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Closing Remarks

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Abstract.
I offer some comments on the importance of our field (rather modestly, we could say that we are central to almost the entire enterprise of astrophysics) and on some of recent developments in our field (an impressive record of difficult problems attacked and – often – solved). Finally I consider some of the work still left to be done, which is assigned to the participants, their colleagues, friends, and students as homework to be done, as far as possible, for the next major stellar atmosphere meeting.

1. Introduction

When I was asked to make the closing remarks at this very interesting and valuable meeting, I was quite worried that the Scientific Organizing Committee had actually meant to ask Jeff Linsky to give this talk, and that some kind of obscure e-mail mishap had occurred which had led the invitation to make the closing remarks to my door instead of his. After all, Jeff is very good at this sort of thing, and both our e-mail addresses begin with "jl".... So it was a great relief to discover during the *excellent* banquet that the SOC had decided to employ Jeff's considerable oratorical talents for something more important, namely offering one of the major toasts at the dinner.

So with the reassurance that this last talk really is my job, here are a few thoughts.

2. Does our field matter?

Our field is sometimes thought of as a rather exotic specialty. But actually what we do is completely central to much of the entire enterprise of modern astrophysics. To a very important extent, we are the eyes and ears of astronomy. Consider the following points:

Most of the visible matter in the universe is in stars (in the Milky Way, about 90% of the identified mass is in stars). Virtually all the empirical information we can obtain about these basic, universal building blocks of the cosmos is through the radiation emitted by their hot surfaces. Understanding the structure and emission processes of stellar atmospheres is thus *essential* for interpreting the signals that we receive from stars, and therefore for learning what hints Nature offers us about these fundamentally important objects.

Because of our interpretive efforts, and the success of the theory of stellar structure and evolution (which of course developed in close collaboration with stellar atmosphere observations and theory), many stars are relatively well understood. Because stars are reasonably well understood, we can use them as powerful probes of the structure and history of galaxies, and of the universe at large.

Finally, our well-being on Earth is obviously determined by our own Sun. Understanding the surface layers of this one particular star, and its varying emissions, is arguably the most socially important project of current astronomy.

Our field is not simply important. I think that it is fair to say that it underlies, and is fundamental to, much of the entire edifice of modern astrophysics.

3. We came a long way in the 20th century!

Less than 100 years ago no one understood that stellar spectral types tell us about atmospheric temperatures. It was only in the 1920's that M. N. Saha showed that stellar spectral types are in fact a temperature sequence. This work was brilliantly extended by Cecilia Payne, Arthur Milne, Ralph Fowler, Albrecht Unsöld, Henry Russell and others. By 1937 Unsöld could write a comprehensive textbook on "Physik der Sternatmosphären" that is still a classic in the field, and still certainly worth reading.

Much work was done during the second half of the 20th century consolidating and exploiting the developing theoretical framework and the expanding range of observations. We have also discovered the many limitations and inconsistencies of the early theory and much effort has been expended to deal with them. Thus, a lot of work in recent decades has focused on such areas as

- a physically more correct treatment of the equations of statistical equilibrium describing the interaction between the sea of particles and the radiation field ("NLTE"),
- the mechanisms of generation and the effects of winds, and the radiation from atmospheres in which important winds occur,
- a reasonably accurate but usable description of the velocity field produced by envelope and atmospheric convection,
- the consequences of microscopic diffusion under the competing influences of gravitation, radiative levitation, and velocity fields,
- the origin and generation of surface magnetic fields and their consequences for the atmosphere and outer layers of a star,
- the diagnosis, origins and effects of stellar activity,
- the correct treatment of non-stationary atmospheres, particularly pulsating and mass-losing atmospheres, and ....

It seems to me that stellar astrophysics got off to a much earlier "power start" than other kinds of astrophysics. A number of factors helped us to get off to an impressive early beginning.

Stars are not only common, but many kinds are intrinsically luminous. Thus a lot of our objects are bright enough to provide really good spectra – even photographically – and these spectra contain a *lot* of information. We have had a rich and varied data base to explore, and a lot of stimulation to model and explain observations, for several decades now.

Stellar astrophysics has developed in parallel with the growing understanding of the physics of atoms, molecules, and atomic nuclei and their interactions. We benefited in particular from the development of workable theory together with a lot of experimental data describing radiation and its interaction with matter. Advances in understanding the physics have led to corresponding advances in understanding stellar atmospheres. We are now in the fortunate situation that much of the basic physics underlying our field is relatively well understood. Furthermore, some physics that is not well understood, or at least has no decent, usable model (e.g. convection) can be treated approximately. Another helpful feature of many stellar atmospheres is that the facets that are still poorly understood today (e.g. stellar magnetism and activity) do not make all inferences from simple, zero-order models completely incorrect or irrelevant.

Another lucky break for stellar theory has been the fact that a lot of important problems have spherical or cylindrical symmetry – the equations are either one-dimensional or at least fully separable, as the depth and wavelength coordinates are in a purely absorptive LTE atmosphere. One-dimensional problems are much more likely than multi-dimensional ones to possess analytical solutions, or can be solved with straightforward numerical methods that can even be carried out by hand, using tables of logarithms or simple calculating machines. This fortunate circumstance has been of great value both to the study of stellar atmospheres and stellar interiors, where early manual numerical integrations played a fundamentally important role (cf. Martin Schwarzschild, in *Structure and Evolution of the Stars*, p. 120: "... for a typical single integration consisting of, say, forty steps less than two days are needed...")

4. Current work

But we have certainly moved on from there. We are responding to circumstances that are rather different from even ten years ago. What are the important drivers of research now?

One aspect of our field that has been changing dramatically for a couple of decades now is the fact that data are *flooding* in at an unprecedented rate, and with unprecedented quantitative accuracy. These data come from a new generation of large telescopes (and re-furbished smaller ones), and – just as importantly – a new generation of imaging devices and (especially) spectrographs. In addition, we have acquired in recent years data on stellar atmospheres in almost the complete wavelength window from the radio and the far and near infrared through to the ultraviolet and X-ray bands, thanks to advances both in ground-based and in orbiting telescopes. Think of the VLA, SOHO, ISO, the Hubble telescope, and Chandra, for example. These data provide fantastic new material and stimulus for theoretical understanding, and tests of ideas and models.

Similarly, the amount of atomic data and the number and kinds of computational results available through the Web is already amazing, and growing every day. Consider, just as typical examples, the huge atomic line data collection maintained by the Vienna Atomic Line Database at **www.astro.uu.se/~vald/**, or the splendid compilation of oscillator strengths and photoionization cross sections produced by the TOPbase collaboration and available (for example) at **heasarc.gsfc.nasa.gov/topbase/topbase.html**. Several excellent archives of computed stellar model atmospheres are also available. The existence of such resources is not only a wonderful resource for our community, but also a tribute to the public spirit of the people who make these databases available to the rest of us.

Everyone is aware that computer power is advancing at a furious pace. Almost every aspect of computer power – CPU speed, RAM size, hard disk capacity, etc – doubles every 18 months or so. We all have the supercomputers of yesteryear on our desks. We not only have the commercial operating systems, but also the remarkably inexpensive Linux distributions with their array of computational and display tools. Numerical and computational techniques and environments are also advancing rapidly, both on the commercial side (you all know the brand names, and about the costs of licenses and the copyright restrictions) and also on the shared side. Check out **netlib.org** for a fantastic collection of freely available and generally well-tested source code for all kinds of computations, from matrix inversion to solvers for differential equations to routines for special functions. Look at **www-rocq.inria.fr/scilab/** for an excellent, free environment for numerical computation.

As a result of these developments, we are relying more than ever on the results of numerical computations to see whether our models have all – or even most – of the essential physics in them. A very considerable fraction of talks at this meeting have concentrated on methods and programmes for numerical computation, or on confrontations of results of numerical computation with observations. In this connection, I would like to re-emphasize a point made at the beginning of the meeting by Bengt Gustafsson, namely that it is *just as important to publish our modelling failures as our successes*, since it is the failures that point the way to missing physics or inadequate models or computational methods, and thus lead us to new basic advances.

What has really developed over the past few years, I think, is the movement of numerical modelling into more and more dimensions. One wonderful example of work in progress of this kind is 3-dimensional modelling of a convective layer with radiative transfer, and magnetic effects in the sun and inhomogeneities in winds provide other examples.

We have participated in and heard about attacks on an impressive series of very important problems.

5. What are some of the big problems today?

There are still a *lot* of challenges left in our field, including some really difficult ones. One way of classifying some of these is by where in the atmosphere they

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come in. I don't really need to spell out what these problems are; we are all pretty familiar with the difficulties they pose.

From the *lower boundary conditions*:

- *Velocity fields*: We badly need a usable but accurate description of the effects of convection. Much work remains to be done on how best to incorporate the effects of pulsations into atmosphere models.

- *Chemical flows*: We still do not have a clear understanding of how to calculate correctly the consequences of diffusion under the influence of radiative and gravitational forces in the region under the atmosphere. The effects of dredge-ups during advanced evolution result in chemically unusual atmospheres for which better structural models are needed.

- *Magnetic fields*: Cool stars possess dynamo magnetic fields which produce rather complex and time-variable structures in the stellar atmosphere; we are far from having adequate models of such situations. Fossil magnetic fields lead to atmospheric electrical currents induced by internal field changes; the resulting dynamic effects on the structure of the atmosphere are not at all well understood.

- *Rotational distortion* Rotational distortion of a star can be detected by the subtle effects it has on line profiles; this field is only starting to be exploited.

From *within the atmosphere*

- *Atomic data*: We have access to a lot of atomic data ranging in quality from reasonably good to superb, but we still need much more – more and more accurate gf values, continuous opacities, damping constants, collision cross sections....

- *Radiative transfer and atmosphere models*: NLTE, line blanketing is coming to be understood, but NLTE models of stellar atmospheres still suffer from missing or inaccurate data and computing power limitations. Atomic line profile redistribution is still treated rather schematically or approximately in most models.

- *Chemical abundances*: Why can't we derive abundances that are accurate to 5% (the precision of the best gf values) instead of 30% or 50%?

- *Magnetic fields*: All kinds of magnetic activity have structural and dynamical consequences for the atmosphere that need to be understood. We have no physical understanding yet as to how magnetic fields lead to very inhomogeneous chemical abundances over the surface of a magnetic Ap star, and our atmosphere models are still drastically simplified compared to the actual stellar atmosphere.

- *Velocity fields*: Velocity fields have effects on atmospheric structure as they alter the radiative transfer and create inhomogeneities; models are only beginning to describe these effects. Velocity fields also strongly affect line profiles, but we are just starting to extract the available information from this source.

- *Chemical stratification*: Clearly this is an important effect in tepid main sequence stars, but has so far hardly been modelled more than schematically.

And from *the upper boundary condition* too

- *Extended atmospheres*: Both the (inhomogeneous) structure and the heating mechanism(s) of chromospheres are poorly understood. The situation is just as bad for coronae. Non-thermal energy loss outwards is still poorly understood.

- *Mass loss*: There is still a lot of uncertainty about driving mechanisms. It is known in some situations that mass loss does not result in a completely mixed wind, but this is still not well understood. The effects of magnetic control on winds are quite uncertain. Instabilities are clearly present in some winds but we do not yet have an adequate understanding of these. Dust formation is still very poorly understood, and its consequences are uncertain.

- *Mass gain*: Models of accretion disks are advancing, but there is still much work to do. Accretion from a companion poses similar complex problems.

- *Magnetic coupling to the exterior*: All kinds of activity couple to mass loss or gain in ways that are difficult to model accurately. Similarly, our understanding of angular momentum gain or loss through coupling to disk or wind is poor, particularly in the presence of a magnetic field.

These problems are assigned to the participants in this meeting, their friends, colleagues, and students, as homework. Do as much as possible, and turn in whatever you have finished at the next major stellar atmosphere meeting. (Be sure to use your best handwriting.)

6. Any clouds on the horizon?

It seems to me that there is one major problem facing our community as we work away on this long list of difficult problems. It is not CPU speed, or disk space, or telescope aperture. The problem is a shortage of people. We work on really difficult problems, so people in this field have to be really good at data analysis, physics, mathematics, and numerical methods. Because what we do is difficult and not always very glamorous, we only attract a small number of new entrants into the field each year. There are not enough of us to keep up with the rapidly evolving situation – with the data in ever-increasing amounts and quality, with computers that can run larger programmes ever faster, and the steadily increasing subtlety and complexity of what our colleagues do. There simply aren't enough of us.

We also do not see each other often enough, and so I would like to offer my personal thanks, and thanks on the part of all the participants in this meeting, to the members of both the Scientific Organizing Committee who are

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