The Peculiar Absorption And Emission Phenomena From Stars To Quasars

E. Danezis[1], L. Č. Popović[2], E. Lyratzi[1], M. S. Dimitrijević[2]

1. University of Athens, Faculty of Physics, Department of Astrophysics, Astronomy and Mechanics, Panepistimioupoli, Zographou 157 84, Athnes – Greece
2. Astronomical Observatory, Volgina 7, 11160 Belgrade, Serbia

Abstract. The spectra of Hot Emission Stars and AGNs present peculiar profiles that result from dynamical processes such as accretion and/or ejection of matter from these objects. In this paper we analyze DACs and SACs phenomena, which indicate the existence of layers of matter with different physical conditions and we propose that these phenomena can explain the spectral lines peculiarity in Hot Emission Stars and AGNs. We also propose a new model with which we can study the density regions in the plasma surrounding the studied objects, where DACs and SACs of a spectral line are created producing the observed peculiar profiles. Finally, we present some tests to justify the proposed model.

Keywords: Hot Emission Stars, AGNs, DACs, SACs.
PACS: 97.10.Ex, 97.10.Fy, 97.20.Ec, 97.30.Eh, 98.54.Aj

THE SPECTRAL LINES IN ASTROPHYSICAL OBJECTS

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

In the classical stellar spectra we observe "normal" absorption lines (Fig. 1). However, in the spectra of hot emission stars (Oe and Be stars) we observe spectral lines with complex and peculiar profiles (combination of absorption and emission spectral lines, e.g. P Cygni profiles etc., Fig. 2). The same phenomena also occur in the case of galactic spectra. This means that "normal" galaxies present spectra without emission lines, which are composed spectra of stars from the galaxy. In contrary Active Galactic Nuclei (AGNs) present emission lines (Hα, Hβ) like active Oe and Be stars (Fig. 3). The peculiar lines are always characteristic of the objects with very dynamical processes (accretion, jets, winds etc.). For example, in the case of stars, the peculiar spectral profiles are created in density regions of matter that we can detect quite away from the stellar object (Fig. 4), while in the case of AGNs, accretion, wind (jets, ejection of matter etc.), Broad Line Regions (BLR) and Narrow Line Regions (NLR) are responsible for the construction of the observed peculiar profiles of the spectral lines (Fig. 5).

The spectral lines of hot emission stars and AGNs may be very broad and satellite lines may appear (Fig. 6). An answer for the origin of satellite lines is the matter that exists between the observer and an object (Fig. 7).

CP876, *The Physics of Ionized Gases: 23rd Summer School and International Symposium,*
edited by L. Hadžievski, B. P. Marinković, and N. S. Simonović

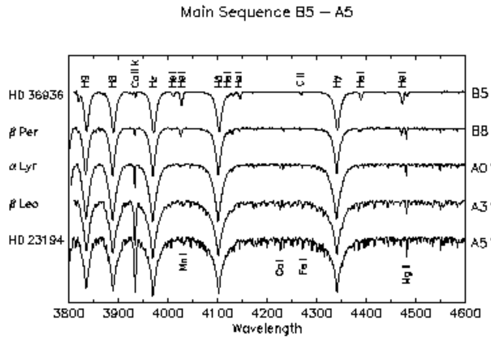

FIGURE 1. Classical Stellar Spectra for different spectral subtype.

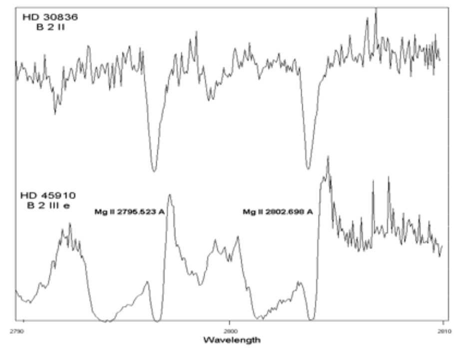

FIGURE 2. Comparison of Mg II resonance lines between the spectrum of a "normal" B star and the spectrum of an active Be star that presents complex and peculiar spectral lines. The combination of an emission and some absorption components construct the P Cygni profile.

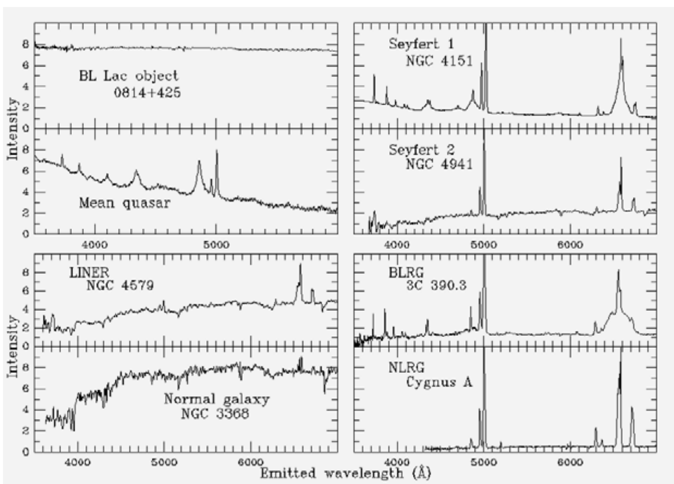

FIGURE 3. Spectra of different types of AGNs.

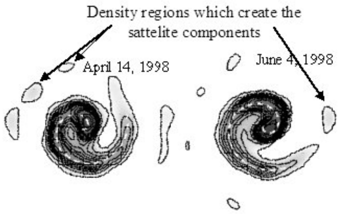

FIGURE 4. Around a Wolf-Rayet star (WR 104) we can detect density regions of matter quite away from the stellar object, able to produce peculiar profiles. (This figure is taken by Tuthill, Monnier & Danchi [1] with Keck Telescope.).

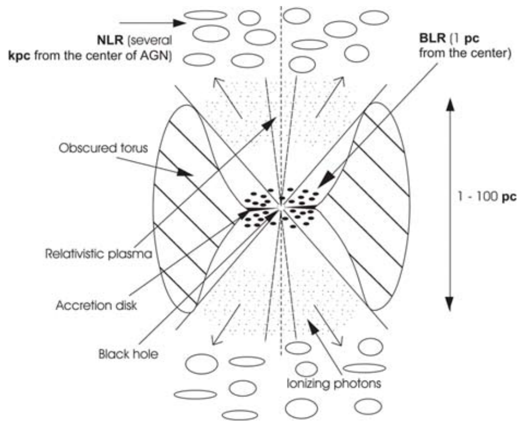

FIGURE 5. In the case of AGNs, accretion, wind (jets, ejection of matter etc.), BLR (Broad Line Regions) and NLR (Narrow Line Regions) are the density regions that construct peculiar profiles of the spectral lines.

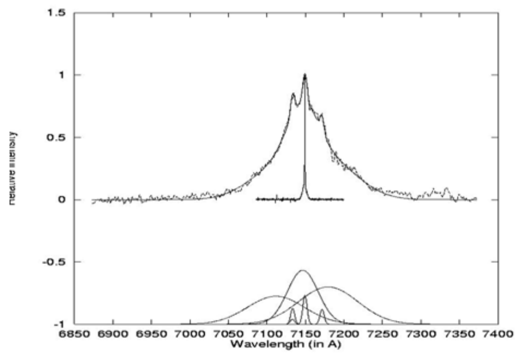

FIGURE 6. Comparison between the observed Hα line of an AGN (III Zw2) with the same line obtained from laboratory plasma. This spectral line is blended with two [NII] satellite lines. The line broadening is a kinematical effect (radial, rotational and random velocities) that arises from the geometry of the emitting region.

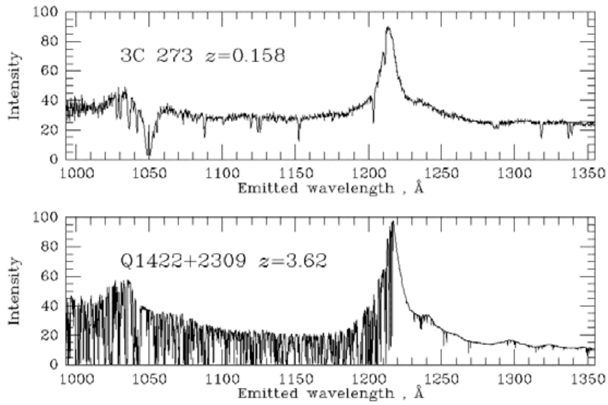

FIGURE 7. Difference between absorption lines in quasar spectra: The absorption lines which are created in the heart of a quasar (up) in comparison with the absorption that can be constructed by matter located between an observer and the quasar.

A MODEL FOR THE REPRODUCTION OF PECULIAR SPECTRAL LINE PROFILES

There are some models to reproduce the observed peculiar profiles in hot emission stars and AGNs. These are several Non-LTE models, which give bad reproduction and several Non-LTE specialized models (e.g. PHOENIX), having very complicated codes that may reproduce the peculiar profiles, but only in some cases.

In order to explain the peculiar profile that we observe in the spectra of hot emission stars and AGNs, Danezis et al. [2, 3] proposed a simple model that is able to explain the structure of the regions that produce these spectral lines. We point out that with this model we can study and reproduce specific spectral lines. This means that we can study specific density regions in the plasma surrounding the studied objects. In order to construct a general model we need to study a number of density regions which produce spectral lines of different ionization potential, meaning different temperature and thus different distance from the studied object.

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

The DACs Phenomenon

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

The line profile of each one of these absorption components is a function of a group of physical parameters, as the radial, the rotational, the random velocities and the optical depth of the region that produces the specific components of the spectral line. These spectral lines were named Discrete Absorption Components (DACs) [4].

DACs are discrete but not unknown absorption spectral lines. They are spectral lines of the same ion and the same wavelength as a main spectral line, shifted at different $\Delta\lambda$, as they are created in different density regions which rotate and move radially with different velocities [2]. DACs are lines, easily observed, in the spectra of some Be stars, because the regions that give rise to such lines, rotate with low velocities and move radially with high velocities (Fig. 8).

It is very important to point out that we can detect the same phenomenon in the spectra of AGNs, so called Broad Absorption Line Quasars (BAL QSOs). In Fig. 9 one can see the C IV UV doublet of the BAL QSO PG 0946+301.

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

The SACs Phenomenon

However, if the regions that give rise to such lines rotate with large velocities and move radially with small velocities, the produced lines have large widths and small shifts. As a result they are blended among themselves as well as with the main spectral line and thus they are not discrete. In such a case the name Discrete Absorption Component is inappropriate and we use only the name Satellite Absorption Components (SACs) [3].

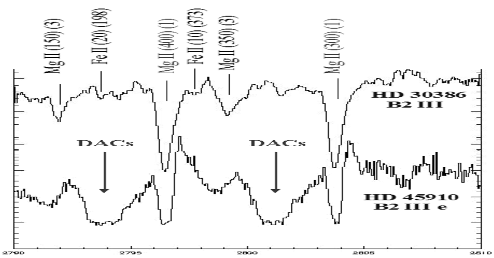

FIGURE 8 Mg II doublet in the UV spectrum of AX Mon, compared with the Mg II lines of the classic B2 star HD30386. In these line profiles we can see the main spectral line and in the left of each one of them a group of DACs.

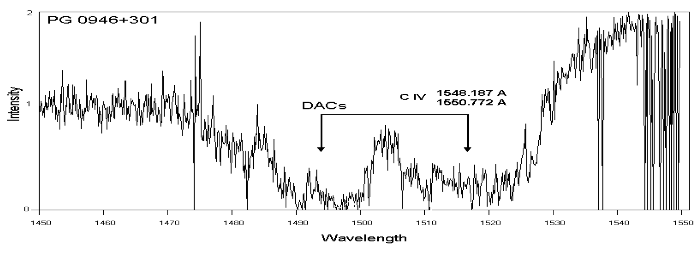

FIGURE 9. C IV UV doublet of the quasar PG 0946+301. We can detect that the two observed C IV shapes indicate the presence of a DACs phenomenon similar to the DACs phenomenon that we can detect in the spectra of hot emission star.

Calculation Of The Peculiar Line Shapes

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

Recently Danezis et al. [2, 3] 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.

The main hypothesis of this model is that the stellar envelope is composed of a number of successive independent absorbing density layers of matter, a number of emission regions and an external general absorption region. By solving the radiation transfer equations through a complex structure, (in more details see [2, 3]) we obtained a function for the line profile, able to give the best fit for the main spectral line and its Satellite Components at the same time:

$$I_{\lambda} = \left[I_{\lambda 0} \prod_{i} e^{-\tau_{ai}} + \sum_{j} S_{\lambda ej} \left(1 - e^{-\tau_{ej}}\right) \right] e^{-\tau_{g}} \qquad (1)$$

where: $I_{\lambda 0}$: is the initial radiation intensity, $S_{\lambda ej}$ is the source function, which, at the moment when the spectrum is taken, is constant and τ is the optical depth in the center of the considered component.

In Eq. (1), the functions $e^{-\tau_{ai}}$, $S_{\lambda ej}\left(1 - e^{-\tau_{ej}}\right)$ and $e^{-\tau_{g}}$ are the distribution functions of each satellite component and we can replace them with a known distribution function (Gauss, Lorentz, Voigt).

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

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

In the case of rapidly rotating hot emission stars, it is very important to insert in the line function (Eq. 1) the rotational, radial and random velocities of the regions which produce the satellite components. In this case we have to assume the geometry for the corresponding regions.

The Spherical Symmetry Hypothesis

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

The spectral line profile was reproduced in the best way when one assumes spherical symmetry for the independent density regions. Such symmetry has been proposed by many researchers [5-11].

However, the independent layers of matter, where a spectral line and its SACs are born, could lie either close to the star, as in the case of the photospheric components of the Hα line in Be stars [12, 13], when spherical symmetry is justified, or at a larger distance from the star, where the spherical symmetry can not be justified.

These lead us to conclude that:

1. In the case of independent density layers of matter which lie close to the star we could suppose the existence of a classical spherical symmetry around the star [5-11].
2. In the case of independent density layers of matter which lie at a larger distance from the photosphere, we could suppose the existence of independent density regions such as blobs, which could cover a substantial fraction of the stellar disk and are outwards moving inhomogeneities, spiral streams or CIRs (Corotating Interaction Regions), which may result from non-radial pulsations, magnetic fields or the stellar rotation and are able to make structures that cover a substantial part of the stellar disk [9, 11, 14-23]. These regions, though they do not present spherical symmetry around the star, they form spectral line profiles which are identical with those deriving from a spherically symmetric structure. In such a case, though the density regions are not spherically symmetric, through their effects on the line profiles, they appear as spherically symmetric structures to the observer.

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

So, in the case of spherical symmetry, Eq. 1 takes the following form:

$$I_\lambda = \left[I_{\lambda 0} \prod_i e^{-L_i \xi_i} + \sum_j S_{\lambda ej} \left(1 - e^{-L_{ej} \xi_{ej}}\right) \right] e^{-L_g \xi_g} \quad (2)$$

where: $I_{\lambda 0}$: is the initial radiation intensity, L_i, L_{ej}, L_g: are the distribution functions of the absorption coefficients $k_{\lambda i}$, $k_{\lambda ej}$, $k_{\lambda g}$, ξ is the optical depth in the centre of the spectral line, $S_{\lambda ej}$: is the source function, that is constant during one observation.

Calculation Of The Distribution Functions L

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

The distribution function (*L*) has the form:

$$\mathrm{L}_{\mathrm{final}}(\lambda) = \frac{1}{2\lambda_0 \mathrm{z}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \left[\mathrm{erf}\left(\frac{\lambda - \lambda_0}{\sqrt{2}\sigma} + \frac{\lambda_0 \mathrm{z}}{\sqrt{2}\sigma} \cos\theta \right) - \mathrm{erf}\left(\frac{\lambda - \lambda_0}{\sqrt{2}\sigma} - \frac{\lambda_0 \mathrm{z}}{\sqrt{2}\sigma} \cos\theta \right) \right] \cos\theta \, d\theta \quad (3)$$

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

$z = \frac{V_{rot}}{c}$ and V_{rot} is the rotational velocity of the region which creates the spectral line.

We use this distribution function $L_{final}(\lambda)$ in the line function $e^{-L\xi}$, when the line broadening is an effect of both the rotational velocity of the density region as well as the random velocities of the ions. This means that now we have a new distribution function to fit every satellite component of a complex line profile that present DACs or SACs. We name this function Gauss-Rotation distribution function (GR distribution function).

In Figs. 10-12 we present the fittings of some hot emission stars and AGNs with the proposed model. The thick line presents the observed spectral line profiles and the thin one the best fits. The differences between the observed spectrum and its fit are some times hard to see, as we have accomplished the best fit.

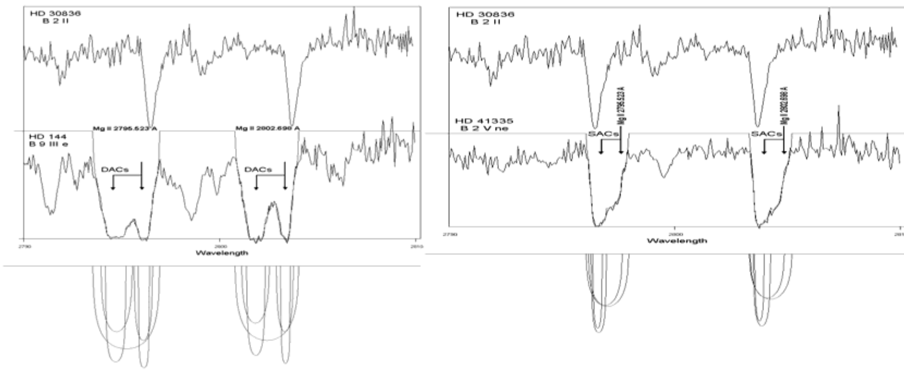

FIGURE 10. Fitting with the proposed model of the Mg II spectral lines of two Be stars that present DACs and SACs, respectively. We point out that we cannot explain and fit these spectral lines with another method. The thick line presents the observed spectral line's profile and the thin one the model fit.

DISCUSSION OF THE PROPOSED MODEL

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

1. It is necessary to check practically and theoretically the presence of blended lines that can deform the line shape as well as the existence of SACs.
2. The resonance lines as well as all the lines originating in a particular region should have the same number of SACs, depending on the structure of this region, without influence of ionization stage or ionization potential of emitters/absorbers. As a consequence, the respective SACs should have similar or same values of the radial and rotational velocities.
3. The ratio of the optical depths in the centre of two resonance lines has to be the same as the ratio of the respective relative intensities.

4. The proposed line function (Eq. 2) can be used in the case that i=1 and j=1, meaning when we deal with simple, classical spectral lines. This means that we can calculate all the important physical parameters, such as the rotational, the radial and the random velocities, the optical depth and the column density, for all the simple and classic spectral lines in all the spectral ranges.
5. We check the correct number of satellite components that construct the whole line profile. At first we fit using the number of the components that give the best difference graph between the fit and the observed spectral line. Then we fit using one component less than in the previous fit. The F-test between them allows us to take the correct number of satellite components that construct in the best way the whole line profile

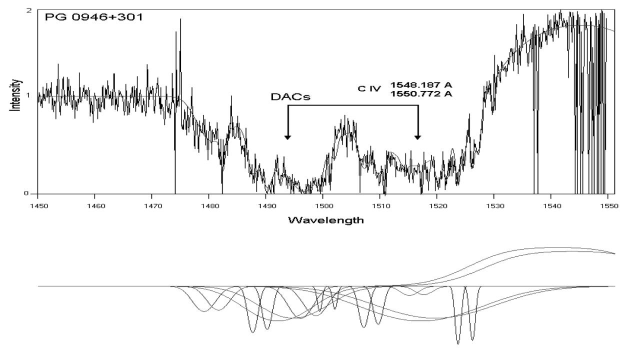

FIGURE 11. Fitting of the C IV UV resonance lines of the BAL QSO PG 0946+301, that present DACs, with the proposed model. We point out that we cannot perfectly fit these spectral lines with another model. The thick line presents the observed spectral line profile and the thin one the model fit.

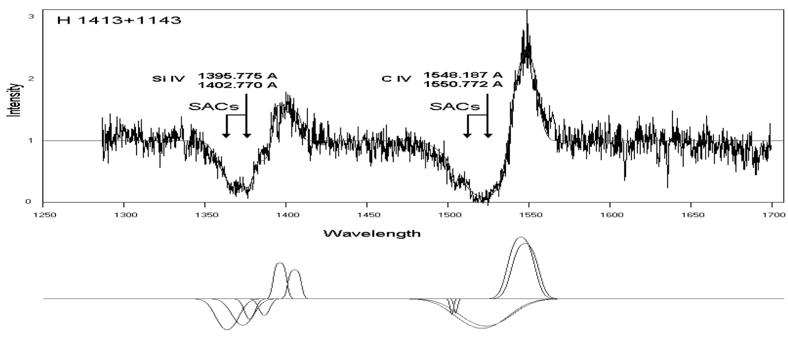

FIGURE 12. Fitting of the Si IV and C IV resonance lines of the BAL QSO H 1413+1143, that present SACs with the proposed model. The SACs phenomenon is able to explain the observed shape. We point out that we cannot perfectly fit these spectral lines with another model. The thick line presents the observed spectral line profile and the thin one the model fit.

TESTING THE MODEL

In order to check the spectral line function (Eq. 2), we calculated the rotational velocity of the He I absorption line at λ 4387.928 Å for five Be stars, using two methods, the classical Fourier analysis and our model. The rotational velocities that we calculate with both methods are almost the same.

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

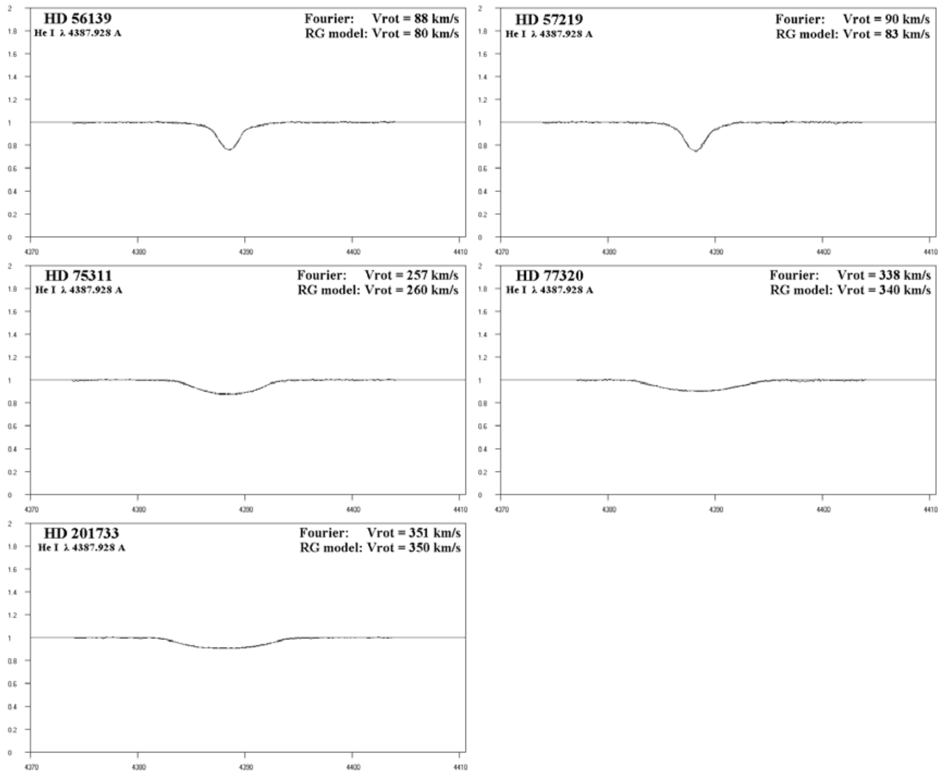

FIGURE 17. The five He I λ 4387.928 Å fittings for the studied Be stars and the measured rotational velocities with both methods. The results are favorable for our model. The thick line presents the observed spectral line profile and the thin one the model fit.

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

We apply the model on the C IV line profiles of 20 Oe stellar spectra taken with the IUE –satellite (IUE Database http://archive.stsci.edu/iue).

We examine the complex structure of the C IV resonance lines (λλ 1548.155 Å, 1550.774 Å). Our sample includes the subtypes O4 (one star), O6 (four stars), O7 (five stars), O8 (three stars) and O9 (seven stars). The values of the photospheric rotational velocities are taken from the catalogue of Wilson [24].

After the study of the C IV spectral lines we detect two components in 9 stars, three in 7 stars, four in 3 stars and five in one star. The results that we present in these figures are favourable for our model. The differences between the average values of the random velocities of the satellite components arise from the small variations of the temperature that exist in each one of the regions that produce the satellite components.

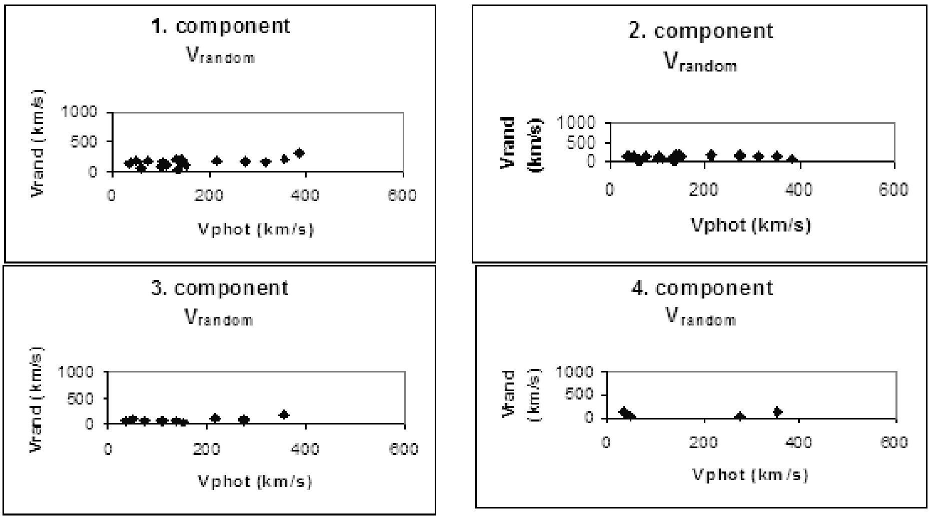

FIGURE 18. Relation between the random velocities and the photospheric rotational velocities of the studied stars.

CONCLUSIONS

We presented an overview of peculiar line profiles from stars to AGNs and a model that can describe peculiar lines.

Here we give some of our conclusions:

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

ACKNOWLEDGMENTS

This research project is progressing at the University of Athens, Department of Astrophysics, Astronomy and Mechanics, under the financial support of the Special Account for Research Grants, which we thank very much. This work also was supported by Ministry of Science and Environment Protection of Serbia, through the projects "Influence of collisional processes on astrophysical plasma line shapes" and "Astrophysical spectroscopy of extragalactic objects".

REFERENCES

1. P. Tuthill, J. Monnier and W. Danchi, *Nature*, **398**, 487 (1999).
2. E. Danezis, D. Nikolaidis, V. Lyratzi, M. Stathopoulou, E. Theodossiou, A. Kosionidis, C. Drakopoulos, G. Christou and P. Koutsouris, *Ap&SS*, **284**, 1119 (2003).
3. E. Danezis, D. Nikolaidis, E. Lyratzi, L. Č. Popović, M. S. Dimitrijević, E. Theodossiou and A. Antoniou, *Mem. S.A.It.Suppl.*, **7**, 107-113 (2005).
4. B. Bates and D. R. Halliwell, *Mon. Not. R. Astr. Soc.* **223,** 673-681 (1986).
5. H. J. G. L. M. Lamers, R. Gathier and T. P. Snow, *Ap. J.,* **258**, 186 (1982).
6. B. Bates and S. Gilheany, *Mon. Not. R. Astr. Soc.*, **243**, 320 (1990).
7. S. Gilheany, B. Bates, M. G. Catney and P. L. Dufton, *Ap&SS*, **169**, 85 (1990).
8. W. L. Waldron, L. Klein and B. Altner, *nvos.work*, 181(1992).
9. Th. Rivinius, O. Stahl, B. Wolf, A. Kaufer, Th. Gäng, C. A. Gummersbach, I. Jankovics, J. Kovács, H. Mandel, J. Peitz, Th. Szeifert and H. J. G. L. M. Lamers, *A&A*, **318**, 819 (1997).
10. L. S. Cidale, *Ap. J.*, 502, 824 (1998).
11. Markova, N.: 2000, *A&A, Supl. Ser.*, 144, 391.
12. Y. Andrillat and Ch. Fehrenbach, *A&A Supl. Ser.,* **48**, 93-136 (1982).
13. Y. Andrillat, *A&A, Supl. Ser.*, **53**, 319-338 (1983).
14. S. R. Cranmer and S. P. Owocki, *Ap. J.*, **462**, 469 (1996).
15. A. W. Fullerton, D. L. Massa, R. K. Prinja, S. P. Owocki and S. R. Cranmer, *A&A*, **327**, 699 (1997).
16. S. R. Cranmer, M. A. Smith and R. D. Robinson, *Ap. J.*, **537**, 433 (2000).
17. D. J. Mulan, *Ap. J.*, **283**, 303 (1984a).
18. D. J. Mulan, *Ap. J.*, **284**, 769 (1984b).
19. D. J. Mulan, *A&A*, **165**, 157 (1986).
20. R. K. Prinja and I. D. Howarth, *Mon. Not. R. Astr. Soc.*, **233**, 123 (1988).
21. L. Kaper, H. F. Henrichs, J. S. Nichols, L. C. Snoek, H. Volten and G. A. A. Zwarthoed, *A&A Supl. Ser.,* **116**, 257 (1996).
22. L. Kaper, H. G. Henrichs, A. W. Fullerton, H. Ando, K. S. Bjorkman, D. R. Gies, R. Hirata, E. Dambe, D. McDavid and J. S. Nichols, *A&A*, **327**, 281 (1997).
23. L. Kaper, H. F. Henrichs, J. S. Nichols and J. H. Telting, *A. & Ap.*, **344**, 231 (1999).
24. R. E. Wilson, *General Catalogue Of Stellar Radial Velocities,* Washington, Carnegie Institution of Washington Publication 601, (1963).