STATUS AND FUTURE OF HYDRODYNAMICAL MODEL ATMOSPHERES

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Abstract

Since about 25 years ago work has been dedicated to the development of hydrodynamical model atmospheres for cool stars (of A to T spectral type). Despite their obviously sounder physical foundation in comparison with standard hydrostatic models, their general application has been rather limited. In order to understand why this is, and how to progress, we review the present status of hydrodynamical modelling of cool star atmospheres. The development efforts were and are motivated by the theoretical interest of understanding the dynamical processes operating in stellar atmospheres. To show the observational impact, we discuss examples in the fields of spectroscopy and stellar structure where hydrodynamical modelling provided results on a level qualitatively beyond standard models. We stress present modelling challenges, and highlight presently possible and future observations that would be particularly valuable in the interplay between model validation and interpretation of observables, to eventually widen the usage of hydrodynamical model atmospheres within the astronomical community.

Key words: stellar atmospheres, dynamics, hydrodynamics, developments

1. Introduction

Model atmospheres are our most important theoretical tool for the interpretation of stellar spectra. They are constructed as time-independent, one-dimensional, plane-parallel or spherically symmetric configuration in hydrostatic and radiative-convective equilibrium. In today’s standard models for late-type atmospheres the radiative energy transport is modelled in a highly realistic manner, while the convective energy transport is usually treated in a rather simplistic manner, assuming mixing-length theory or related concepts. Since the assumptions behind the construction of such “classical” model atmospheres are obviously not fulfilled, for now about 25 years efforts have been invested to overcome the limitations of the classical models: the result are “hydrodynamical” model atmospheres which from first principles account for the time-dependence, and three-dimensional character of the gas flows primarily related to convection in the surface layers of late-type stars. They allow for deviations — not necessarily small ones — from the equilibrium conditions assumed in standard models. The convective energy transport is described by the very nature of hydrodynamical models quite realistically, the radiative energy transport with reasonable accuracy. We say “reasonable” since the convective flows exhibit no symmetries and their time-dependence renders the radiative transfer problem computationally much more demanding than in standard models. Some trade-offs in the descriptions have to be made which limit the level of the achieved precision. The higher degree of physical realism of hydrodynamical models leads to a rich set of atmospheric processes which are not present in standard models: hydrodynamical models harbour waves and shocks, and can describe the macroscopic transport and mixing of stellar matter.

Despite the obviously sounder physical foundation of hydrodynamical model atmospheres their general application has been rather limited. In order to understand why this is, and how to progress, we want to review the present status of hydrodynamical modelling. The paper reflects the outcome of a discussion between the authors within an ongoing project on the photometric properties of late-type giant star atmospheres. One might perhaps say that the authors represent the astronomical community in micro-format: the first author works mostly theoretically and has been actively involved in the development of hydrodynamical model atmospheres, while the second author is mostly working observationally being a typical “end-user” of model atmospheres. In our discussion questions concerning the status and future of hydrodynamical model atmospheres were put bluntly: Generally, has the development of hydrodynamical model atmospheres been worth the effort? And, concerning their presently limited general application and usage: Which spectral type can be modelled? Why are there no model grids available? Why are there no ready-to-use libraries of synthetic spectra and colours available? Can one expect this to happen anytime soon? What is needed to drive further developments? In the following we shall try to give answers or at least make reasonable projections concerning the questions posed above. We want to convince the reader that hydrodynamical model atmospheres are indeed a useful tool for interpreting and understanding stellar spectra,
and that they will undoubtedly play an increasingly important role in the future.

2. PROBING ATMOSPHERES ACROSS THE HRD

We conducted a small survey among three research groups\(^1\) to obtain an overview which atmospheric parameters have been probed by hydrodynamical modelling across the Hertzsprung-Russell diagram (HRD). While not complete we believe that Fig. 1 gives a representative view of the state of affairs. A sizeable fraction of the HRD has been covered by 3D hydrodynamical atmospheres, on the main-sequence stretching from A- to L-type spectra. Naturally, the Sun and its vicinity has been intensively studied. The bottom of the red giant branch is probed by several models too, albeit very sparsely for more evolved objects. Besides the models depicted in Fig. 1 also a number of hydrodynamical white dwarf (DA type) model atmospheres has been constructed, and models of sub-solar metallicity. Some “uncharted territory” remains: e.g. atmospheres of horizontal branch stars, of T-type (or cooler) brown dwarfs and planets, or of primordial stars.

Figure 1. Atmospheres probed with 3D hydrodynamical models in the HRD — here in effective temperature-gravity plane. Shown are models of three different research groups (squares; the star denotes a 3D hydrodynamical model of Betelgeuse by Freytag et al. 2002). Not all models constructed in the groups are depicted, but the coverage of the parameter space is representative. Note, that also models of sub-solar metallicity as well as models for white dwarf atmospheres have been calculated.

Many of the models depicted in Fig. 1 are of experimental nature, and have not necessarily been published yet. Hitherto, the exploration of the HRD has not been performed in a systematic manner, but has rather been driven by interests of the various researchers in particular problems. We nevertheless conclude that at present most of the atmospheres in the HRD are — at least in principle — accessible to 3D hydrodynamical modelling.

3. IMPACT OF HYDRODYNAMICAL MODEL ATMOSPHERES

What kind of astrophysical impact did hydrodynamical model atmospheres have so far? Perhaps most importantly they led to qualitative and quantitative progress in our theoretical understanding of the atmospheric dynamics and role of inhomogeneities. Hydrodynamical model atmospheres provide information about velocity fields and thermal inhomogeneities in the layers where the formation of spectral lines takes place. Knowledge of this information allows to abandon the classical free parameters of micro- and macro-turbulence which are used to describe the line broadening of macroscopic velocity fields in standard line formation calculations. In this respect hydrodynamical model atmospheres have reached a level of realism — in particular in the case of the Sun — which allows to reproduce observed spectral line profiles virtually perfectly without introducing any free parameters (see e.g. Asplund et al. 2000). As an immediate consequence abundance analyses are put on a firmer footing, providing high-fidelity abundances from hydrodynamical modelling.

The realistic description of the convective energy transport in hydrodynamical model atmospheres allows to abandon another free parameter entering the calculation of standard stellar model atmospheres — the mixing-length parameter. It is introduced within the framework of mixing-length theory to parameterise the efficiency of the convective energy transport, and in this way controls to some extent the temperature gradient in convectively unstable layers. The temperature gradient influences predicted spectral properties (general shape of the spectral energy distribution, spectral line profiles, photometric colours, etc.).

In recent years full-fledged model atmospheres were beginning to replace more idealised outer boundary conditions employed in stellar structure models (see e.g. Baraffe et al. 1998). In particularly this sort of application demands for a reliable description of the temperature profile between optically thick and thin layers. Since hydrodynamical model atmospheres can provide the temperature profile independent of mixing-length theory a major factor limiting the predictive power of stellar structure models is removed.

Last but not least, hydrodynamical models can make predictions about atmospheric phenomena which are connected to time-dependent processes. E.g. the structure of stellar chromospheres, coronae, and dust-driven winds is related to wave processes which can only be described using dynamical models.

\(^1\) Chan, Robinson, Kim, et al.; Nordlund, Stein, Asplund, Trampedach, et al.; CO3BOLD-group: Steffen, Freytag, Ludwig, Wedemeyer-Böhm, et al.
In the following sections we shall give a number of examples intended to illustrate the points above. The results would not have been possible to obtain with standard model atmospheres. Moreover, they were selected to show that hydrodynamical models did not only advance basic theoretical understanding but also had impact on the interpretation of observations.

3.1. High-fidelity abundances

In a recent paper [Asplund et al. (2004)] reported a new determination of the solar O abundance based on 3D hydrodynamical model atmospheres together with improved atomic data to obtain a consistent value of the O abundance from all available spectroscopic abundance indicators for the first time. The analysis suggests a significant downward revision of the solar O abundance, and together with related changes of the abundances of C, N, and Ne suggests an overall decrease of the solar metallicity by 35% with respect to the often quoted abundances of [Anders & Grevesse (1989)]. While the new O abundance is in accordance with the O abundance of the local interstellar medium, it is in conflict with results from helioseismology. At the moment it is unclear where the resolution of this conflict may be found. The conflict has nevertheless spawned discussions and renewed efforts in the modelling of the solar structure, nicely exemplifying how progress in our understanding is most often driven by discrepancies rather than consistencies. The discrepancy in this particular case became apparent by the higher precision of the abundance determination that the application of hydrodynamical model atmospheres made possible.

A similar example is the work by [Barklem et al. (2003)] where the authors apply hydrodynamical model atmospheres combined with non-LTE calculations in the determination of the Li abundance in metal-poor halo stars. As a result, already existing discrepancies are aggravated between the Li abundance in old halo stars and the primordial Li abundance as inferred by the WMAP analysis of the cosmic microwave background. Here the application of hydrodynamical models gave confidence that the discrepancy is not just an artefact due to leaving out granulation induced systematic effects in the spectral line formation calculations.

This issue has been studied by [Steffen & Holweger (2002)] for the case of the Sun, but with a wider scope and considering different chemical species & spectral lines with different formation properties. The authors set out to provide upper bounds for the possible errors of spectroscopic abundance analyses associated with photospheric temperature inhomogeneities due to granulation. They find in general a strengthening of lines if temperature inhomogeneities are present. In this example hydrodynamical model atmospheres have made it possible to study this problem with a higher degree of realism in the first place.

3.2. Stellar structure independent of MLT

Mixing-length theory (hereafter MLT) was introduced into the theory of stellar structure in the early 1950s [Vitense 1953]. It had the big advantage of providing a simple recipe for calculating the convective energy flux needed in the model construction. Simultaneously it introduced (at least) one free parameter — the mixing-length parameter — which had plagued the predictive power of stellar structure models ever since. The mixing-length parameter is usually empirically calibrated by comparing the stellar models with the Sun. The question is, however, whether the scaling across the HRD provided by the MLT is indeed correct, in other words, whether the mixing-length parameter is actually constant as assumed when calculating the evolution of a star in the HRD. Many investigations have been undertaken to obtain empirical estimates for the mixing-length parameter over a wider range of stellar parameters. No clear picture emerged so far. On the one hand side, many physical effects can produce effects similar to variations of the mixing-length parameter. On the other hand, short-comings of the model can also mask or introduce changes of the mixing-length parameter.

From the viewpoint of stellar structure MLT is mostly important in a thin boundary layer close to the stellar surface, in this sense becomes a stellar atmosphere problem. Classical stellar atmospheres themselves rely on MLT, hence cannot provide new information. Hydrodynamical model atmospheres, however, can provide an estimate of the efficiency of the convective energy transport from first physical principles which can be translated into an equivalent mixing-length parameter. [Ludwig et al. (1999)] used hydrodynamical models to provide theoretical estimates of the mixing-length parameter for late-type stars located in the HRD in vicinity of the Sun.

Proper treatment of convection is particularly important in case of late-type giants (i.e., stars on the red giant and asymptotic giant branches, RGB & AGB). Being intrinsically bright they can be effectively used for tracing distant stellar populations (or those heavily obscured by interstellar dust), in order to derive properties of their chemical evolution, star formation histories, etc. A realistic representation of their interiors and atmospheres by theoretical models would be indeed crucial in this context, in order to provide a reliable background for a correct interpretation of the observables. However, late-type giants, partly because of their very extended nature, are very complex and correct representation of dynamical phenomena in their interiors (and immediate vicinity too — see Sect. 3.3) relies heavily on the proper treatment of convection, as even a minor change in the mixing-length parameter may notably shift the position of a star in the HRD. In their pioneering attempt to probe the interiors of late-type giants with 3D hydrodynamical models, [Freytag & Salaris (1999)] found considerable vari-
Two 1D models with non-zero turbulent pressure are given to right; turbulent pressure in all cases equals to zero). The thick solid line is a 3D hydrodynamical model (averaged on surfaces of equal geometrical depth), thin lines are 1D plane-parallel models calculated using different mixing-length parameter ($\alpha_{\text{MLT}} = 1.0, 1.5, 2.0, 2.5$ and $f = 0$), and dashed-dotted ($\alpha_{\text{MLT}} = 2.0$ and $f = 1.0$) and dashed-dotted (dashed ($\alpha_{\text{MLT}} = 2.0$ and $f = 1.0$) and dashed-dotted ($\alpha_{\text{MLT}} = 2.0$ and $f = 2.0$) lines (see text for more details and discussion).

3.3. The realm of time-dependent phenomena

By construction classical stellar atmospheres assume a steady-state situation, hence cannot make predictions about time-dependent phenomena. Fortunately, progress in observational techniques now allows to study atmospheric processes in ever increasing detail where time-dependence is an important aspect. The interpretation of these observations demands for models where time-dependence is properly accounted for.

As the first example in this category we would like to mention dust driven winds around late-type stars, which are the result of the interaction of stellar pulsations, dust condensation, and radiation pressure on the formed dust grains. To obtain reliable models it is essential to incorporate the time-dependence of pulsations and dust formation in the models. First models able to account for both aspects in the time-dependent framework appeared more than 10 years ago (Fleischer et al. 1992, Feuchtinger et al. 1993). The work of Höfner (1999) marks another milestone in this ongoing development, since here for the first time the frequency-dependence of the radiation field was included in a dynamical wind model for an AGB star. More recently, first attempt have been made towards a full 3D hydrodynamical modelling of an AGB star atmosphere (Freytag & Höfner 2003).

Another area where the inclusion of time-dependent processes is essential is the structure of stellar chromospheres and coronae. Their heating is provided by the dissipation of acoustic or magneto-hydrodynamic waves, as well as magnetic reconnection driven by forces on the magnetic field lines exerted by fluid motions. Historically, so called semi-empirical atmosphere models have been constructed to reproduce observed spectral features. While by construction being able to reproduce the particular observations, they lack the ability to rigorously test our physical understanding, and also lack the power to predict atmospheric properties in a regime of stellar parameter distinct from the very ones they have been adjusted to. A prominent example...
of the impact of a hydrodynamical model atmosphere in this area is the work of Carlsson & Stein (1995) who constructed a one-dimensional time-dependent model of the solar chromosphere. As a consequence of their modelling efforts they proposed a shift of the paradigm how to describe stellar chromospheres in general. Recently, Wedemeyer et al. (2004) addressed the same problem with a three-dimensional hydrodynamical model. The detailed spatial information the model provides can be exploited for the prediction of otherwise unavailable properties. Figure 3 shows a predicted image of the structure of the solar chromosphere as seen in the 1 mm radio continuum as potentially observable by the Atacama Large Millimeter Array (ALMA).

Perhaps now stretching a bit the notion of what a model atmosphere should actually model we would also like to mention an application of hydrodynamical model atmospheres which at present gets increasingly interesting due to dedicated satellite missions: the excitation of solar-like oscillations. It is believed that the solar 5 min oscillations are excited by the “noise” generated by the stochastic granular gas motions. Nordlund & Stein (2001) and Stein & Nordlund (2001) have demonstrated for the case of the Sun that hydrodynamical model atmospheres can provide an estimate of the power which is injected into the oscillations by the granular flow field. The advantage of the method is that the description of the stochastic flow in is quite realistic while in analytical approaches one has to rely on approximations of the flow properties whose validity are difficult to judge. Recently, Stein et al. 2004 have applied the method to a broader range of stars.

Related to the above issue is the question of the ultimate photometric stability, the stability of the photospheric position (the photometric centroid) of a red giant in the plane of the sky.

4. FUTURE DEVELOPMENTS: THEORY & OBSERVATIONS

In this section we want to give some projections of the future in terms of model developments, model results, and observations which aid model developments. We also want to explain why extended grids of hydrodynamical including spectral diagnostics have not been available so far.

4.1. COMPUTATIONAL CHALLENGES

Hydrodynamical model atmospheres are often perceived as computationally “heavy weight” — as a supercomputing application. Today however, such a notion is not fully justified as long as we are considering “typical” hydrodynamical models, i.e. models of modest spatial (about 100 grid points per dimension, meaning in total $10^6$ points) and wavelength resolution (4–7 equivalent wavelength points). Despite the obvious limitations in spatial and wavelength resolution such models describe the atmospheric dynamics with a high degree of fidelity (see e.g. Asplund et al. 2000). Of course, hydrodynamical models are being improved in terms of spatial and wavelength resolution. But progress in this respect is rather slow and mostly parallels the increase of computer performance since the computational costs scale as the forth power of the spatial resolution per dimension (linearly with the total number of grid points, and one power due to a related linear decrease of the time step), and linearly with the number of employed wavelength points. High resolution models in fact still demand for supercomputing resources.

However, being content to reproduce spectral diagnostics with typical hydrodynamical models, such a model...
takes $\approx 1$ month on PC-type machine to compute in the case of the Sun. Due to tighter constraints on the time stepping related to the radiative transfer red giants and A-type stars need $\approx 10 \ldots 100$ times longer computing times. All in all this is not so bad since low-cost PC-clusters or fast parallel machines are now commonly available. So, what keeps modelists from providing grids of hydrodynamical model together with spectral diagnostics like flux distributions and colours? Two stumbling blocks have prevented this.

Stumbling block 1: the calculation of the spectral diagnostics is computationally very demanding. The spectrum synthesis calculation of a spectrum with about $10^5$ wavelength points for a 1D atmosphere takes $\approx 10$ PCmin. The full spatial-temporal information of a typical hydrodynamical model atmosphere corresponds to $\approx 10^6$ equivalent 1D atmospheres. The given computing time for a synthetic spectrum refers to calculations under the assumption of LTE. Non-LTE aspects might increase this number substantially. Obviously, at the moment tackling the spectral synthesis problem head on does not work. However, this is perhaps not necessary since the full spatial-temporal information is not needed, but mostly time and spatial (i.e. stellar disk integrated) averages. It is likely that one can come up with certain "short-cuts" which allow a more economic evaluation of the overall spectral characteristics. The development of such procedures is pending.

Stumbling block 2: there is an increased demand on the computing logistics. The operation of hydrodynamical model atmosphere codes is not fully automated. Manual intervention starts with the construction of reasonable initial models. Even hydrodynamics codes which are considered as robust demand for initial conditions which are physically not too far apart from actual conditions. Hence, a certain degree of (human) creativity is needed for constructing initial models for atmospheric parameters not studied before. Moreover, large amounts of numerical data are generated during a hydrodynamical model run. While storage of data of a single run does not pose a problem, the data of a larger number of runs usually demand for disk-array-capacity of storage. The output undergoes analysis steps producing spectral information and further auxiliary diagnostics. A fully automatic end-to-end organisation of the process has not been achieved yet, though it will be indeed important when simultaneously handling of the order of hundred or more models.

The stumbling blocks described before are not of principal nature, and will be overcome. The steady increase of computing power and size of available storage space provide almost automatically alleviates the situation. Perhaps the present bottleneck for the speed of development is the available woman- or man-power scattered out over the few involved working groups. Nevertheless, we believe that in the foreseeable future grids of hydrodynamical models including some observational diagnostics will become available.

4.2. Observations Aiding Model Developments

What kind of observations are the modelist waiting for which would aid model development and validation? Similar to classical model atmospheres "1D like" observables can be used the check the validity of hydrodynamical models as well. Precise measurements of the center-to-limb variation for different kinds of stars can be used to test the thermal structure of a model, i.e. its average thermal profile and thermal fluctuations. Spatially unresolved, high resolution spectra allowing to measure spectral line shifts and bisectors provide statistical constraints on the velocity field combined with the temperature fluctuations. The measurement of stellar radii puts constraints on the temperature structure of the convective envelope, allowing to test model predictions of the mixing-length parameter. The observations listed above are partly already available, and have been used in the validation of hydrodynamical models. They are particularly useful if combined with independent supplementary information concerning the global stellar structure, like the stellar mass, luminosity, and chemical composition.

Beyond the classical observables, “multi-D” observables (i.e. those specifically related to spatial or temporal inhomogeneity) can provide further useful additional constraints. They are now in reach or going to get into reach due to refined observing techniques, or newly established techniques like optical interferometry. The direct measurement of convective scales and their brightness contrast would provide a direct test of hydrodynamical model atmospheres. This could be combined with the time-wise statistics of the granulation pattern. The time domain could also be more indirectly addressed by observing the result of macroscopic transport or mixing processes competing with other processes. An example would be deviations from equilibrium chemistry due to the competition between transport and formation of a particular chemical constituent. A specific case is the distribution of condensates (clouds) in the atmospheres of very cool stars, brown dwarfs, and planets.

5. Conclusions & Final Remarks

We hope that we convinced the reader that most convective stellar atmospheres are now accessible to 3D hydrodynamical modelling. 3D hydrodynamical model atmospheres have been already been proven useful in the development of our theoretical understanding of cool star stellar atmospheres in general, and the interpretation of observations. Their “esoteric” character is diminishing, as methodological developments, as well as the steady increase of computing power, have been and are transforming them more and more into a standard tool for stellar
physics. While not quite there yet, we believe that grids of hydrodynamical model atmospheres including some spectral diagnostics will become available in the foreseeable future. Being aware that prediction are hard to make — especially when it comes to the future of such rapidly evolving field of modern astrophysics — we think that this is going to happen within five years from now. Observers who are not that patient and think that their work could benefit from input from predictions from hydrodynamical models are encouraged to seek collaborations with model developers. As welcomed effect of such collaborations further model developments could be spawned since models would have to be adapted to the particular observational needs.

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