Macroturbulent broadening: a single snap-shot approach to investigate pulsations in massive stars?

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Abstract. We present a brief progress report of our project aimed at the investigation of the so-called macroturbulent broadening affecting the line-profiles of O and early B-type stars, and speculate about the possible use of this spectroscopic feature as a single snap-shot approach to investigate pulsations in massive stars.

1. Introduction

In addition to the mass and the stellar wind properties, stellar rotation is also a crucial parameter for the evolution of massive stars (e.g. Maeder & Meynet\textsuperscript{2000}, and the associated series of papers in the last two decades). The advent of CCD detectors and high resolution spectrographs has made it possible to confirm the hypothesis proposed\textsuperscript{1} by several authors (e.g. Slettebak\textsuperscript{1956}, Conti & Ebbets\textsuperscript{1977}, Howarth et al.\textsuperscript{1997}, and references therein) that rotation is not the only dominant broadening agent shaping the metal line-profiles in OB type stars. A type of extra-broadening, usually claimed to be associated with large scale velocity fields, and even called macroturbulent broadening at some point, is clearly contributing to the total broadening in these stars (Simón-Díaz & Herrero\textsuperscript{2007}; Dufton et al.\textsuperscript{2006}; Lefever et al.\textsuperscript{2007}; Markova & Puls

\textsuperscript{1}At this time, this hypothesis was based on indirect arguments such as, for example, the small number of narrow lined O type stars and B supergiants (B Sgs) found in the analyzed samples.
The main consequence of this confirmation is that previous determinations of projected rotational velocities in OB stars need to be revised. In addition, other important issues such as, e.g., what is the physical origin of this apparently ubiquitous line-broadening, or what is the impact of this phenomenon on our knowledge of massive star evolution also arise from this observational result. These questions will certainly be treated in the next years. We refer the reader to Simón-Díaz (2011) for a detailed review on the advances on this topic in the last years (some of them updated here). In this contribution we concentrate on recent advances of the IACOB project (P.I. Simón-Díaz) concerning the characterization of the macroturbulent broadening, and speculate about one possible application of this spectroscopic feature that came up while working on this project: Aerts et al. (2009) have recently revived the suggestion that macroturbulent broadening may be identified with the surface motions generated by the superposition of numerous high order non-radial oscillations. If this hypothesis is finally confirmed on observational grounds, could hence macroturbulent broadening be used as a single snap-shot approach to investigate pulsations in massive stars?

2. The IACOB project: line-broadening in OB stars

The IACOB spectroscopic survey of Galactic OB stars is an ambitious observational project which has compiled the largest homogeneous, high-resolution database of optical spectra of massive stars observable from the Northern hemisphere to date. The IACOB project aims at the scientific exploitation of this unique spectroscopic dataset. One of the drivers of this survey is the characterization of the macroturbulent broadening in the whole massive star domain, and the investigation of its physical origin. Two type of observations were hence planned within the project. On the one hand, we observed a large sample of O and early-B type stars (including dwarfs, giants and supergiants up to B2) to measure their projected rotational velocities and quantify the amount of extra-broadening present in these stars. On the other hand, we are obtaining time series of spectroscopic observations for a small sample of selected (bright) candidates to investigate the possible pulsational origin of this extra-broadening. Some results of this investigation are indicated below.

2.1. Characterization of the line broadening in OB stars

The analysis of the IACOB spectra using a combined technique based on the Fourier transform (FT) and goodness-of-fit (GOF) methods (Simón-Díaz et al., in prep.) is allowing to review previous determinations of projected rotational velocities and characterize the extra-broadening in ~ 150 Galactic OB stars. Preliminary results from this study (Fig. 1) indicate that the extra-broadening is a common feature not only in B Sgs, but also in B giants and O-type stars of all luminosity classes.

The first obvious consequence of this analysis is that previous $v \sin i$ determinations in OB stars not accounting for the extra-broadening must be revised downwards

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2 Already Lucy (1976) suggested a pulsational origin of the macroturbulent broadening.

3 A similar result has also been found from an independent study by Markova et al. (2011).
Macroturbulent broadening and pulsations in massive stars

Figure 1. Projected rotational velocities ($v \sin i$) and size of the macroturbulent broadening (characterized here assuming a radial-tangential Gaussian broadening profile, $\Theta_{RT}$, see Simón-Díaz 2011) from a sample of IACOB spectra. Note that only stars with $v \sin i \leq 100$ km s$^{-1}$ are included in these plots. The accurate determination of the extra-broadening contribution in stars with larger $v \sin i$ is complicated by subtle effects (e.g. the placement of the continuum in the fitting process) which require a more careful study, and hence have been excluded for the moment.

in many cases. In addition, the ubiquitous presence of the macroturbulent broadening makes it very important to investigate the physical driver of this extra-broadening and its implications on the evolution and the stellar and wind properties of massive stars.

2.2. Should macroturbulent broadening in massive stars be actually called pulsational broadening?

Non-radial pulsations (NRP) as the shaping agent of the line-profiles of OB stars in addition to stellar rotation were suggested by Lucy (1976) and Aerts et al. (2009) as a likely explanation for the macroturbulent broadening. In Simón-Díaz et al. (2010) we presented the first observational evidence of the existence of a tight connection between the size of this extra-broadening and parameters describing observed line-profile variations (LPVs) in a sample of 13 Sgs with spectral types ranging from O9.5 to B8. This result renders stellar oscillations the most probable physical origin of the extra-broadening in B Sgs. However, this is not the last word, some other tests are needed to firmly declare NRP as the only physical phenomenon to explain the unknown broadening: (i) the same type of result should be reproduced for other stars in which the extra-broadening is detected (including OB dwarfs, giants and supergiants); (ii) it must be observationally confirmed that the temporal behavior of the observed LPVs is compatible with the type of oscillations considered by Aerts et al. (2009); (iii) stars with a substantial macroturbulent broadening must be located inside the predicted instability strips in which stellar pulsations occur (or an even stronger constraint, stars outside instability strips should not show any extra-broadening).

We are investigating these three points in parallel within the IACOB project. A preliminary analysis of time series spectra of four new targets (classified as O7.5 Iabf, O9.5 Iab, O6.5 V((f))z, and B1 I, respectively) obtained with the Mercator telescope during 8 nights seems to fit into the correlation found by Simón-Díaz et al. (2010).
The second point requires long and extensive time series. In the last two years we have been compiling new high-resolution time series spectra for some of the stars studied in Simón-Díaz et al. (2010) (plus the four stars mentioned above) using the 1.2m Mercator and 2.5 m NOT telescopes at the Roque de los Muchachos observatory (La Palma, Spain) and the 2 m NAO telescope at the Rozhen observatory (Bulgaria). The analysis of these observations is now in progress.

Regarding the last point, we are performing the quantitative spectroscopic analysis of the whole IACOB sample by applying the automatic tools presented in Simón-Díaz (2011) and Castro et al. (2012). Figure 2 indicates the location of ~40 stars with spectral types ranging from O4 to B2 (including dwarfs, giants, bright giants and supergiants) in the $\log g - \log T_{\text{eff}}$ diagram along with the instability domains for p- and g-mode oscillations predicted by Pamyatnykh (1999), Saio et al. (2006), and Miglio et al. (2007). Three groups of stars with increasing size of the extra-broadening are indicated in blue ($\lesssim 20$ km s$^{-1}$), green ($20-40$ km s$^{-1}$), and red ($\geq 40$ km s$^{-1}$), respectively. It is important to remark that this figure represents a preliminary overview of the work in progress. However, it is already interesting to see the distribution of points corresponding to stars with different characteristics (size) of the extra-broadening. In particular, it is remarkable that while red and blue dots seem to support the pulsational origin (as considered by Aerts et al., i.e., originated by low amplitude, high-order g modes), the presence of green dots outside the instability domains motivates the investigation of the possibility that other types of pulsations could also mimic the macro-

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4Detected binary stars are excluded from this analysis.

5This refers mainly to the instability domains provided in the figure. While for stars with masses $\leq 18 M_\odot$ we consider the new (revised) computations by Miglio et al. (2007) and Saio et al. (2006), for larger masses the plotted instability domain refers to the old computations by Pamyatnykh (1999). Although not included in the figure, we are aware of the recent works by Saio (2011) and M. Godart (PhD thesis, priv. comm.) which we plan to incorporate to our study.
Macroturbulent broadening and pulsations in massive stars

Macroturbulent broadening profiles and OB dwarfs and giants. Indeed, low-amplitude low-order p and g modes occur in stars in that part of the HRD and the beating between such modes can also give rise to extra-broadening whenever the modes are not properly resolved in a full pulsational analysis (see, e.g., [Morel et al. 2006]).

3. Macroturbulent broadening: a single snap-shot approach to investigate pulsations in massive stars?

Observational asteroseismology is a very important field of stellar Astrophysics, but also very expensive in terms of observational time. The resulting information extracted from the seismic data (and its modeling) of a given star is unique, since it is the only way to have access to the properties of the stellar interiors. However, very long and extensive time series of photometric and spectroscopic observations are needed to this aim. Obviously, there is no other way to be able to do a proper frequency analysis and mode identification, necessary for a seismic modeling; but, if the macroturbulent broadening – NRP connection is finally confirmed, this spectroscopic feature may perhaps also be used as a first, less expensive approach to investigate pulsations in massive stars. In particular, with just one spectrum of a given star (we need the spectrum to have a certain resolving power, but a very large signal-to-noise is not requested) we would be able to say if the star is pulsating in the way expected from the fact that a macroturbulent line shape is observed. We could hence analyze large samples of OB stars of different spectral types and luminosity classes and easily conclude which of them have the “same kind of” pulsational properties (roughly speaking!). We could then correlate the size of the extra-broadening with other stellar and wind properties. We could also select candidates to obtain the spectroscopic and photometric time series necessary for a proper seismic modeling, as in [Schrijvers et al. 2004]. We may also use the type of result presented in Fig. 2 to obtain to a first order observational constraints for the predicted instability domains for the type of pulsations where this spectroscopic feature is expected. In view of this promising possibilities, the characterization and investigation of this extra line-broadening in the context of stellar pulsations is more than justified.

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6A similar type of study was performed by [Telting et al. 2006] for the case of early B-type near-main sequence stars without emission lines.
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