

## On the origin of macroturbulence in hot stars

C. Aerts<sup>1,2</sup>, J. Puls<sup>3</sup>, M. Godart<sup>4</sup>, M.-A. Dupret<sup>5</sup>

<sup>1</sup> Instituut voor Sterrenkunde, Celestijnenlaan 200D, B-3001 Leuven, Belgium

<sup>2</sup> Department of Astrophysics, IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL, Nijmegen, the Netherlands

<sup>3</sup> Universitäts-Sternwarte, Scheinerstrasse 1, D-81679 München, Germany

<sup>4</sup> Institut d'Astrophysique et Géophysique, Université de Liège, allée du Six Août 17, B-4000 Liège, Belgium

<sup>5</sup> Observatoire de Paris, LESIA, 5 place Jules Janssen, 92195 Meudon Principal Cedex, France

### Abstract

Since the use of high-resolution high signal-to-noise spectroscopy in the study of massive stars, it became clear that an ad-hoc velocity field at the stellar surface, termed macroturbulence, is needed to bring the observed shape of spectral lines into agreement with observations. We seek a physical explanation of this unknown broadening mechanism. We interpret the missing line broadening in terms of collective pulsational velocity broadening due to non-radial gravity-mode oscillations. We also point out that the rotational velocity can be seriously underestimated whenever the line profiles are fitted assuming a Gaussian macroturbulent velocity rather than an appropriate pulsational velocity expression.

### Macroturbulence in hot massive stars

Velocity fields of very different scales occur in the atmospheres of hot massive stars. Apart from the rotational velocity, which is usually assumed to be uniform across the stellar disk and which can vary from zero speed up to the critical value (of several hundred  $\text{km s}^{-1}$ ), line-prediction codes also include a certain amount of microturbulence (of order a few  $\text{km s}^{-1}$ ) to bring the observed profiles into agreement with the data. Microturbulence is related to velocity fields with a scale that is shorter than the mean free path of the photons in the atmosphere (we refer to Cantiello et al. 2009, for a thorough explanation).

In recent years, the number of hot massive stars that have been studied with high-resolution spectroscopy with the goal to derive high-precision fundamental parameters has increased quite dramatically (e.g. Ryans et al. 2002, Lefever et al. 2007, Markova & Puls 2008 and references therein). This has led to the need to introduce an ad-hoc velocity field, termed macroturbulence, at the stellar surface in order to explain the high-quality data to an appropriate level. This need for macroturbulent broadening was, in fact, already emphasized by Howarth et al. (1997) from his study of massive stars from low-resolution UV spectroscopy from the space mission IUE. In contrast to microturbulence, macroturbulence refers to velocity fields with a scale longer than the mean free path of the photons. In practice, the studies listed above resulted in the requirement to introduce macroturbulence of the order of several tens of  $\text{km s}^{-1}$ , and quite often even supersonic velocity fields.

The abovementioned studies including macroturbulence rely on single snapshot spectra and did not take into account pulsational velocity fields so far, as it is done in time-resolved high-resolution spectroscopy of pulsating hot stars (e.g., Aerts & De Cat 2003). A natural step

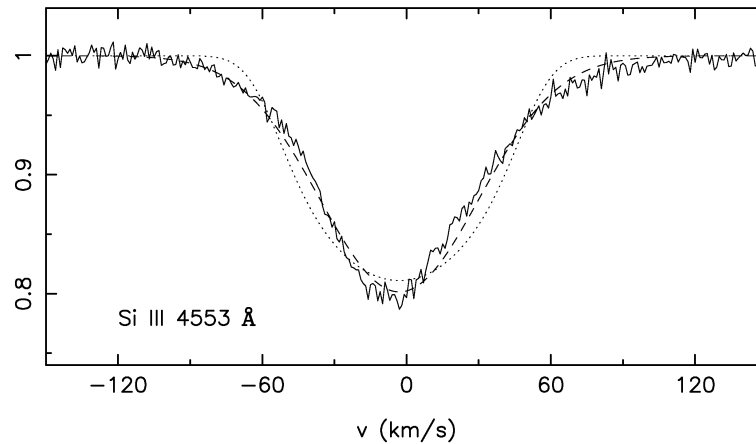


Figure 1: A simulated Si line in the spectrum of a massive hot star (full line) including, besides microturbulence and rotation, also the collective effect of numerous very low-amplitude gravity-mode oscillations which broaden the line wings. The input rotation was  $v \sin i = 45 \text{ km s}^{-1}$ . This profile is fitted with a model taking only rotational broadening and microturbulence into account (dotted line, estimated  $v \sin i$  is  $57 \text{ km s}^{-1}$ ) as well as with a model including microturbulence, rotation and Gaussian macro-turbulence (dashed line, estimated  $v \sin i$  and macro-turbulence are, respectively, 5 and  $32 \text{ km s}^{-1}$ ).

is to investigate whether the needed macro-turbulence may simply be due to the omission of pulsational broadening in the line-prediction codes used for fundamental parameter estimation. In fact, for pulsating stars along the main sequence, one also needs to add some level of macro-turbulence whenever one ignores (some of) the detected pulsations in line profile fitting of time-resolved or averaged spectra (e.g., Aerts & De Cat 2003; Morel et al. 2006). We investigate this hypothesis in the present paper.

#### Line-profile computations in the presence of stellar oscillations

We computed the excited non-radial oscillations with mode degree up to 10 for a stellar evolution model representative of the pulsating evolved B1Ib star HD 163899 with the Code Liégeois d'Évolution Stellaire (Scuflaire et al. 2008) and with the non-adiabatic pulsation code MAD (Dupret 2001). This model has  $T_{\text{eff}} = 18,200 \text{ K}$ ,  $\log g = 3.05$ ,  $R/R_{\odot} = 17.8$ ,  $\log(L/L_{\odot}) = 4.5$ ,  $M/M_{\odot} = 13$ ,  $Z = 0.02$  and an age of 13 million years. The 241 excited  $m = 0$  modes are all gravity modes with frequencies between 0.08 to 0.68 cycles per day and ratios of horizontal to vertical velocity displacement in the range 0.3 to 25. They give rise to 2965 rotationally split components. These were used to compute 504 sets of time-resolved spectroscopic line profiles of 50 profiles each, with peak-to-peak amplitudes for the radial velocity between  $0.7$  to  $15 \text{ km s}^{-1}$  and for rotational velocities between  $25$  and  $125 \text{ km s}^{-1}$ , which is below 25% of the critical value, following the method of Aerts et al. (1992). Such radial-velocity amplitudes are well below those observed for hot B and A supergiants (e.g., Kaufer et al. 1997; Prinja et al. 2004) so that we can be sure not to have overestimated the effects of oscillations on the lines. These profiles were then fitted ignoring the oscillations but allowing for a Gaussian macro-turbulent velocity.

Using a goodness-of-fit approach, we confirm the finding that the inclusion of an ad-

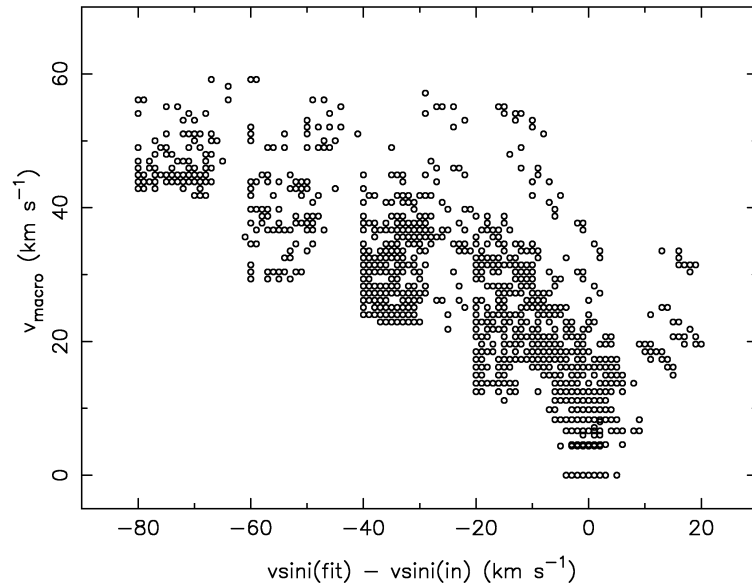


Figure 2: The macroturbulent velocity as a function of the rotational velocity estimate, derived from line profile fits ignoring the presence of pulsational broadening but allowing an ad-hoc Gaussian macroturbulence parameter, for the simulations described in the text.

hoc macroturbulence parameter leads to better fits than those obtained when only allowing rotational and microturbulent broadening (Fig. 1). The pulsational broadening ignored in the line profile fits is compensated by allowing a macroturbulent velocity. These ad-hoc velocities are sometimes in excess of the speed of sound to ensure a good fit (Fig. 2). At first sight, it might seem surprising to need such high macroturbulent speeds to explain the collective effect of oscillation modes that have by themselves only very low velocity amplitude. However, this is easy to understand if one realises that line widths depend on velocity squared, such that numerous small velocities add up to give a very significant effect in the overall line broadening when the collective effect of the modes is interpreted by a single ad-hoc parameter. This is particularly the case for gravity-mode oscillations which impact strongly on line wings. On the other hand, such low-amplitude modes do not alter seriously the observed quantities behaving linearly with velocity, such as the radial velocity variations of the star, because their collective effect tends to cancel out in this case.

As a side result of our line fits with macroturbulence, we report a risk to underestimate the projected rotational velocity appreciably when using the Fourier Transform (FT) method to estimate the projected rotational velocity from the first minimum of the FT (Simón-Díaz & Herrero 2007), as is illustrated in Fig. 3. While this method works well in general and is able to recover the correct input value of the rotational broadening for most of the cases, it is sometimes fooled when too asymmetric pulsational broadening is present and, in this case, one derives too low estimates for  $v \sin i$ . This is also the case for the results from a goodness-of-fit approach (see Fig. 1).

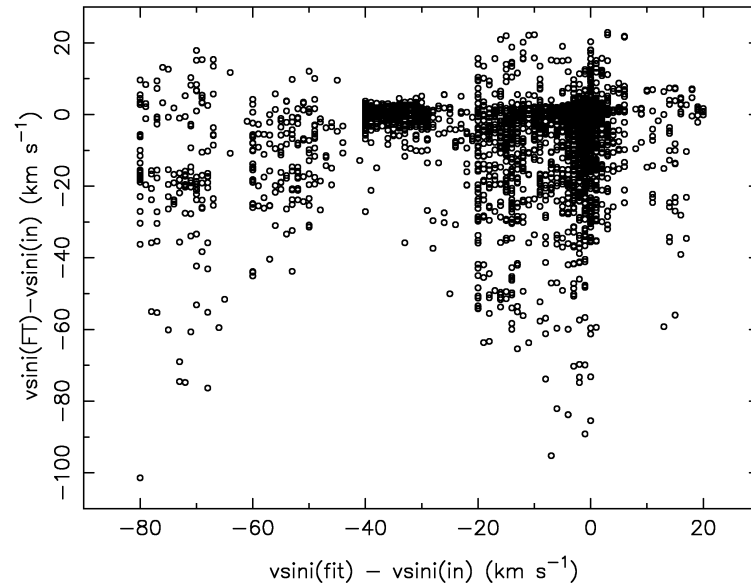


Figure 3: The excess of the rotational velocity estimated from the Fourier transform method (FT) versus the input value is plotted as a function of the excess of the estimated rotational velocity from line profile fits allowing for macroturbulence (fit) versus the input value.

### Conclusions

We have shown that pulsational velocity broadening due to the collective effect of numerous low-amplitude gravity mode oscillations offers a natural and appropriate physical explanation for the occurrence of macroturbulence in hot massive stars. Our computations of course do not exclude other and/or additional physical interpretations of the macroturbulent velocities reported in the literature.

We ignored rotational and non-adiabatic effects in the computations of the velocity eigenfunctions of the non-radial modes used for the line profile simulations. Codes to incorporate each of these effects separately are available (e.g., Townsend 1997, De Ridder et al. 2002) and their influence on the line profiles are well understood. In particular, they will not alter the line wings of the profiles dramatically as long as the rotational velocity remains below 25% of the critical velocity (Aerts & Waelkens 1993) and would thus not alter the main conclusions of our work, while implying a very serious increase in CPU time.

From the observational side, high-precision multi-epoch observations of unblended metal lines are needed to evaluate appropriately the effect of pulsational broadening. Such type of data have not been used so far to estimate macroturbulence.

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