Session A

Current status of modelling

Modelling of Stellar Atmospheres
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The Current Status in the Modelling of Stellar Atmospheres

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Abstract. The old question whether models of stellar atmospheres are wrong, adequate, or even overelaborated, is discussed with a number of examples from contemporary research as a background. A simple quality classification scheme for models of different types is presented. It is concluded that, in spite of rapid recent progress, we are far from having fully satisfactory theoretical representations of stellar atmospheres. Reasons for continuing the efforts to reach a higher degree of physical consistency in model atmosphere work are discussed.

The aim of science is, on the one hand, a comprehension as complete as possible, of the connection between sense experiences in their totality, and, on the other hand, the accomplishment of this aim by the use of a minimum of primary concepts and relations.
Albert Einstein

1. Introduction

The theory of stellar atmospheres seems to be a relatively mature field of science. The first attempts at understanding stellar spectra were made already in the 19th century by Fraunhofer, Kirchhoff and Ångström, and important contributions towards a real theory were given in the first decades of the 20th century by Saha, K. Schwarzschild, Payne and Eddington. In the following decades to the middle of last century, L. Biermann, Böhm-Vitense, Chandrasekhar, B. Strömgren, Underhill and Unsöld contributed to the buildning of models of stellar atmospheres, with a gradually more refined consideration of energy transport by radiation and by convection. With the advent of electronic computers the modelling could be much more elaborate, taking departures from Local Thermodynamical Equilibrium into consideration. During the last two decades it has also been possible to make more realistic models of the dynamical processes in stellar atmospheres, such as convection and pulsation, in the former case also with allowance for inhomogeneities with 3D hydrodynamics and 3D radiative transfer.

This development is very impressive. It reflects and responds to an even more impressive development of astronomical instrumentation. For instance, it is now possible with high-resolution spectrometers at large telescopes to get spectra of hundreds of thousands of stars, of a quality which 30 years ago could only be acquired for the Sun. This has led to an increased demand for detailed modelling of stellar atmospheres and spectra. Other technological advances which also have been drivers in the development are progress in computer technology and numerical algorithms. Some of this progress, for instance in spectrographic techniques or in numerics, was in fact initiated by the modelling advances, but in most cases the development has gone the other way. That is, modelling has lagged behind the technology development with an origin "outside" the research field of stellar atmospheres. This is still the case. One example is the fact that stellar abundances, if measured from equivalent widths of weak absorption spectral lines, may be derived with an error proportional to the error in equivalent widths and the error in transition probabilities. These two latter quantities may in many cases be derived with an accuracy better than 10%, while the resulting abundance could still be uncertain by almost a factor of 2. This is because the conversion from measured equivalent width to abundance must be made by using a model atmosphere, and the errors in that, and thus in the resulting abundance estimate, may be very considerable.

A question to ask in this situation is then: *Is the current status in the modelling of stellar atmospheres satisfactory?* During the history of this field of research this question has been continuously debated, and strong opinions have been expressed many times both for answering "yes!" and "no!". Schematically, one could say that the *users* of the theory and the models, for instance those studying galactic chemical evolution from systematic surveys of stellar abundances, have taken rather optimistic views regarding the adequacy of the models. Often, the argument supporting this attitude has been the reasonably high consistency obtained in the abundance analysis when different criteria, or spectra of stars of different types in objects assumed to have the same abundances like star clusters, have been analysed. Also, the remarkable fit of model or "synthetic" spectra to the observed ones has been persuasive. In a discussion of this situation long ago Bernard Pagel (see Gustafsson, 1980) dubbed this category of believers in, or optimistic users of, stellar model atmospheres "the broad sweepers", in contrast to "the ultimate refiners". These latter scientists take a more sceptical attitude towards the realism of the models, in particular arguing that these are not selfconsistent, not even relative to the underlying postulates, and even less relative to physics in general. For instance, in standard models there are often free *ad hoc* parameters, like mixing-length parameters and microturbulence, which are just used for fitting observed and calculated spectra but have an unclear physical meaning. The assumption of Local Thermodynamic Equilibrium is in itself dubious, and the assumption of plane-parallel or spherically symmetric stratification in a model where convective energy transport occurs is even contradictory. An "ultimate refiner" may also argue that this very terminology of attitudes is misleading – the goal is not refining, like adding further details to enable still more accurate fits to observations, but sooner establishing a physically sound basis for the modelling. From this point of view, much of the work on stellar atmospheres and analysis of stellar spectra until the last decade is highly dubious, or even fundamentally wrong.

This may be enough to warn the reader that the answer to the question posed on how satisfactory current models are, will be highly controversial. The fundamental question is whether the field of stellar atmosphere theory is indeed as mature as it seems, or whether it is sooner in its infancy in the sense that it first now is being put on a physically acceptable basis. One might consider atomic physics as an analogy. Certainly, many results in atomic spectroscopy were known already in the 19th century, as well as theoretical findings like those of Rydberg. His formulae and the Bohr and Sommerfeldt models summarized data and had predictive power, though with some free parameters. Yet, one could not say that the theory was in good shape until the advent of Quantum Mechanics, in the 1920'ies. Similarly, one might argue that the theory of stellar atmospheres is not satisfactory until reasonably self-consistent physics, like the Navier-Stokes equations or the MHD equations are used to describe the atmospheric gas motions in 3D, and the Boltzmann transfer equation and the equations of Statistical equilibrium, or the corresponding time-dependent equations, are used for radiative transfer, with all relevant cross sections determined and applied, and no free parameters of any significance introduced.

The sceptic may argue that the art of theoretical physics has always been, and is still, the art of making the most fruitful approximations. Could not the LTE approximation, or the Mixing-Length Approximation, or the Approximation of Plane-parallel Symmetry, be useful, and much better than a dead-lock situation where, as a result of the technical difficulties in handling the full problem, no models at all can be offered to the community for important applications? Then, however, the focus is on whether the approximate models offered really are good enough for the purpose they are used, or for the error bars claimed in the application results. The answer to the question whether the current status is satisfactory or not is thus very much related to the question *for what* the models are to be used. Here, I shall try to discuss this further, by taking a number of examples that I am familiar with from current modelling.

2. Are there reasons today to consider the models excellent?

An argument for advocating that contemporary models are indeed excellent has been mentioned already: the models are able to reproduce stellar spectra to a not seldom astonishing degree. E.g., if a standard plane-parallel LTE model atmosphere of a dwarf or a giant in the spectral class interval F-K is used to generate a synthetic spectrum, almost all visible mismatch between the model and the star may be explained away as being due to unsatisfactory atomic data, in particular erroneous f values or damping constants. This is in particular the case if the usual fundamental parameters T_{eff}, $logg$, abundances and micro/macro turbulence are allowed to be free to fit the spectrum optimally. In this way, T_{eff}, $logg$ and abundances may be adjusted to compensate for departures from the LTE Boltzmann/Saha distribution. However, if these parameters are known independently effects of such departures usually show up, indicating that errors of up to 200 K in T_{eff}, 0.5 dex in $logg$ and 0.2 dex in abundances may well result in the free fitting case.

Other effects that show up if spectra of very high resolution and signal/noise are available, are line shifts and asymmetries which the standard models do not reproduce. These effects are clear signs of convective motions in the atmospheres, and are indeed well reproduced by 3D convective models (Nordlund and Dravins 1990, Asplund et al. 2000, Allende Prieto et al. 2002). Another effect which may be traced is that abundances derived from features formed at low temperatures in the atmospheric surface layers, such as molecular lines, may depart systematically from abundances derived from lines formed at greater depths. A

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good example is the oxygen abundances of metal-poor solar-type stars derived from standard models. The abundances are different if OH lines are used, as compared with OI lines. Also this effect may be explained as a result of 3D convection, leading to much cooler surface temperatures due to adiabatic expansion of the rising gas (Asplund and Garcia Perez 2001).

From this we conclude that even an excellent fit to most features in observed spectra may not be a good argument for rating the models excellent in themselves. Even though the old saying: "Give me three free parameters, and I can fit any erroneous data, with any questionable theory", is slightly exaggerated, all the information inherent in a rich stellar spectrum is yet so "non-orthogonal" at large that the relatively few parameters at hand may still be used to strongly suppress the warning signs of mismatching spectral features. This is in particular the case when the basic atomic and molecular data are not of the highest quality, so that much of the mismatch may also be explained away by referring to that.

As regards the atomic and molecular data, the situation has improved considerably in recent years. There is important improvement due to *ab initio* calculations of atomic absorption data by Bob Kurucz and in the Opacity Project (see Kupka et al. for references) and by several groups for molecular line absorption (Jørgensen 1996, Hauschildt, Allard and Barman 2001). Another interesting example is the progress in the theory of collision broadening by HI (Barklem, Piskunov and O'Mara 2000 and references therein), as is illustrated in Figure 1. Extension of this work opens up the application of HI line wings for establishing an accurate temperature scale for solar-type stars (Barklem et al. 2002), not the least for metal-poor ones.

We should also say that agreement between observed high-quality spectra and the 3D convection models of Stein and Nordlund (1998) and Asplund et al. (1999) for the Sun, Procyon and Pop II dwarfs (see references given above) marks a very important increase in the quality of stellar-atmosphere modelling. This is illustrated in Figure 2. These 3D models are not only free from extra non-physical parameters, they are also able to reproduce stellar absorption lines with a significantly higher accuracy. One result of this effort is much improved stellar abundances, among those astonishingly great revisions (of about -0.2 dex) of the solar CNO abundances (cf. Allende Prieto, Lambert and Asplund 2002). For stellar photospheric models, these must be rated among the most excellent presently available. However, departures from LTE are still not included and may well be a significant.

3. Aren't many models at least satisfactory?

In a number of important respects, considerable improvements have recently been made in the techniques of stellar atmospheric modelling. In addition to the treatment of convection by 3D simulations, progress has been made in extensive statistical-equilibrium (i.e. non-LTE) calculations for static models as well as for radiation-driven winds of hot stars, for winds driven by radiation on dust grains from cool pulsating stars, as well as for less dynamic cool stellar photospheres in LTE but with extensive molecular line blanketing.

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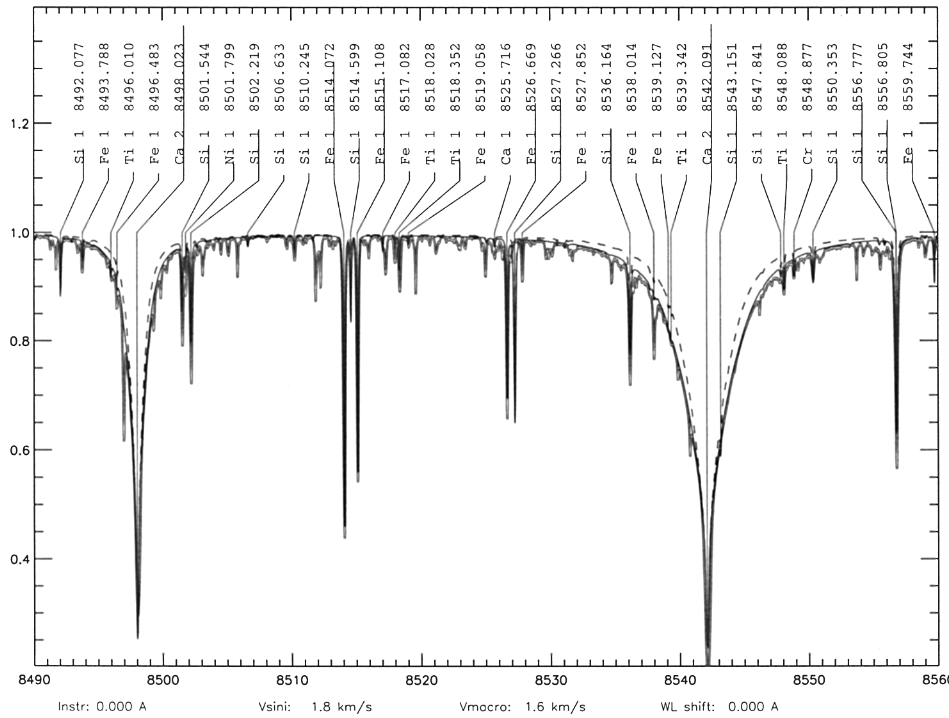

Figure 1. An illustration of the improvement in atomic data for stellar-atmosphere modelling in recent years. The observed solar flux in the region of the strong infrared Ca II triplet is shown as the heavy line. The two other curves display fluxes calculated with the Holweger-Müller semi-empirical solar model, the dashed line with the collision broadening from collisions with hydrogen atoms based on classical Unsöld theory, and the thin solid line with the theory of Barklem and O'Mara (1998). There is no extra fitting parameter behind the latter curve. The figure is due to Paul Barklem.

In the convection simulations, the methods of Nordlund and Stein have mostly been applied to solar-type dwarfs. However, Freytag (2001) has initiated simulations of full red supergiant stars by representing them in a cartesian grid of about 200x200x200 points. When solving the hydrodynamical equations, with radiative transfer in LTE and in the gray approximation, he finds a small number of giant convection cells, not so different in size from what M. Schwarzschild (1975) suggested in a classical paper, but rather different morphologically from the situation for dwarfs. The observational implications of Freytag's models will be of interest to explore.

The non-LTE calculations have been much advanced by the Approximate Lambda Iteration method, initiated by Cannon, Rybicki and Scharmer, and later advanced by Scharmer and Carlsson (1985), Werner and Husfeld (1985), Hamann (1986) and others. The art of treating very complex model atoms and

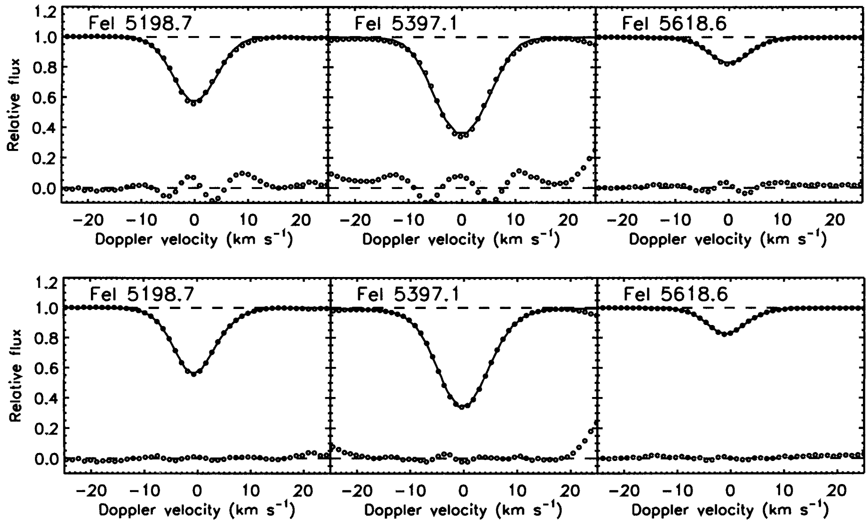

Figure 2. Three iron spectral lines in the spectrum of Procyon (F5 IV), dotted, as compared with calculated lines from a flux-constant plane-parallel model atmosphere (full lines, upper panels) and from a 3D convective model atmosphere (lower panels). The differences between observed and calculated spectra, multiplied by a factor of 5, are shown by dotted curves in the lower parts of each panel. From Prieto Allende et al. (2002). The 3D convective model, with detailed radiative energy transfer, obviously produces a much better fit without introducing free parameters, and the model may be considered to be of Type IIa in the classification scheme of Sec 5 but not of Type I, since the LTE assumption is made. It could well – as departures from LTE are found to be important – be degraded to Type IIIa.

molecules, with "super levels" (Anderson, 1989 , Hubeny and Lanz, 1995) or multi-level operator splitting (Hauschildt, 1993), has been developed so that excitation conditions and radiative transfer of very complex model atoms are now possible to explore, with thousands of atomic levels and millions of spectral lines, and to include more or less explicitly in a self-consistent way in model atmospheres (Hauschildt, Allard and Baron, 1999).

The radiation driven winds of early-type stars have been modelled by line-blanketed non-LTE models. An interesting recent example is the study by Herald et al. (2001) of two Wolf Rayet (WN8) stars, with stationary clumped winds with parametrized radial velocity as a function of radius cf. Figure 3. Another example is the study of Eta Carinae by Hillier et al. (2001). These studies tend to lead to predicted spectra in reasonable agreement with the observations. However, the adopted velocity profile and the clumping parameter are as yet not derived from the hydrodynamics in a self-consistent way.

For cool giants, relatively detailed models of pulsating atmospheres were developed by Bowen (1988) and later by Fleischer, Gauger and Sedlmayr (1992),

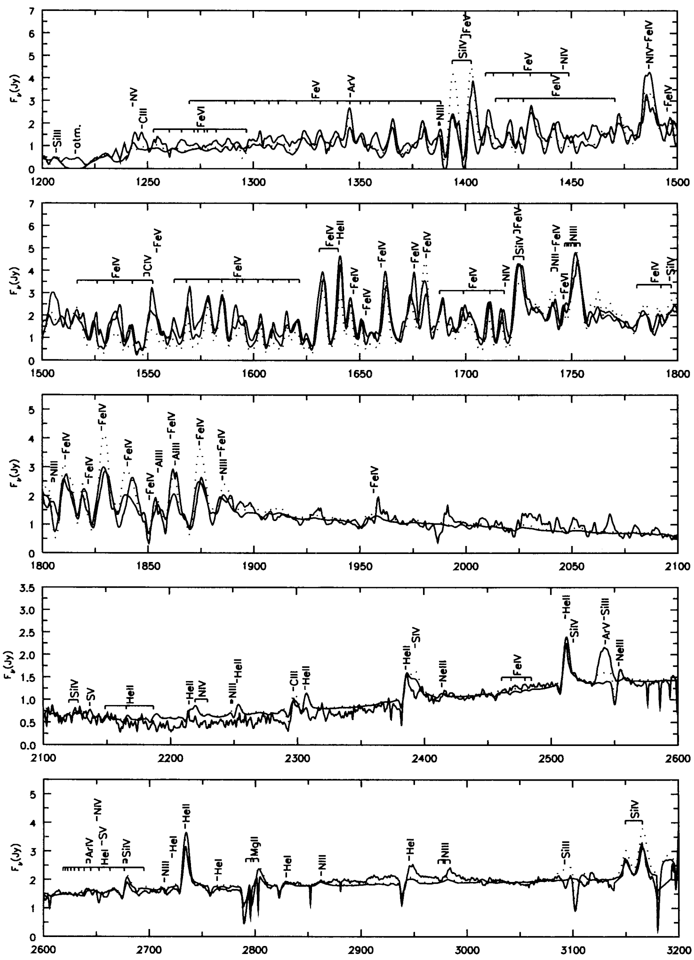

Figure 3. The UV spectrum of the WN8 star WR 40 (heavy solid line) as compared with two line-blanketed non-LTE models with massive clumped winds at different effective temperatures, 47 000 K (light solid line) and 44 000 K (dotted line), respectively, from Herald et al. (2001). Although the fits to observed spectra are not fully satisfactory, for instance for some important P Cyg profiles and N II and Si II line strengths, these models provide better fits than found previously for H, He and N II-IV features in general. The effective temperature adopted (45 000 K) is higher than previous estimates, while the mass loss rate derived ($3 \cdot 10^{-5}$ solar masses/year) is significantly lower due to the assumed clumpiness. Overall spherical symmetry is assumed and both the wind velocity and the clumpiness (the volume filling factor) are parametrized as functions of radius. It is not clear that these parametrizations are adequate enough to make the models candidates for a classification as Type IIa-b in the scheme of Sec. 5.

Hofmann, Scholz and Wood (1998), and by Höfner and collaborators (Höfner et al. 1998, and references cited therein, Höfner and Sandin, 2002). The pulsation itself is as presently often introduced by a piston in the bottom of the atmosphere model, with parametrized amplitude and period, but the response of the atmosphere is treated in considerable detail in the most recent models, by solving the hydrodynamical equations and allowing for dust formation and dust dynamics, and frequency dependent radiative transfer. The highly time-variable spectra of the models have been calculated and compared favourably with observed spectra of miras. Interesting future developments of these models are a consistent description of the pulsating star with its atmosphere (for a first step, see Hofmann, Scholz and Wood 1998), including a full non-gray radiative transfer. The treatment of departures from spherical symmetry, for instance by adopting methods like those of Freytag, are not as yet possible since the resolution of shocks in the pulsating models needs a very high local density of grid points.

Also for detailed modelling of more static cool stars, progress is noticeable. This is due to the calculation and compilation of extensive molecular data, in particular made by Jørgensen, Plez, and others. Final grids of spherically symmetric LTE model atmospheres are now being made (Gustafsson et al. 2002), and corresponding models in statistical equilibrium are already possible (Hauschildt et al. 1999). Even the LTE models tend to show good agreement with observations, e.g, the comparison by Alvarez and Plez (1998) for M giants in Figure 4 (also Gustafsson and Höfner 2003), or the fit by Schweitzer et al. (2002) of models of L dwarfs with dust and methane absorption to observations. Although these models have interest for applications, and may be used to explore the great abundance sensitivity of the atmospheric structure for cool stars, the need for further development with a more realistic representation of convection and depatures from LTE is obvious. Such models are almost within reach. For the coolest stars, a more detailed understanding of dust formation is very much needed.

The problem of modelling red-giant star atmospheres is discussed in detail by Gustafsson and Höfner (2003).

4. Then, what is most unsatisfactory, and what can be done about it?

Although progress is considerable along several lines in stellar atmospheric modelling, one cannot say that fully satisfactory models have as yet been possible to calculate, for any stars. The criteria of full internal or external (physical) consistency have as yet not been reached. Also, in all cases mentioned above, there are still mismatches found or expected in comparisons with observations, with their now available higher accuracy.

A basic reason for this shortcoming of the models is that there are still astrophysical processes in stellar atmospheres that are not well understood. Among these are mass-loss, coronal heating, dynamos and the roles of magnetic fields, dust formation, and instabilities in stellar winds. As long as processes like these are not physically understood, we cannot expect full success in our modelling attempts.

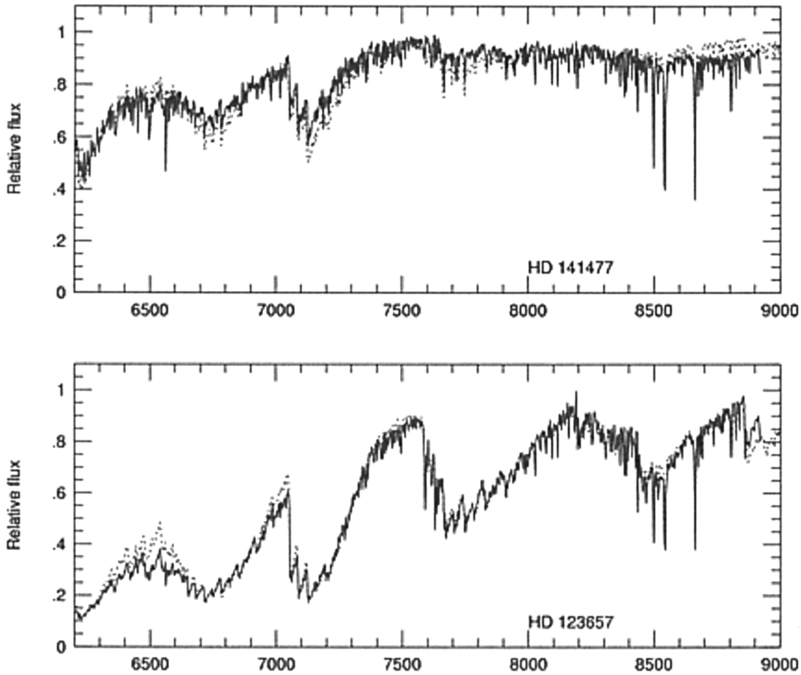

Figure 4. Observed spectra for the two M giants HD 141477 (M0 III) and HD 123657 (M5 III), as compared with spectra for spherically symmetric MARCS models with $T_{eff} = 3800\,\mathrm{K}$, $log\, g = 1.5$, and $T_{eff} = 3500\,\mathrm{K}$, $log\, g = 0.9$, respectively, from Alvarez and Plez (1998). The excellent fits indicate the high quality in the underlying molecular (notably TiO) data, but in spite of that, these 1D models in LTE and with mixing-length convection must be regarded to be of Type IIIb in the classification scheme of Sec. 5.

One might possibly think that future advances in computer technology will almost automatically resolve these problems – the full solution of the MHD equations and the complete radiative transfer problem would then provide simulations in which, for instance, mass-loss or dynamos will be produced. These models might then act as experiments in which the physical mechanisms may be further explored. This may, however, be overoptimistic. First, at least some of the processes like dust formation may require further theoretical and laboratory studies. Furthermore, in order to model phenomena like 3D plasma shocks, it may well be necessary to develop numerical algorithms that are based on some new physical understanding and physically based approximations of the complex reality. The time scale in order-of-magnitude improvements in computer performance is certainly remarkably short, but we cannot only count on that. Our problems are basically physical in character, and we probably have to behave like proper physicists. This means that our physical understanding, also of the properties of already existing models, should be deepened, while waiting for more computer power. Similarly, our search for vital observations, designed to distinguish between different alternative physical ideas and types of models, should be developed, just as observations that are insensitive to model uncertainties but sensitive to fundamental parameters of stars should be further developed for applications.

5. A classification scheme for model atmospheres

With the background presented above, I shall now look at our topic in a somewhat more general perspective, in the light of the Einstein quotation that was given initially. The word "model" is used with different meaning in science, and even in astrophysics. Sometimes, a *mathematical* model is thought of, i.e. essentially a set of mathematical equations, chosen to describe the essentials of physics involved. Sometimes the word is used almost in equivalence with "theory", i.e. containing not only certain equations but also assumptions behind them, range of application, ideas about testing methods and conditions under which the model should be refuted, etc. In other cases a much less ambitious concept, more similar to "scenario" is thought of. For many users a model atmosphere is just a table, e.g. of how temperature and pressure are presumed to change with optical depth in a stellar atmosphere. A rather extensive though not systematic or well defined vocabulary has emerged to describe the character of the assumptions underlying these tables.

Among the terms used to characterize models are "flux-constant models", typically meaning that energy conservation has been assumed for a static model, "semi-empirical models", indicating that a number of free parameters like the temperature as a function of depth are set so that the observed spectrum or spectral-energy distribution (and for solar models the centre-to-limb variation) are matched, "non-LTE models", suggesting that the assumption of Local Thermodynamic Equilibrium has not been made, at least not completely, etc. These terms often have historical background and are not very clear, sometimes not even to the users of them. Here, I would like to suggest a simple classification scheme for model atmospheres of different types:

- *Model atmospheres of Type I (physically consistent models)*

  Model atmospheres built on physical laws that are generally accepted, which are internally consistent, where the neglect of physical phenomena and numerical approximations are verified by detailed studies, and with a minimum of free parameters and all them representing well defined physical quantities (such as stellar radius, mass, chemical composition, some unknown atomic cross sections, etc).

- *Model atmospheres of Type IIa (approximate physical models)*

  Models like above but where certain physical phenomena or terms are neglected or approximated in ways that are reasonable but not (yet) proven to be fully correct, however without introducing severe losses of consistency.

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- *Model atmospheres of Type IIb (semi-empirical models)*

  Models like those of Type I but where a considerable number of parameters, like flow velocities or temperatures at different depths, are not determined from basic physical principles but estimated from fitting to observations, and where the resulting models are tested and found not to be in conflict with any important physical principles.

- *Model atmospheres of Type IIIa (physically incomplete models)*

  Models where certain physical phenomena are neglected, in spite of the fact that they are known or strongly suspected to be very significant for the atmospheric structure.

- *Model atmospheres of Type IIIb (physically inconsistent models)*

  Models where important physical phenomena are described with approximations that are known to be physically inadequate or severely inconsistent, or where free parameters are introduced that cannot be given a reasonable physical interpretation but still matter for the resulting model structure.

An interesting property of the modelling methods, related to their quality, is the possibility to apply them directly to different types of problems or different stars. Thus, computer programs for models of Type I should in principle be possible to use to study most aspects of a stellar atmosphere, or to cover wide areas in the HR diagram, by just changing the stellar fundamental parameters of the models. For Type II modelling more cumbersome changes would then be needed – for instance some of the approximations may be definitely untested or wrong in new corners of the HR diagram. Type III models are often rather specifically tailored for certain stars, or even certain limited aspects of these stars.

Looking back at existing model atmospheres, such as those referred to in Sec. 2 and 3 above, few, if any, models yet qualify for Type I classification. Some of the most advanced models are approaching Type IIa, while Type IIb is rare. Most models still must be classified as being of Type IIIa or IIIb. From the point of view of a worker in the field, *it seems very significant to raise the level of ambition so that all important astronomical conclusions from applying model atmospheres should be based on models of Type I or II.* How does it look from a more external point of view?

6. Is there a future in this?

Obviously, there is much work to be done in the field of stellar atmosphere modelling. Will it be done? Or is there a declining interest in this area, from the astronomical community as a whole and not the least from those outside the field whose interest and support are needed?

I would guess not. What will keep the interest alive and even strengthen it? Some circumstances come to mind:

(1) The solar-terrestrial relation, once the basic argument for the rise of astrophysics ("The New Astronomy") in the USA during the second half of the

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19th century (cf. Meadows, 1984), is a very good reason for developing solar, and stellar, research. The reason for "stellar research" in this last sentence is the fact that we probably will never understand the history and future of our Sun without further detailed studies of solar-type stars. The solar-stellar connection certainly gets more interesting also as a result of the discovery that planetary systems occur frequently around solar-type stars.

(2) The interest in processes of structure formation in dynamical systems is strongly increasing in many fields of science. One important issue is to which extent there are general principles still to be found behind these processes. Stellar atmospheres offer an interesting example, perhaps simple enough to really be understood in considerable detail. Fundamentally, there is a basic source of energy under the deep layers close to equilibrium in several respects. A strong energy flux is carried through the atmosphere, which is driven far from equilibrium in the outer layers. There, a plethora of interesting and beautiful structures emerge. Stellar atmospheres may be seen as good examples of what Ilya Prigogine called "dissipative structures". To which extent could other scientists learn from our systems?

(3) The systematic exploration of the first generations of stars in (and even before) the Galaxy has just begun, with quite interesting findings (e.g. Nissen et al. 2002, Hill et al. 2002 and Christlieb et al. 2002). This work seems to lead to important new results regarding the conditions and nucleosynthesis in the Early Universe. The cumbersome and detailed observations that are now being performed certainly deserve very detailed model atmospheres in the analysis.

(4) The discovery of the possible re-acceleration of the Universe, with a non-zero cosmological constant, or a "quintessance", by observing distant supernovae of type Ia at different redshift (Perlmutter and Riess 1999) raises the question of what systematic errors are involved in the interpretation of the supernova spectra and light-curves. For example, how do they depend on somewhat different initial metallicity? This is, partly, a question to our community of stellar-atmosphere modellers.

(5) The new large IR interferometers at VLT and Keck, as well as the future ALMA array in millimetre and sub-millimetre wavelengths, will contribute data on structures of stellar surfaces and circumstellar envelopes. These results will stimulate interest in further modelling of inhomogeneities in stellar atmospheres and winds.

(6) Progress in modelling will in itself make challenging suggestions to observers at interferometers, new infrared satellites, high-resolution solar telescopes, etc. Earlier, when models contained a number of free parameters, they were more used for fitting purposes. The more advanced and realistic the models become, the more challenging the predictions, also of qualitatively new phenomena, they should deliver. This may also stimulate interest in our branch of science.

So, what speaks against this picture of a promising future? One circumstance one might fear is that, as detailed observations and simulations are presented, the complexity gets so overwhelming that the field turns into "weather", a seemingly endless and rather chaotic mess of phenomena, for which new generalizing principles are very difficult to formulate or of only limited value when interpreting observational data and simulation results. This does not mean that observations or simulations are not useful, just that it could seem rather intractable to understand or develop them further. This would mean that the field in this sense really would become mature, and most probably stagnate, in particular if no profound discrepancies between models and observations would remain. Referring to the discussion above, in any case it seems that we are far from that situation, if we are not so lazy that we are satisfied with computer experiments and forget about real understanding, real theory. Also, referring to experience from many other branches of science, one might instead foresee a much more promising future. How many times have we not seen quite new, indeed qualitatively new, phenomena emerge as a result of improved theory or observations?

7. An old conclusion, reiterated

In a paper from 1740 the Uppsala astronomer Anders Celsius discussed the nature of a bright cloud seen close to the lunar limb during a solar eclipse some years earlier. A primary question was whether this cloud (now supposed to be a solar prominence) really belonged to the region around the solar disk. Celsius concluded: *Whatever the truth may be, physicists should pursue this exploration with diligence, and their hypotheses and findings should be verified further by the observations and experiences of future generations.* This conclusion seems highly relevant also for more current studies of stellar atmospheres.

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8. Discussion

ANDERSEN: I found that your division between the satisfactory and miserable status of modelling stellar atmospheres was quit biased since you listed as satisfactory results which FIT observational data, while self-consistent models that actually try to PREDICT stellar parameters from fundamental principles was listed as miserable. The aim of this community for the next meeting should be to predict various stellar properties and not just be contained with fitting observations on the basis of several free parameters.
GUSTAFSSON: I tried to give examples of arguments one could use for advocating that the present status of stellar-atmosphere modelling is excellent, satisfactory, unsatisfactory and miserable, respectively. I stated as clearly I could, that most of the examples that are advocated to be satisfactory could as well be claimed unsatisfactory, just because they involve fitting parameters, which in some cases are not even physically well defined. Moreover, I did not list any models as miserable, but our understanding of certain phenomena, like dynamics and dust formation. Certainly, these phenomena deserve much more work and attention, and those who already work on them need our support and appreciation. I agree that a meeting on physically self-consistent stellar modelling would be interesting.

Figure 5. Dr. Celsius diagnosing stellar model atmospheres

COWLEY: This is a comment on a situation that is considered to be lousy. The most fundamental abundance set - the standard abundance distribution - SAD - which we think represents the best composition of our sun comes - except for highly volatile elements - from CI meteorites: from rocks! We cannot tell from our own analyses, how these rocks differ in abundance of refractory elements, from the sun. So those who study the history of solar system materials are at a loss - because our analysis is still not good enough.
GUSTAFSSON: I agree that one should aim at solar abundance analysis accurate enough to serve the purposes of solar-system cosmogonists. However, for certain isotopic ratios, for sometime, it would hard to compete with carbonaceous chondrite analyses.

LINSKY: New interesting phenomena can be found and exploited by studying the interaction between stellar wind and the interstellar medium. An example is the measurement of mass loss rates for G-M dwarfs down to 10 -15 $M_\odot$/year by studying hydrogen walls around stars (see Poster F-14). My general point is that we should address the question of where do stellar atmospheres end. Any comments?
GUSTAFSSON: I agree, thank you for reminding us about the fact that the stellar atmosphere is a transition region affected by and affecting the layers below and above. Much of the interaction in the atmospheres relies on precisely this

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fact.

PISKUNOV: What level of dynamo theory would you consider as satisfactory?
GUSTAFSSON: Basically, we should be able to predict magnetic fields configuration and development on time scales from years to billions of years, as a function of stellar mass, age and chemical composition. I suppose this involves a full MHD modelling of the entire or much of the star as it evolves. The situation is satisfactory when these predictions agree with relevant observations and the underlying theory is physically self consistent.

SAPAR: What was the real time scale of the Betelgeuse clip demonstrated?
GUSTAFSSON: About 10 years

STEE: You never mention stellar interferometry as a tool to constrain stellar atmospheres models. I think that with the VLTI we will have a very good instrument to put very strong constraints since we will be able to see that stars are not plane-parallel or spherical!
GUSTAFSSON: I did mention the significance of getting images of stars - I think the results from VLTI and future interferometers will not only be very important data to compare with model predictions, complimentary to stellar spectra, but they will probably drive interest to stellar physics in general - compare the significance that astounding images have for studies of galaxies and nebulae.

References

Allende Prieto, C., Lambert, D.L., Asplund, M. 2002, ApJ 573, L137

Allende Prieto, C., Asplund, M., López, R.J.G., Lambert, D.L. 2002, ApJ 567, 544

Alvarez, R., Plez, B. 1998, A&A 330, 1109

Anderson, L.S. 1989, ApJ 339, 558

Asplund, M., Nordlund, Å., Trampedach, R., Stein, R.F. 1999, A&A 346, L17

Asplund, M., Nordlund, Å., Trampedach, R., Allende Prieto, C., Stein, R.F. 2000, A&A 359, 729

Asplund, M., García Pérez, A.E. 2001, A&A 372, 601

Barklem, P.S., O'Mara, B.J. 1998, MNRAS 300, 863

Barklem, P.S., Piskunov, N., O'Mara, B.J. 2000, A&AS 142, 467

Barklem, P.S., Stempels, H.C., Allende Prieto, C., et al. 2002, A&A 385, 951

Bowen, G.H. 1988, ApJ 329, 299

Celsius, A. 1740, *De annulo in eclipsi solis totali circa lunam lucido*, Dissertation at Uppsala University, respondent Jonas Brundstedt

Christlieb, N., Bessell, M., Beers, T.C. et al. 2002, Nature, in press

Fleischer, A.J., Gauger, A., Sedlmayr, E. 1992, A&A 266, 321

Freytag, B. 2001, ASP Conf. Ser. 223, 785

Gustafsson, B. 1980, in *ESO Workshop on Methods of Abundance Determination for Stars*, eds. P.E. Nissen, K. Kjaer, p. 31

Gustafsson, B., Höfner, S. 2003, in *AGB stars*, eds. H. Habing and H. Olofsson, Springer (New York), in press

Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2002, in prep.

Hamann W.-R. 1986, A&A 160, 347

Hauschildt, P.H. 1993, J. Quant. Spectrosc. Radiat. Transfer 50, 301

Hauschildt, P.H., Allard, F., Baron, E. 1999, ApJ 512, 377

Hauschildt, P.H., Allard, F., Barman, T., 2001, in ASP Conf. Ser. 231

Herald, J.E., Hillier, D.J., Schulte-Ladbeck, R.E. 2001, ApJ 548, 932

Hill, V., Plez, B., Cayrel, R., et al. 2002, A&A 387, 560

Hillier, D.J., Davidson, K., Ishibashi, K., et al. 2001, ApJ 553, 837

Hofmann, K.-H., Scholz, M., Wood, P.R. 1998, A&A 339, 846

Höfner, S., Jørgensen, U.G., Loidl, R. et al. 1998, A&A 340, 497

Höfner, S., Sandin, C. 2002, A&A, in press

Höfner, S., Gautschy-Loidl, R., Aringer B. et al. 2002, A&A, submitted

Hubeny, I., Lanz, T. 1995, ApJ 439, 875

Jørgensen, U.G. 1996, in IAU Symp. 178, 441

Kupka, F., Piskunov, N., Ryabchikova, T.A. et al. 1999, A&AS 138, 119

Meadows, A.J. 1984, in *Astrophysics and twentieth-century astronomy to 1950, Part A*, ed. O. Gingerich, Cambridge Univ. Press, p. 59

Nissen, P.E., Primas, F., Asplund, M., Lambert, D.L. 2002, A&A 390, 235

Nordlund, Å., Dravins, D. 1990, A&A 228, 203

Perlmutter, S., Riess, A. 1999, COSMO-98, AIP Conf. Proc. 478, 129

Scharmer, G.B., Carlsson, M. 1985, J Comp Phys 59, 56

Schwarzschild, M. 1975, ApJ 195, 137

Schweitzer, A., Gizis, J.E., Hauschildt, P.H., et al. 2002, ApJ 566, 435

Stein, R.F., Nordlund, Å. 1998, ApJ 499, 914

Werner, K., Husfeld, D. 1985, A&A 148, 417

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