Convection and Turbulence

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Abstract Convection and turbulence in the atmospheres of A-types and cooler stars produce observable effects. A discussion of the 1-D parameterization via mixing-length, microturbulence and macroturbulence is presented, along with a comparison of various calibrations. Overcoming some of the limitations of 1-D model atmospheres, 2-D and 3-D hydrodynamic simulations can yield improved fits to observed line profiles without the need for these parametrisations.

Keywords Convection · Turbulence · Line: profiles · Stars: atmospheres

1 Introduction

Convection and turbulence produce observable effects in the atmospheres of A-type stars and cooler. These are directly seen as granulation on the Sun due to surface convection cells. We indirectly infer their presence by the need for microturbulence and macroturbulence in 1-D spectrum syntheses, as well as curvatures observed in spectral line bisectors. As we shall see, convection and turbulence are characterised by free parameters in 1-D model atmospheres. These parameters can vary with depth in the atmosphere. The use of the more-realistic 2-D and 3-D models do not need these ad hoc parameters and imply that their use in 1-D models should be properly constrained.

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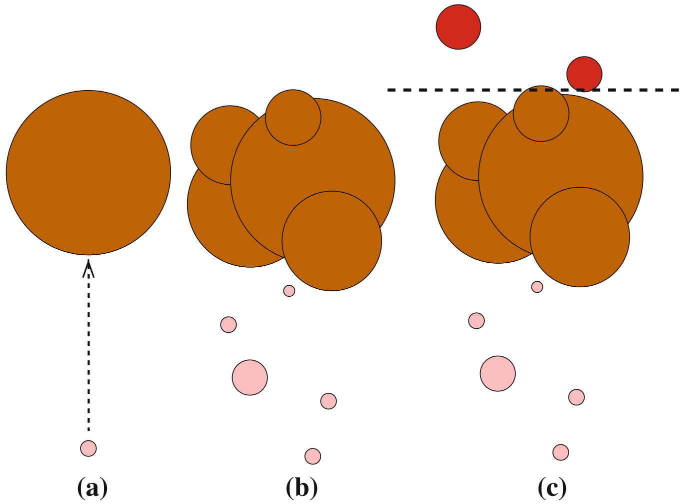

Fig. 1 Schematic bubble representations of convection treatments. In mixing-length theory (**a**), a single bubble rises within the atmosphere, while in turbulent convection bubbles of varying sizes rise (**b**). In (**c**) we have overshooting above the convection zone

2 Convection Theory

2.1 Mixing-Length Theory

Convection in stellar atmospheres is usually based on the mixing-length theory (MLT) (Böhm-Vitense 1958; Kippenhahn et al. 2013). In this model, a single bubble of gas rises a certain length l, relative to the pressure scale height H, before dispersing (Fig. 1a) and l/H is called the mixing-length. The problems with this theory is that it is clearly far too simple and that mixing-length is a totally free parameter. There is no prescription for mixing-length.

2.2 Turbulent Convection

Canuto & Mazzitelli (1991, 1992) proposed a model of turbulent convection in order to overcome one of the most basic short-comings of MLT, namely that a single convective element (or "bubble" or "eddy") is responsible for the transport of all the energy due to convection. This new model (CM) accounts for eddies of various sizes that interact with each other (Fig. 1b). The CM convection model was implemented in the ATLAS9 code by Kupka (1996) and is included in the LLMODELS9 (Shulyak et al. 2004). The CM model has no user adjustable free parameters. An improved variant is the self-consistent (CGM) method of Canuto et al. (1996).

2.3 Convective Overshooting

Convective bubbles rise above the convection zone into the stable regions (Fig. 1c). This is called overshooting, and should be present in our model atmosphere calculations. The ATLAS9 models introduced an “approximate overshooting” which has not been without its critics (see Castelli et al. 1997 for full details). The following quote from Kurucz’ web site (http://kurucz.harvard.edu) aptly summarises the situation:

> Convective models use an overshooting approximation that moves flux higher in the atmosphere above the top of the nominal convection zone. Many people do not like this approximation and want a pure unphysical mixing-length convection instead of an impure unphysical mixing-length convection.

2.4 Atmospheric Structure

Figure 2 gives a comparison of the various convective models for $T_{\rm eff} = 7{,}000$ K and $\log g = 4.0$. The CM model remains close to the radiative temperature gradient. MLT gives more convective flux than CM, even when $l/H = 0.5$. Overshooting produces an excess of convective flux in higher layers, which produces a noticeable bump in the temperature-depth relation compared to MLT without overshooting. At $T_{\rm eff} = 8{,}000$ K, CM gives essentially radiative temperature gradient with significantly less convective flux than MLT, while approximate overshooting introduces flux into higher layers (Heiter et al. 2002). There is a rapid decline of heat transport in the atmosphere and the layers immediately below as $T_{\rm eff}$ increases. This results in convection becoming unimportant for obtaining the atmospheric temperature structure above $T_{\rm eff} = 8{,}000$ K, but well below $T_{\rm eff} \sim 10{,}000$ K where the atmosphere becomes (nearly) radiatively stable according to the Schwarzschild criterion (Landstreet 1998, Fig. 7).

2.5 Balmer Profile Variations

The temperature sensitivity of Balmer lines makes them an excellent diagnostic tool for late A-type stars and cooler. However, as emphasised by van’t Veer-Menneret & Mégessier (1996), Hα and Hβ profiles behave differently due to convection: Hα is significantly less sensitive to mixing-length than Hβ. Both profiles are, nevertheless, affected by the presence of overshooting, with Hβ being more influenced than Hα (Fig. 3). Since Hα is formed higher in the atmosphere than Hβ, Balmer lines profiles are a very good depth probe of stellar atmospheres. Naturally, Balmer profiles are also affected by microturbulence, metallicity and, for the hotter stars, surface gravity (Heiter et al. 2002).

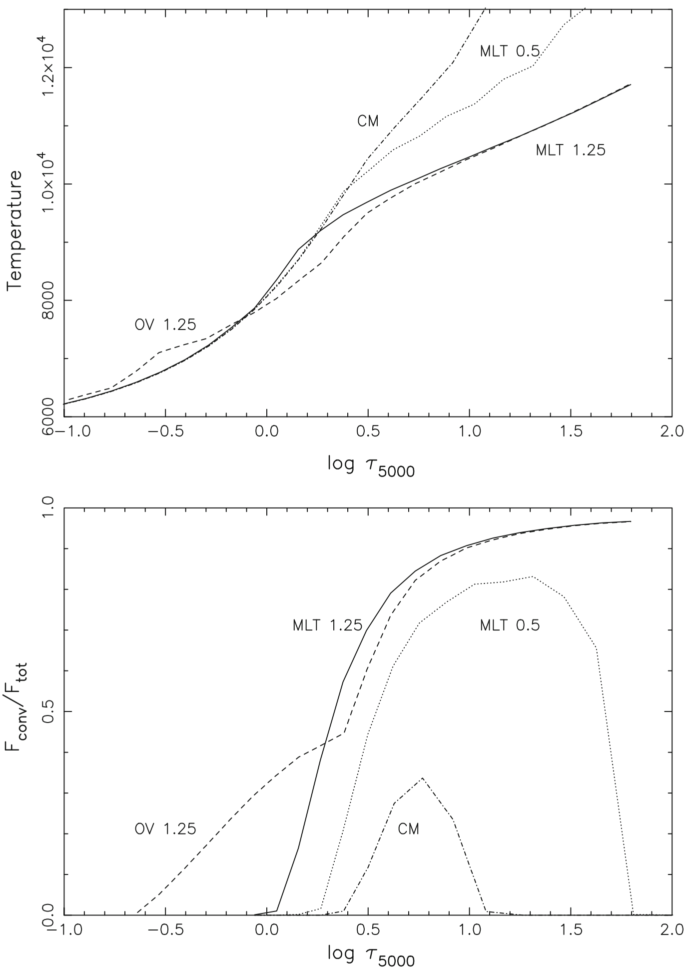

Fig. 2 Models with $T_{\mathrm{eff}} = 7{,}000$ K and $\log g = 4.0$ showing differences arising from changing the treatment of convection. The *upper panel* shows the variation of temperature with optical depth, while the *lower panel* shows the ratio of convective flux to total flux as function of optical depth. The *filled circles* in the *upper panel* show the temperature structure of a fully radiative model

2.6 What to Use in ATLAS *Models?*

In their studies of Hα and Hβ profiles of A and F stars (Gardiner et al., 1999; Smalley et al., 2002) found good agreement with fundamental stars for CM and MLT ($l/H \sim 0.5$) without approximate overshooting. However, Gardiner et al. (1999) found that $l/H = 1.25$ gave better results for stars in the temperature range $6{,}000 < T_{\mathrm{eff}} < 7{,}000$ K. Overall, the ATLAS models with no overshooting and $l/H = 1.25$ given by Castelli et al. (1997) are a good choice for use in stellar parameter determinations.

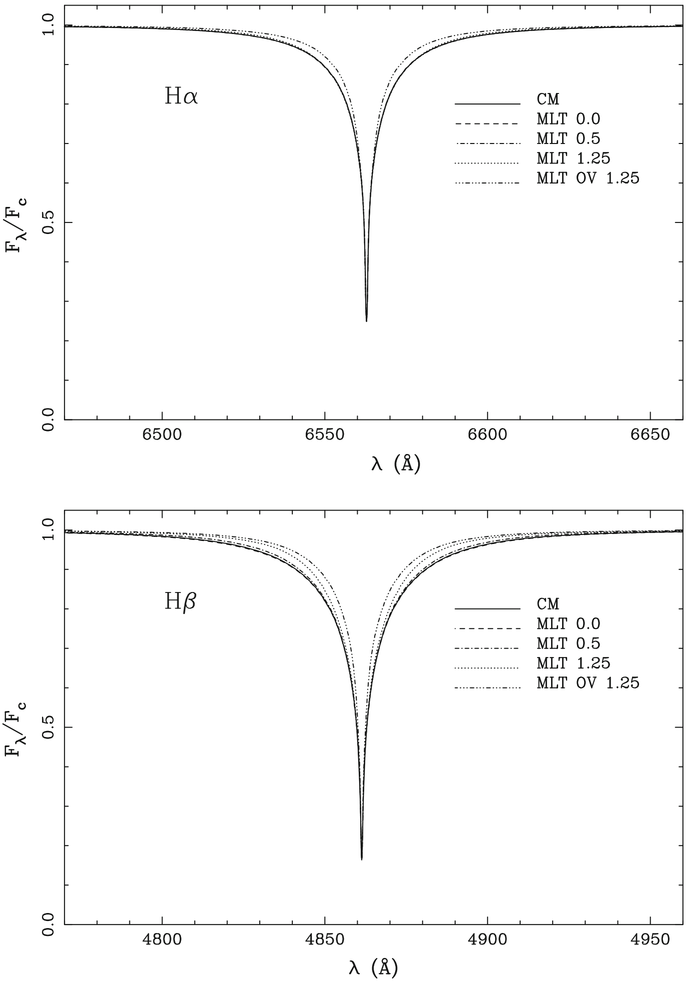

Fig. 3 The effects of convection on the predicted shape of Balmer profiles for models with $T_{\rm eff} = 7{,}000\,\mathrm{K}$, $\log g = 4.0$, [M/H] = 0.0 and $\xi_t = 2\,\mathrm{km\ s^{-1}}$. H$\alpha$ (*upper panel*) is unaffected by the values of l/H, but sensitive to "approximate overshooting", while Hβ (*lower panel*) is sensitive to both

3 Microturbulence

Microturbulence (ξ_t) is a free parameter introduced to allow abundances from weak and strong lines to agree. It is an extra source of broadening, which is added to thermal broadening of stellar lines (Struve & Elvey 1934). Physically, it is postulated as small-scale turbulent motions within the atmosphere, where the size of the turbulent elements is less than the unit optical depth (Gray 2008).

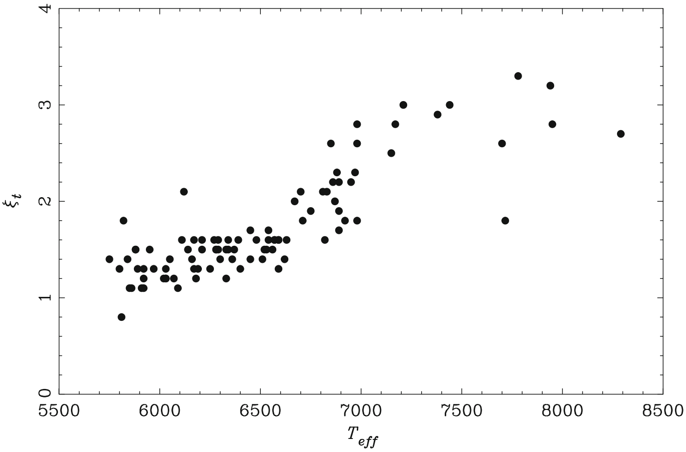

Fig. 4 The variation of microturbulence with effective temperature. Based on results of Gray et al. (2001) for stars near the main sequence (Smalley 2004). Note the apparent relatively abrupt change in behaviour between 6,500 and 7,000 K

Observations show that microturbulence does vary systematically with effective temperature (Chaffee 1970; Nissen 1981; Coupry & Burkhart 1992; Gray et al. 2001). Figure 4 shows the variation of ξ_t with $T_{\rm eff}$ for near main-sequence stars ($\log g >$ 4.0) based on the results given by Gray et al. (2001). There is a relatively abrupt change in behaviour between 6,500 and 7,000 K, which is related to the change from weak subsurface convection to the fully convective atmospheres of cooler stars. Microturbulence increases with increasing $T_{\rm eff}$, peaking around mid-A type, before falling away to zero for B-type stars (Landstreet et al. 2009, Fig. 2).

The microturbulence of 1-D modelling is not turbulent motions, but rather velocity gradients within the atmosphere. Hence, microturbulence should no longer be a free parameter, but ought to be constrained within model atmosphere calculations. Indeed, Kurucz presented an empirical method for constraining depth-dependent microturbulence within ATLAS (Kurucz 2005).

3.1 Microturbulence Calibrations

Unless determined during an analysis, a value of microturbulence needs to be adopted in spectrum syntheses. As we have seen there is clear evidence that microturbulence varies with $T_{\rm eff}$.

During this workshop we have seen SME (Valenti & Piskunov 1996) in action. Valenti & Fischer (2005) found a *"strongly correlated values of* ξ_t *and* $[M/H]$*, suggesting that* ξ_t *and* $[M/H]$ *are partially degenerate."*, but since their analysis found no significant dependence with $T_{\rm eff}$ they adopted a fixed value. Indeed, inspection

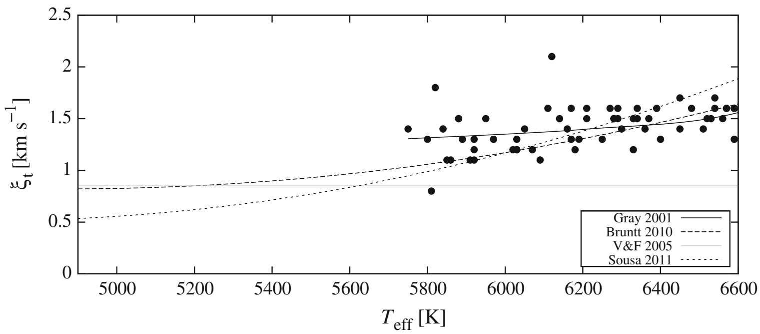

Fig. 5 Comparison of microturbulence values from the four different sources discussed in the text. The points are those from Gray et al. (2001) with the fit as given by Smalley (2004) (*solid line*), the *dashed-line* is the calibration of Bruntt et al. (2010), the constant value adopted by Valenti & Fischer (2005) is given as a *grey line*, and the *dotted-line* gives the fit to the Sousa et al. (2011) values by Gómez Maqueo Chew et al. (2013)

of Fig. 4 does show that for Solar-type stars the variation with $T_{\rm eff}$ is quite small. However, analyses using EW-based methods do find a significant variation with $T_{\rm eff}$. Examples are Sousa et al. (2011) using the ARES/MOOG combination we have also used at this workshop and the VWA-based results of Bruntt et al. (2010). A calibration based on the Sousa et al. (2011) results was presented in Gómez Maqueo Chew et al. (2013). Figure 5 compares the microturbulence values from these analyses.

4 Macroturbulence

Observations of spectral lines in Solar-type stars show extended shallow wings, which are the manifestation of granulation. The effect can be strong in giants and supergiants. It is seen in A-type stars, and even B-type supergiants (Przybilla et al. 2006). These large-scale velocities within atmosphere are what we call macroturbulence.

Macroturbulence is commonly implemented using the Radial-Tangential Model (Gray 1975, 2008). The model considers Doppler broadening in both the radial and tangential directions within the atmosphere, usually assuming that half the surface is radial and the other half is tangential, and that both have the same velocity ($\zeta_{\rm RT}$). It is another free parameter and the model is an ad hoc function convolved with the disk-integrated stellar spectrum. It is not even a local model in the way that microturbulence is, where it is incorporated into atmospheric radiative transfer.

Figure 6 compares calibrations of Gray (1984), Valenti & Fischer (2005) and Bruntt et al. (2010). There are noticeable differences, which would affect the determination of $v \sin i$ for example. It is worth noting that the often used calibration of Valenti & Fischer (2005) is, as clearly stated in their paper, an *upper limit*, since macroturbulence was determined by assuming $v \sin i = 0\,{\rm km\,s^{-1}}$. They also warn that their calibration might underestimate macroturbulence above ~5,800 K.

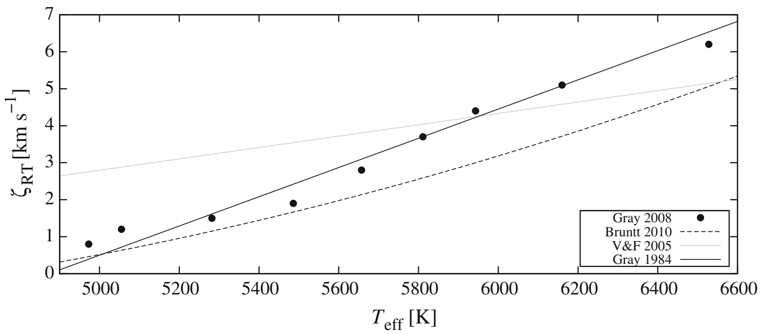

Fig. 6 Comparison of macroturbulence calibrations. The points are from the tabulation in Gray (2008), the *dashed line* from Bruntt et al. (2010), the Valenti & Fischer (2005) upper limit is given as the *grey line*, and the *black line* is Gray (1984)

5 Line Asymmetries

Velocity fields are present in stellar atmospheres which can be measured using line bisectors (Dravins 1987). Compared to Solar-type stars, the line bisectors in A-type stars are reversed, indicating small rising columns of hot gas and larger cooler downdrafts (Landstreet 1998). It is these motions that are thought to be responsible, at least in part, for the existence of microturbulence. In addition, since macroturbulence is linked to granulation, the line asymmetries can be represented by a mixture of both micro- and macroturbulence in the classical, 1-D framework. The results from 3-D numerical simulations of solar granulation can account for observed line profiles without the need for any microturbulence or macroturbulence (Asplund et al. 2000). Similar results have been found for Procyon (Gray 1982; Allende Prieto et al. 2002), which is also a star with well-known physical parameters (e.g. Kervella et al. 2004). However, hydrodynamic models of A-type stars do not yet reproduce the 'reversed' bisectors (Steffen et al. 2005).

6 Realistic Convection Models

None of the current 1-D models of convection are totally satisfactory, so what do 2-D and 3-D hydrodynamic simulations reveal?

A 2-D calibration of mixing-length was given by Ludwig et al. (1999), which was broadly in agreement with that found by the observational studies of convection mentioned earlier. Allende Prieto et al. (2002) presented line profile calculation in both 1-D and 3-D for Procyon, finding that the 3-D profiles were a better fit to the observations. Recently, 3-D simulations of mass mixing-length variations (Trampedach & Stein 2011) and granulation sizes and contrasts (Trampedach et al. 2013) show similar variations with T_{eff} and $\log g$.

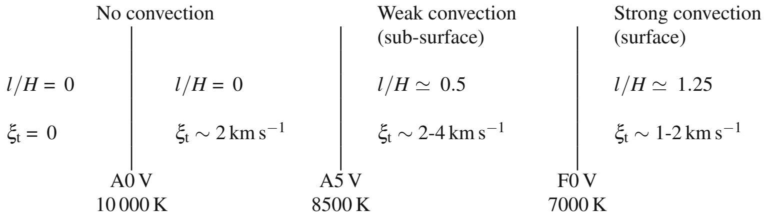

Fig. 7 The Convection Recipe for main-sequence stars from Smalley (2004)

Microturbulence and macroturbulence predictions from CO5BOLD 3-D stellar atmospheres (Steffen et al. 2009, 2013) give overall turbulence values close to the observed values for the Sun and Procyon, but microturbulence is slightly underestimated and macroturbulence is slightly overestimated.

Asteroseismology also has a role in improving our understanding of convection and turbulence. For example, Bonaca et al. (2012) in their analysis of *Kepler* data found a mixing-length lower than the Sun and that it increased with increasing [M/H]. Evidence has also been found for granulation in A-type stars (Kallinger & Matthews 2010; Balona 2011).

7 A Convection Recipe

Smalley (2004) presented a schematic variation of microturbulence and mixing length with $T_{\rm eff}$ for stars near the main sequence (Fig. 7). For stars hotter than A0 there is no convection or significant microturbulence. For early A-type stars the atmospheric temperature gradient is radiative, not because convection is absent, but because the convection simply carries almost none of the flux. There are velocity fields as indicated by the modest microturbulence values. These velocity fields increase as we go through mid to late A-type stars, and inefficient convection is required within the atmosphere. Once convection becomes efficient (F-type and later) the value of microturbulence is found to drop, while the mixing-length increases.

8 Summary

Convection and turbulence are parameterized in 1-D models via mixing-length, microturbulence and macroturbulence. While these are free parameters, they should not be and calibrations ought to be used in spectral analyses. Hydrodynamic 3-D models and detailed observations should be able to provide suitable prescriptions for these 1-D parameters.

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