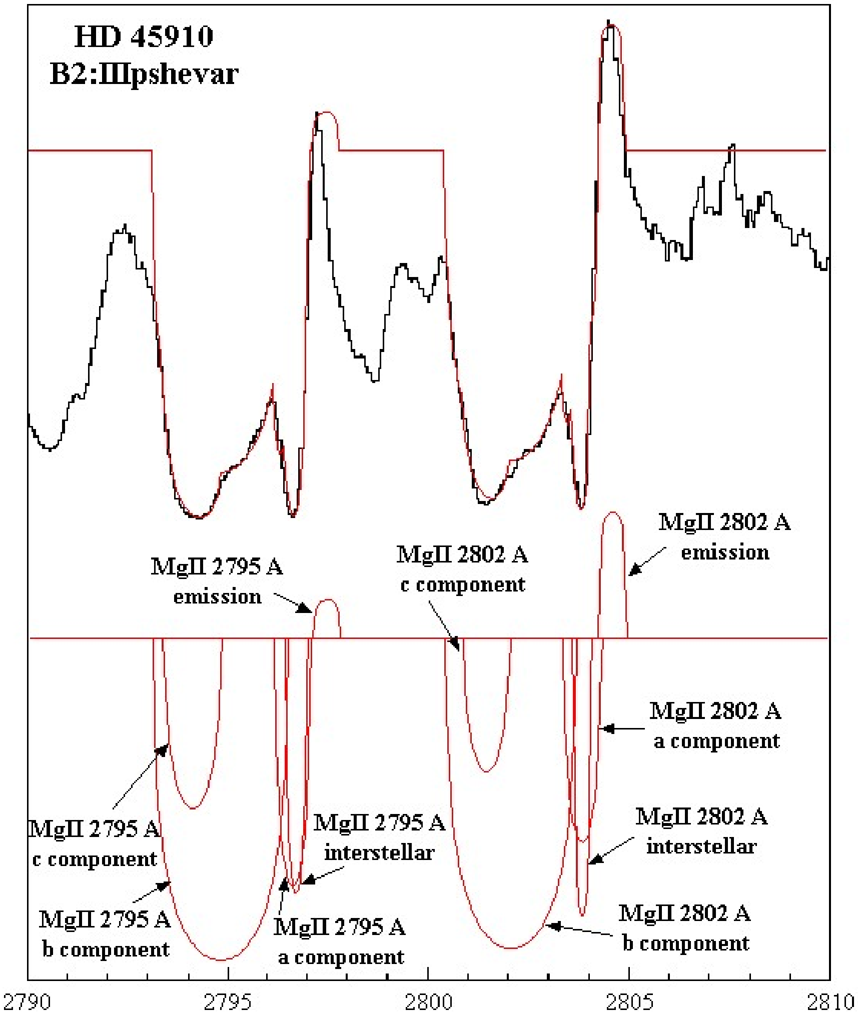
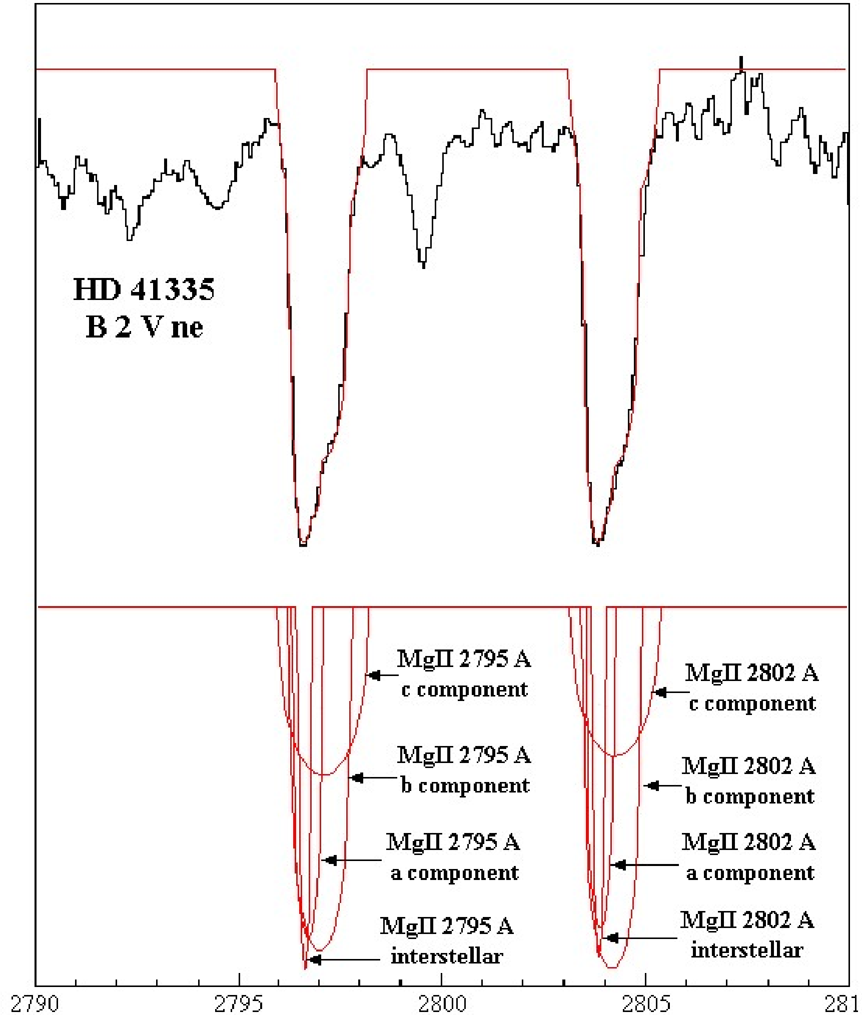
Conclusions

1. The MgII resonance lines λλ 2795.523, 2802.698 Å in the spectra of Be stars





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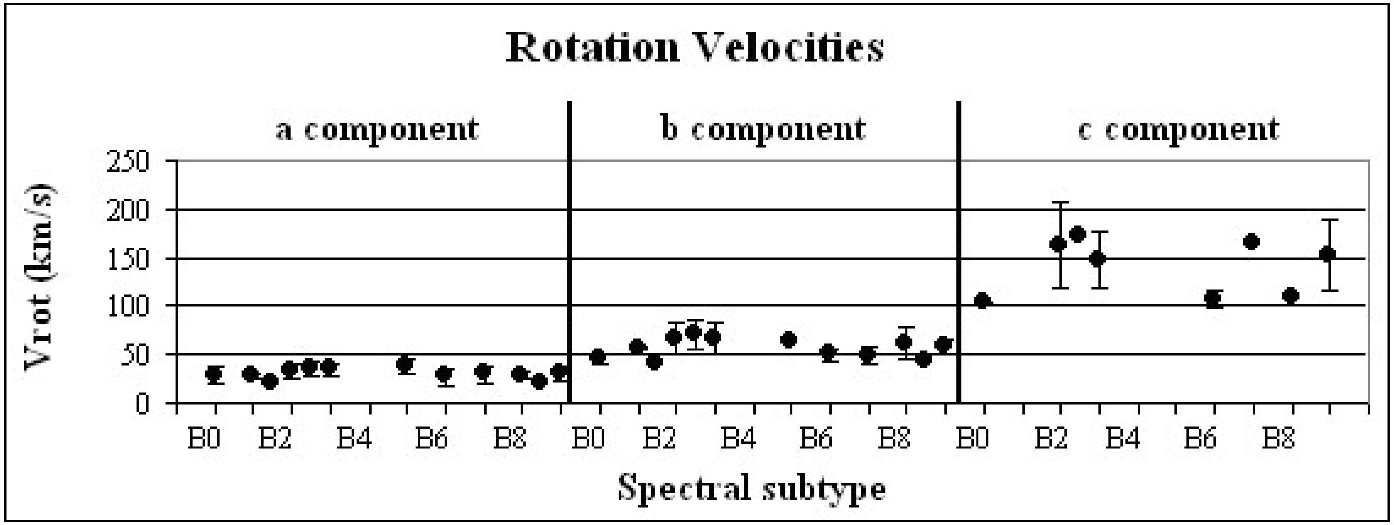

Mean values of the rotational velocities of the three SACs as a function of the spectral subtype. The rotational velocity presents a uniform fluctuation, which we could not accept as accidental.

Three rotational velocity groups are presented. The rotational velocity of the first SAC presents a small dispersion around the value of 31±7 km/s whereas in the case of the second SAC the dispersion increases around the greater value 60±15 km/s. The third SAC's rotational velocity increases more and presents a greater dispersion around the value 143±36 km/s. **These velocity groups do not appear in all the studied Be stars.**

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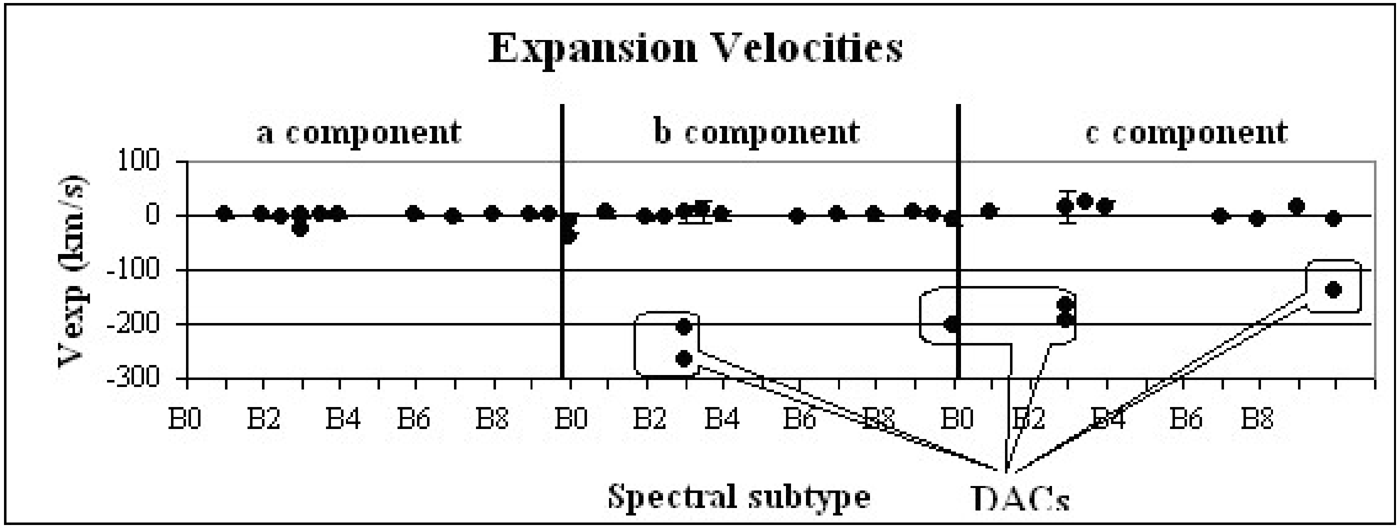

Mean values of the radial expansion /contraction velocities of all the SACs as a function of the spectral subtype.

The apparent expansion/contraction radial velocity of the three SACs present the values of -2 km/s, 0 km/s and +9 km/s.

In the case of the stars that present DACs, meaning HD 193237, HD 45910 and HD 144, the radial velocity is about -227 km/s and -169 km/s for the second and the third component, respectively.

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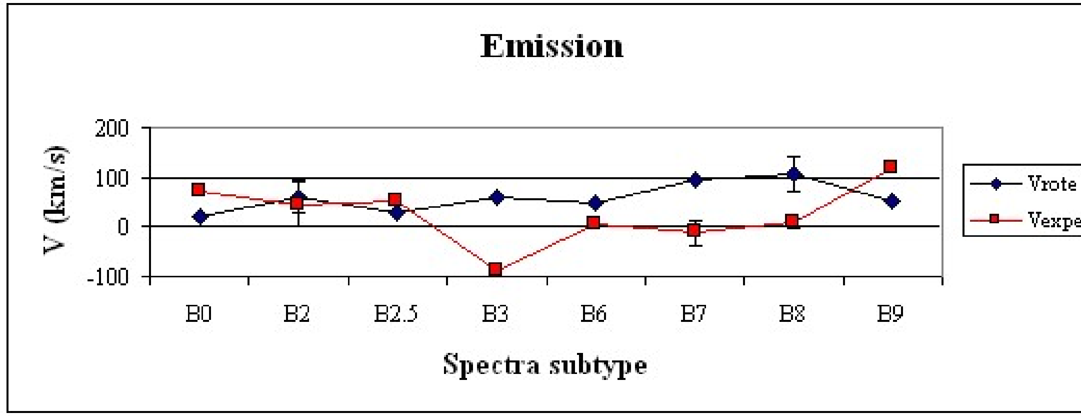
Conclusions

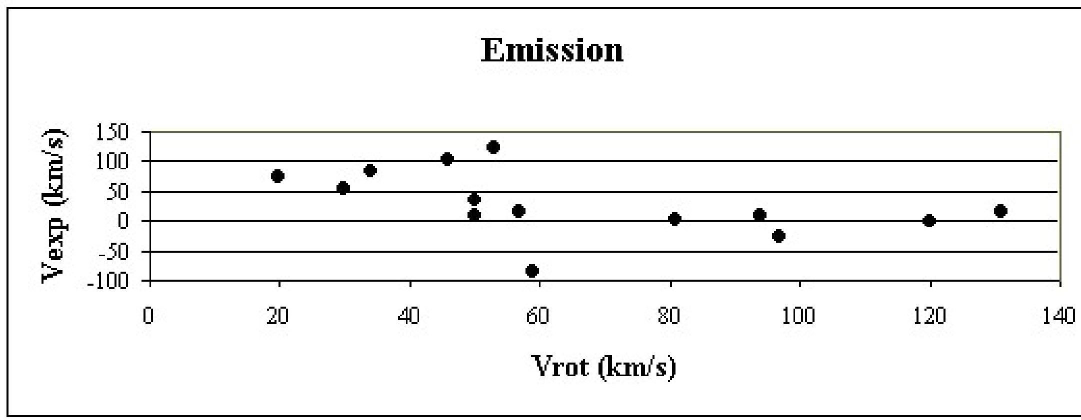
1. The MgII resonance lines $\lambda\lambda$ 2795.523, 2802.698 Å in the spectra of Be stars

The stars that present emission are of spectral subtypes **B0, B2, B2.5, B3, B6, B7 B8 and B9**. Thus, the emission does not appear in the spectra of the middle spectral subtypes of the Be stars (Kondo et al. 1975).

Apparent rotational and radial velocities of the emission component as a function of the spectral subtype.



Apparent radial velocities of the emission component as a function of the respective apparent rotational velocities. As the values of the rotational velocity increase, the values of the radial velocity decrease.



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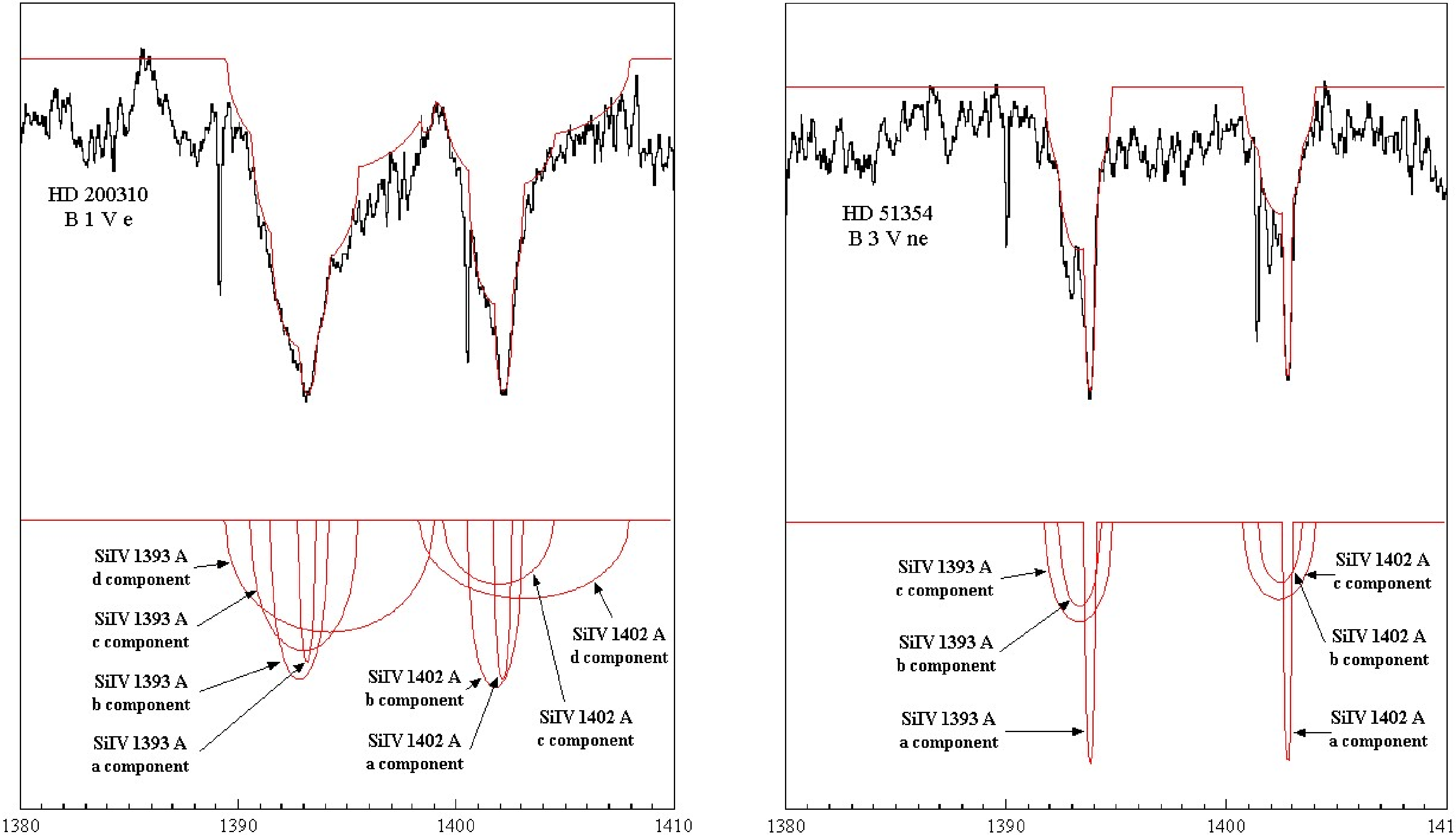
Conclusions

2. The SiIV resonance lines λλ 1393.755, 1402.77 Å in the spectra of BeV stars



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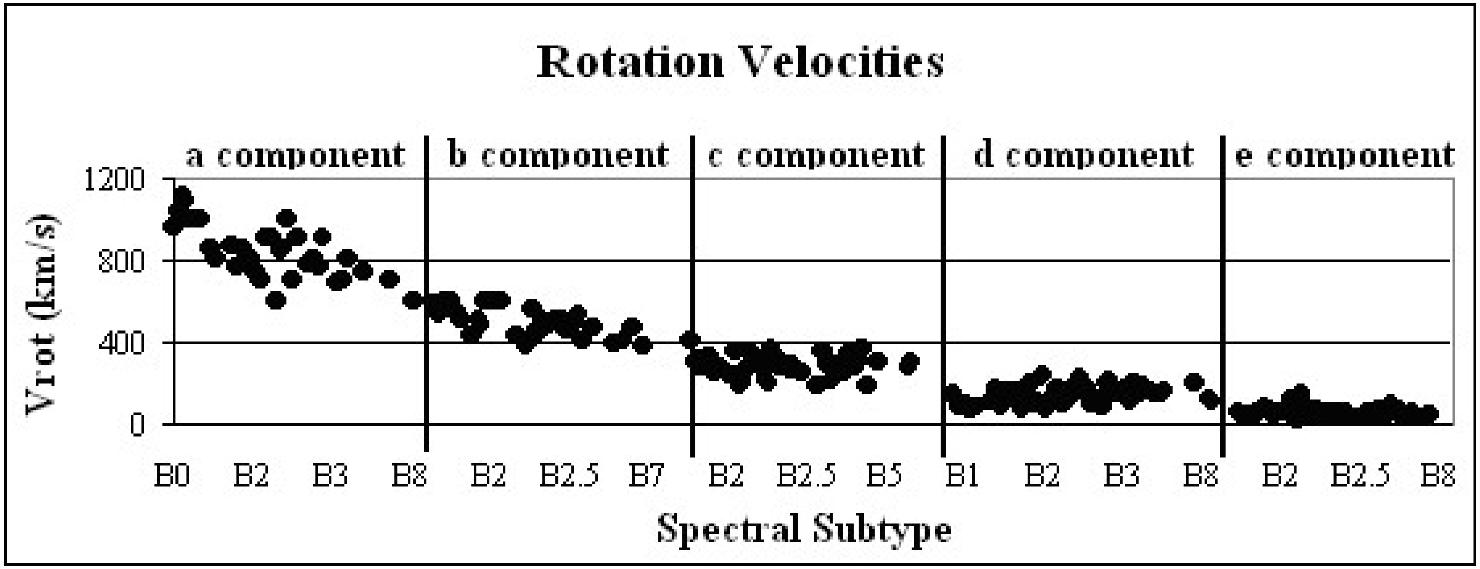

Mean values of the apparent rotational velocities of the five SACs as a function of the spectral subtype.

Five rotational velocity groups are presented, with the mean values of 830 km/s, 492 km/s, 285km/s, 137 km/s and 51 km/s. **These velocity groups do not appear in all the studied BeV stars.**

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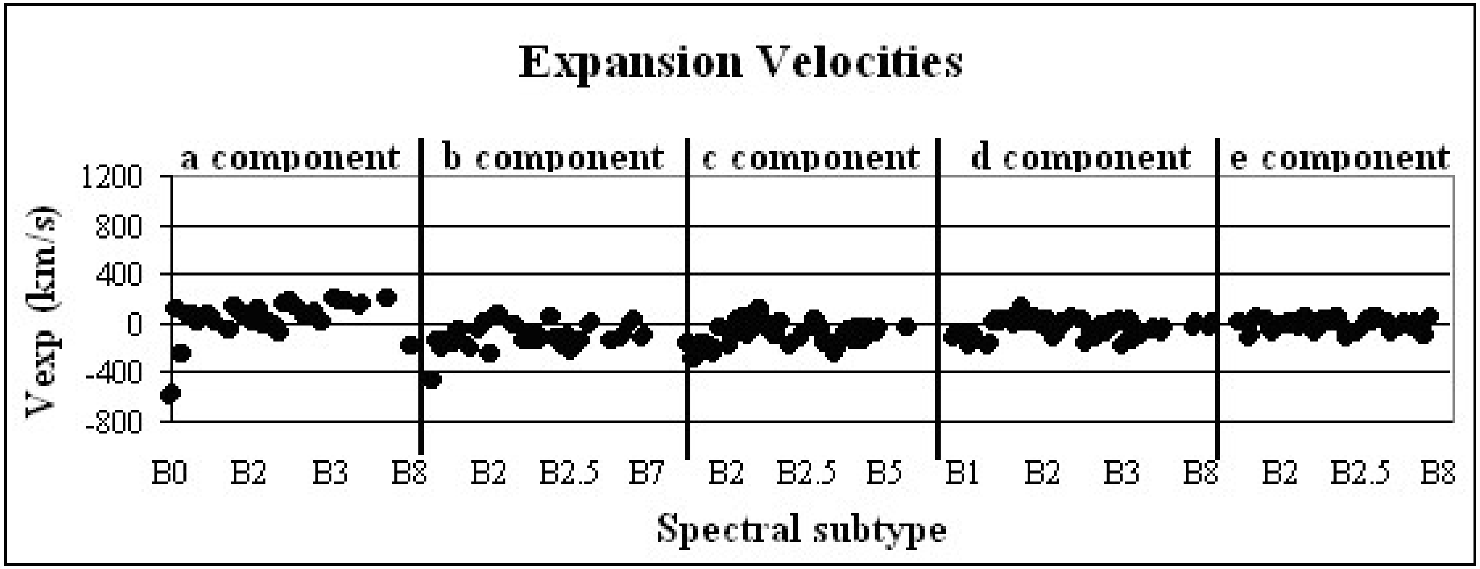

Mean values of the apparent radial expansion /contraction velocities of all the SACs as a function of the spectral subtype.
The apparent radial expansion/contraction velocity of the five SACs present the values of 31 km/s, -131 km/s, -105 km/s, -54 km/s and -25 km/s.
None of the studied BeV stars presents DACs in the SiIV resonance lines.

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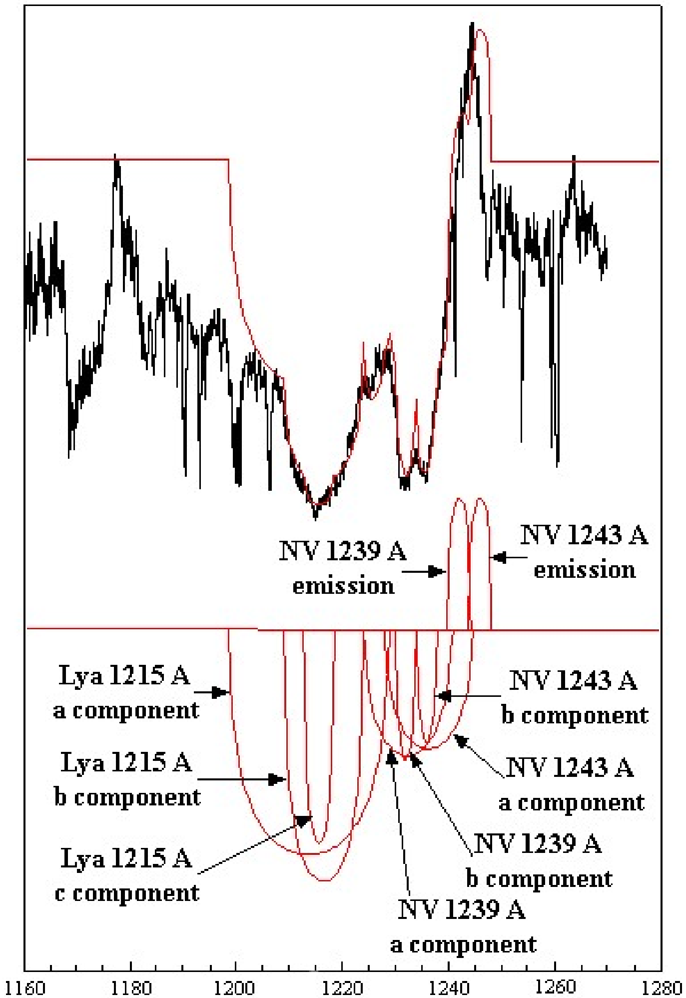
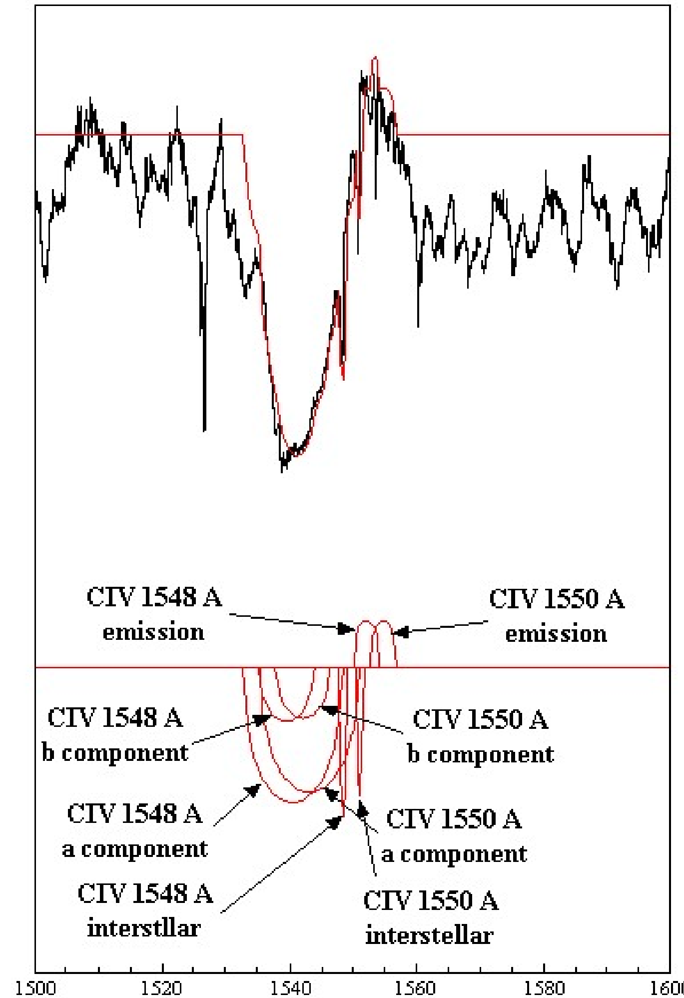
Conclusions

3. The post coronal regions in the Oe stellar atmospheres.
The example of the Oe star HD 175754





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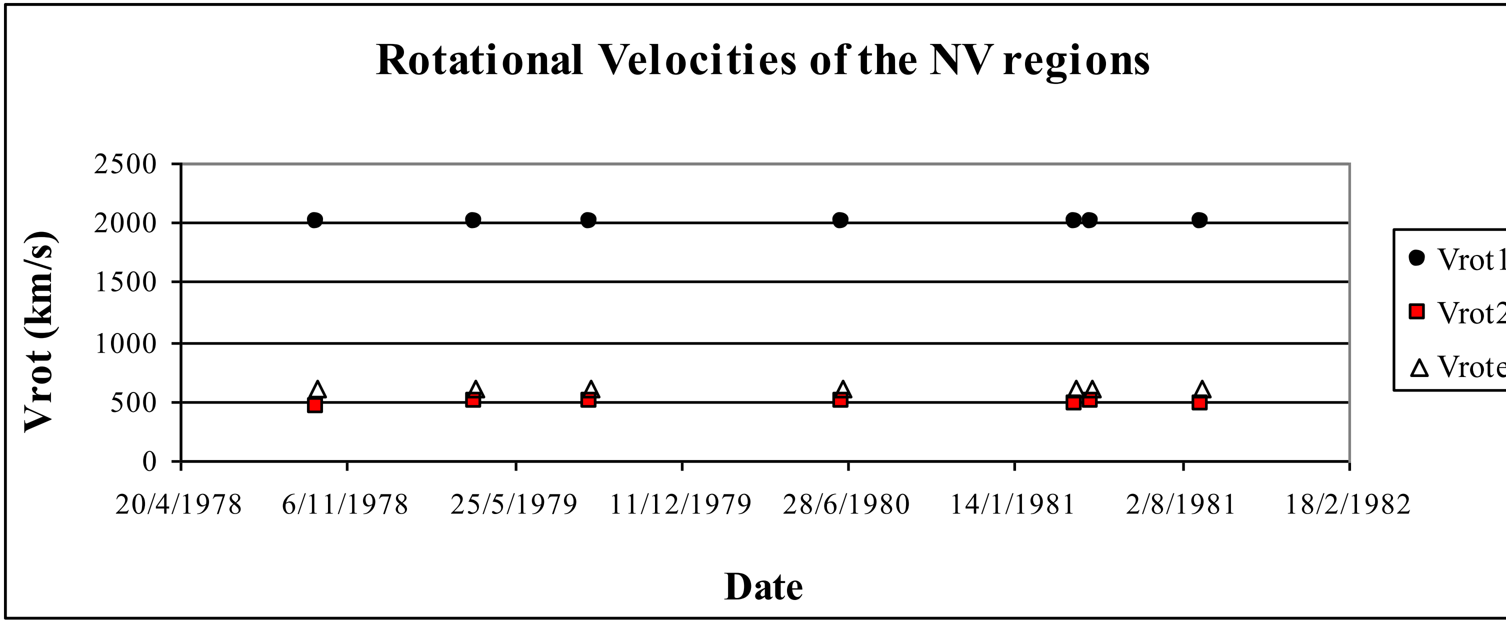

Rotational velocities of the two absorption components (2000 km/s and 485 km/s) (SACs) and the emission component (600 km/s) of the NV doublet in the spectra of the Oe star HD 175754, as a function of the date. All the components present almost constant rotational velocities with time.

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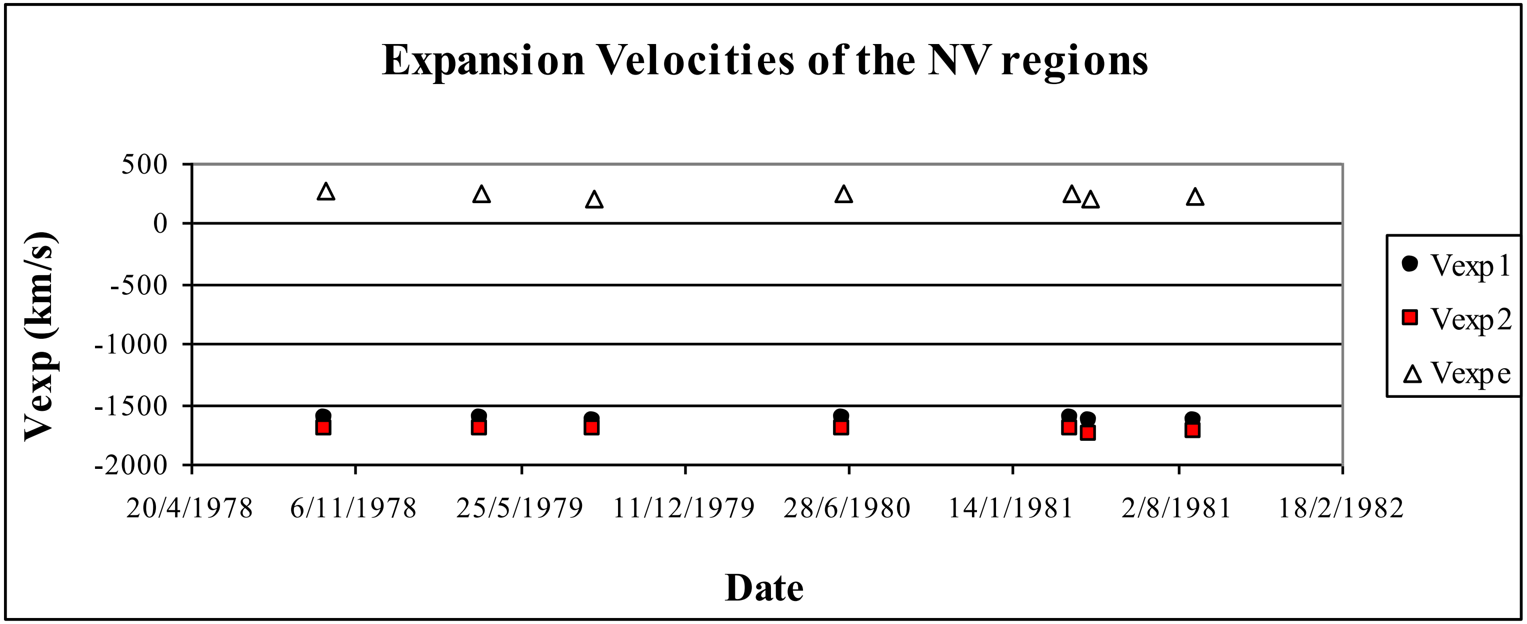

Radial expansion/contraction velocities of the two absorption components (-1629 km/s and -1725 km/s) (SACs) and the emission component (+242 km/s) of the NV doublet in the spectra of the Oe star HD 175754, as a function of the date. All the components present almost constant radial velocities with time.

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Present and Future Work

1. Study of the regions which create the SiIV resonance lines in the UV spectra of Be stars of the rest luminosity classes.

2. Study of the velocity fields’ evolution in many Be atmospheric regions in different distances from the photosphere, through the study of the regions which create UV lines of different ionization potential ions (CIV, AlIII, AlII, FeII etc), in order to study the variations of the velocity fields, along the Be atmospheres.

3. Study of the regions which create the spectral lines of ions with similar ionization potential with MgII, such as FeII, FeIII, CII, SII etc., in the UV spectra of Be stars. All these regions lie in almost the same distance from the star and we intend to check whether they present the same behaviour as the MgII regions.

4. Study of the FeII lines of different multiplets, in the UV spectra of Be stars, in order to check any possible differentiations with the excitation potential.

5. Study of the $H\alpha$ regions (external regions) of Be stars of all luminosity classes.

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6. All the above studies in the UV spectra of Oe stars of all luminosity classes.

7. Study of the variation with time of the atmospheric regions, which create the SACs, through the study of many ionization potential ions of specific hot emission stars.

8. Application of the model to the spectra of AGNs.

All the above will enable us to study all the atmospheric regions of hot emission stars and to conclude to whether there is a uniform mechanism which can produce the SACs phenomena.

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Thank you!!!