A new model for the structure of the DACs regions in the Oe and Be stellar atmospheres

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Abstract

As it is already known, the spectra of many Oe and Be stars present Discrete Absorption Components (DACs) which, because of their profiles' width as well as the values of the expansion / contraction velocities, they create a complicated profile of the main spectral lines. This fact is interpreted by the existence of two or more independent layers of matter, in the region where the main spectral lines are formed. Such a structure is responsible for the formation of a series of satellite components (DACs) for each main spectral line. In this paper we present a first approximation to a mathematical model reproducing the complex profile of the spectral lines of Oe and Be stars that present DACs. This model presupposes that the regions, where these spectral lines are formed, are not continuous but consist of a number of independent absorbing density layers of matter, followed by an emission region and an external general absorption region. When we fit the spectral lines that present DACs, with this model, we can calculate the values of the apparent rotation and expansion / contraction velocities of the regions where the DACs are formed.

Introduction

Peton (1974) first pointed out, in the visual spectrum of the double system AX Mon (HD 45910), the existence of a secondary component of the absorption line FeII λ 4233A, 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".

Underhill (1975) observed sharp components of the ions N II, C II and Mg II in the spectrum of HD 58350 and attributed the one of the velocity of 230 km/s to a gas cloud accelerated from the star and moving rapidly out of the star and the other of the velocity of about 25 km/s to a moving circumstellar shell.

Lamers et al. (1982) noted the possibility of the presence of 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.

Franco et al. (1983) studied the P Cygni profiles of the above mentioned resonance lines of HD 175754 observed at different epochs and they reported variability at the secondary satellite component. They proposed for this star two different mechanisms for the explanation of the variability, namely, a thermal mechanism in a hot region at $Tc=2\times10^5$ K which produces the principal stationary component and a mechanism which gives rise to the secondary by ionization of cooler high velocity stellar material from X-rays coming from inner coronal region.

Mullan (1984a,b, 1986) suggested that the satellite components may result from "corotating interaction regions" (CIRs), which may form in stars' winds and depend on asymmetries in the wind velocity or density.

Danezis (1984, 1986) and Danezis et al. (1991) studied the UV spectra of the gaseous envelope of AX Mon taken by the IUE satellite (at phase 0.568) and noted that the absorption lines of many ionization potential ions, not only of those presenting P Cygni profile, are accompanied by two strong absorption components of the same ion and the same wavelength, shifted at different Δλ, in the violet side of each main spectral line. 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. These layers of matter can rotate and move with different apparent velocities.

The existence of satellite components in the UV spectrum of AX Mon has been verified by Sahade et al. (1984) and Sahade & Brandi (1985) at the phase of 0.095. Also, Hutsemekers (1985) in the UV spectrum of another Be star, HD 50138, noticed a number of satellite components that accompanied the main spectral lines.

Bates & Halliwell (1986), naming the satellite components as "discrete absorption components" (DACs), constructed a model of ejection of gas parcels from above the star's photosphere, accelerated by radiation pressure. In order to describe the DACs, many suggestions about the properties of the winds have been made, which propose that the DACs are due to disturbances in the wind such as material that forms spiral streams as a result of the star's rotation (Mullan 1984a, Prinja & Howarth 1988) or to mass ejections constructing "shells", "puffs" or gas "parcels" (Henrichs 1984, Underhill & Fahey 1984, Bates & Halliwell 1986, Grady et al. 1987, Lamers et al. 1988).

Willis et al. (1989) argued against these components being formed in discrete mass conserving density enhancements, such as shells or blobs. They proposed that they result from "largely chaotic structures in the wind" and that "they are formed by different material at different times", because of radiative instability (Mulan 1984, Owocki et al. 1988, Prinja et al. 1988).

Bates & Gilheany (1990) and Gilheany et al. (1990) pointed out that "it is difficult to identify unambiguously DAC and wind signatures from a single spectrum of a star, as the UV spectrum of late B stars is very crowded with photospheric lines". So, in their study of twelve B5 – B9 supergiants they employed a code based on spherical symmetry, they fitted "Gaussian profiles to the spectra and derived values for the observed component velocity widths and equivalent widths". They concluded to the non-simultaneous appearance of DACs in different ions and they attributed the presence of DACs to mass-loss (Burki et al. 1982).

However, Danezis & Theodossiou (1988, 1990) could not find satellite components (DACs) of the main spectral lines of another Be star, 88 Herculis. 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, this in the red side of the main lines. The existence of the spectral lines in the red side of the main lines has been proposed by Doazan in 1983. This fact indicates contraction of the outer layers of the gaseous envelope.

Waldron et al. (1992) studied "the time-dependent hydrodynamical influence of a spherically symmetric propagating density pulse/shell in the stellar wind" of the O4I(n)f star HD 66811 (ζ Puppis) and suggested that "the DACs behaviour is associated with these density pulses which are injected into the supersonic wind by some unknown initiating mechanism". In a later study of ζ Puppis (1994), based on "the long-term regularity of occurrence (Kaper et al. 1990), the short-term behaviour that appears to be related to the stellar rotation rate (Prinja 1988, 1992) and the observed photospheric and wind-line variability that appears to be correlated"

(Henrichs 1990), they suggested that "the mechanism responsible for initiating DACs may be dynamically linked to the photosphere and that they must appear due to the inherently unstable nature of radiatively driven winds". In this study they tried to give an explanation to the large-scale ejection phenomena by modelling the full time-dependent hydrodynamic response of a stellar wind to a spherically symmetric propagating density shell, which suggests that a substantial amount of material must be present in front of the stellar disk to reproduce the observations. They concluded to DACs' behaviour in UV P Cygni line profiles being the result of the density shells (Lamers et al. 1978, Henrichs et al. 1980, 1983), which are hydrodynamically stable and propagate through the supersonic wind structure as stable solitary waves. They also concluded to the following: "the shell accelerates in conjunction with the underlying wind structure, the velocity fluctuations are small and the shell dynamics are found to be essentially independent of the adopted energy equation".

Henrichs et al. (1994) in their study on ξ Per agree with the suggestion that "the DACs are formed in absorbing layers in the line of sight, projected against the stellar disk" and proposed that "similar density structures must also be present in the emitting volume around the star". They suggested that the DACs originate in expanding high-density regions behind fronts due to amplified radiative instabilities in the wind.

Telting et al. (1993, 1994) studied the Be star γ Cas and proposed a model for the description of the envelope, which combines two types of stellar winds: "a dense equatorial disc in which the Balmer emission lines and the IR excess are formed and a rapidly expanding radiation-driven wind streaming from higher latitudes of the star, which forms the UV resonance lines". They calculated the same values for the outflow velocity of DACs of different doublets in many spectra, indicating that these DACs must be formed in "one particular outflowing high-density wind structure".

Cranmer & Owocki (1996), based on "the lack of emission variability in UV P Cygni lines (Prinja & Howarth, 1988) and significant infrared variability (Howarth 1992)", as well as to the fact that "the observed strong absorption dips can be produced if the structure of the wind is large enough in order to cover a substantial fraction of the stellar disk", suggested that the DACs originate from "moderate size wind structures such as spatially localized clouds, streams or blobs". They proposed a hydrodynamical model considering an azimuthally inhomogeneous radiation-driven wind for the formation of large-scale CIRs. They suggested that DACs could derive by CIRs resulting from a magnetic field (Mulan 1984a,b, 1986), with closed and open magnetic loops above the stellar surface (Underhill & Fahey 1984) and "for which the surface mass loss "eruption" lasts long enough to make structure that covers a substantial portion of the stellar disk".

Rivinius et al. (1997) studied the optical spectra of B hypergiants and suggested a model for the time-dependent wind variations, which accepts "spherical steady wind with randomly distributed and outwards moving inhomogeneities ("blobs")". They proposed that when the "blobs" are in front of the stellar disk they give rise to the DACs appearance, otherwise they only contribute to some extra radiation emitted in all directions (Lamers 1994). Because of the presence of the DACs at very low velocities, they suggested that the "blobs" originate not in the wind but in the photosphere or in even deeper layers.

Prinja et al. (1997) detected an "extremely narrow DAC" ("Super DAC") in all the spectral lines of the B supergiant γ Ara, which "demonstrates ionization stratification in the wind and is likely due to a very dense region that covers most of the projected surface of the visible hemisphere of the star". They suggested that the wind of this star may be “equatorially enhanced” probably because of its rapid rotation and that the “Super DAC” is formed in the equatorial region or results from CIRs or “arises from time-dependent wind fluctuations, (perhaps enhanced mass loss) which do not invoke latitude-dependence, but simply represents denser gas accelerating more slowly to a lower terminal velocity”.

Fullerton et al. (1997) in their study of the B supergiant HD 64760 suggested that the wind is not spherically symmetric and the wind structures that are responsible for the DACs are not radial, but extend for more than 90º in azimuth and about 30º in longitude and have a spiral shape. These spirals corotate with the stellar surface, implying that they are linked to photospheric phenomena, and form density regions in the stellar wind. They concluded to the interesting fact that “the radial expansion of the wind of HD 64760 is not too different from the outflows derived for spherically symmetrical, steady-state models of the winds of early-type stars”. They proposed that this may be due to the possibility that “the radial expansion of the wind may not be strongly affected by the presence of the spirals”. They explained the appearance of different ions’ DACs by “the presence of an ionization or density gradient across the width of the spirals, such as that the inner edge favors the presence of more highly ionized species”.

Cidale (1998) studied the MgII lines in Be stars considering spherical symmetry for the expanding circumstellar medium to which she attributed the presence of the blueshifted absorption components and proposed that “a decelerating wind yields denser outer regions which could enhance the emission”.

Kaper et al. (1996, 1997, 1999) studied a series of 10 bright O stars and described the shape of the individual absorption components by an exponential Gaussian. They calculated the same velocity in resonance lines formed by different ions and proposed that the edge variability is directly related to the DACs (Henrichs et al. 1988, 1994, Prinja 1991), which actually have an impact on the position of the edge. They suggested that the DACs are related with interacting fast or slow moving wind streams of higher density, corotating with the star (CIRs). The curved streams cause fast wind material to collide with slow wind material in front of it, constructing high density regions, and the star’s rotation results to the interaction region having also spiral shape and corotating with the star. The wind material, though, due to the conservation of its angular momentum, does not corotate with the star, but it moves radially and meets the interaction region at distance from the star. They proposed that “the DACs are not formed in the CIRs themselves, but originate in the so-called radiative-acoustic kinks trailing the CIRs”. As the DACs found in different ions’ resonance lines have the same velocity, they should originate from high density regions, which should be geometrically extended in order to be observable by covering a significant fraction of the stellar disk. They also suggested that because of the stable appearance of DACs over long time periods, “the physical process responsible for the formation of slow (or fast) streams has to be rather stable”, meaning that the streams may be due to non-radial pulsations or, less likely, a surface magnetic field.

Cranmer et al. (2000) studied the DACs that appear in the spectra of γ Cas in order to determine the nature of the interaction between winds and disks of Be stars (Telting & Kaper 1994). They pointed out that the outflowing gas responsible for the DACs formation is denser than the mean undisturbed polar wind. They proposed that the density region responsible for the appearance of DACs may be due to “the existence of compressible shocks propagating through the polar wind”. They stressed out that “the mean DAC structure does not seem to rotate with the star, meaning that it is independent of the more localized spiral-shaped opacity modulations embedded within it". It is interesting that, as some of the spectral features could not be fitted with a Gaussian function, they decided to fit it by a sum of two or more Gaussians, without implying, though, that "the central velocities of these extra terms should be interpreted as independent dynamical wind features". They confirmed the suggestion that "DACs do not represent isolated mass-conserving "blobs", but instead they indicate the presence of a rotating pattern or perturbation through which wind material flows". They detected slower acceleration or even deceleration of the regions responsible for DACs compared to the mean stellar wind.

Markova (2000) studied the line-profile variability in P Cygni's optical spectrum and concluded to the fact that the recurrence of DACs is hardly related to the stellar rotation and that the DACs are not due to single mass-conserving features, such as outward moving blobs, but that they may originate from outward moving, large-scale, high-density perturbations, which possibly originate from the photosphere, but develop in the outer wind and through which wind material flows. These perturbations may be spherically symmetric density shells or curved structures like kinks.

Danezis et al. (1991, 1995, 1997a,b 1998, 1999, 2000a,b,c, 2001,a,b,c, 2002,a,b,c), Theodossiou et al. (1993, 1997), Laskarides et al. (1992a, 1992b, 1993a, 1993b), Stathopoulou et al. (1995, 1997), Lyratzi et al. (2001, 2002a,b) Kyriakopoulou et al. (2001) and Christou et al. (2001) apart from their study on the UV spectrum of Be stars, where they found satellite components, they have also studied the UV spectrum of several Oe stars and detected satellite components, not only for the spectral lines of low ionization potential, but also for the resonance lines of NV, CIV, SiIV and the spectral line NIV.

The main idea of our research

It is obvious from the above that many suggestions have been made in order to explain the DACs phenomenon. Most researchers have suggested mechanisms that allow 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, 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 DACs result from independent high density regions in the stars' environment.

Specifically, in this paper we test the ideas proposed by Danezis (1984, 1986) and Danezis et al. (1991). In these papers they proposed that probably:

1. DACs are not unknown absorption spectral lines, but spectral lines (satellite absorption components) of the same ion and the same wavelength as a main spectral line, shifted at different Δλ. In addition, DACs are not always discrete absorption spectral lines, but in most cases lines that are blended among themselves as well as with the main spectral line. In such a case they are not

observable, but we can detect them through the analysis of our model. This means that when we deal with a significant spectral line, which is accompanied by satellite absorption components, we should not regard them as independent spectral lines, but as a unified formation which must be dealt with as one spectral line splited into a series of components. Finally, as Peton (1974) first pointed out, these components appear as “satellites” in the violet or in the red side of the main spectral line as a function of the time or the phase in the case of a binary system. For these reasons we prefer to name them Satellite Absorption Components (SACs) and not Discrete Absorption Components (DACs).

2. This hypothesis may be correct only if the main spectral line and its satellite absorption components (SACs) are born in different, independent density regions, where the prevailing conditions allow the existence of matter, able to form the main spectral line and its satellite absorption components (SACs) in the same time.
3. In the case of absorption spectral lines presenting SACs, as well as a P Cygni profile, the emission spectral line is created in an independent emitting density region.

All the above, are just simple theoretical suppositions. A very important question is whether such a complex structure of the regions, where the spectral lines that present SACs are born, may lead to the formation of a function for the line’s profile able to reproduce, in the best way, the main spectral line and its satellite absorption components (SACs) in the same time. Our main purpose in this paper is to give an answer to this question. By solving the equations of radiation transfer through a complex structure as the one described, we try to 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 (SACs) in the same time. Such a best fit, through the function of the line’s profile, enables us to calculate parameters of the independent layers of matter which form the main spectral line and its satellite absorption components (SACs), such as the apparent rotation and expansion / contraction velocities.

Applications of this model we have presented at JENAM ’98 in Prague (Danezis et al. 1998), at JENAM 2000 in Moscow (Danezis et al. 2000a,b,c), at the 4th Hellenic Astronomical Society Conference at Samos, Greece (Danezis et al. 1999), at the 5th Hellenic Astronomical Society Conference at Crete, Greece (Danezis et al. 2001a,b,c, Lyratzi et al. 2001, Kyriakopoulou et al. 2001, Christou et al. 2001) and at the IAU Symposium 210, Uppsala, Sweden (Danezis et al.2002a,b,c, Lyratzi et al. 2002a,b).

Finally, we would like to point out once again that our main purpose is to propose a model able to reproduce every spectral line at the specific moment when the spectrum is taken.

Description of the method

Fundamental Hypotheses

i) The stellar envelope is composed of a number of successive independent absorbing density layers of matter, followed by an emission region and an external general absorption region.
ii) The angular velocity of rotation is constant.
iii) Thermal and natural broadening of spectral lines is negligible. This means that the whole width of the line is measured as V_{rot}.

iv) The observer lies on the equatorial plane.
v) None of the phenomena are relativistic.
vi) The only effect of a shell's expansion or contraction is a Doppler shift of the center of the lines.

Mathematical expression

We assume that we have a radiation of intensity I_λ passing through an area of gaseous material of constant density ρ, thickness ds and absorption coefficient k_λ.
The effect of the shell on the radiation intensity is given by:

$$dI_\lambda = -k_\lambda I_\lambda \rho ds$$

For a shell of total thickness s and an initial radiation intensity of $I_{\lambda 0}$ the effect will be:

$$I_\lambda = I_{\lambda 0} \exp\{-\tau\} \tag{1}$$

where $\tau = \int_0^s k_\lambda \rho ds$.

Now consider this radiation intensity passing through a second shell, of density ρ_b, thickness s_b and absorption coefficient $k_{\lambda b}$. The radiation intensity exiting this second shell will be:

$$I_{\lambda b} = I_\lambda \exp\{-\tau_b\}$$

where: $\tau_b = \int_0^{s_b} k_{\lambda b} \rho_b ds$.

Substituting (1) for I_λ yields:

$$I_{\lambda b} = I_{\lambda 0} \exp\{-\tau\} \exp\{-\tau_b\}.$$

Generalising for i absorbing shells, the final exiting radiation will be:

$$I_{\lambda i} = I_{\lambda 0} \prod_i \exp\{-\tau_i\}. \tag{2}$$

Consider now a shell that is both absorbing and emitting (henceforth called in this paper a "mixed" shell), with k_λ and j_λ being the respective coefficients. Its effect on the radiation intensity $I_{\lambda i}$ will be:

$$dI_{\lambda i} = -k_\lambda I_{\lambda i} \rho ds + j_\lambda \rho ds$$

And the total effect of such a shell of thickness s_e, and density ρ_e on a radiation flow of intensity $I_{\lambda i}$ will be:

$$I_{\lambda e} = I_{\lambda i} \exp\{-\tau_e\} + \int_0^{\tau_e} \frac{j_{\lambda_e}}{k_{\lambda_e}} e^{-\tau_e} d\tau$$

where $\frac{j_{\lambda_e}}{k_{\lambda_e}}$ is the source function $S_{\lambda e}$ and $\tau_e = \int_0^{s_e} k_{\lambda e} \rho_e ds$.

At the moment when the spectrum is taken, each emission line, with a given wavelength λ, is created in a specific region of the stellar envelope with a given value for $S_{\lambda e}$, that is $S_{\lambda e}$=const. So:

$$I_{\lambda e} = I_{\lambda i} \exp\{-\tau_e\} + S_{\lambda e}\left(1 - \exp\{-\tau_e\}\right). \tag{3}$$

Now consider that an outer shell of general absorption follows the mixed shell. Its effect on the radiation intensity will be:

$$I_{\lambda final} = I_{\lambda e} \exp\{-\tau_g\}$$

in which we replace $I_{\lambda e}$ by the radiation intensity exiting the mixed shell, given by equation (3). Thus:

$$I_{\lambda final} = \left[I_{\lambda 0} \prod_i \exp\{-\tau_i\} \exp\{-\tau_e\} + S_{\lambda e}\left(1 - \exp\{-\tau_e\}\right) \right] \exp\{-\tau_g\}$$

If we consider the absorption of the mixed shell as an independent absorption, we can include it to the product $\prod_i \exp\{-\tau_i\}$ and have:

$$I_{\lambda final} = \left[I_{\lambda 0} \prod_i \exp\{-\tau_i\} + S_{\lambda e}\left(1 - \exp\{-\tau_e\}\right) \right] \exp\{-\tau_g\}$$

A similar expression will apply to the radiation flux:

$$F(\lambda)_{final} = \left[F_0(\lambda) \prod_i \exp\{-\tau_i\} + S_{\lambda e}\left(1 - \exp\{-\tau_e\}\right) \right] \exp\{-\tau_g\}$$

Let us consider the parameters τ_i, τ_e, τ_g. As stated above, each τ is given by:

$$\tau = \int_0^s k_\lambda \rho ds \, .$$

We substitute for $k_{\lambda i}$, $k_{\lambda e}$, $k_{\lambda g}$ the product of two functions:

1. Omega (Ω) is an expression of k_λ and has the same units as k_λ.
2. L_i, L_e, L_g are the distribution functions of $k_{\lambda i}$, $k_{\lambda e}$, $k_{\lambda g}$ respectively. Each L depends on the values of the apparent rotational velocity as well as of the radial expansion or contraction velocity of the density shell, which forms the spectral line.

That is: $\tau = L \int_0^s \Omega \rho ds$

We set: $\xi = \int_0^s \Omega \rho ds$, meaning that ξ is an expression of τ.

The resulting, final form of the radiation flux function is:

$$F_{\lambda final} = \left[F_0(\lambda) \prod_i \exp\{-L_i \xi_i\} + S_{\lambda e}\left(1 - \exp\{-L_e \xi_e\}\right) \right] \exp\{-L_g \xi_g\} \tag{4}$$

Equation 4 gives the function of the complex profile of a spectral line, which presents SACs. This means that the graphical representation of equation 4 must reproduce not only the main spectral line, but its SACs as well. As we can deduce from the above, the calculation of $F_{\lambda final}$ does not depend on the geometry of the absorbing or emitting independent density layers of matter.

The decision on the geometry is essential for the calculation of the parameters L_i. This means that 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, presenting SACs, that we study.

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

1. The spectral line's profile was reproduced in the best way when we supposed 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).

2. However, the independent layers of matter, where a spectral line and its SACs were 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), in which case spherical symmetry is justified, or at a greater distance from the star, where the spherical symmetry can not be justified.

These thoughts lead us to the conclusions that:

1. In the case of independent density layers of matter that lie close to the star we could suppose the existence of a classical spherical symmetry (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 that lie at a greater distance from the photosphere, we could suppose the existence of independent density regions such as blobs, which should cover a substantial fraction of the stellar disk (Cranmer & Owocki 1996) and are outwards moving inhomogeneities (Rivinius et al. 1997), spiral streams (Fullerton et al. 1997, Cranmer et al. 2000, Markova 2000) or CIRs, which may result from non-radial pulsations, magnetic fields or the star's rotation (Mullan 1984a,b, 1986, Prinja & Howarth 1988, Kaper et al. 1996, 1997, 1999) and are able to make structures that cover a substantial portion of the stellar disk (Cranmer & Owocki 1996, Kaper et al. 1996, 1997, 1999). These regions, though they do not present spherical symmetry around the star, they form spectral lines' profiles which are identical with those deriving from a spherically symmetric structure. This means that these line profiles present the same values for V_{rot}, V_{exp} and ξ as the ones deriving from a classical spherical symmetry. In such a case, though the density regions are not spherically symmetric, through their effects on the lines' profiles, they appear as spherically symmetric structures to the observer.

This means that in both cases, where either the symmetry is spherical or it appears as spherical through its effects on the lines' profile, the calculation of L_i, is justifiably based on the supposition of spherical symmetry.

The above mentioned thoughts led us to suppose spherical symmetry (or apparent spherical symmetry) for the density regions where the main spectral line as well as its SACs are born, in order to calculate the parameters L_i.

Calculation of the distribution functions L

If we consider that the density shell of matter, where the spectral line is produced, lies between angles $-\theta_0$ to $+\theta_0$ from the equatorial plane, then:

$$L = \int_{-\theta_0}^{\theta_0} \cos\theta d\theta = [\sin\theta]_{-\theta_0}^{+\theta_0} = 2\sin\theta_0 , \qquad (5)$$

for every λ_i: $|\lambda_i - \lambda_0| < \dfrac{\lambda_0 z_0 \cos\theta_0}{1 - z_0^2 \cos^2\theta_0}$

and

$$L = 0 ,$$

for every λ_i: $\left|\lambda_i - \lambda_0\right| \geq \frac{\lambda_0 z_0 \cos\theta_0}{1 - z_0^2 \cos^2\theta_0}$,

Normalizing equation (5) we have: $L_i = \sin\theta_0 = \sqrt{1 - \cos^2\theta_0}$. (6)

As θ_0 lies between the values of $-\frac{\pi}{2}$ and $\frac{\pi}{2}$, equation (5) yields to:

$$\cos\theta_0 = \frac{-\lambda_0 + \sqrt{\lambda_0^2 + 4\Delta\lambda^2}}{2\Delta\lambda z_0} < 1 \tag{7}$$

and

$L = \sqrt{1 - \cos^2\theta_0}$, if $\cos\theta_0 < 1$

and

$L = 0$, if $\cos\theta_0 \geq 1$

where:

λ_0 is the wavelength of the centre of the spectral line.

If we consider that the density shell, which forms the spectral line, moves radially, then: $\lambda_0 = \lambda_{lab} + \Delta\lambda_{\exp}$, where λ_{lab} is the laboratory wavelength of the spectral line produced by a particular ion and $\Delta\lambda_{\exp}$ is the radial Doppler shift and $\frac{\Delta\lambda_{\exp}}{\lambda_{lab}} = \frac{V_{\exp}}{c}$.

$z_0 = \frac{V_{rot}}{c}$, where V_{rot} is the apparent rotational velocity of the i density shell of matter.

$\Delta\lambda = \left|\lambda_i - \lambda_0\right|$, where the values of λ_i are taken in the wavelength range we want to reproduce.

As we can understand from the above, the spectral line's profile, which is formed by the i density shell of matter, must be accurately reproduced by the function $e^{-L_i\xi_i}$ by applying the appropriate values of V_{roti}, V_{expi} and ξ_i.

Discussion of the proposed model

Introducing the previous final reproduction function of a complex spectral line (equation 4), we would like to note and clarify the following:

1. As we have already mentioned, for each trio of the parameters V_{roti}, V_{expi} and ξ_i, the function $I_{\lambda i} = e^{-L_i\xi_i}$ reproduces the spectral line's profile formed by the i density shell of matter, meaning that for each trio we have a totally different profile. This results to the existence of only one trio of V_{roti}, V_{expi} and ξ_i giving the best fit of the i component. In order to accept as best fit of the observed spectral line, what is given by the trinities (V_{expi}, V_{roti}, ξ_i) of all the calculated SACs, we must adhere to all the physical criteria and techniques, such as:

i) 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, as well as the existence of SACs.

ii) The resonance lines as well as those that form in these regions of the star shells that are close to each other (small difference in ionization potential) must have the same number of SACs.

iii) The resonance lines and the spectral lines of ions, which have similar ionization potentials, must have approximately the same values for V_{exp} and V_{rot}, as they form in the same regions. This means that the values of V_{exp} and V_{rot} of the absorption and emission SACs must lay in a range accepted by the statistical error.

2. The profiles of every main spectral line and its SACs are fitted by the function $I_{\lambda i} = e^{-L_i \xi_i}$. This function produces symmetrical line profiles. However, we know that most of the spectral lines we have to reproduce are asymmetric. This fact is interpreted as a systematical variation of the apparent radial velocities of the density regions where the main spectral line and its SACs are created. In order to approximate those asymmetric profiles we have chosen a classical method. This is the separation of the region, which produces the asymmetric profiles of the spectral line, into a small number of sub-regions, every one of which is dealt with as an independent absorptive shell. In this way we can study the variation of the density, the radial shift and the apparent rotation as a function of the depth in every region which produces a spectral line with an asymmetric profile. All the above must be taken into consideration during the evaluation of our results and one should not consider that the evaluated parameters of those sub-regions correspond to independent matter shells, which form the main spectral line or its SACs.

3. We suggest that the width of the blue wing is the result of the merging of the profiles of the main spectral line and its SACs. Thus, the blue wing of each SAC gives the apparent rotational velocity of the density shell, in which it forms. This means that, in order to have measurements with physical meaning, we should not calculate the width of the blue wing of the final spectral line but the width of the blue wings of each SAC.

4. By the study of the resonance lines of a great number of stars, we measured a statistical error between 10 and 35 km/s.

5. Finally, it is clear that the function $I_{\lambda i} = e^{-L_i \xi_i}$ can produce every spectral line, which is created in a region that presents spherical or apparent spherical symmetry.

We would like to point out that the final criterion to accept or reject a best fit, is the ability of the calculated values of the physical parameters to give us a physical description of the events developing in the regions where the spectral lines presenting SACs are created. This means that the calculated values of the physical parameters should not go against the classical physical theory.

In order to test the accuracy of the spectral lines' fits deriving from equation 4, we presented a series of poster papers at the JENAM 1998 in Prague and its applications were presented at the JENAM 2000 in Moscow. A new series of applications was also presented at the IAU Symposium 210 (Uppsala, Sweden, 2002). A summary of two of these papers is presented as an application in this paper.

Application to the spectral lines of selected Oe and Be stars

Mg II regions in the gaseous envelope of Be V stars

Danezis et al. (2002a) by applying the above presented model, studied the variation of the calculated parameters V_{rot} and V_{exp} of the density regions where the Mg II resonance lines (λλ 2795.523, 2802.698 A) are formed of a series of 21 Be V stars of all the spectral subtypes. In figures 1-3 we present three best fits of the Mg II resonance lines of the stars HD 41335, HD 148184 and HD 217543. The thick line presents the observed spectral line's profile and the thin one the model's fit. The differences between the observed spectrum and its fit are some times hard to see, as we have accomplished the best fit. Some of our conclusions are presented in diagrams 1-3. In diagram 1 we present the expansion / contraction velocities of all the absorption components as a function of the spectral subtype. In diagram 2 we present the rotation velocities of all the absorption components as a function of the spectral subtype. In diagram 3 we present the expansion / contraction velocities of the emission component as a function of the respective rotation velocities. In these three diagrams one can see that all the studied stars present discernible or indiscernible SACs of the Mg II resonance lines. The indiscernible SACs appear in the spectra of the stars with spectral subtypes B0-B1 and B4-B8. This is due to the fact that the SACs of the Mg II resonance lines in the spectra of the stars of these spectral subtypes present similar radial velocities. In this case, we can separate these lines by the systematic differentiations of the apparent rotation velocities and the values of ξ_i. The SACs of the Mg II resonance lines are discernible in the spectra of the stars with spectral subtypes B2-B3, as they present different radial shifts. We would also like to point out that in this case the density regions present much greater values of the apparent rotation velocities.

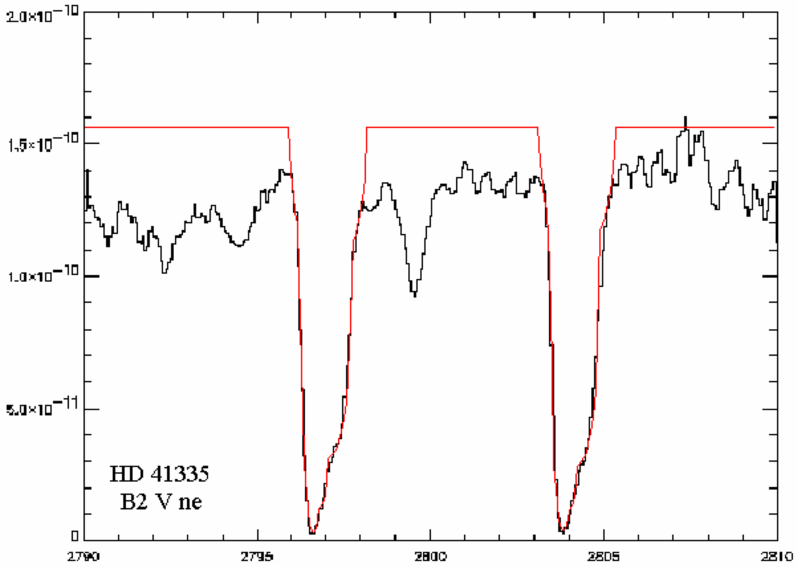

Figure 1: Best fit of Mg II lines λλ 2795.523, 2802.698 A of the Be star HD 41335. The thick line presents the real spectral profile and the thin one the model's fit. The differences between the real spectrum and its fit are hard to see, as we have accomplished the best fit.

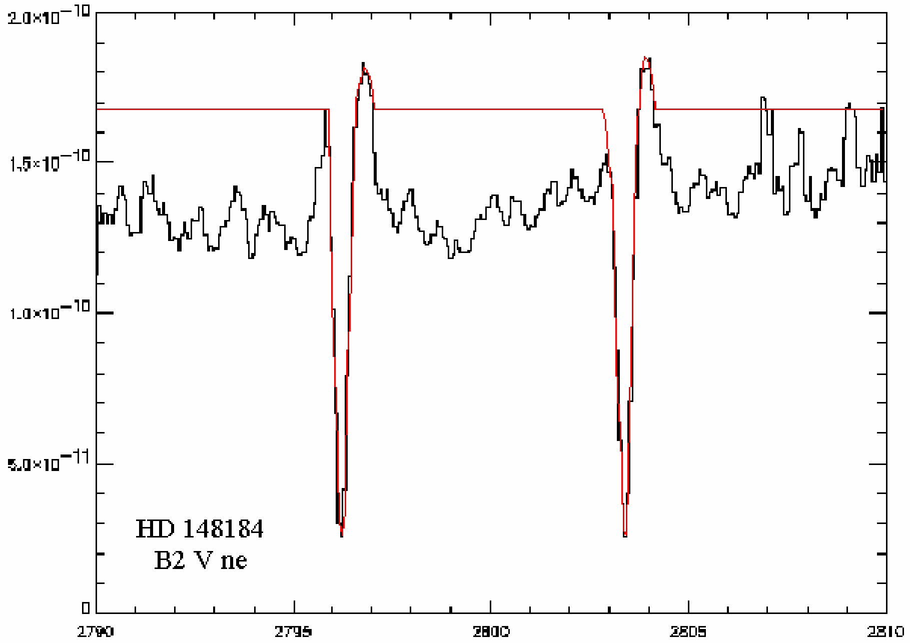

Figure 2: Best fit of Mg II lines λλ 2795.523, 2802.698 A of the Be star HD 148184. The thick line presents the real spectral profile and the thin one the model's fit. The differences between the real spectrum and its fit are hard to see, as we have accomplished the best fit

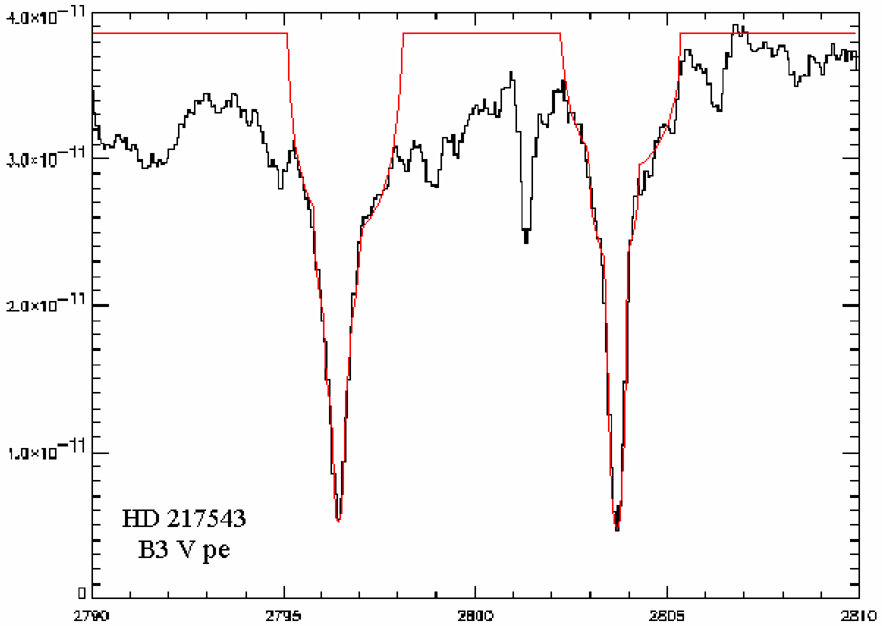

Figure 3: Best fit of Mg II lines λλ 2795.523, 2802.698 A of the Be star HD 217543. The thick line presents the real spectral profile and the thin one the model's fit. The differences between the real spectrum and its fit are hard to see, as we have accomplished the best fit

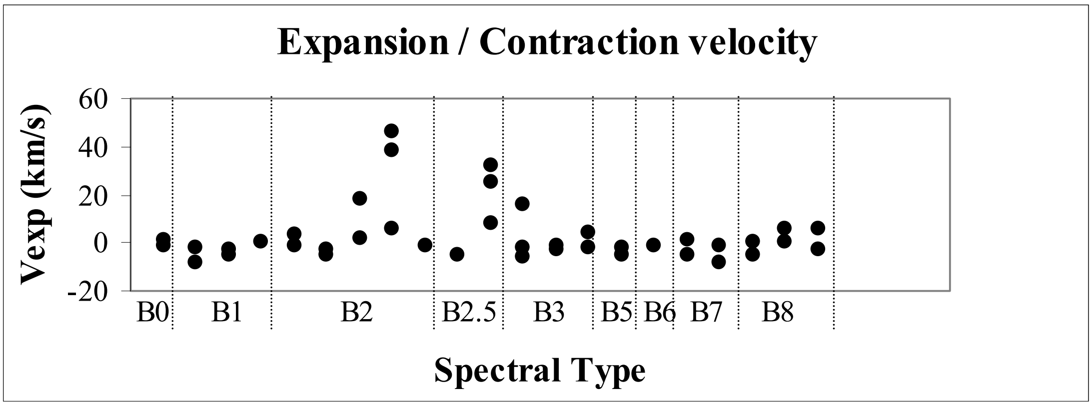

Diagram 1 : Expansion / contraction velocities of all the absorption components of Mg II as a function of the spectral type.

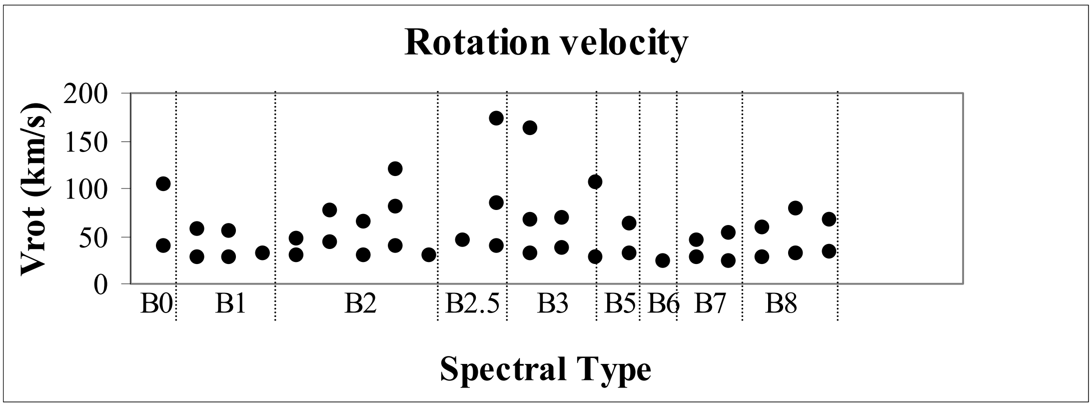

Diagram 2 : Rotation velocities of all the absorption components of Mg II as a function of the spectral type.

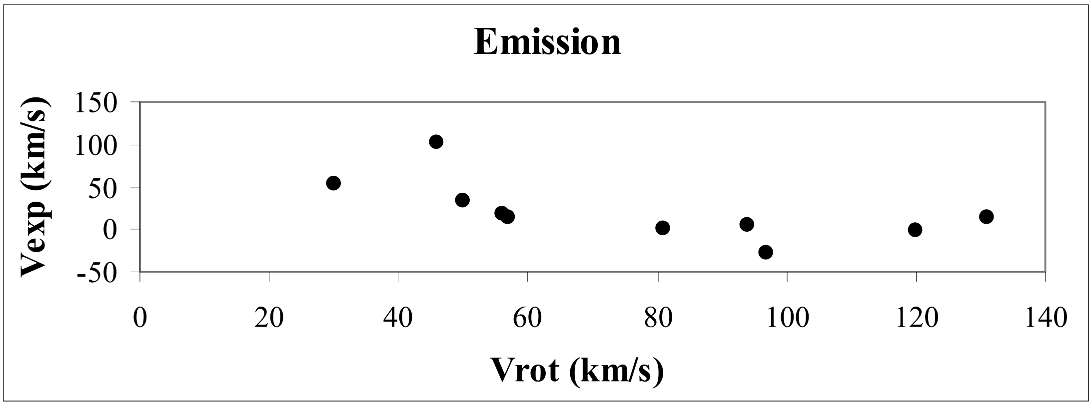

Diagram 3 : Expansion / contraction velocities of the emission component of Mg II as a function of the respective rotation velocities.

The coronal and post-coronal regions of the moving atmosphere of the Oe star HD66811 (ζ Puppis)

Danezis et al. (2002b) by applying the above presented model, studied the variation of the calculated parameters V_{rot} and V_{exp} and ξ of the density regions where the spectral lines CIV, NIV, NV and SiIV are formed of the star HD 66811 (ζ Puppis) at three different moments (1979, 1988, 1995). Our purpose was to study the variations of the parameters V_{rot} and V_{exp} and ξ of the SACs that present the complex profiles of these spectral lines. In figures 4 and 5 we present two best fits of the NV and SiIV resonance lines of the stars HD 41335, HD 148184 and HD 217543. The thick line presents the observed spectral line’s profile and the thin one the model's fit. The differences between the observed spectrum and its fit are some times hard to see, as we have accomplished the best fit. Some of our conclusions are presented in diagrams 4-7.

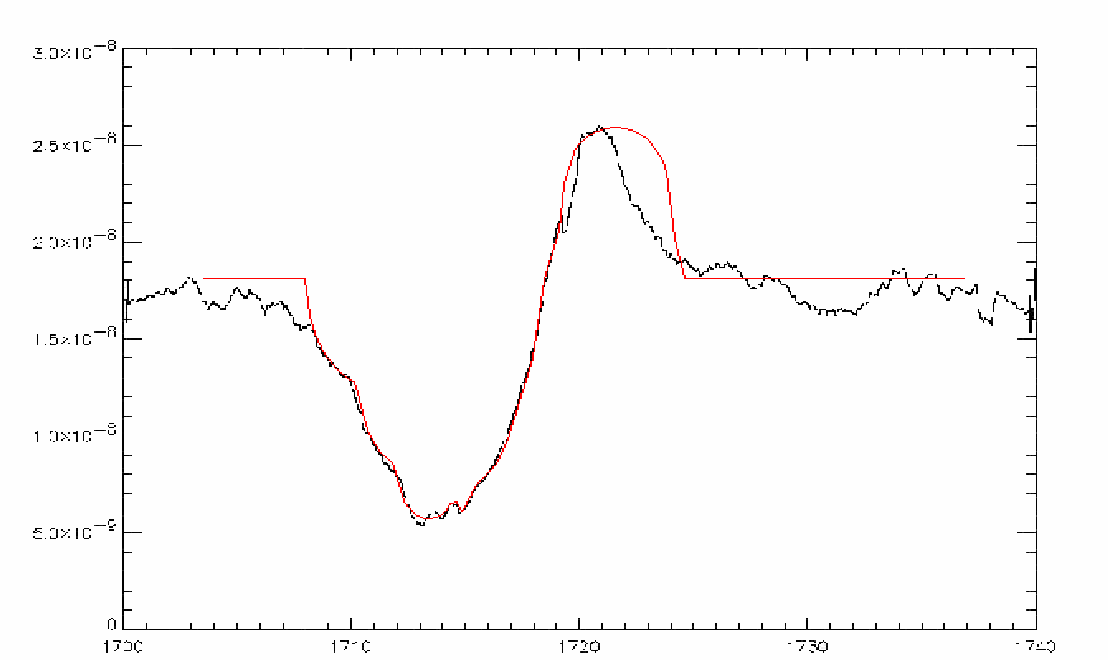

Figure 4: Best fit of N IV λ 1718.8A line of the Oe star HD66811. The thick line presents the real spectral profile and the thin one the model's fit. The differences between the real spectrum and its fit are some times hard to see, as we have accomplished the best fit

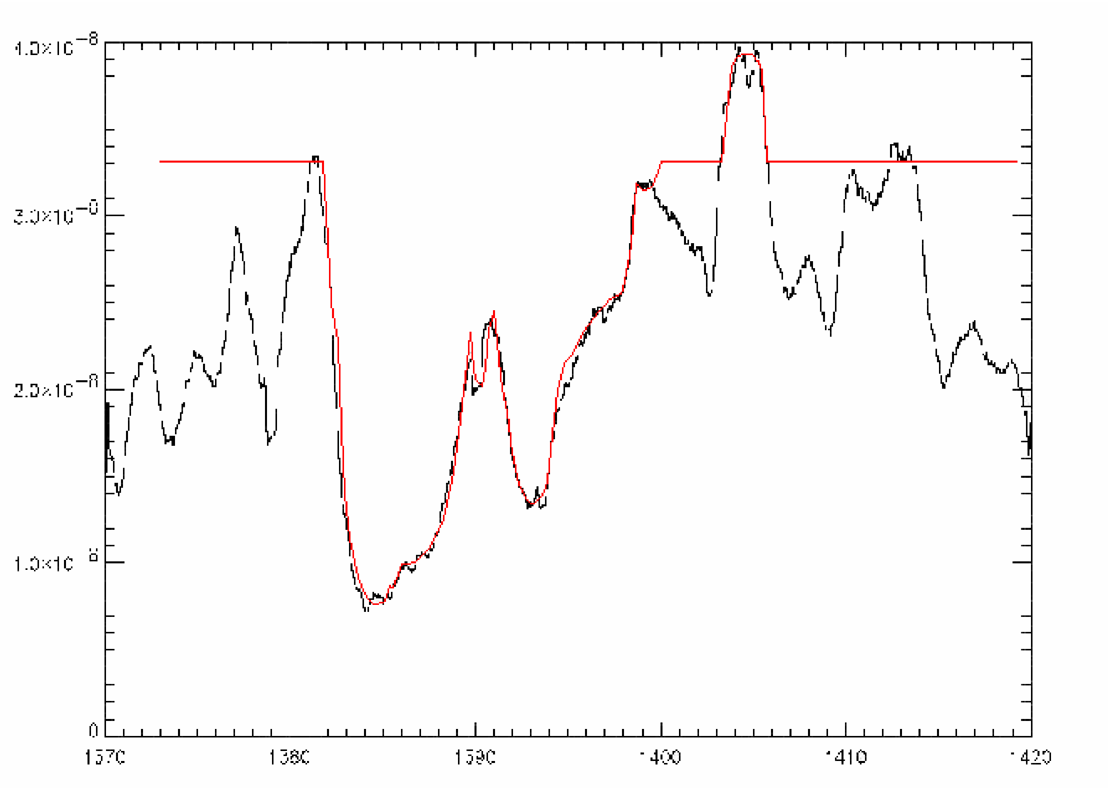

Figure 5: Best fit of Si IV λλ 1393.75, 1402.73A line of the Oe starHD66811. The thick line presents the real spectral profile and the thin one the model's fit. The differences between the real spectrum and its fit are some times hard to see, as we have accomplished the best fit

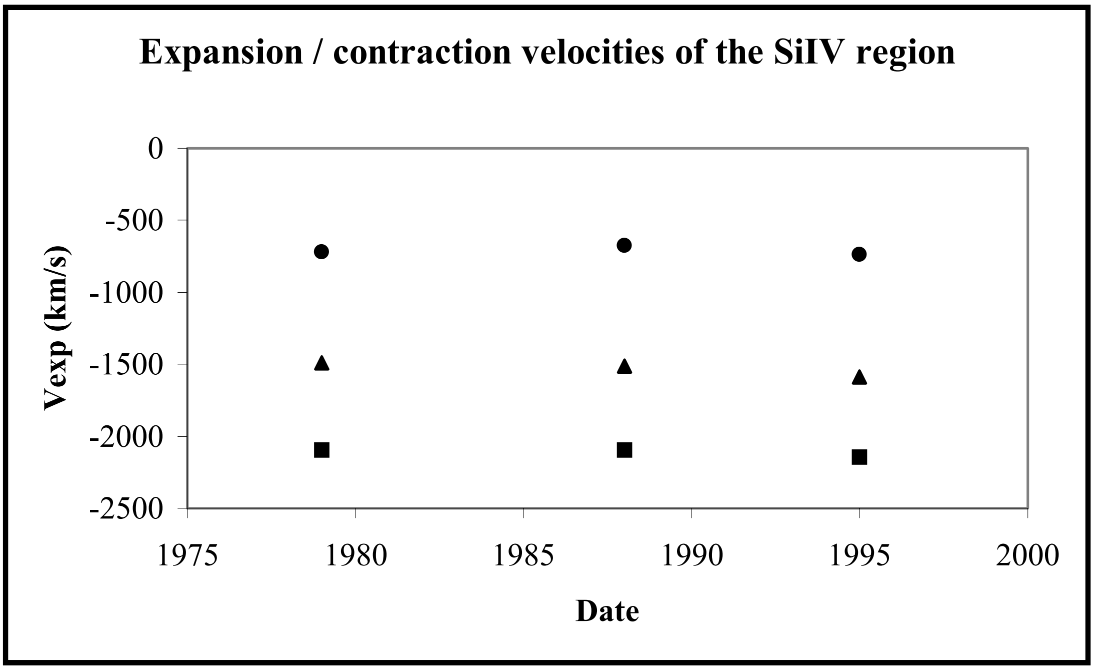

Diagram 4: Apparent radial velocities of expansion / contraction of the density regions where the Si IV lines of the star HD 66811 are created, as a function of time.

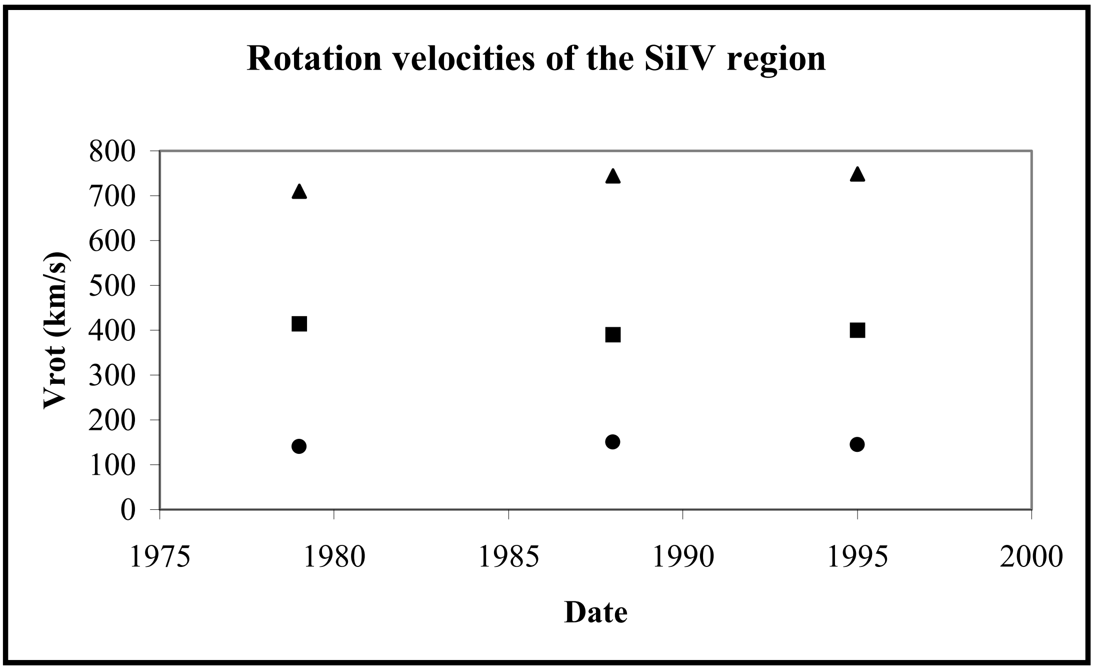

Diagram 5: Apparent rotation velocities of the density regions where the Si IV lines of the star HD 66811 are created, as a function of time.

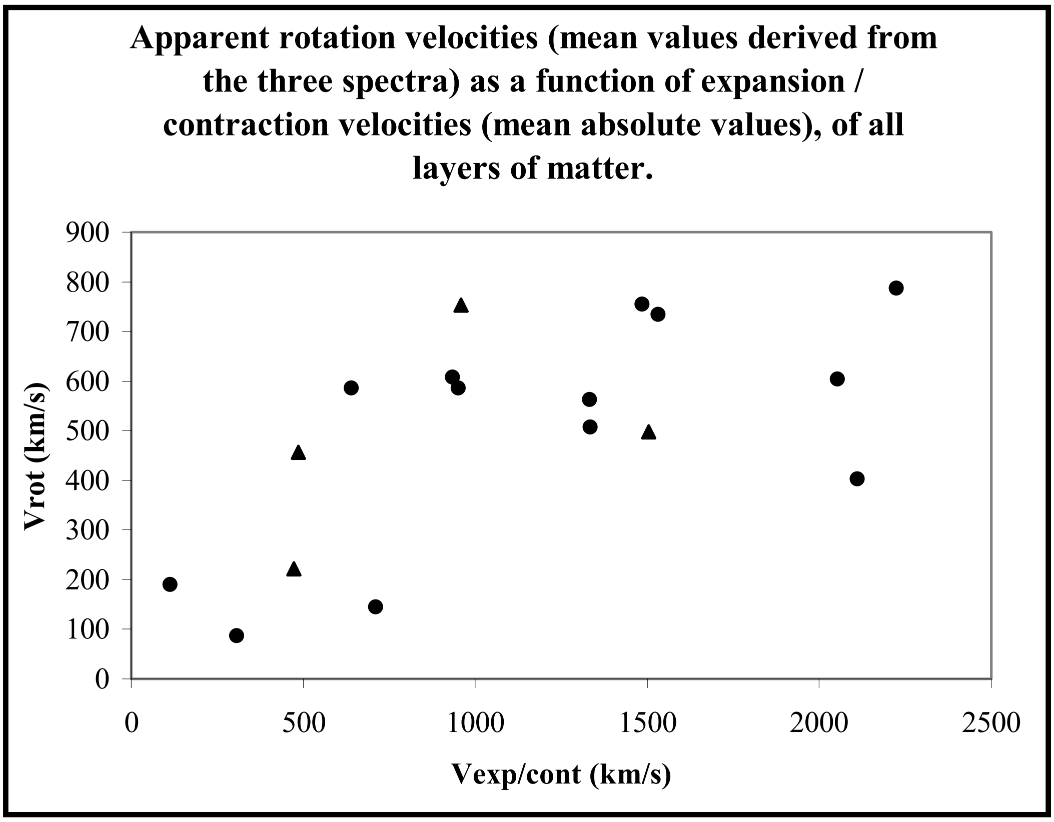

Diagram 6: Mean apparent rotation velocities as a function of the absolute mean velocities of expansion / contraction, for the density regions (absorbing and emitting) of the star HD 66811. Velocities related to absorbing layers of matter are shown with circles. Velocities related to emitting layers of matter are shown with triangles.

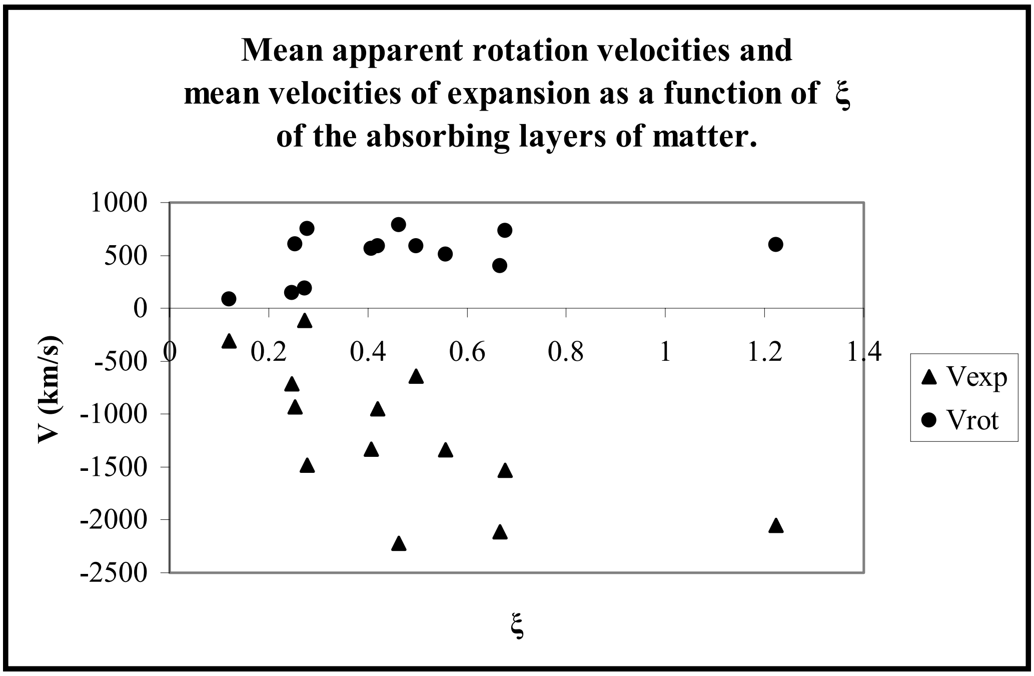

Diagram 7: Mean apparent rotation velocities and mean expansion velocities of the absorbing layers of matter of the star HD 66811, as a function of ξ.

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