The A-Star Puzzle
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Convection in stars

F. Kupka

Max-Planck-Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, 85741 Garching, Germany email: fk@mpa-garching.mpg.de

Abstract. Convection is one of the most intricate processes studied in stellar astrophysics and has challenged both theorists and observers since the beginnings of astrophysics. But during the last two decades observational data of unprecedented resolution and accuracy have been collected in solar and stellar research which permit a new look at the field. An enormous increase of computer speed now permits solving more complete model equations with more accurate numerical approximations. Modelling and theoretical understanding of convection, however, are lagging behind observational progress and are still wanting.

As a background to the contributions to this session on convection, I first provide an overview on its basic physics and its observational evidence. I point out why astrophysicists have a general interest in improvements of our understanding of stellar convection and then focus on convection in A-stars with their unique combination of convection zones. I summarise how this richness of different manifestations can arise in A-stars, such as convection zones near the surface and in the core, several on top of each other, or some of them depleted by diffusion processes, suppressed by or even creating magnetic fields, suspected to create a chromosphere in some of them, or influenced by binaries, to name just a few. In the last part I will present a few recent results on modelling of convection in A-stars.

Keywords. Convection, hydrodynamics, turbulence, stars: atmospheres, stars: interior

1. Introduction

Conferences on stellar astrophysics frequently devote an entire session to the topic of convection. Why is there such an ongoing interest in that particular field? Back in the 1920s the existence of a convection zone near the solar surface and in stars in general had been intensively debated until Unsöld (1931) proved that the layers at and below the bottom of the solar photosphere have to be convective due to partial ionisation of hydrogen. The latter lowers the adiabatic temperature gradient to such an extent that the plasma is unstable to buoyancy and hence fulfills Schwarzschild's criterion of convective instability (Schwarzschild 1905). Although a simple model for this process was proposed a year later (Biermann 1932), the well-known mixing length theory (MLT), it turned out to be extremely difficult to make accurate predictions of heat transport, mixing, and other properties, and not only just the rough order of magnitude estimates which can be obtained from this early model and its siblings. Indeed, during the last three decades convection has become the largest single factor of uncertainty in many problems of stellar evolution, stellar structure, pulsational stability, or model stellar atmospheres, to name just a few.

As a response to this demand, research has been performed and considerable progress has been achieved in our understanding of solar and stellar convection through new types of observations. Examples include high resolution spectra and time series of spectra of solar granules, as well as accurate measurements of the depth of the solar convection zone by means of helioseismology. At the same time, numerical simulations of solar and stellar convection have become more and more powerful because of enhanced numerical resolution and more realistic microphysics.

Despite such success, actual calculations of stellar structure, pulsation, and evolution are still based on the classical MLT in a variation similar to that given by Böhm-Vitense (1958). One reason is that numerical simulations are computationally too expensive to be directly linked to those calculations. For those convection models which are in widespread use, "local tuning" of a model parameter could be performed with numerical simulations so as to match a particular physical quantity. But in that case, a suitable numerical simulation has to be available for close enough physical parameters (i.e., effective temperature, surface gravity, etc.), because as always in uncharted territories, extrapolations can be dangerous. The contributions to this session have once more shown what kind of unexpected phenomena may actually occur in such seemingly simple physical systems as atmospheres and envelopes of A-stars.

2. Physics of convection

The basic physical scenario underlying stellar convection is simple. For a fluid with a density ρ stratified as a function of depth by gravitational forces such that $\rho_{\mathrm{top}} < \rho_{\mathrm{bottom}}$, a temperature stratification in which cold fluid is situated on top of hot one ($T_{\mathrm{top}} < T_{\mathrm{bottom}}$) can be unstable. This will indeed be the case, if the temperature gradient is steep enough. Then hot fluid which moves upwards will expand adiabatically by an amount sufficiently large for its density to become smaller than the density of the surrounding, colder fluid at the new location further upwards and a net buoyancy will prevail. Of course, this requires other physical processes such as radiative cooling, viscous friction, or "external forces" (rotation, magnetic fields, etc.) not to interfer too much so as to suppress the process of moving upwards while expanding. This *buoyancy driven instability*, which may occur in the Sun and in stars, was first described by Schwarzschild (1905) and requires, in modern notation, the local temperature gradient to be steeper than the adiabatic one, $\nabla > \nabla_{\mathrm{ad}}$.

In the case of the Sun there are actually two effects which together are responsible for the convective instability. The first is caused by partial ionisation of hydrogen lowering ∇_{ad} such that $\nabla > \nabla_{\mathrm{ad}}$ (Unsöld 1931). The same can also occur as a result of the single or the double ionisation of He. Other species are usually not sufficiently abundant to provide a convective instability through this mechanism. A second possible source of convective instability generally also coincides with regions of partial ionisation: high opacity. Instead of decreasing ∇_{ad}, a high opacity directly increases ∇. This is readily understood by looking at the dimensionless temperature gradient for purely radiative energy transport in the diffusion approximation, $\nabla_{\mathrm{rad}} = (3\kappa_{\mathrm{ross}} P L_r)/(16\,\pi\,\mathrm{a\,c\,G}\,T^4 M_r)$. Here, P is the pressure, L_r is the luminosity at radius r, T is the temperature, M_r is the mass inside r, κ_{ross} is the Rosseland opacity, and the other symbols have their usual meaning as physical and mathematical constants, including the radiative constant a. For large κ_{ross}, $\nabla_{\mathrm{rad}} > \nabla_{\mathrm{ad}}$ and hence convection can set in such that finally $\nabla_{\mathrm{rad}} > \nabla > \nabla_{\mathrm{ad}}$ within and around an opacity peak. The third reason for convective instability, high luminosity, can also be understood from considering ∇_{rad}: if the energy production ε_{c} in the core of a star is large, which occurs for instance in sufficiently massive stars, then because of $\varepsilon_{\mathrm{c}} = \mathrm{d}L_r/\mathrm{d}M_r \approx L_r/M_r$, the ratio L_r/M_r and thus ∇_{rad} are large as well.

The most direct observational evidence for convection in stars is provided by the solar granules. Observations of sufficient quality to undoubtfully reveal their shapes and sizes were first made by M. Schwarzschild (1959) (see also Leighton 1963) with a stratoscope. Previous observations from the ground were resolution limited by atmospheric seeing effects. Naturally, similar observational evidence cannot be given for the case of convection in the cores of stars. The lower mass limit for core convection to occur throughout

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the Main Sequence lifetime is found to be $\sim 1.2\ M_\odot$ using state-of-the-art microphysics and assuming solar element abundances. But the presence of convection in the cores of more massive stars is a very solid theoretical result known since the beginning of stellar evolution calculations (Ledoux 1947 and references therein). Massive stars are commonly considered to have no convection zones in their envelopes, as hydrogen and helium are essentially fully ionised. A revision of opacity sources has changed this picture: stars with at least $7\ M_\odot$ and a sufficiently high (i.e., solar) metallicity are now also predicted to have one or even two convection zones within their envelope due to opacity peaks from higher ionisation stages of the Fe-group elements (cf. Stothers 2000). The upper of these two zones is also important for A-stars (see Sect. 4).

Models of stellar convection have to account for physical effects interacting with the basic instability. Among them are radiative losses which go along with a comparatively very low viscosity. Forces acting on large scales (say on the scales of granules or larger), including those originating from magnetic fields or a global mean flow caused by rotation or pulsation, may inhibit or modify convection. Finally, there is a direct competitor which also causes buoyancy driven instabilities. Heavy fluid on top of lighter one is unstable to small fluctuations, the Rayleigh-Taylor instability. Such conditions can occur because of a gradient ∇_μ in the mean molecular weight μ. The competition between instabilities driven by either a temperature gradient or a gradient of mean molecular weight was first studied in detail by Ledoux (1947). He derived that $\nabla - \nabla_{\rm ad} > \nabla_\mu$ for a stratification to be unstable. Schwarzschild & Härm (1958) noticed difficulties when calculating convective cores of massive stars, where $\nabla_\mu > 0$ (i.e., stable) while $\nabla > \nabla_{\rm ad}$ (i.e., unstable according to Schwarzschild 1905) in some region just outside the core. This scenario is known as semi-convection or diffusive convection. An accurate stability criterion for this situation has to account for the differences in the diffusivities of heat, $K_{\rm h}$, and molecular weight (or concentration), $K_{\rm c}$. Only if $\nabla - \nabla_{\rm ad} > (K_{\rm c}/K_{\rm h})\nabla_\mu$, semi-convection will actually occur (cf. Canuto 1999). The opposite case in which $\nabla < \nabla_{\rm ad}$ (i.e., stable) while $\nabla_\mu < 0$ (i.e., unstable) was first studied by Stern (1960) in a geophysical context (salt-fingers) and later by Stothers & Simon (1969) and Ulrich (1972) for astrophysical problems. It is also known as inverse μ-gradient effect or thermohaline convection and may be important in nuclear shell burning of stars or when there is some form of mass transfer onto the stellar surface. For this type of “convective instability” to occur, $|\nabla_\mu| > (K_{\rm h}/K_{\rm c})(\nabla_{\rm ad} - \nabla)$ (see also Canuto 1999). This problem and its relation to A-stars have been discussed by Vauclair (2005).

3. Astrophysical interest in convection

The main physical consequences of convection are heat transport, mixing, and interactions with mean flow and magnetic fields and the dynamo generation of magnetic fields. Convective heat transfer changes (usually reduces) temperature gradients and causes horizontal temperature inhomogeneities. These in turn change the emitted radiation of stellar atmospheres compared to a purely radiative environment. Convection can thus be observed through its effects on photometric colours and spectral line profiles. As a consequence thereof, it contributes to the uncertainties in secondary distance indicators based on photometric indices (Smalley *et al.* 2002 and references therein). Provided sufficient mechanical energy is transfered through the photosphere, it can also cause chromospheric activity indicators such as UV emission lines to appear (Sect. 4).

Through changing the vertical temperature gradient in stars convection affects stellar structure and evolution. This is particularly evident for evolutionary tracks computed for the Pre-Main Sequence (PMS) phases or for any evolutionary stages beginning with the lower tip of the red giant branch. Even the location of the Main Sequence within the HR diagram is influenced through the dependence of the radii of stars with deep convective envelopes, such as the Sun, on the efficency of convection just underneath the surface. This causes one of the main uncertainties in mass determinations based on stellar model calculations and complicates the interpretation of the observed HR diagram. An extensive comparison of different models of convection on the PMS evolution was recently given by Montalbán *et al.* (2004). Particularly instructive are 1 $M_{\odot}$ models of solar metallicity which are shown therein and which all match the solar effective temperature and luminosity for the present age of the Sun. Due to the effects of convection alone their evolutionary tracks differ by up to several 100 K at 10$\times$ solar luminosity in both earlier and later stages of evolution. Other calculations demonstrate how the change of assumed convective efficiency of MLT models for the upper envelope of stars with less than 1.5 $M_{\odot}$ changes the location of (or radii at) the Zero-Age Main Sequence, the shapes of the Pre-Main Sequence tracks, and masses determined from such model calculations.

Convection zones are usually well mixed, provided the velocities are large enough to overcome molecular diffusion (segregation or levitation). Accurate predictions of mixing efficiency become a lot more difficult for layers which are stably stratified, when overshooting from an adjacent convection zone can occur. This affects the evolution of convective cores and consequently the stellar evolution at stages from the turn-off point of the Main Sequence onwards and particularly on the asymptotic giant branch (AGB, see, e.g., contributions to the Granada workshop in Gimenez *et al.* 1999). The final results of these processes become visible in differences in the terminal phases of a star including post-AGB development (see also the comments and references in Kupka 2003) and supernovae (see contributions in van der Hucht *et al.* 2003). The effects of convective mixing can also be observed at the Sun and similar stars through the amount of Li depletion stemming from PMS (and Main Sequence) evolution. The ^{7}Li isotope is destroyed at temperatures around 2.5×10^6 K and a deep convective envelope ranging from the photosphere to the burning temperatures of Li during PMS phases or also later on will remove some fraction of this species from the observable and much cooler surface layers (see contributions in da Silva *et al.* 2000).

Convection is thought to drive p-mode oscillations in solar-like stars through stochastic excitation (Kumar & Goldreich 1989). In other types of stars such as RR Lyrae stars, Cepheids, or white dwarfs convection is expected to modulate the pulsation and introduce nonlinearities which are observable in the light curves of these objects (see Feuchtinger 1999 for the RR Lyrae stars). A different example of interaction of convection with a large scale velocity field is the transport of angular momentum (which is also discussed by Talon 2005). The redistribution of angular momentum in the solar envelope can be derived from helioseismology (see Gilman (2000) for a review). Numerical simulations of rotating convective shells, particularly those presented by Miesch *et al.* (2000), have made considerable steps towards recovering the averaged longitudinal angular velocity profile in the equatorial and mid-latitude regions of the Sun which in turn has been reconstructed from helioseismological inversions.

A closely related effect of the convection-rotation interaction is the creation of magnetic dynamos (see Gilman (2000) for further references). Sunspots and the solar activity cycle are the visible results of a process powered by convection. Interestingly, sunspots were also studied as the first astrophysical examples of the inhibition of convection through a magnetic field (Biermann & Cowling 1938, Biermann 1941, Cowling 1953). While sunspot models have evolved considerably (Solanki 2003), they have not led to a general answer to the question: under which conditions do magnetic fields inhibit convection? Solar magnetograms by Domínguez Cerdeña *et al.* (2003) have shown there are considerable

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fields of 50 to 150 G in the intergranular lanes of quiet solar regions. These fields can only modify convection, but not suppress it. Gough & Tayler (1966) have derived analytical stability results for several configurations with a vertical field component and found the necessary field strengths for suppression of convection to be several kG for conditions typical for sun spots. Cool magnetic Ap stars hence range an interesting transition region, but a thorough study of magnetoconvection in these objects has not yet been made.

4. Convection in A-stars

The existence of convection zones in the photospheres of A-stars was first predicted by Siedentopf (1933). He extended Unsöld's argument for the lowering of $\nabla_{\rm ad}$ as the cause of solar convection to all stars which have a region of partial ionisation of hydrogen reaching the photosphere from below (as with the Sun the role of opacity became clear only later on when more accurate microphysics data were available).

Evidences from spectroscopy for the presence of convection in A-stars include the peculiar behaviour of Balmer lines as a function of effective temperature $T_{\rm eff}$ when trying to match theoretical line profiles with the observed data (see Smalley 2005). Another indication are the shapes of line bisectors and detailed high resolution line profiles (see Kupka *et al.* 2005) for A-stars with low projected rotational velocity ($v \sin i$) as well as the necessity to introduce a large "microturbulent velocity" $\xi_{\rm t}$ of several km s^{-1} when comparing spectral lines from the same ion but having different strengths with observations. Remarkably, $\xi_{\rm t}$ appears to be (roughly) a function of $T_{\rm eff}$ (see also Smalley 2005). Likewise, chromospheric activity indicators such as UV emission lines disappear only for A-stars with $T_{\rm eff}$ greater than about 8300 K (Simon *et al.* 2002). The main conclusions from these observations are that convective velocity fields of several km s^{-1} are present in A-stars, appear to have a filamentary topology (columns of fast upflow embedded in slow downflows), while the temperature gradient must be close to the radiative one except for the coolest A-stars with $T_{\rm eff}$ not much greater than 7000 K.

All these observational evidences deal with the photospheric convection zone caused by partial ionisation of hydrogen which stems from both a peak in opacity and a minimum in $\nabla_{\rm ad}$ for near surface temperatures and densities. Both disappear for the late B-stars. Further inside the envelopes of A-stars, partial ionisation of He I and He II can extend the upper convection zone and cause a second convection zone (due to He II) to appear. In both cases the instability is primarily caused by the lowering of $\nabla_{\rm ad}$. Layers in between the two zones are usually found to be subadiabatic ($\nabla < \nabla_{\rm ad}$). Both zones can disappear due to diffusion of He from the bottom of the mixed (convective or overshooting) zone further down into the envelope. Diffusion is also responsible for further convection zones which may appear deeper inside the envelope of A-stars: radiative levitation can accumulate ions of Fe-group elements in layers with T around 200000 K (as has been discussed by Michaud 2005). The traditional claim that envelope convection is not important for the evolution of A-stars is based on the notion that such "thin" convection zones barely alter the stellar radius in comparison with a purely radiative envelope model. But if the chemical composition of A-star envelopes is to be modelled, diffusion has to be taken into account in its two forms of gravitational settling and of radiative levitation and at that point envelope convection cannot be ignored any more. Contrary to the case of surface convection, observational evidence about the properties of the deeper envelope convection zones can only be obtained indirectly, from comparisons of abundance peculiarities and perhaps at some point from asteroseismology.

Compared to their envelope convection zones the convective cores of A-stars have received a more general attention. The most important problems related to them are the extent of well mixed stably stratified layers above the convective cores due to overshooting, the influence of stellar rotation on that mixing process, and the possibility of convective core dynamos. Convective mixing of stably stratified layers is thought to be observable through the colour distributions of open clusters, the exact position of binary pairs near the turn-off of the Main Sequence, and through changes of the internal composition by nuclear reactions in later stages of stellar evolution. Convective overshooting changes the local temperature gradient by making it more flat close to the convection zone and steeper a little further away compared to what would happen for purely radiative transport of energy. A much more important consequence of overshooting is the extra mixing provided by (He rich) material flowing into the envelope and (H rich) material being drained into the core which changes the lifetime of the star and its final composition at the end of the Main Sequence. The extent of mixing is frequently measured as a fraction d of the pressure scale height at the boundary of the convective core. Many simple models for overshooting use this measure and the application of such models has been criticized by Yıldız (2005) at this conference. These prescriptions also fail because the definition of d loses its meaning for smaller convective cores: the pressure scale height diverges in the centre of a star and to expect d to be a "constant" in this mass range (or any mass range) is hopeless and misleading. More meaningful measures could be based on the amount of core mass mixed by overshooting, as has been suggested by several researchers. Indeed, models similar to that one discussed in Sect. 6 provide the mixed mass fraction of stably stratified layers as an output result instead of requiring it to be an input parameter. Further progress in our understanding of core convection in A-stars can also be expected from numerical simulations such as those discussed in Browning *et al.* (2005), particularly for questions concerning the influence of rotation and possible dynamo mechanisms in the convective core of A-stars.

The influence of rotation and tidal forces through close binaries on the convection zones near the surface pose further unresolved problems in the physics of A-stars. Both might be needed to fully understand the observed data such as line profiles of A-stars. How shall theoreticians match all these challenges?

5. Simulations and models

The main problem of constructing convective stellar models is that the underlying equations describing the structure and dynamics of fluids (the fully compressible Navier-Stokes equations coupled to equations for radiative transfer, magnetic fields, etc.) are highly nonlinear and have to be solved numerically. Because of the extremely high stratification, density and pressure in a star change by many orders of magnitude from the core to the photosphere. As a consequence, a vast range of time scales is encountered in stars from radiative cooling of fluid at the surface (on the order of seconds) to the thermal time scale of gravitational contraction (on the order of 10^5 to 10^7 years). Likewise, the vast difference between buoyancy or inertial forces and their inherent time scales on the one hand and the time scales of viscous dissipation and radiative conduction in the stellar interior on the other allows for an enormous range of spatial scales on which dynamical processes can occur (up to 9 orders of magnitude). The way taken around this is to explicitly account for the length and the time scales of the most relevant to the physical problem. In the case of convection these are the spatial scales of up- and downflow patterns (and corresponding horizontal flows), such as granules and plumes, and the time scales of the flow (speed of sound or flow motion) as well as the time required to achieve a quasi-stationary equilibrium state. The latter is set by the boundary conditions or radiatively cooled layers. This approach is also called "large eddy simulation"

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and is underlying all the numerical simulations of A-stars presented in this session. The physical picture behind this technique is that of volume averages performed within a computational domain.

Convection models are usually developed to predict averages over horizontal areas which allows a dimensional reduction of the problem. The physical idea underlying these models in general is that of an ensemble average. In this case equations are derived from the underlying dynamical equations with some additional approximations or heuristic assumptions to obtain a closed set for the prediction of equilibrium ensemble quantities such as the convective enthalpy (heat) flux or the (turbulent) pressure generated by the flow. Such ensembles quantities can also be computed from numerical flow simulations by considering a sufficiently large number of "states" generated through time integration which are averaged later on. This procedure is computationally much more expensive. However, no rigorous theory exists for the construction of more affordable ensemble averaged equations.

In a direct comparison the advantage of numerical simulations is that they explicitly account for the nonlinearities of the most important, energy carrying scales and the spatially inhomogeneous nature of convection. High computational costs are their most important drawback, if integral properties of a large numbers of objects have to be computed, for instance during the automated analysis of millions of spectra expected from the GAIA mission. Similar limitations hold for the modelling of complete stars or groups of stars and their time evolution. Possible caveats are the required independence of the results on specific (artificial) boundary conditions and properties of unresolved scales which both have to be excluded carefully. Convection models, on the other hand, are designed to be computationally affordable. However, their range of validity cannot be determined from first principles or from studying related physical scenarios such as geophysical or laboratory flows alone. Most convection models are derived from methods developed to describe homogeneous turbulence while stellar convection is demonstrably inhomogeneous, as shown by the solar granules. Hence, for the time being models always have to be carefully tested with observations (and suitably tested numerical simulations) to corroborate their applicability.

6. Modelling convection in A-star envelopes

For a long time MLT remained the standard model of convection for A-stars. Xiong (1990) first suggested a nonlocal model for A-star envelopes. This model describes the transport of velocity and temperature fluctuations created by convection as a diffusion process. It had previously been used to model convection in the cores of massive stars by Xiong (1985). Canuto (1992), Canuto (1993), and Canuto & Dubovikov (1998) suggested a new model which abandoned the diffusion ("down-gradient") approximation for nonlocal transport and also avoided the use of a mixing length to compute the dissipation rate of turbulent kinetic energy. An improvement of that model of nonlocal transport was suggested by Canuto *et al.* (2001) and in this form the convection model was adopted by Kupka & Montgomery (2002) to compute envelope models for A-stars. These computations ranged from the mid-photosphere down into layers where $T \sim 100000$ K. Figure 1 shows a comparison of the convective enthalpy (heat) flux for a mid A-type Main Sequence star with a numerical simulation by Freytag (1995) and with an MLT model tuned to match the peak flux of the nonlocal model. The MLT model would require a mixing length four times as large to obtain the convective flux found in both the nonlocal model and the numerical simulation for the lower lying (He II) convection zone. Compared to that a modification of the original model of Canuto *et al.* (2001) for nonlocal

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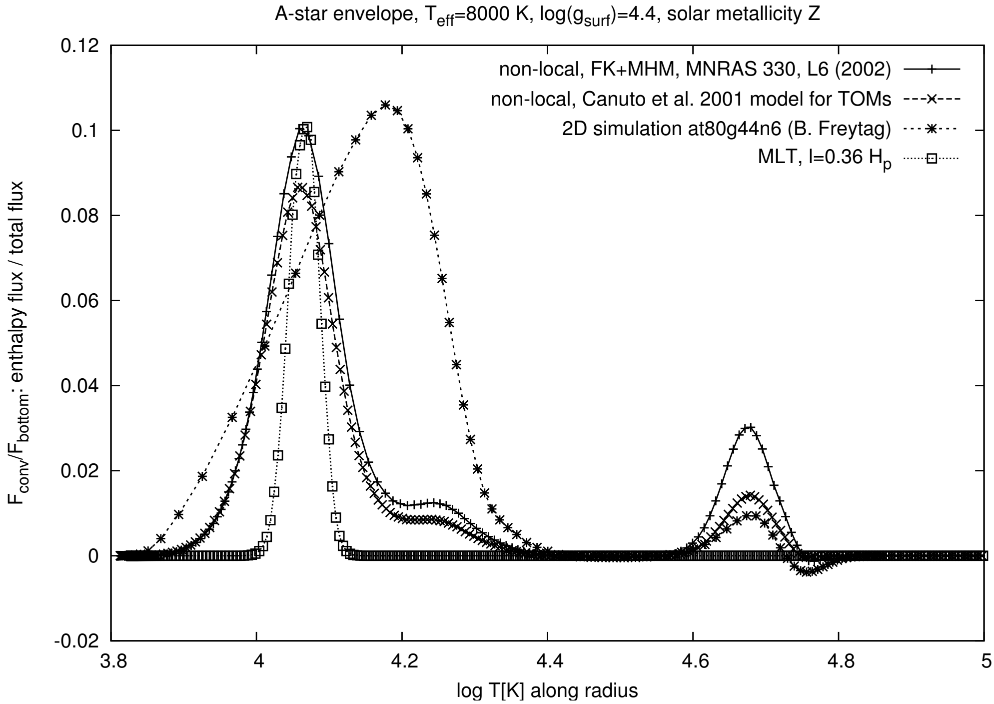

Figure 1. Relative convective heat flux for a mid A-star as obtained from a nonlocal model with two different closure approximations compared to averages from a 2D numerical simulation (courtesy B. Freytag) and an MLT model adjusted to match the peak flux.

transport as done by Kupka & Montgomery (2002) results only in a small change. The simulations shown by Freytag (2005) at this conference improve over their predecessors in Freytag (1995) also by replacing the 2D geometry with a 3D one and by using updated microphysics. Still, the MLT model remains to be by far the one most discrepant from the others.

That discrepancy is even more evident when considering the velocity fields. A comparison for the vertical root mean square convective velocity for the same nonlocal model, the MLT model, and the numerical simulations by Freytag (1995) has already been shown by Kupka (2003). For the MLT model the flow remains localised to the middle of the partial ionisation zones, predicts too small velocities for the lower lying convection zone, and neglects overshooting. The nonlocal model compares well to the simulation also quantitatively, although the surface velocities are clearly lower. The horizontal root mean square velocities allow a similar conclusion, as can be seen in Fig. 2. A local model such as MLT provides no framework to compute horizontal flow velocities and the extent of the convectively mixed region would again be grossly underestimated.

The performance of the nonlocal model used by Kupka & Montgomery (2002) for A-star envelopes was recently corroborated when Montgomery & Kupka (2004) computed models for envelopes of DA white dwarfs with the same code. Interestingly, much larger values of the mixing length parameter are required for an MLT model to match the peak fluxes of the nonlocal model, while the quantitative agreement of the latter with 2D numerical simulations of Freytag (1995) is comparable to that one found for A-stars. Limitations of the current nonlocal model become clear when computations for deep

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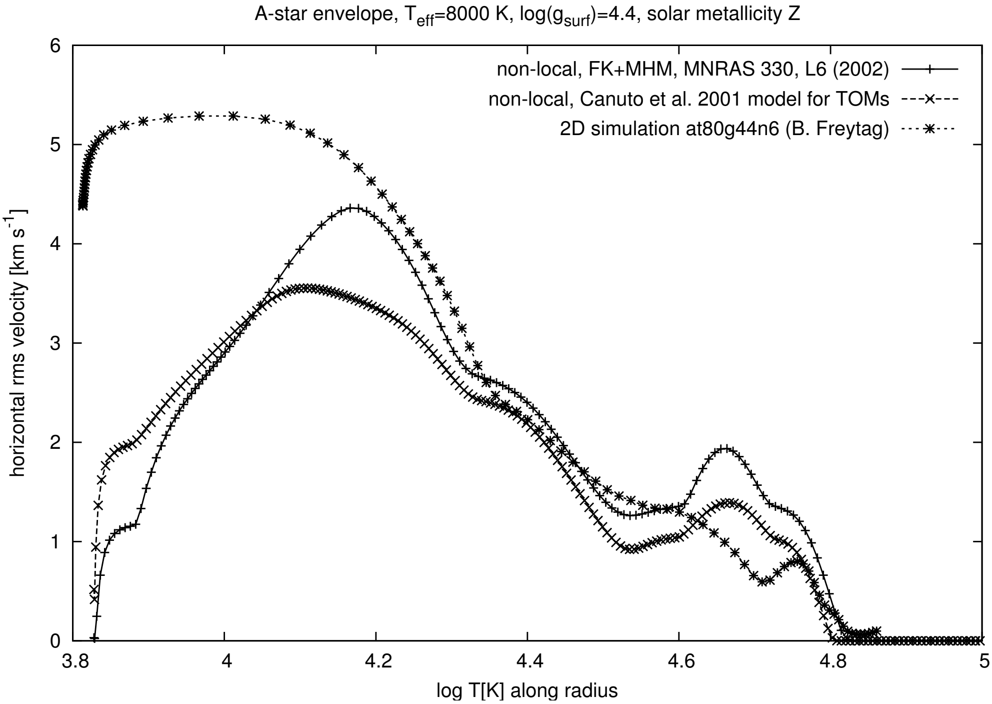

Figure 2. Horizontal root mean square convective velocity for a mid A-star as obtained from a nonlocal model with two different closure approximations (for TOMs – third order moments) compared to averages from a 2D numerical simulation (courtesy B. Freytag).

convection zones (similar to the case discussed by Trampedach 2005) are performed. Further improvements to the nonlocal transport model such as that one suggested by Gryanik & Hartmann (2002) are thus now investigated. Preliminary studies based on numerical simulations for solar granulation by F. Robinson appear encouraging.

7. Conclusions

Observations of solar and stellar convection have demonstrated the numerous shortcomings of MLT like convection models, but have not provided a way out through simple parameter calibrations. Nonlocal models appear to be a valuable alternative at least for the case of A-stars. Recently, numerical simulations of A-stars in 3D have been started and some first (surprising !) results have been presented here, together with a host of new observational data. The field thus provides further challenges to anyone interested in a theoretical understanding of stellar convection, and such challenges are usually fun for observers, too. The study of solar and stellar convection hence is neither in its infancy, nor is it a “mature field”, nor stagnant. It is in fact right in the middle of new developments which have long been waited for by researchers in several fields of astrophysics.

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Discussion

MOSS: I would assume that in the surface region of A stars the simulations of convection are relatively easier because of the shallow depth-reduced stratification. A quite successful model exists for photospheric solar convection in the presence of large magnetic fields. So, can/will simulations soon be able to tell us something useful about near-surface convection in A stars in the presence of global-scale kG-strength magnetic fields?

KUPKA: Yes, I think that this is feasible. At least if one does not aim at including a global field distribution and the up-/downflow structure of convection at the same time, but rather restricts oneself to a study based on a series of box type convection simulations with a large scale field entering the simulation domain. That should be sufficient to tell us about convection suppression in Ap stars and its relation to the geometry of the global scale field.

VAUCLAIR: A comment: we now have a powerful tool for studying convection in stars and obtaining constraints on it: stellar seismology. Due to helioseismology we know the depth of the solar convection zone with a precision of 0.1%. In the future, we hope to be able to use asteroseismology to obtain constraints on stellar convective zones.