Bulletin de la Société Royale des Sciences de Liège, Vol. 80, 2011, p. 86 - 91

Macroturbulent broadening in Massive Stars and its possible connection to Stellar Oscillations

S. Simón-Díaz[1,2]

[1] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain.
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain

Abstract: In this contribution, I review what we have learnt about macroturbulent broadening in the last decade and present first results of a long term observational project aimed at investigating the possible connection between this spectroscopic feature and the stellar variability phenomena and oscillations.

1 Introduction

1.1 Macroturbulent and rotational broadenings in OB stars

Macroturbulent[1] broadening is the name commonly assigned to a type of non-rotational broadening observed in the line profiles of B Supergiants (Sgs). It was first invoked to explain the lack of narrow line spectra in the first large spectroscopic databases of these objects (Slettebak 1956, Conti & Ebbets 1977). This was a puzzling result since the rotational velocity of a star is expected to decrease when it evolves from an O Main Sequence star to a B Sg due to the increase in stellar radius and mass loss rate. In addition, in a large enough sample, some of the B Sgs should have low $v\,\sin i$ values (from the statistical distribution of the inclination angle, i). From those observations it was concluded that an extra broadening (probably associated to macroturbulent motions in the outer layers of the star) was affecting the spectra of B Sgs.

The presence of this extra broadening, differing in shape from rotational broadening, can be perfectly identified in high resolution spectra (see Fig. 1). The figure presents the Si III 4552 line in the spectra of three stars: the left panel shows a narrow lined early B-type star in which the effect of the rotational broadening is very small, either because the star rotates slowly, or because the star is seen (almost) pole-on; the other panels show two stars selected to illustrate a case in which the rotational broadening dominates (middle panel) and a case in which a non negligible contribution of the *macroturbulent* broadening is present (right panel). It is important to remark that (i) the shape of the line profile of the stars at the far right in Fig. 1 is a consequence of the effect of both broadening contributions, and (ii) *macroturbulent* broadening must not be confused with microturbulent broadening (which is present in the three line profiles).

[1]From now on this word will be written in italics, to emphasize that macroturbulent broadening is unlikely related to large scale turbulence as explained in the text.

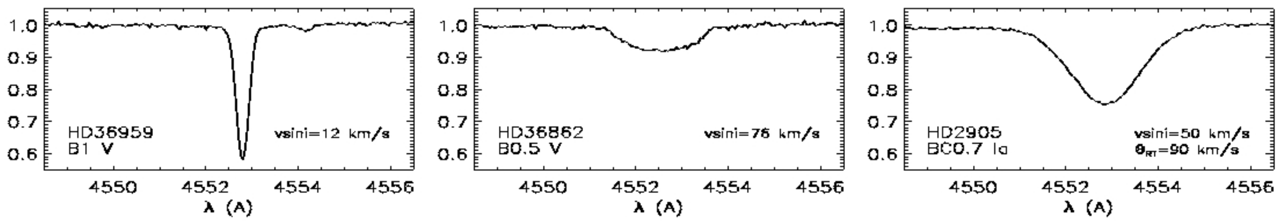

Figure 1: Three illustrative examples of Si III line profiles affected by different broadening mechanisms. The spectra are taken from the IACOB spectroscopic database.

1.2 Characterization of the macroturbulent broadening

The advent of high resolution spectroscopic observations of B Sgs enabled the development of methods to disentangle and measure relative contributions of rotation and extra broadening mechanisms. Two main techniques have been proposed. Ryans et al. (2002) applied a goodness-of-fit method to a sample of high quality spectra of B Sgs, and obtained acceptable results for a model in which the *macroturbulent* broadening dominates and rotation is negligible. However, the reliability of this method is limited by two facts: first, there is degeneration of line profiles for different pairs ($v \sin i$, $v_{\rm mac}$); and second, results depend on the type of profile considered for the *macroturbulent* broadening (e.g. Gaussian, radial-tangential; see Simón-Díaz et al. 2010). Simón-Díaz & Herrero (2007), following Gray (1976), investigated the applicability of the Fourier transform (FT) method in the case of OB-type stars. The strength of this method is that it can separate the rotational broadening from any other broadening mechanism using the FT of a line profile[2]. This method probed to be very powerful and has been increasingly used for the determination of projected rotational velocities in O and B stars ever since.

But the determination of $v \sin i$ is only half of the way; the size of the extra broadening still needs to be determined. The easiest way is to consider metal lines, not affected by other important broadenings (basically Stark broadening) as are the He I and He II lines. There are again two methods to do so (based on the goodness-of-fit method or on the fitting of the first lobe of the FT), but in both cases one has to decide the type of profile defining the extra broadening. Two cases have been investigated (see e.g. Dufton et al. 2006, Aerts et al. 2009, and Simón-Díaz et al. 2010): an isotropic Gaussian profile, and a radial-tangential Gaussian profile. Indirect arguments obtained by the comparison of the $v \sin i$ derived by means of the FT method and the goodness-of-fit method using both types of profiles allowed Simón-Díaz et al. (2010) to prefer the latter.

One can also use He I and He II lines, but in this case, appropriate stellar atmosphere code predictions for these lines need to be used to account for the Stark broadening. The determination of the stellar parameters and the extra broadening must be performed at the same time.

1.3 *Macroturbulent* broadening in B Sgs

In the past decade several studies using both the FT and goodness-of-fit methods have derived *macroturbulent* broadening from the Si III 4552 line profile in B Sgs (see Dufton et al. 2006, Lefever et al. 2007; Markova & Puls 2008, Fraser et al. 2010). These studies have taught us that (i) the size of this extra broadening increases from late- to early-B Sgs (see Fig. 1 in Simón-Díaz et al. 2010), and

[2]Two important remarks to keep in mind: (i) this argument is only valid under the hypothesis considered by the convolution method, which assumes that the effects of the different broadening mechanisms act independently to broaden the emergent flux profile; (ii) the $v \sin i$ provided by the FT method may differ from its actual value in the case of highly asymmetric profiles.

(ii) if interpreted as turbulent motions, *macroturbulent* broadening would represent highly supersonic velocities in most of the cases.

Since the extra broadening is present in photospheric lines and affects the whole profile, even wavelengths close to the continuum (i.e. whatever is producing this broadening has to be deeply rooted in the stellar photosphere, and possibly deeper, in layers where we do not expect any significant velocity field in these stars), the interpretation of this extra broadening as the effect of turbulent motion is quite improbable.

1.4 What is the physical origin of macroturbulent broadening in massive stars?

One physical mechanism suggested as the origin of this extra broadening relates to oscillations. Many OB Sgs show photometric and spectroscopic variability. Lucy (1976) postulated that this variability might be a pulsation phenomenon, and macroturbulence may be identified with the surface motions generated by the superposition of numerous non-radial oscillations. More recently, Aerts et al. (2009) computed time series of line profiles for an evolved massive star broadened by rotation and thousands of low amplitude non-radial gravity mode oscillations and showed that the resulting profiles could mimic the observed ones.

Stellar oscillations are hence a plausible explanation for the extra broadening in B Sgs, but this hypothesis needs to be confirmed observationally.

2 The project, observational data set and first results

2.1 Aim of the project

In 2008, we began a long term observational project aimed at investigating the macroturbulent broadening in O and B stars and its possible connection to spectroscopic variability phenomena and stellar oscillations. The project is a joint international collaboration between researchers in Spain (IAC: S. Simón-Díaz (PI), A. Herrero, N. Castro), France (CEA-Saclay: K. Uytterhoeven), Germany (USM: J. Puls), Belgium (KULeuven: C. Aerts) and Bulgaria (IA-NOA, N. Markova).

2.2 Observational data set

Our initial observational dataset is based on spectra obtained with FIES@NOT (see *The IACOB spectroscopic database of Northern Galactic OB stars*, Simón-Díaz et al. 2011). The IACOB database includes high resolution, high signal-to-noise ratio spectroscopic observations in the optical range of $\sim$100 O and B stars in our Galaxy, along with short time-series observations (two 4 nights campaigns in 2008 and 2009) for a selected sample of candidates.

The IACOB observations will continue in the next semesters. In addition, we have been awarded several additional nights to obtain new time series of spectra with the 1.2 m MERCATOR telescope at Roque de los Muchachos observatory (Spain) and the 2 m BG NAO telescope (Bulgaria).

2.3 First results

2.3.1 Macroturbulent broadening: also present in the O star domain

The investigation of *macroturbulent* broadening in massive stars has been constrained to B Sgs so far. The main reason is that there are many isolated, strong metal lines in the optical spectrum of this type of stars. The usual lines considered for this study are Si III 4552, Si II 4130, and/or C II 4267. In the case of O stars, there are not many isolated, strong metal lines available, and the determination of *macroturbulence* broadening by means of He I and He II lines is not so straightforward.

A careful examination of the IACOB spectroscopic database has allowed us to identify one metal line appropiate for the determination of $v \sin i$ and the size of the extra broadening in the case O stars: the O III 5592 line. From the analysis of this line we have been able to confirm for the first time in a systematic way that the extra broadening is not only present in B Sgs, but also in O-type stars[3] of all luminosity classes (see Simón-Díaz et al. 2011). Interestingly, the increasing trend of the size of the extra broadening with spectral type previously found for B Supergiants continues in the O star domain. In addition, there is a clear separation between dwarfs, giants and supergiants.

2.3.2 Observational evidence for a correlation between macroturbulent broadening and line-profile variations in early B Sgs

In Simón-Díaz et al. (2010), we analysed the spectroscopic time series of the selected bright candidates obtained with FIES@NOT (13 early-B Sgs, complemented with 2 early-B dwarfs and 2 late-B Sgs). In agreement with earlier studies of spectroscopic variability in O and B Sgs (e.g. Howarth et al. 1993; Fullerton, Gies & Bolton, 1996; Prinja et al., 2004; Morel et al. 2004; Kaufer et al. 2006; Markova et al. 2008), we found clear signatures of line-profile variations (LPVs). To quantify these LPVs, we used the first and third moments of the line profiles ($\langle v \rangle$ and $\langle v^3 \rangle$, see Aerts, Christensen-Dalsgaard & Kurtz, 2010, for definitions).

We applied a combined FT + goodness-of-fit method to the Si III 4567 or O III 5592 lines in the time-series spectra, assuming a radial-tangential Gaussian definition to characterize the *macroturbulent* broadening, to obtain $v \sin i$ and the size of the extra broadening ($\Theta_{\rm RT}$). We then investigated the possible connection between *macroturbulent* broadening and the detected LPVs, finding a clear positive correlation between the average size of the macroturbulent broadening, $\langle \Theta_{\rm RT} \rangle$, and the peak-to-peak amplitude of $\langle v \rangle$ and $\langle v^3 \rangle$ variations. To our knowledge, this was the *first clear observational evidence for a connection between extra broadening and LPVs in early B and late O Sgs.* Interestingly, a similar trend can be obtained from the simulations by Aerts et al. (2009).

2.4 A *macroturbulent* broadening – stellar oscillations connection?

Non-radial oscillations have often been suggested as the origin of LPVs in photospheric lines in OB Sgs, as well as the driver of large scale wind structures; however, a firm confirmation (by means of a rigorous seismic analysis) has not been achieved yet. From a theoretical point of view g-mode oscillations can occur (e.g. Saio et al, 2006, Lefever et al. 2007). The latter results, along with our observational confirmation of a tight connection between macroturbulence and LPVs render stellar oscillations the most probable physical origin of macroturbulent broadening in B Sgs; however, it is too premature to consider them as the only physical phenomenon explaining the unknown broadening.

2.5 The future of the project

First results from our project are encouraging; however, there are still some things to be done before firmly concluding that *macroturbulent* broadening in massive stars should be actually called **pulsational broadening**. One of the tasks we plan to accomplish in the near future is the quantitative spectroscopic analysis of the stars included in the IACOB database to locate them in the ($\log T_{\rm eff}$, $\log g$) diagram. By overplotting the instability strips in this diagram, we want to investigate whether

[3]Similar results have been obtained from the analysis of a small sample of low luminosity O-type stars using model fitting (N. Markova, priv. comm.).

there is a correlation between candidates in which stellar oscillations are expected and the appearance of the *macroturbulent* broadening. We also plan to extend the type of study performed for early B Sgs to other candidates in the O star domain. Finally, with the time series of spectra we are gathering for selected candidates, we aim at investigating the temporal behaviour of the LPVs. From the preliminary analysis of the time-series spectra already obtained (see Simón-Díaz et al. 2009) we have found that the RV variations in the B Sgs suggest variabilities on two time-scales: variations of the order of half a day to several days, with amplitudes of the order of 1-9 $\mathrm{km\,s^{-1}}$, and a faster variation of tens of minutes at low amplitude (< 2 $\mathrm{km\,s^{-1}}$). However, this analysis is limited by the severe aliasing resulting from the short time span of the time series. Therefore, to step forward in our project towards a pulsational analysis of selected targets, it is necessary to increase as much as possible the time span of our temporal series. This is needed to resolve the frequencies properly in order to interpret them in terms of stellar oscillations.

The confirmation of the macroturbulent-pulsation connection will open a bright future in the realm of massive stars, not only in terms of traditional, time-independent, spectroscopic analysis, but also from a seismic point of view. Both studies will provide independent observational constraints to models of stellar structure and evolution of massive evolved stars.

Acknowledgements

I'm really grateful for the help, support, and useful comments of the people in the collaboration.

References

Aerts, C., Christensen-Dalsgaard, J. & Kurtz, D. W. 2010, *Asteroseismology* (Berlin: Springer)

Aerts, C., Puls, J., Godart, M. & Dupret, M.-A. 2009, A&A, 508, 409

Conti, P. S. & Ebbets, D. 1977, ApJ, 213, 438

Dufton, P. L., Ryans, R. S. I., Simón-Díaz, S., Trundle, C. & Lennon, D. J. 2006, A&A, 451, 603

Fraser, M., Dufton, P. L., Hunter, I. & Ryans, R. S. I. 2010, MNRAS, 404, 1306

Fullerton, A. W., Gies, D. R. & Bolton, C. T. 1996, ApJS, 103, 475

Gray, D. F. 1976, *The Observations and Analysis of Stellar Photospheres*, 1st ed. (New York: Wiley)

Howarth, I. D., Bolton, C. T., Crowe, R. A., Ebbets, D. C., Fieldus, M. S., Fullerton, A. W., Gies, D. R., McDavid, D., et al. 1993, ApJ, 417, 338

Kaufer, A., Stahl, O. Prinja, R. K. & Witherick D. 2006, A&A, 447, 325

Lefever, K., Puls, J., & Aerts, C. 2007, A&A, 463, 1093

Lucy, L. B. 1976, ApJ, 206, 499

Markova, N., Prinja, R. K., Markov, H., Kolka, I., Morrison, N., Percy, J., & Adelman, S. 2008, A&A, 487, 211

Markova, N. & Puls, J. 2008, A&A, 478, 823

Morel, T., Marchenko, S. V., Pati, A. K., Kuppuswamy, K., Carini, M. T., Wood, E. & Zimmerman, R. 2004, MNRAS, 351, 552

Prinja, R. K., Rivinius, T., Stahl, O., Kaufer, A., Foing, B. H., Cami, J. & Orlando, S. 2004, A&A, 418, 727

Ryans, R. S. I., Dufton, P. L., Rolleston, W. R. J., Lennon, D. J., Keenan, F. P., Smoker, J. V. & Lambert, D. L. 2002, MNRAS, 336, 577

Saio, H., Kuschnig, R., Gautschy, A., Cameron, C., Walker, G. A. H., Matthews, J. M., Guenther, D. B., Moffat, A. F. J., et al. 2006, ApJ, 650, 1111

Simón-Díaz, S., Herrero, A., Uytterhoeven, K., Castro, N., Aerts, C. & Puls, J. 2010, ApJ, 720, L174

Simón-Díaz, S., Uytterhoeven, K., Herrero, A. & Castro, N., 2009, AIPC, 1170, 397

Simón-Díaz, S. & Herrero, A. 2007, A&A, 468, 1063

Simón-Díaz, S., Castro, N., Garcia, M., Herrero, A., & Markova, N. 2011, in Proceedings of the 39th Liège Astrophysical Colloquium, eds. G. Rauw, M. De Becker, Y. Nazé, J.-M. Vreux & P.M. Williams, BSRSL 80, 514

Slettebak, A. 1956, ApJ, 124, 173

Discussion

J. Sundqvist: About using the Fourier Transform (FT) method to infer $v \sin i$ when macrotubulence is important. It was shown by Aerts and colleagues that if indeed macroturbulence is due to pulsations, then the FT method may give you erroneous estimate of $v \sin i$. Can you comment on this?
S. Simón-Díaz: You are right; this conclusion arises from the analysis of the simulated profiles by Aerts et al., and it is also based on well established arguments (e.g. the FT technique must be used with care in the case of asymmetric profiles). This is something we are also investigating in our observational project. In the analysis of the time series observations we have found that the $v \sin i$ provided by the FT and goodness-of-fit methods (when a radial-tangential definition of macroturbulence is assumed) are in quite good agreement. In addition the dispersion of $v \sin i$ values, derived by both methods is similar, and not as large as the one found from the analysis of Aerts et al. simulations. Finally, we have found cases in which macroturbulence is quite large and the first zero of the FT from the time series profiles is quite stable.
We are planning to apply the FT technique in well known pulsators in which $v \sin i$ is derived independently by means of a seismic analysis. We are also investigating whether there is any correlation between the third moment of the line profile and the position of the first zero in the FT. Note that in case of $\langle v' \rangle = 0$ the line is symmetric and the FT should be giving right $v \sin i$ values.
J. Puls: This comment also refers to the talk by Fabrice Martins. It has to be noted that the positions of the first zero's in the Fourier Transform (FT) (related to $v \sin i$) remain unaffected from extra-broadening only if the broadening function can be described by certain functions, by a Gaussian (or related functions). When the broadening would be due to the collective effects from oscillations, this is not longer true, as shown by Aerts et al. (2009). In so far, the different positions of the first zero's in the FTs as a function of time (as shown by Sergio Simón-Díaz) are consistent with the hypothesis of a relation to pulsations.

I. Antokhin: In your fits of spectral line profiles, do you take into account gravitational darkening?
S. Simón-Díaz: No. In these stars the rotational velocities are not expected to be very large. So gravitational darkening is negligible.