1st workshop:
Astrophysical winds and disks
Similar phenomena in stars and quasars
Platamonas, Greece, September 3-8, 2009

Studying the complex spectral line profiles in the spectra of hot emission stars and quasars

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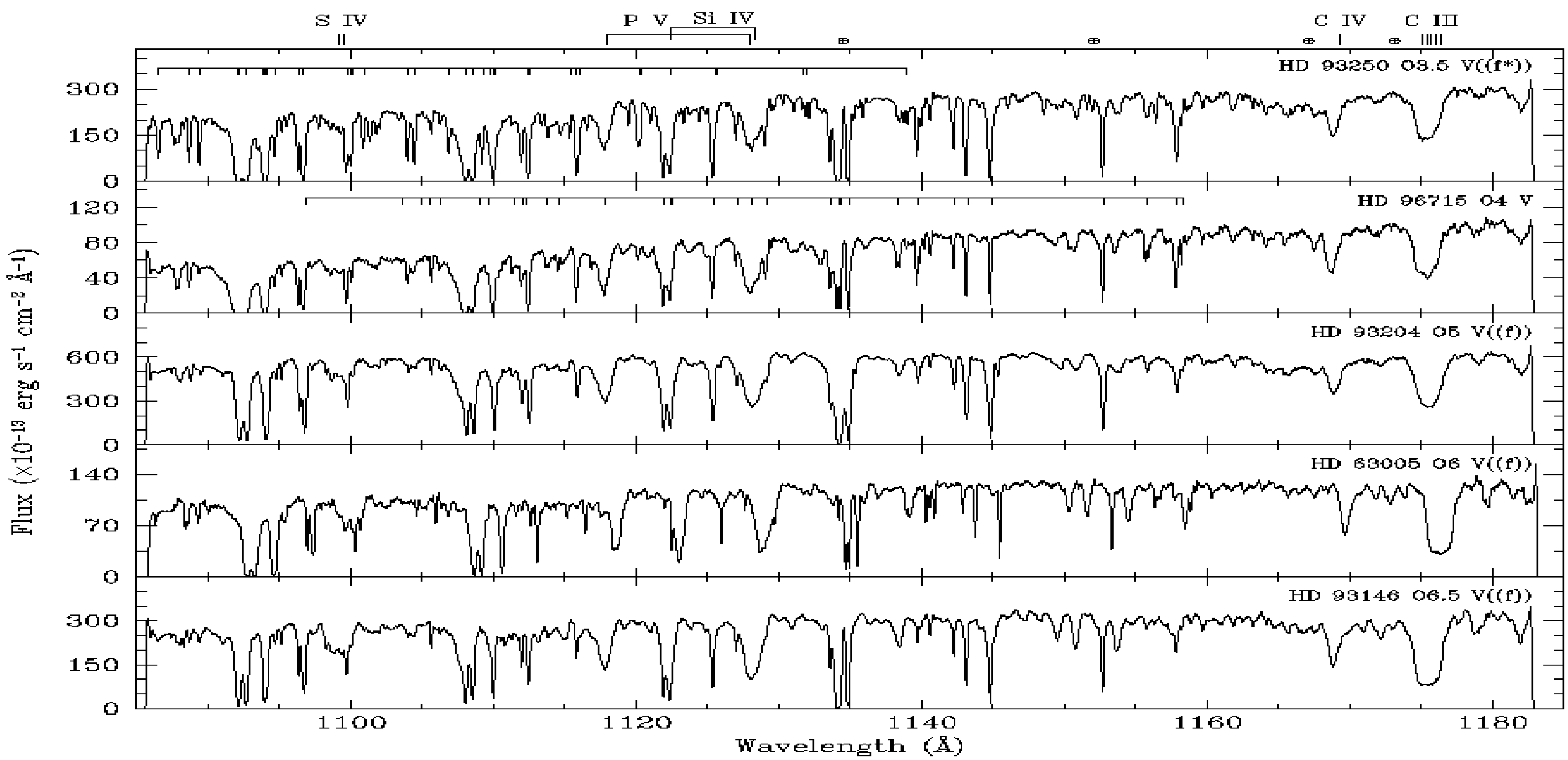
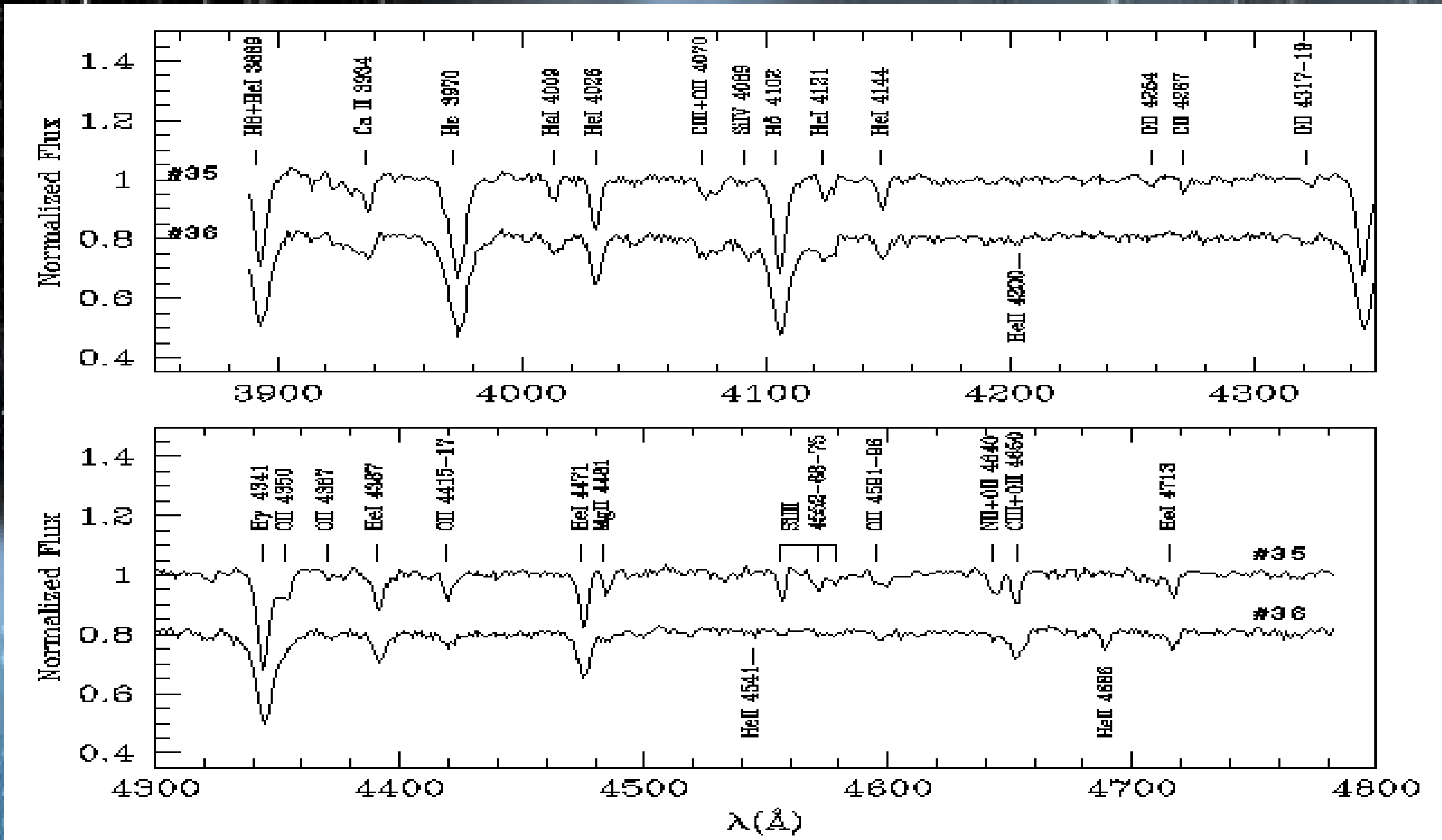
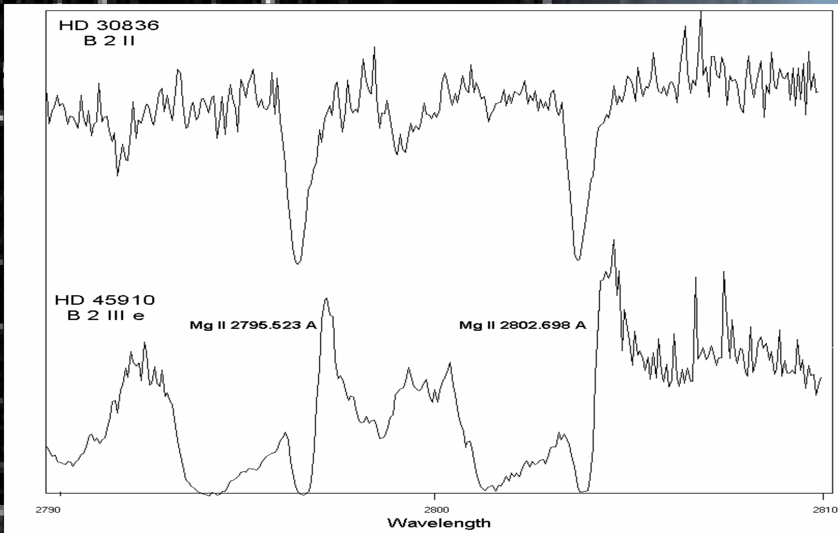
All the stars of the same spectral type and luminosity class present the same absorption lines in their spectra

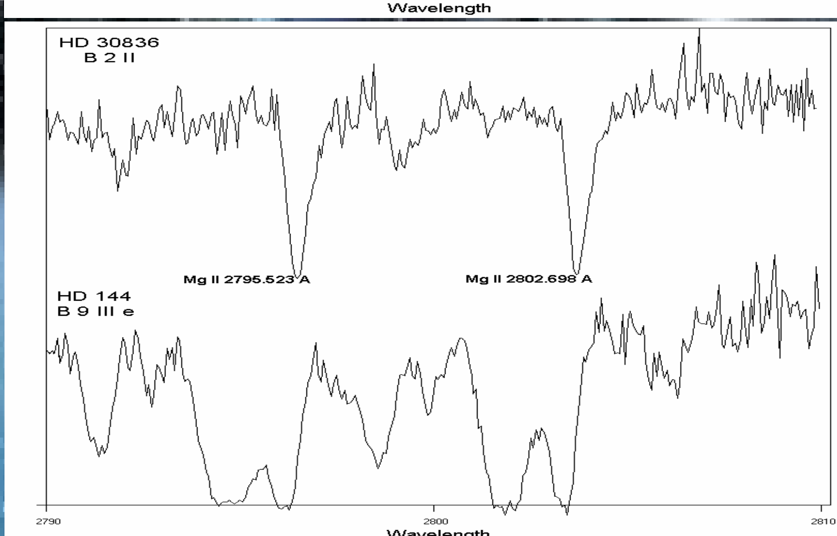


A group of O type stars of the same luminosity class that present the same absorption lines



Two Be stars of the same luminosity class present the same absorption lines in their spectra.





All the Stars…?

In the UV spectral region, some hot emission stars (Oe and Be stars) present some absorption components that should not appear in their spectra, according to the classical physical theory.

In these figures we can see the comparison of Mg II resonance lines between the spectrum of a normal B star and the spectra of two active Be stars that present complex and peculiar spectral lines. As we can observe the Be stars present some absorption components that do not appear in the spectrum of the classical B star.

Some people confuse the phenomena that we can detect in the atmospherical regions around classical hot stars with the phenomena of hot emission stars.

The group of hot emission stars is a sub-group of hot stars and present different phenomena and problems.

It is known that the classical definition of hot emission stars is that they present emission lines in Ballmer series. So we tried to find mechanisms, such as the wind or the disk models, that would be able to explain these emission lines.

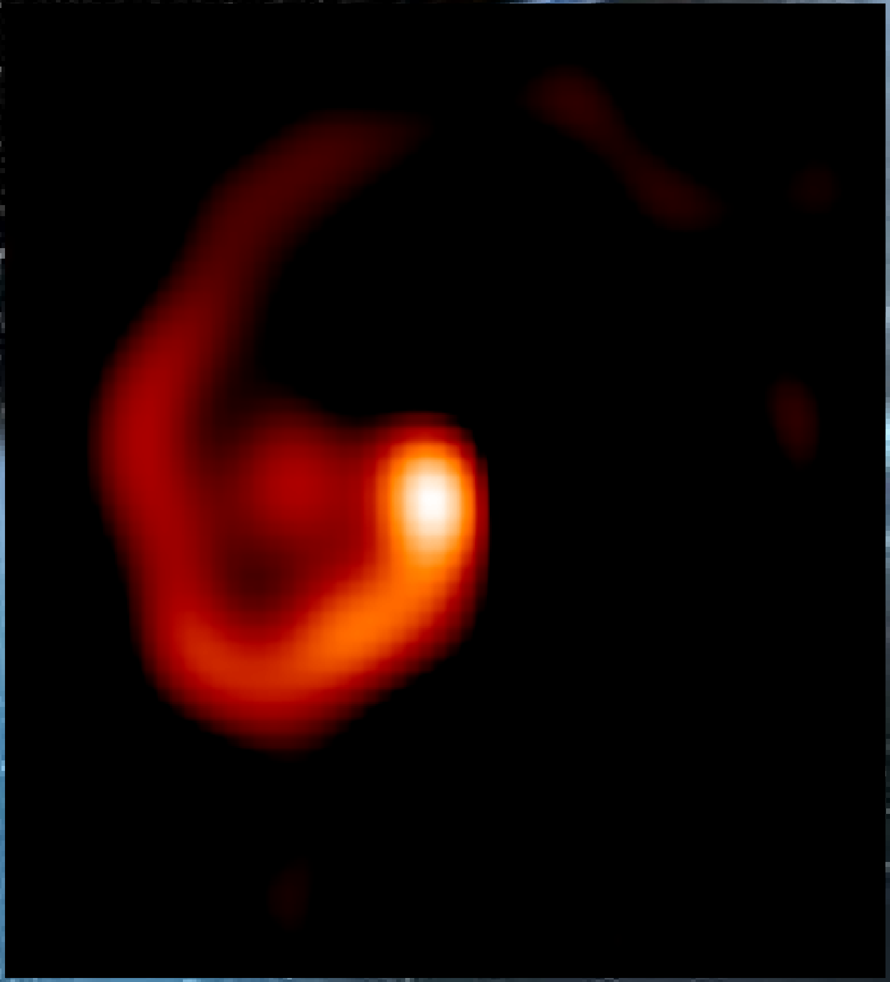
The problem is that, in the UV region, these models can not reproduce the very complex line profiles and the absorption components that should not exist, according to the classical physical theory.

In order to understand the origin of these problems, it is necessary to point out some general characteristics of Hot Emission stars.

General characteristics of Hot Emission stars (Oe and Be Stars)

according to Doazan-Thomas model

1. Rapid rotators



Hot emission stars are rapid rotators and when the rotational velocity takes a critical value, the star ejects plasma violently from a zone around the equator (Underhill & Doazan 1982, Part II, chapter 10).

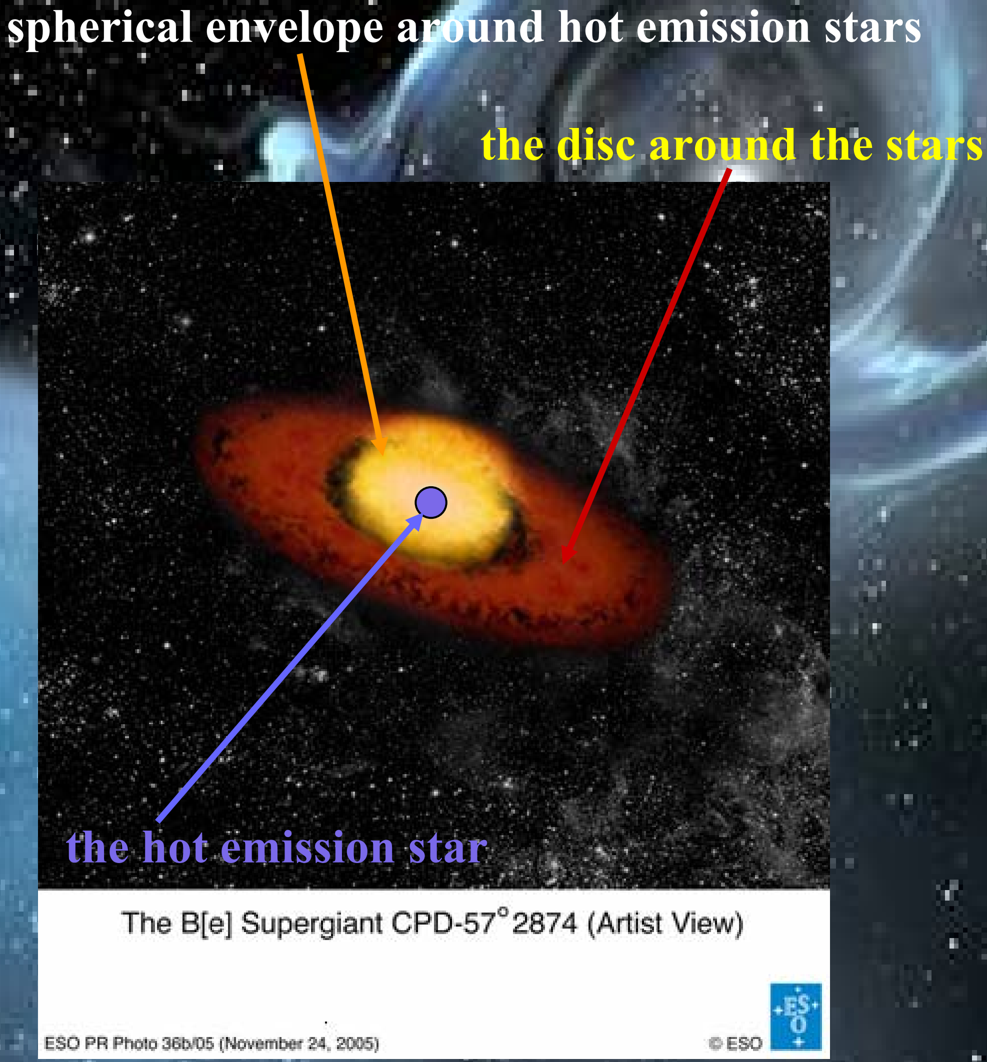
2. Ejection of matter

The violent mass ejection, like flares, from active regions is one of the main characteristics of hot emission stars, which also distinguishes them from the classical hot stars.

The mass ejection may last for quite long time and results to the fact that near the stars the ejected plasma forms spiral streams due to turbulence and the stellar rotation. These structures form density regions 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, Waldron et al. 1994, Cranmer & Owocki 1996, Rivinious et al. 1997, Kaper et al. 1996, 1997, 1999, Markova 2000).

As a result, the material that comes from the star has not the form of a classical stellar wind.

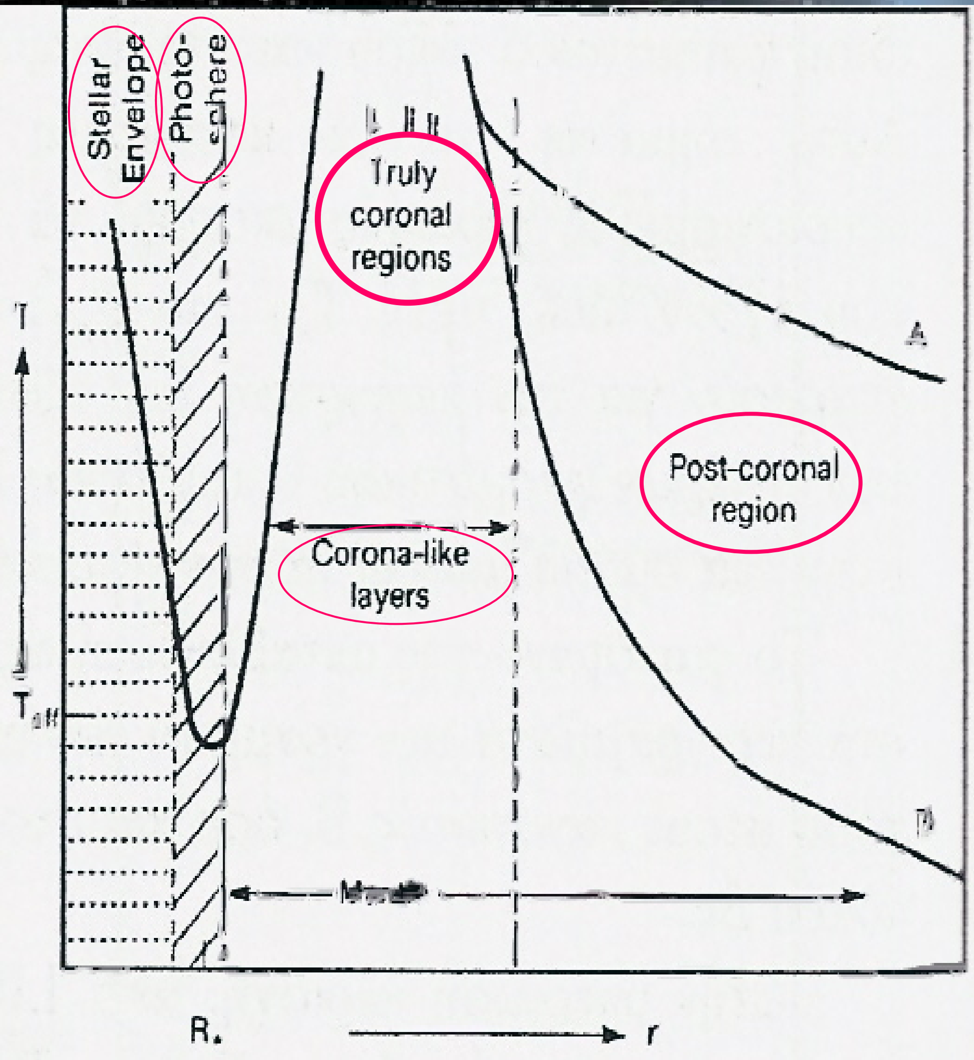
The environment around a hot emission star
The example of the Be supergiant CPD-57 2874



The ejected plasma evolves to **a spherical shell around the star,** which evolves to an equatorial disk, that, far away from the star, concludes to a classical stellar wind.

As a result, the stellar wind models may be used for the outer regions of the equatorial disk, but not for the inner layers.

3. The high temperature regions



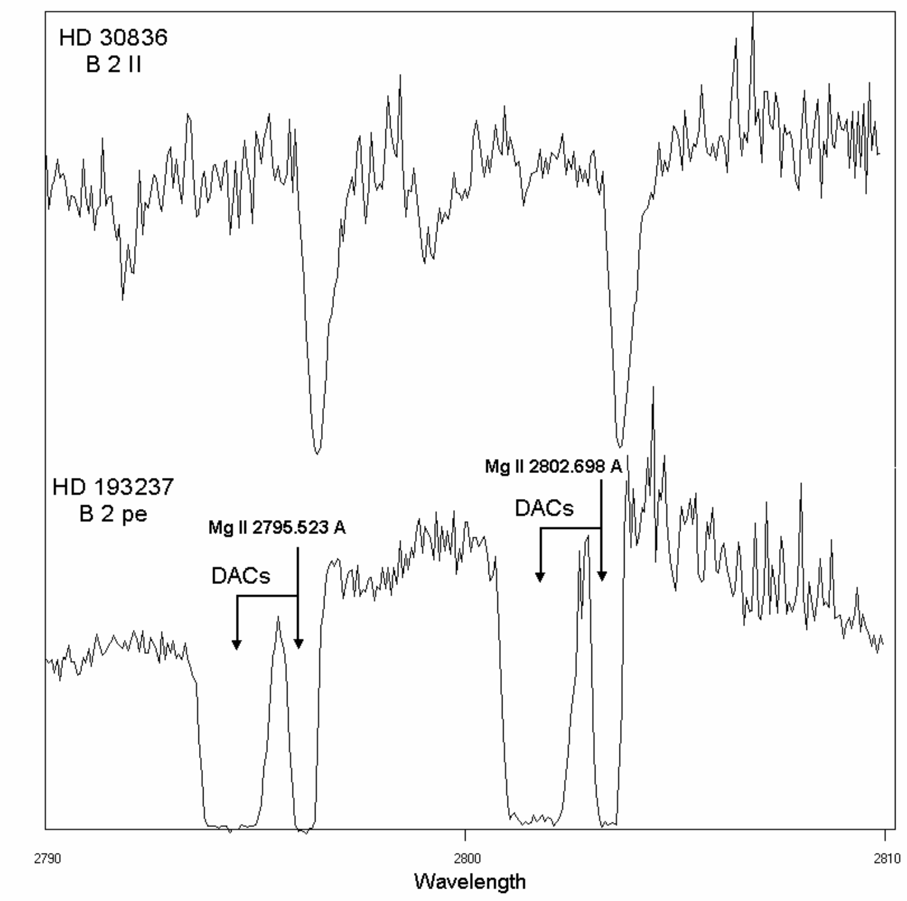
Underhill, A. B. & Doazan, V.: 1982, B Stars with and without emission lines, NASA SP–456, Part II, chapter 10

Near hot emission stars there are density regions that have the characteristics of chromosphere, corona and post-coronal regions (Underhill & Doazan 1982, Part II, chapter 13, Franco & Stalio 1983, MmSAL, 54, 537, Franco et al. 1983, A&A, 122, 97). We detect the corona of hot emission stars in X-rays, while in UV we detect the post-coronal regions (Si IV, C IV, N IV, N V lines e.t.c.).

The DACs phenomenon

In the case of <u>hot</u> emission stars we call the absorption spectral lines that do not correspond to any known absorption line of the same spectral type stars **DACs (Discrete Absorption Components)**

(Bates & Halliwell 1986 MNRAS)



The DACs phenomenon is a characteristic of a sub-group of hot emission stars

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 $\Delta\lambda$, as they are created in different density regions, which rotate and move radially with different velocities.

(Danezis 1984, 1986, Danezis et al. 1991, 2003 and Lyratzi & Danezis 2004)

How are DACs created?

The density regions which create the observed DACs in the stellar spectra, according to our model may be:

1. Spherical shells around hot emission stars
2. (Apparent) spherical density regions rotating around their own centers

1. Spherical shells around Hot Emission Stars

Successive and independent spherical envelopes

The ejected plasma evolves to a thin spherical shell around the star. Some times we have repeated ejection of matter (Danezis 1981 PhD Thesis).

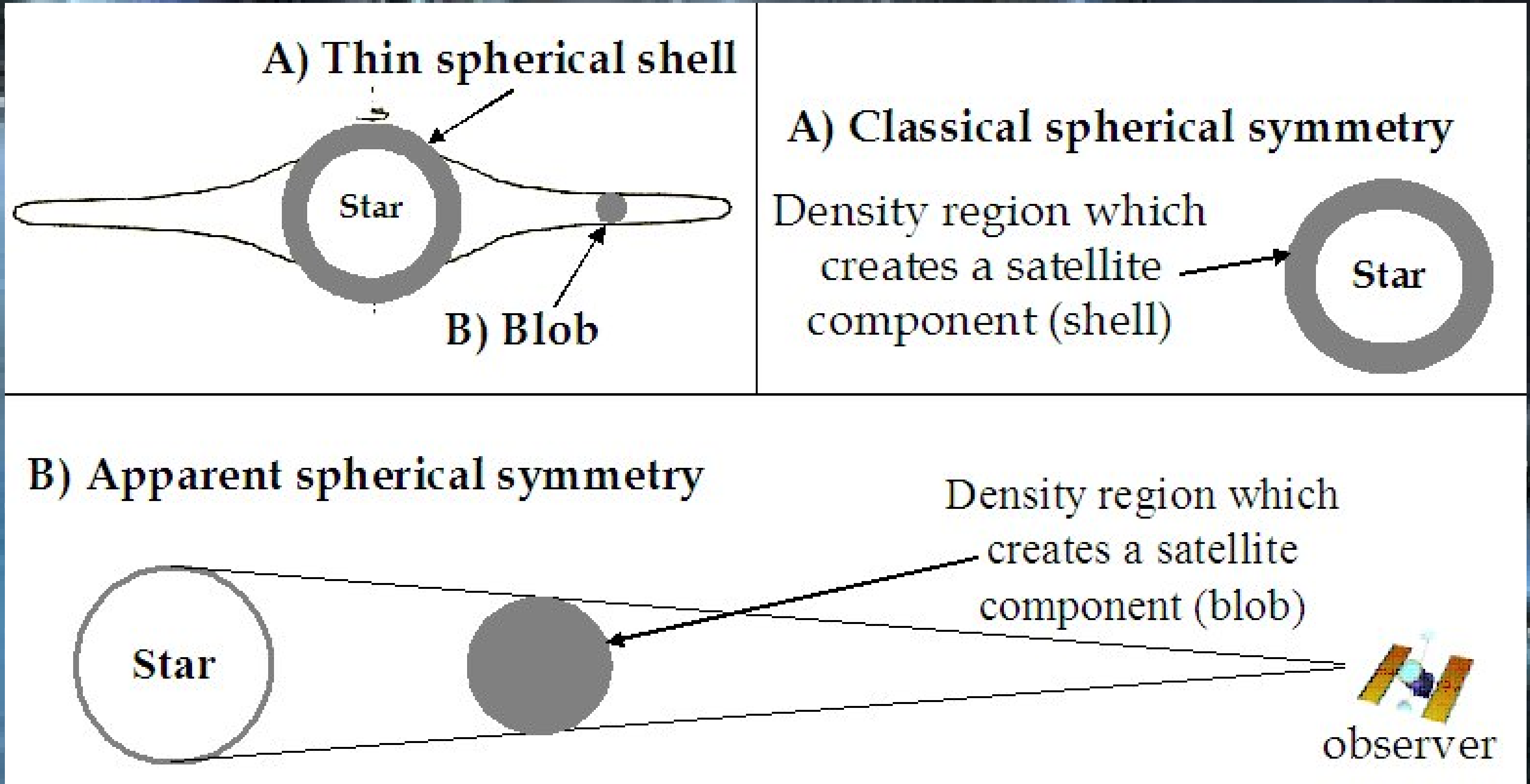
This means that we can detect not one, but many successive thin and independent spherical shells around the star. These spherical shells rotate rapidly because they lie near the rapidly rotating star and they are the origin of the very broad spectral lines that present rotational velocities with values around the critical.

2. (Apparent) spherical density regions rotating around their own centers

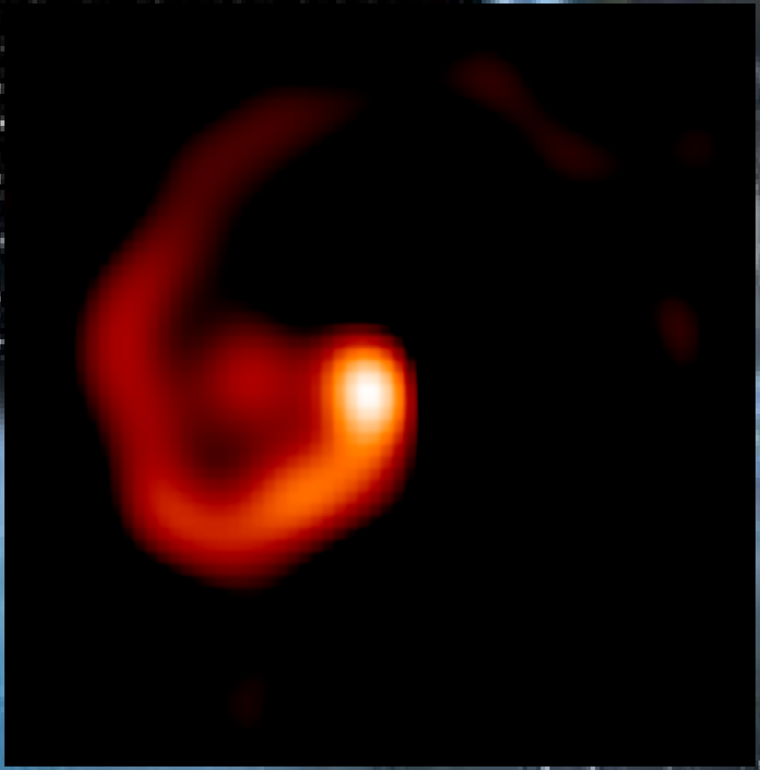
The mass ejection may last for quite long time and results to the fact that near the star the ejected plasma **forms spiral streams due to turbulence, the stellar rotation and the topical magnetic fields. These structures form density regions such as shells, blobs or puffs** (Underhill 1975, Henrichs 1984, Underhill & Fahey 1984, Bates & Halliwell 1986, Grady et al. 1987, Lamers et al. 1988, Waldron et al. 1992, Waldron et al. 1994, Cranmer & Owocki 1996, Rivinious et al. 1997, Kaper et al. 1996, 1997, 1999, Markova 2000).

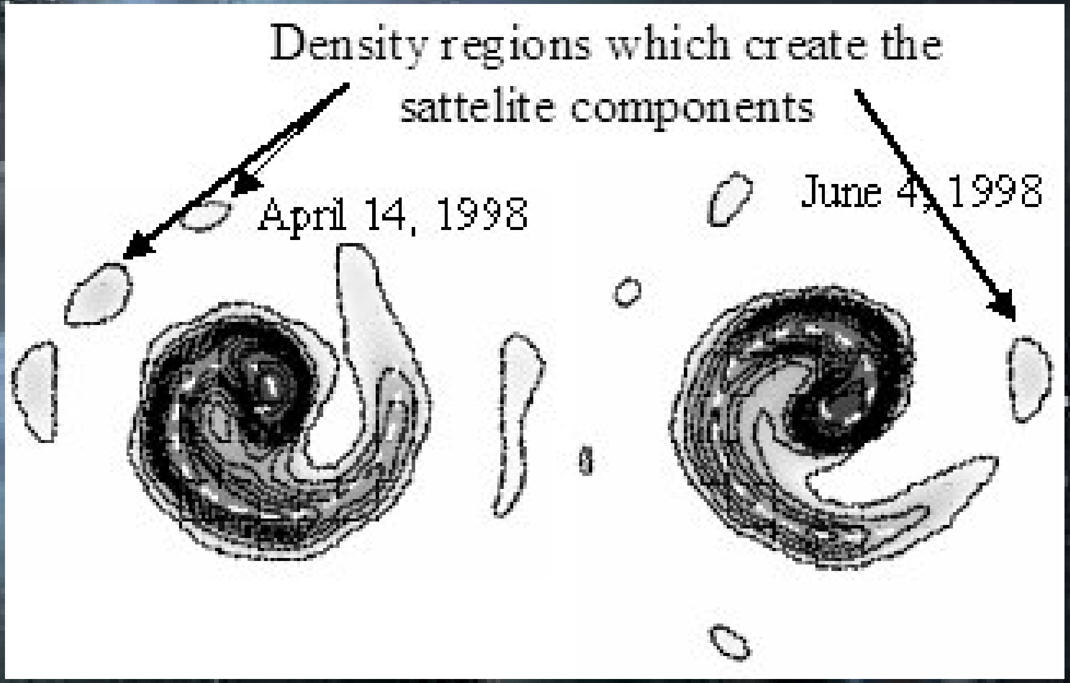
We can detect this kind of density regions of matter in the spherical shells around the star or in the disc and other areas around the stars.

These spherical blobs, arising from spiral streams or turbulences, are the origin of a group of satellite spectral lines with intermediate or small broadening.



(Apparent) spherical density regions around a Wolf-Rayet star

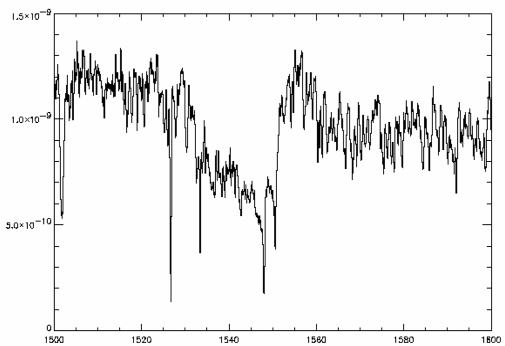




Around a Wolf-Rayet star (WR 104) we can detect density regions of matter, quite away from the stellar object, able to produce DACs or SACs (Satellite Components)

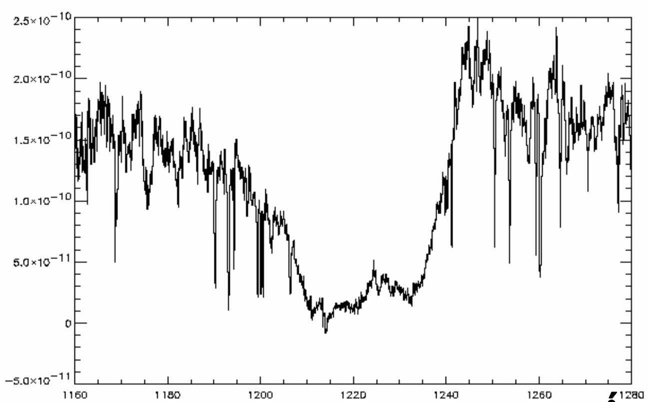
Another problem of this group of hot emission stars is:

HD 37022, SWP07481



C IV λλ 1548.155, 1550.774 Å

HD 164794, SWP02202



N V λλ 1238.821, 1242.804 Å

The presence of very complex profiles of the spectral lines that we can't reproduce theoretically.

This means that
we could not know the physical conditions that exist in the high density regions that create these spectral lines.

The origin of the complex profiles

In order to explain this complex line profiles our scientific group proposed the SACs phenomenon (Satellite Absorption Components).

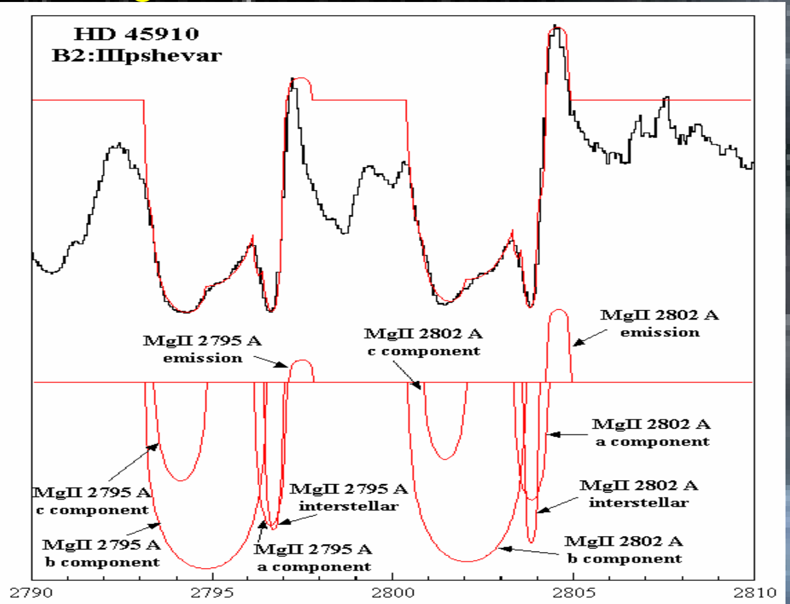
If the regions that create the DACs rotate with large velocities and move radially with small velocities, the produced lines have large widths and small shifts.

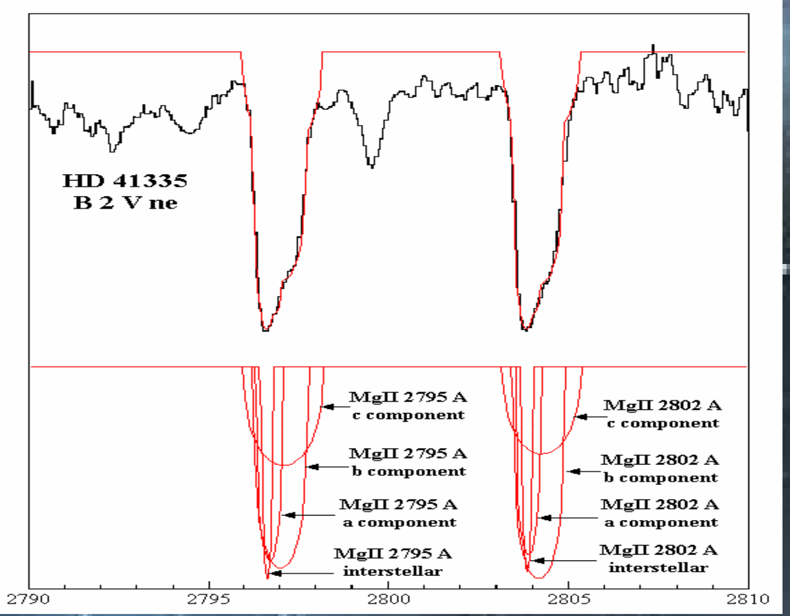
As a result, they are blended among themselves as well as with the main spectral line and thus they are not discrete. In such a case the name Discrete Absorption Components is inappropriate and we use only the name:

Satellite Absorption Components (SACs)

(Sahade et al. 1984, 1985, Danezis 1984, 1987, Lyratzi & Danezis 2004, Danezis et al. 2006)

DACs / SACs: a similar phenomenon





The Mg II line profiles of the star AX Mon (HD 45910), which presents DACs and the star HD 41335, which presents SACs are produced in the same way.

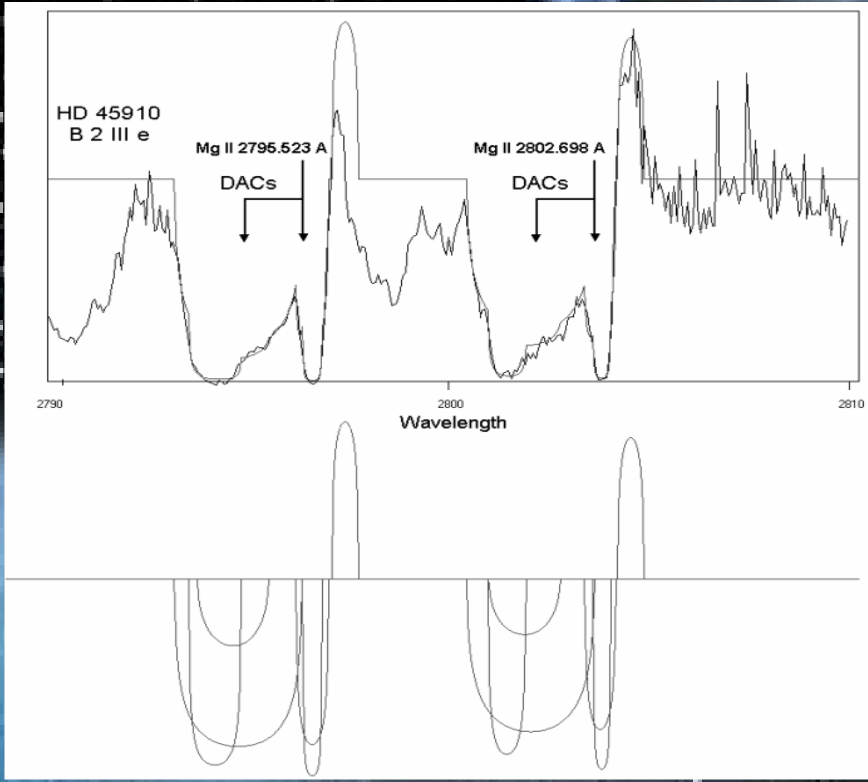
The only difference between them is that the components of HD 41335 are much less shifted and thus they are blended among themselves.

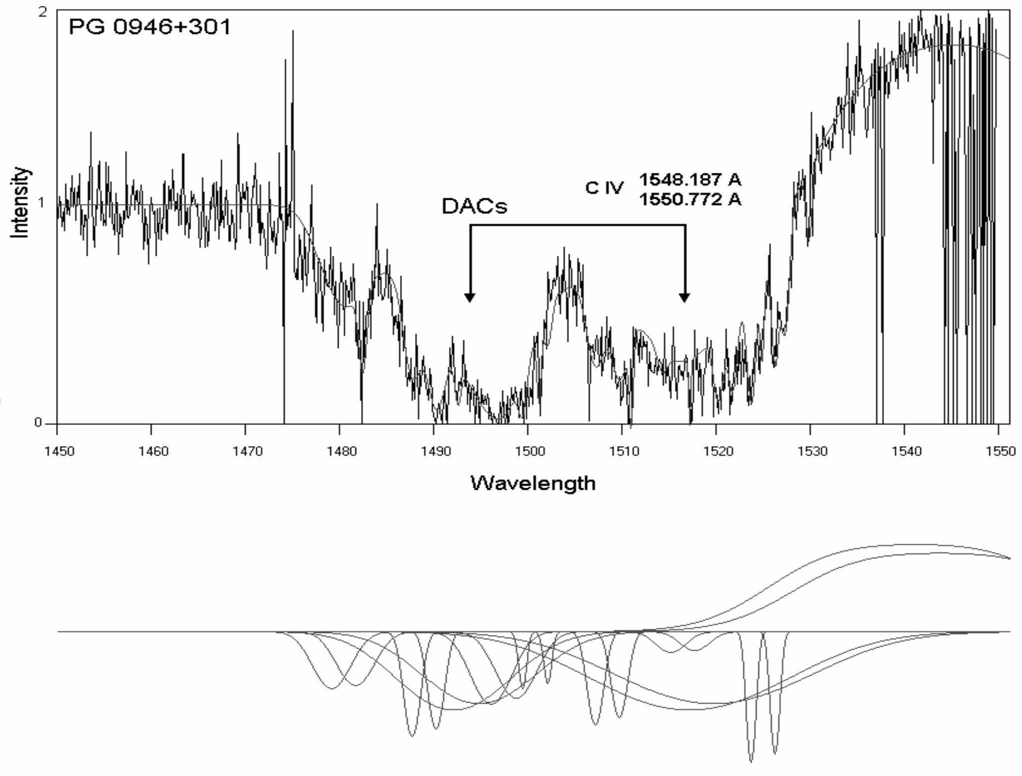
The black line presents the observed spectral line's profile and the red one the model's fit.

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

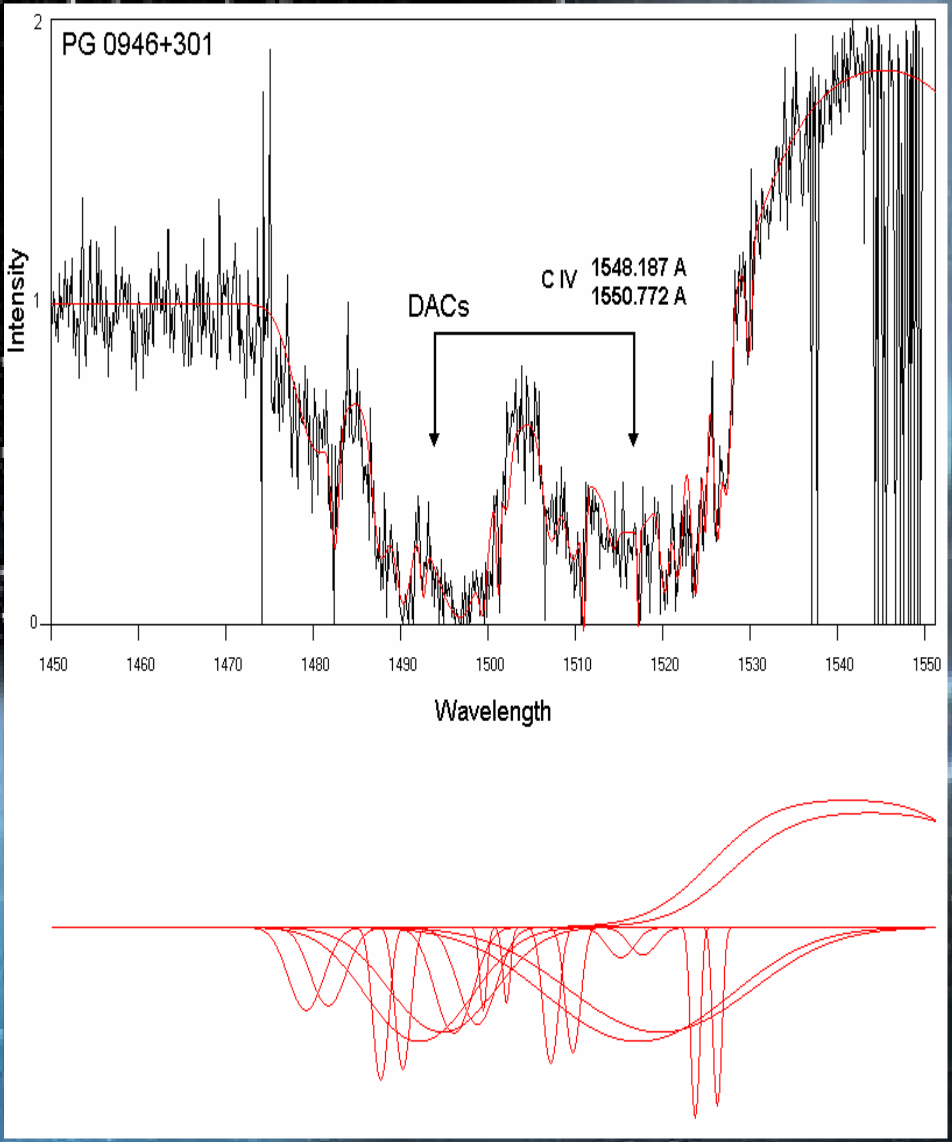
(Danezis et al. 2006)

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





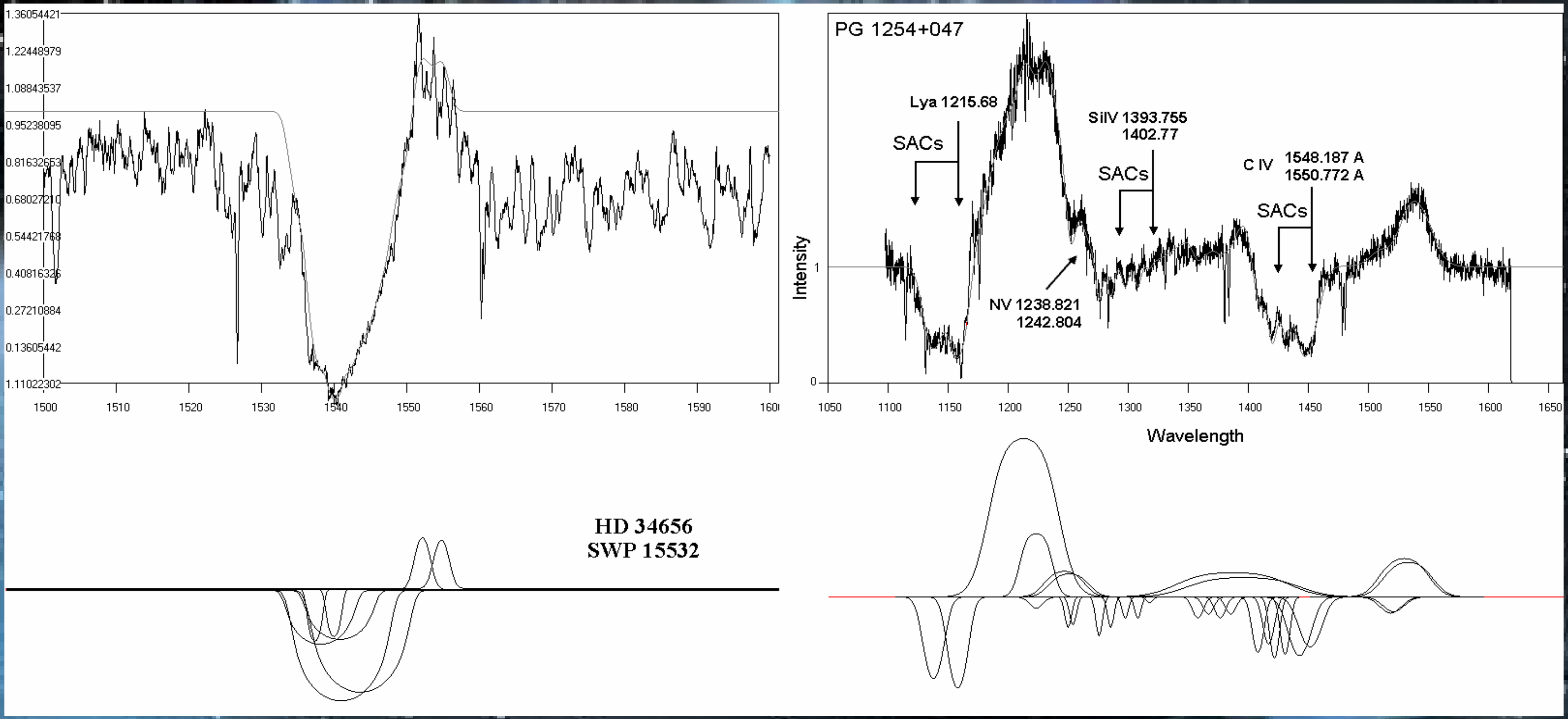
The C IV UV doublet of an AGN (PG 0946+301) (right). Based on the values of radial displacements and the ratio of the line intensities we conclude that the two observed C IV shapes indicate the presence of a DACs phenomenon similar with the DACs phenomenon that we can find in the spectra of hot emission stars (HD 45910) (left).



The two discrete features do not correspond to the two resonance lines, as the two members of the doublet have small difference in wavelength (1548.187Å and 1550.772 Å) and they both lie at the right feature.

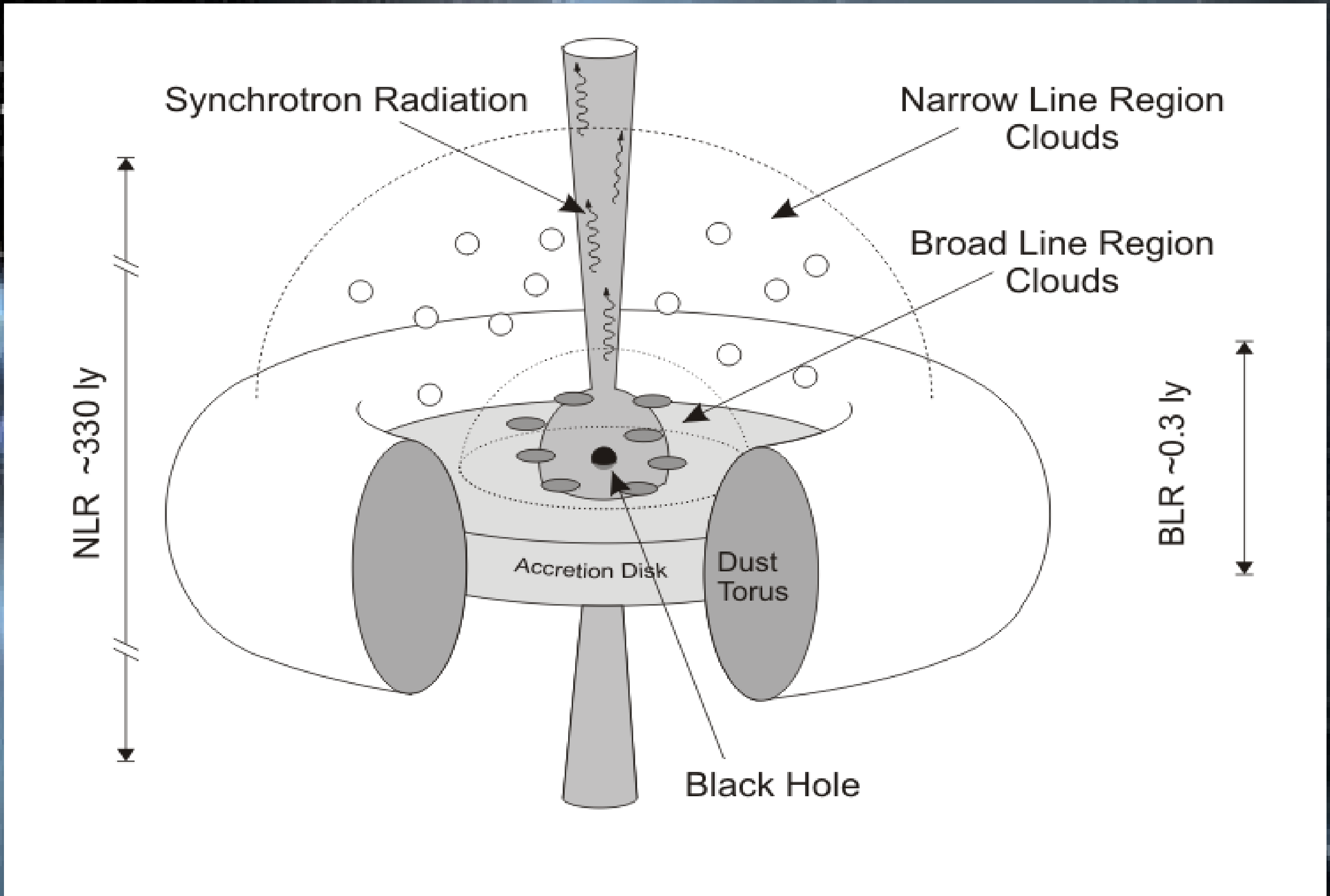
Here, as in most cases of DACs, we have a combination of DACs and SACs phenomenon.

Since the DACs phenomenon is present in AGNs spectra, we also expect the presence of SACs phenomenon which is able to explain the observed absorption lines' complex profiles.



Similarity of SACs phenomenon in Oe star's HD 34656 spectrum with AGNs PG 1254+047 spectrum.

The origin of DACs/SACs phenomenon in AGNs



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

The line function

In order to reproduce theoretically the spectral lines that present DACs or SACs we need to calculate the **line function** of the complex line profile.

What is a line function?

It is the function that relates the intensity with the wavelength. This function includes as parameters all the physical conditions of the region that creates the line profile.

By giving values to these parameters, we try to find the right ones in order to have the best theoretical fit of the observed line profile.

If we accomplish the best fit, we accept that the theoretical values of the physical parameters are the actual ones that describe the physical conditions in the region that produces the specific spectral line.

The problem

If we could construct a line function able to reproduce theoretically any spectral line of any ion, it should include all the atomic parameters. As a result the line function would be very complex.

Also, if we wanted a time dependent line function , we should also include as parameter the time.

The existence of many parameters, makes the solution of the radiation transfer equations problematic.

Another problem is to choose the correct values of so many parameters.

Our proposition

In order to calculate the line function 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.**

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.

Additionally:

Our idea was to study a specific spectral line of a specific ion. This means that we do not need to include the atomic parameters in the used model, as in such a case the atomic parameters remain constant.

In this way, we were able to solve the radiation transfer equations and to find the correct group of parameters that give the best fit of the observed spectral lines.

Before the presentation of our ad hoc model (GR model), we would like to point out that:

In order to study the (e) phenomenon in the spectra of hot emission stars, many ad hoc models (like wind models) have been proposed.

However, as Underhill & Doazan mention:

"… these models were all constructed to represent only the observations made in the visible and infrared regions, and they all produce good agreement between the observed and computed spectral features……"

(Underhill & Doazan, 1982, *B Stars with and without emission lines*, NASA SP–456, p. 361)

Generally until now, as Underhill and Doazan (1981, p 360) mention, all the models that have been proposed :

"…are ad hoc; as such, they cannot and do not pretend to be physically self-consistent. In this respect, one must keep in mind the arbitrary nature of certain hypotheses on which their construction is based, and one must not expect this picture of reality to closely describe a real star."

Any ad hoc model should be judged by its application on real astronomical objects.

All the above, result to our need for a theoretical model, able to explain and reproduce the complex structure of the UV spectral lines of real astronomical objects (e.g. hot emission stars and quasars).

This has been the scientific work of our teems.

The model that we proposed is not just theoretical, but it has given consistent results in the case of all the real stars that we have studied (see e.g. Lyratzi et al. 2007 PASJ, 59, 357).

Based on our theoretical idea, we are able to reproduce the observed complex profiles of the spectral lines of this category of real stars, which since now have not been reproduced by any other model, as far as we know.

With the model that we propose, we can calculate the values of many kinematical parameters, as well as the column density, the absorbed energy, the optical depth in the center of the absorption or emission components, the FWHM and the Gaussian typical deviation of the ion random motions.


The GR line function

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

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

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

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

where:

$I_{\lambda0}$: is the initial radiation intensity,

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

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

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

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

- We can calculate I(λ) by solving the radiation transfer equations.
- This means that in order to conclude to this form we did not have to take into account the geometry of the absorbing or emitting independent density layers of matter.

It is for the factor L that we have to take into account the geometry and all the physical conditions of the region that produces the spectral line.

The decision on the geometry is essential for the calculation of the distribution function that we use for each component.

This means that for a different geometry we have a different shape for the spectral line profile of each SAC.

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

In this case we must define the geometry for the corresponding regions.

In the case of the following line function:

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

The $e^{-L_i \xi_i}$ and $S_{\lambda ej}\left(1 - e^{-L_{ej}\xi_{ej}}\right)$ are the distribution functions of the absorption and the emission satellite component, respectively.

The factor L must include the geometry and all the physical conditions of the region that produces the spectral line. These physical conditions indicate the exact distribution that we must use.

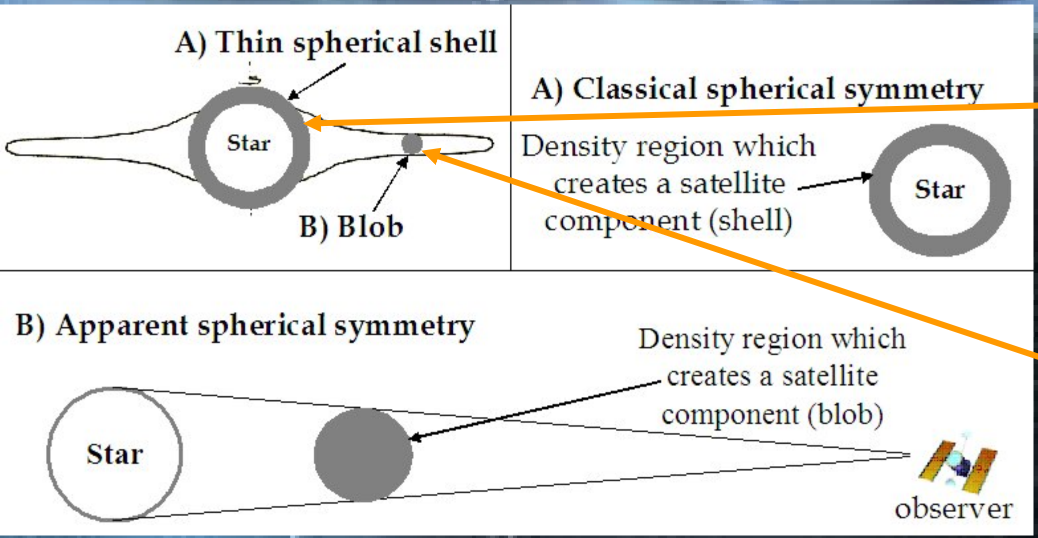
This means that

if we choose the right physical conditions in the calculation of the factor L, the functions $e^{-L_i \xi_i}$ and $S_{\lambda ej}\left(1-e^{-L_{ej}\xi_{ej}}\right)$ may take the form of a **Gauss, Lorentz or Voigt** distribution function.

In this case we do not use the pure mathematical distributions that do not include any physical parameter, but the physical expression of these distributions that our groups constructed.

In our model we choose the **spherical geometry**. This means that the density layers of matter that produce the specific spectral line present spherical symmetry **around their centers**.

We remind that the density regions which create the observed DACs in the stellar spectra



may be:

a) Thin spherical shells around hot emission stars or

b) (Apparent) spherical density regions in the disc around the stars

As a first step, our scientific group constructed a distribution function L that considers as the only reason of the line broadening the rotation of the regions that produce the spectral lines. We called this distribution:

Rotation distribution

(Danezis et al., 2003, Astrophysics & Space Science, 284, 119-1142)

But, as we know, in a gaseous region we always detect random motions. This means that these motions are a second reason of line broadening. The distribution function that expresses these random motions is the Gaussian.

If we consider that a spectral line has as broadening factors the rotation of the regions and the random motions of the ions, we should construct a new distribution function L that would include both of these reasons (rotation and random motions).

Our scientific group constructed this distribution function L and named it

Gauss-Rotation distribution (GR distribution).

The analytical form of the GR distribution function ($L_{final}(\lambda)$) is:

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

$$erf(x) = \frac{2}{\pi} \int_0^x e^{-u^2} du$$

$$\lambda_0 = \lambda_{lab} \pm \Delta\lambda_{rad} \longrightarrow V_{radial}$$

$$z = \frac{V_{rot}}{c} \longrightarrow V_{rotation}$$

$$\sigma \longrightarrow V_{random} = \frac{\sigma c \sqrt{2 \ln 2}}{\lambda_0} \longrightarrow V_{random}$$

Danezis et al. 2007 PASJ, Danezis et al. SPIG 2006

Using the GR model

We can calculate some important parameters of the density regions that construct the DACs-SACs like:

Direct calculations

- Apparent rotational velocities (V_{rot}) of absorbing or emitting density layers
- Apparent radial velocities (V_{rad}) of absorbing or emitting density layers
- The Gaussian typical deviation (σ) of the ion random motions
- The optical depth (ξ_i) in the center of the absorption or emission components

Indirect calculations

- The random velocities (V_{rand}) of the ions
- The FWHM
- The absorbed or emitted energy (Ea, Ee)
- The column density (CD)

Finally, our main goals during this workshop are:

1. Discuss and define our future work on these subjects, as well as on new ideas and propositions.
2. Continue our collaboration and begin new ones with other scientific teams, on subjects of mutual interest.

Generally:

All the propositions for collaboration and future work may be found on the information board and they will also be announced during the final general round table.

Thank you very much for your attention!!!