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Fifty Years of Research on Stellar Atmospheres*

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Abstract: I would like to begin by saying what a pleasure it is for me to be here. For my entire adult life I have wanted to come to Australia. Actually, I have been invited to visit here twice before, but each time I was thwarted by circumstances beyond my control. But this time I was determined to (a) prove that the third time is indeed the charm, and (b) pay homage to Walter Stibbs, who in my mind is the epitome of a scholar and a gentleman. I have known Walter as colleague, teacher, and friend, not to mention as an inspiration, both professional and personal. So I am here today to try to give some sense of progress in the study of stellar atmospheres, a field that Walter has graced with his virtuosic touch. I will follow an unabashedly personal path, describing the development as I experienced it. I will focus almost entirely on early-type stars, where we may reasonably expect the atmospheric layers to be homogeneous, and in radiative equilibrium. Only at the end will I mention our nearest stellar neighbor, the Sun, which, because we can study it in so much detail, offers counterexamples to almost all of the the theory that works so well for early-type stars. I offer apologies in advance to anyone this approach may offend.

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1 Why Study Stellar Atmospheres?

These days, the subject of stellar atmospheres seems, to some people, rather old fashioned compared to 'exciting' parts of modern astrophysics. On the observational side we have been in a period of great discovery for at least three decades, and the pace seems only to accelerate. On the theoretical side, we have brought to bear deep new physics, such as General Relativity, and Elementary Particle Theory. In a more prosaic vein, I can relate that once, back in the early '60s, Ed Salpeter came to visit his friend Martin Schwarzschild at Princeton. While there, he went around to the younger staff, and asked what we were doing. I told him that I was making models of stellar atmospheres. He was silent for a moment, and then said 'Why in the world would you want to do that? After all, the entire atmosphere is only 10^{-10} of the mass of a star!' With a touch of embarrassment, I must confess that I didn't know a good response then. But I do now:

(a) The atmosphere of a star is what we can see, measure, and diagnose.
(b) It is therefore the source of the data needed to convert the observer's color-magnitude diagram to the theorist's L–$T_{\rm eff}$ diagram, and thus guides and constrains stellar evolution theory.
(c) Atmospheric analyses give chemical abundances, and reveal the results of cosmochemistry from the earliest moments of formation of the universe.
(d) Hence work on stellar atmospheres provides one of the two major tests of the Big Bang, the 'creation myth' of Western culture.
(e) Work in the field has challenges even for lesser mortals like me because these are the layers in which there is a transition from the near-perfect thermodynamic equilibrium of a stellar interior to the total blackness of space. This is a strongly *nonequilibrium regime*.

2 Back to the '50s

Let's go back 40 years and ask how it looked to me when I entered Caltech as a graduate student. On the observational side, the astronomy group at Caltech was doing some very exciting work. There were good spectrographs at the 100″ and 200″ telescopes built with large Babcock gratings. The Greenstein stellar abundance project was active, and was making great discoveries. As a result, we had visitors from all over the world who added breadth and depth to the level of activity. Most of the spectroscopic effort was still photographic, but there was some pioneering photoelectric work with the dual-channel scanner built by Code and Oke at the 100″ coude. In fact that was the tool I used to gather observational data for the analysis of O-star spectra in my PhD thesis under the guidance of Oke.

On the theoretical side, as an undergraduate I had been told that work on stellar interiors and evolution was tractable, and was yielding great payoffs. But my teachers said that stellar atmospheres theory is hard, though I was not told the real reasons why. In graduate school I took the course from Greenstein; he was a brilliant researcher, but as a teacher he was terribly disorganised, and students called his course the 'hour of mystery'. Nevertheless, even then I realised that analyses of stellar spectra gave a *wealth* of data instead of just two numbers, $L(M, t)$ and $R(M, t)$, considered central to stellar evolution theory.

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At that time, the textbooks from which we tried to learn were:

- S. Chandrasekhar (1950), *Radiative Transfer* (Dover 1960)
- V. Kourganoff (1952), *Methods in Transfer Problems* (Dover 1963)
- L. H. Aller (1953), *Atmospheres of the Sun and Stars*, 2nd ed. (1963)
- A. Unsöld (1955), *Physik der Sternatmosphären*

In addition we were referred to papers on line formation by E.A. Milne and A.S. Eddington in the *MNRAS* written in the epoch 1910–1930.

Chandra's book was useful for learning the 'method of discrete ordinates', but had only one brief chapter on stellar atmospheres. Kourganoff's book was quite useful in learning the basics of radiative transfer. But mainly we made do with Aller's and Unsöld's books. The basic physical paradigm presented in these books applies to STATIC, PLANAR, GREY, LTE (Local Thermodynamic Equilibrium) atmospheres. Unfortunately, the students were unaware that far better resources existed, even at the time I was working on my thesis, namely:

- **R. v. d. R. Woolley & D. N. W. Stibbs (1953)**, ***The Outer Layers of a Star***
- J. C. Pecker & E. Schatzman (1959), *Astrophysique Generale*
- V. A. Ambartsumian (ed.) (1958), *Theoretical Astrophysics*
- V. V. Sobolev (1960), *Moving Envelopes of Stars*

Of all these books, the one by Woolley & Stibbs, which I discovered one day in the Caltech bookstore, is by far the best. It has thorough discussions of all the major topics, and it is beautifully written, maintaining throughout an excellent balance between mathematical rigour and physical insight. It was from this superb book that I first began to get some of the basic concepts of rate equations and departures from LTE (e.g. in the Rosseland cycle). For the first time, the theory began to make sense. It was truly a branch of theoretical and mathematical physics, not just an *ad hoc* potpourri of theoretical and empirical odds and ends! This book made a profound impression on me, and has motivated much of my own work in the following decades.

The book edited by Ambartsumian contains an excellent and inspiring article by Sobolev on line-formation in expanding atmospheres. Shortly after I finished my thesis, a second good book by Sobolev became available:

- V. V. Sobolev (1963), *Treatise on Radiative Transfer*.

Still later, the book *Selected Papers on the Transfer of Radiation* (1966) edited by D. Menzel, which contains some of the great foundation stones of stellar atmospheres theory, was published:

- A. Schuster (1905), *Ap. J.*, **21**, 1 (Scattering Lines)
- K. Schwarzschild (1906), *Nac. Kon. Ges. Wiss. Gott.*, **195**, 41 (Radiative Equilibrium)
- K. Schwarzschild (1914), *Sitz. Kon. Prus. Akad.*, 1183 (Absorption vs. Scattering and new mathematical techniques)
- E. A. Milne (1930), 'The Thermodynamics of Stars', in *Handbuch der Astrophysik*, **3**, Part I, Chapter 22, 65

These papers, though old, were written by masters, and contain deep physical insight; they are very much worth reading even today! Unfortunately, at the time I was a student, all of these great papers were unknown to me.

3 Triumphs of the '40s and '50s

Despite the oversimplified physical assumptions that had to be made, and the complete absence of any significant computational capability during the '40s and '50s, very important progress was made in developing a basic theoretical understanding of stellar atmospheres. Some of the important milestones are:

(1) The *exact* temperature distribution in a grey (i.e. frequency-independent) opacity atmosphere in radiative equilibrium was derived by Mark (1948). A very readable account of this work is given in Woolley & Stibbs.
(2) The monumental study of the quantum mechanical structure and opacity of the H^- ion by Chandrasekhar (see Figure 7 in Chandrasekhar & Breen 1946) allowed identification of H^- as the major opacity source in the atmospheres of the Sun and solar-type stars (Chandrasekhar & Münch 1946).
(3) These developments in turn provided the basic theoretical structure for calculating realistic curves of growth to analyse the strengths of spectrum lines in large numbers of stars (e.g. the Greenstein project).

4 The New Era Dawns: on to the '60s

One of the most basic features of work on stellar atmospheres is that virtually all the important process are highly nonlinear. The traditional methods of mathematical analysis are often powerless to address such problems. So the development of high-speed electronic computers in the early '60s was a breakthrough. For the first time it became possible to at least *model* the radiative transfer in stars; by now we can actually try to *simulate* it with a high degree of realism.

With the advent of computers, people realised that they could enforce energy balance in static, NON-GREY, planar, LTE atmospheres. There was a very active group at the Harvard Smithsonian Observatory who pioneered this effort, and discovered numerical procedures to determine the temperature distribution in non-grey atmospheres. At that time the solution of the transfer equation was based on integral-operator techniques developed by Strömgren. These methods were computationally rather costly, and could merely *stabilise* rather than *converge* in the presence of a large amount of scattering, as is the case in O stars, which were my main interest. Nevertheless, it was possible to make large grids of *continuum* models (Mihalas 1965; Strom & Avrett 1965).

And even at that early time the computers were fast enough so that one could try to make LTE LINE-BLANKETED atmospheres. Strom & Avrett (1964) and Mihalas (1966) computed hydrogen line overlap at the Balmer series limit in A stars, Mihalas & Morton (1965) explored the effects of lines on the UV spectra of hot stars. Strom & Kurucz (1966) developed their very powerful ODF (opacity distribution function) method which allows one to include the effect of millions of spectrum lines. The ODF method has since been applied by many authors, and yields results in very good agreement with detailed spectral scans and colors (see e.g. Castelli & Kurucz 1994).

5 Work in the '70s: Non-LTE

In about 1967, I gave a talk at Boulder. Afterwards, Dick (Richard N.) Thomas, who had invited me, told me, in his usual blunt way, that everything I had done was wrong; and he explained why. Stellar atmospheres have low density. Therefore collisions are relatively unimportant, and the state of the material is *driven by the radiation field*. But in turn, the radiation field is *determined by* the state of the material through its emissivity and opacity. We therefore must solve an intricate and highly nonlinear problem with detailed rate equations (which give the steady state in populations of atomic levels), directly coupled to the transfer equations, which give the radiation field. I realised that what he said had to be correct, and I moved to Boulder for a year to learn about these ideas, and, I hoped, how to construct static, non-grey, planar, non-LTE models.

The basic picture is very simple: for each level l, the number of transitions into the level must exactly equal the number of transitions out. The ways into the level can be categorised as:

- radiative excitation ($l' \to l$)
- collisional excitation ($l' \to l$)
- radiative de-excitation ($u \to l$)
- collisional de-excitation ($u \to l$)
- radiative recombination ($\kappa \to l$)
- dielectronic recombination ($\kappa \to l$)

Here l' denotes a level lower in energy than l, u denotes a level of higher energy, and κ denotes the continuum.

Likewise, the ways out of level l are:

- radiative excitation ($l \to u$)
- collisional excitation ($l \to u$)
- radiative de-excitation ($l \to l'$)
- collisional de-excitation ($l \to l'$)
- photoionisation ($l \to \kappa$)
- autoionisation ($l \to \kappa$)

But there is a hitch. The spectrum lines mainly *scatter* radiation, and are *not*, at the atmospheric depths we can observe, strongly coupled to the thermal field of the material. Put another way, the upward radiative rates in a line transition are determined by the local radiation field, which may originate at a distant point in the medium, and the downward rates are practically independent of local conditions, being determined mainly by the spontaneous transition rate. Thus scattering in the lines becomes the *central problem* to be solved in any non-LTE calculation. To gain a feeling for the problem, assume coherent scattering, in which case the line source function can be characterised as:

$$S(\tau) = (1-\epsilon)J(\tau) + \epsilon B(\tau) \tag{1}$$

where the mean intensity $J(\tau)$ is in turn given by

$$J(\tau) = \Lambda_\tau[S(t)] \equiv \int_0^\infty S(\tau)E_1|t-\tau|dt. \tag{2}$$

Here $\epsilon \sim C_{ul}/A_{ul} \ll 1$ in spectrum lines. Λ_τ is known as the Lambda operator. The standard iteration procedure is: (a) set $J(\tau) = B(\tau)$ as an initial estimate; (b) use equation (2) to compute a new estimate of $J(\tau)$; (c) use the resulting $J(\tau)$ in equation (1) to get a new $S(\tau)$; and (d) go back to step (b) if the solution has not converged.

In Woolley & Stibbs's book it is shown that this Lambda iteration procedure converges quickly near the surface, but leaves an initial error in the solution unchanged at infinite depth. It is for this reason that the method fails for $\epsilon \ll 1$. For example, the exact solution for constant B has $J(0) = \sqrt{\epsilon}B$, and $J(\tau) \to B(\tau)$ (i.e. *thermalises*) only for $\tau \gtrsim 1/\sqrt{\epsilon}$. But each Lambda iteration propagates information about the existence of the surface only over an optical depth range of $\Delta\tau \sim 1$, so that if we started with an initial guess that $J_0(\tau) \equiv B(\tau)$, we would need of order $1/\sqrt{\epsilon}$ iterations to obtain anything close to the right answer! For strong spectral lines where ϵ is often $\sim 10^{-6}$, and can even be as small as $\sim 10^{-11}$, we would require a prohibitive number of iterations. The situation is *much worse* for noncoherent scattering. If we have complete redistribution of emitted photons over a Doppler profile, the thermalisation depth, hence the number of iterations, is $\sim 1/\epsilon$, and for a pure Lorentz profile it is $\sim 1/\epsilon^2$.

5.1 Feautrier to the Rescue

In 1964, Paul Feautrier discovered way to solve the transfer equation with arbitrarily complicated scattering terms (integrals over angle, frequency) as a second-order difference equation posed as a two-point boundary-value problem. Mathematically, he wrote the transfer equation, with appropriate boundary conditions, as a tridiagonal difference-equation system of the form:

$$\mathbf{A}_d\boldsymbol{\psi}_{d-1} + \mathbf{B}_d\boldsymbol{\psi}_d + \mathbf{C}_d\boldsymbol{\psi}_{d+1} = \mathbf{L}_d. \tag{3}$$

$\mathbf{A}_d$, $\mathbf{B}_d$, and $\mathbf{C}_d$ are $NJ \times NJ$ matrices that represent the transfer equation, where NJ is the number of discrete angles and frequencies needed to describe the scattering kernel, and $\boldsymbol{\psi}_d$ is the solution vector, of length NJ at depth-point d. This development was a *breakthrough* because the method was powerful, robust, and easy to code. Suddenly it became possible to solve difficult scattering problems with no difficulty.

5.2 Complete Linearisation

Despite the great step forward afforded by Feautrier's work, we were still not home. The essence of the problem is interlocking among transitions. That is, the radiation field in one transition can, in general, influence populations in levels other than those of the transition under consideration. Ultimately, we must consider all photons as belonging, in the words of John Jefferies, to a 'collective photon pool'. Such deep levels of coupling are quite daunting. Until the end of the '60s several workers had tried various iterative techniques for dealing with this problem, with mixed success. Auer and I followed the path of trying to incorporate constraints into the transfer equation by using a linearisation technique. Focusing first on the issue of determining the temperature distribution, we found that we could solve the transfer equation and radiative equilibrium constraint in this way. Later we added a statistical equilibrium equation for the first two levels of hydrogen, to explore the formation of Lyman α. But when we attempted to add more transitions, the methodology fell apart. Finally we decided to treat all variables in the problem as equally fundamental: the radiation field at all frequencies, the temperature, and all level populations, simultaneously (Auer & Mihalas 1969). The mathematical approach entailed writing the whole nonlinear system and then linearising it. The result is a tridiagonal system for the corrections to current values of physical variables of the form:

$$\mathbf{A}_d \delta\boldsymbol{\psi}_{d-1} + \mathbf{B}_d \delta\boldsymbol{\psi}_d + \mathbf{C}_d \delta\boldsymbol{\psi}_{d+1} = \mathbf{L}_d, \tag{4}$$

where

$$\delta\boldsymbol{\psi}_d = (\delta J_1, \delta J_2, \ldots, \delta J_{NJ}, \delta N_{\mathrm{tot}}, \delta N_e, \delta n_1, \ldots, \delta n_L). \tag{5}$$

Here NJ is the number of frequencies in the spectrum, and NL is the number of levels in the model atom.

This system can be solved by the same algorithm used to solve equation (3). What it gives is the coupling, to first order, of the change in any one variable, at any depth, to the change in any other variable, at all depths. If we start from a reasonably good solution (e.g. obtained from LTE), we typically could get an accurate non-LTE solution in a small number of corrections. The good news is that it worked! It could be considered to be another breakthrough. But the bad news is that this direct computation is very costly, scaling as $(NJ+NL+NC)^3$ where NC is the number of physical constraints (e.g. radiative and hydrostatic equilibrium, charge and number conservation, etc). Because of this unfavourable scaling, one had to be very parsimonious in setting up a calculation: choosing the levels in the atomic model, choosing the important transitions to be treated, and managing an adequate frequency spectrum.

The first calculations we did were for the hydrogen lines in O stars (Auer & Mihalas 1970). We immediately hit paydirt. We found that non-LTE effects increased the equivalent widths of the hydrogen Balmer lines by about a factor of 2 to 3, bringing the theoretical calculations into agreement with observations for the first time. Later (Auer & Mihalas 1972) we extended the work to He I and He II in O stars, and found similarly large effects. In retrospect it should have been obvious that O stars would be the best candidates for large departures from LTE, because the radiation field, hence the radiative rates, at the relevant temperatures are so large. We were also able to do analyses for He I (Auer & Mihalas 1973a), N III (Mihalas & Hummer 1973), Ne I (Auer & Mihalas 1973b), Mg II (Mihalas 1972), and Ca II (Mihalas 1973). For Mg II and Ne I we were able to remove long-standing discrepancies between stellar and nebular abundance estimates. For N III we got insight into the basic emission mechanism for the $\lambda\lambda$4634–40 lines. But eventually we had to give up because the atomic models for other ions were becoming more complicated, and worse, we needed NON-LTE LINE-BLANKETED models to know fluxes, hence photoionisation rates, in the ultraviolet part of the spectrum. At the time, construction of such models seemed to be 'mission impossible'. But, as we shall see, fortunately we were totally wrong!

6 Flowing along in the '80s

6.1 *Extended and Expanding Atmospheres; Partial Redistribution*

Partly inspired by the discovery and observations of stellar winds, and the development of a good theory of radiatively-driven winds (Castor, Abbott & Klein 1975), a number of workers learned how to solve the transfer equation in spherical geometry with atmospheric expansion. Then we were in a position to consider EXTENDED, non-grey, non-LTE, MOVING atmospheres. An essential trick in this work was to transform to the comoving frame of the fluid. Methods were developed for treating line formation with complete and partial frequency redistribution in moving atmospheres to compare with observational data. This work is summarised in the very nice book by Sen & Wilson, referenced below. It was also found that partial frequency redistribution in the scattering process is very important for the interpretation of resonance lines in the solar spectrum.

6.2 *New Books*

In this era, a number of new texts and important conference proceedings appeared.

Textbooks:

- D. Mihalas (1978), *Stellar Atmospheres*, 2nd ed. (Summary of work of the '70s; now obsolete, but a new edition coming in 200?)
- C. Cannon (1985), *Transfer Spectral Line Radiation* (Probably the best available book on spectral line formation)
- K. K. Sen & S. J. Wilson (1998), *Radiative Transfer in Moving Media* (Excellent summary of the work of the '80s)

Conference proceedings on numerical methods:

- W. Kalkofen, ed. (1984), *Methods in Radiative Transfer*
- J. Beckman & L. Crivellari, eds. (1985), *Progress in Stellar Spectral Line Formation Theory*

- W. Kalkofen, ed. (1987), *Numerical Radiative Transfer*
- L. Crivellari, I. Hubeny & D. Hummer, eds. (1991), *Stellar Atmospheres: Beyond Classical Models*

But I personally was spending less effort on transfer per se, and started work on problems of radiation hydrodynamics instead.

7 Rebirth and New Growth into the '90s

While my back was turned, in the '80s and the '90s there was an explosion of new and better work. Some very intelligent people looked at the problems that had stumped us during the '70s with what the Buddhists call 'beginner's eyes', and saw solutions! There were three principal contributing factors:

(1) The development of ALI (C. Cannon, L. Auer, R. Buchler, W.-R. Hamman, G. Olson, G. Scharmer, K. Werner).
(2) The synthesis of ALI with complete linearisation (Hubeny & Lanz 1995).
(3) The availability of huge atomic databases (C. Iglesias, F. Rogers, M. Seaton).

The greatest improvements in modelling capability have resulted *not* from increases in computer speed/size, but from *better algorithms, and more complete physical data*.

7.1 ALI: Approximate (or Accelerated) Lambda Iteration

The exact origin of ALI is obscure. Many different paths were taken by different workers that perhaps contributed to the technique. My own opinion is that it is rooted, ultimately, in Cannon's (1973a; 1973b) ideas about 'operator perturbation' techniques, in which one uses an approximate representation of an operator to form equations that are easy to solve, and then applies a 'touch-up' to that solution using the exact operator.

The ALI method is *powerful*. As before, take the source function to be

$$S(\tau) = (1-\epsilon)J(\tau) + \epsilon B(\tau). \tag{6}$$

But instead of standard Λ iteration, which fails when $\epsilon \ll 1$, we use a different iteration scheme:

$$S^{n+1}(\tau) = (1-\epsilon)\Lambda^*_\tau[S^{n+1}(t)] + (1-\epsilon) \times \left\{\Lambda_\tau[S^n(t)] - \Lambda^*_\tau[S^n(t)]\right\} + \epsilon B(\tau). \tag{7}$$

Then

$$S^{n+1}(\tau) = \left[1-(1-\epsilon)\Lambda^*_\tau\right]^{-1}\left[(1-\epsilon) \times \left\{\Lambda_\tau[S^n(t)] - \Lambda^*_\tau[S^n(t)]\right\} + \epsilon B(\tau)\right]. \tag{8}$$

The problem is to choose Λ^* so that it is (a) easy to construct, and (b) easy to invert. Sharmer (1981) used physical insight and physical approximations (the Eddington–Barbier relation) to develop his Λ^*. From a mathematical point of view, the critical requirement to assure rapid convergence of the iteration is to have eigenvalues of $[1-(1-\epsilon)\Lambda^*_\tau]^{-1} < 1$. The smaller, the better. In a remarkable paper by Olson, Auer & Buchler (1986), it was shown that using just the *diagonal elements* of Λ^*_τ gives a very good approximate operator Λ^*. Such a matrix is trivial to invert. A tridiagonal representation of Λ^* is even better, and requires little more effort to invert. Furthermore, the ALI approach can be generalised to work for moving media and partial redistribution. In short, ALI is probably the most important computational advance in radiative transfer of this century, because it makes it possible to solve economically problems that even a decade ago appeared to be utterly intractable.

7.2 Non-LTE Line-blanketing

These days, non-LTE calculations of complete stellar spectra are the rule rather than the exception. A consequence of this fact is that the systematic errors in diagnostics of stellar effective temperatures, surface gravities, and element abundances have decreased markedly, and we can now begin to rely on the numbers. One of the key ideas in such computations was the ingenious idea of Anderson (1985; Grigsby et al. 1992) to group atomic levels into *superlevels* that contain multiple states of similar energies and other properties, coupled by *superlines* that represent significant fractions of a transition array. I have heard estimates that the two ideas of superlevels and ALI can speed up calculations by factors of a thousand to a million!

To illustrate how big a change ALI has made, I mention just a couple of representative calculations. For example, compare the Grotrian diagrams for Fe I and Fe II in Figure 1 of Thévenin & Idiart (1999), which contain 256 and 190 levels, and 2117 and 3443 radiative transitions, respectively, to the pitifully tiny transition arrays considered by Auer & Mihalas in their work of 25 years ago. The diagram of the transition array included in the new work is literally black on the page! Or one might look at the spherical, non-LTE line-blanketed models of ϵ Canis Majoris (B2 II) published by Aufdenberg et al. (1998), which include up to 3035 atomic levels, 37,151 radiative transitions, and 183,591 frequency-sample points. This huge calculation converged after 10 iterations, taking about 2.5 hours per iteration, on a massively parallel computer. Or one can be dazzled by the NextGen models being constructed by a team led by Hauschildt (Hauschildt, Allard & Baron 1999; Hauschildt et al. 1999) which are spherical, non-LTE line-blanketed models spanning the range $3{,}000\,\mathrm{K} \le T_{\mathrm{eff}} \le 10{,}000\,\mathrm{K}$ for dwarfs, and $3{,}000\,\mathrm{K} \le T_{\mathrm{eff}} \le 6{,}800\,\mathrm{K}$ for giants. In the former set of models there were 4,143 non-LTE levels, 49,324 primary non-LTE transitions, 218,009 secondary non-LTE lines, 385,484 background LTE lines, and 1,566,411 LTE molecular lines. It is exhausting even to consider such numbers! In the latter calculation, approximately 1.9×10^8 molecular lines were included. And in their Figure 13, one sees departures from LTE ranging by factors of about 3–5 above and below unity, on diagrams that are so dense with curves (numbers of levels) that they print black. Clearly we have made *tremendous* progress. I must say that I, personally, feel like a denizen of Kitty Hawk watching the take-off of a Boeing 747 at O'Hare airport!

8 Today's Varsity Team

Perhaps much to the amazement of many astrophysicists, the 'old' field of stellar atmospheres is in a state of renaissance. And is often the case in any revolution, the important players on the stage are the youngest and most vigorous workers in the field. It is hard to choose favorites, but in my own estimation, the authors to watch for when deciding whether or not to read a particular paper include the following: F. Allard, J. Aufdenberg, E. Baron, S. Dreizler, W.-R. Hamman, P. Hauschildt, J. Hillier, I. Hubeny, T. Lanz, and K. Werner. These people, and their students, are moving the ball forward very quickly at the present time.

9 The Sun

One of the most educational, and continually humbling, experiences of my life was the time I spent working at the High Altitude Observatory in Boulder. It was there I first got a close look at the extreme complexity of a seemingly mundane star like the Sun. The Sun has a deep convection zone, which, coupled to its differential rotation, drives a powerful dynamo that creates magnetic field at a rapid rate. I realised then that, because we are deprived of spatial information about the actual distribution of radiation on the disks of stars, virtually all of the work I have discussed above must certainly be a very *high-order abstraction* of a reality we cannot yet observe. We must be prepared to abandon it if such information ever becomes available from, say, space interferometry.

High-resolution observations of the solar surface made at observatories having exquisite seeing, using instruments with image-reconstruction techniques, show that it is a seething layer of tiny stuctures in constant motion. There are the well-known granules (the tops of convective elements dying as a result of uninhibited radiative losses to space); but between the granules are darker lanes of downflowing material, riddled with unresolved magnetic flux tubes. These flux tubes outline a supergranulation network, and can arrange themselves into structures such as sunspots, and others that are unstable, and give rise to violent flare events. Recent observations made with TRACE (Transition Region And Coronal Explorer) and the Michelson Doppler Imager aboard SOHO show that the magnetic field of the Sun is constantly being replenished by new flux emergence on very short timescales, while old magnetic field regions dissolve under the effects of field-line reconnection.

The observational data now in hand: 1) allow one to infer the *internal* structure of the Sun, almost to the core, from a detailed study of the five-minute oscillation modes; 2) show that the solar atmosphere, even in the continuum, is arranged in *anything but* homogeneous layers; and 3) guarantee that theorists, studying the flow of partially ionised material in the presence of a highly filamentary magnetic field, will face severe challenges for *at least* a century. Progress in this study will require a high level of scientific skill, and *an open mind*. Anyone who wishes to partake in it would do well to read carefully, and understand, the parable of Agassiz and the sunfish on pages 17 and 18 of Ezra Pound's *The ABC of Reading* (1960).

Finis

Now I would like to return to one of the purposes of this meeting: to honor the gentleman who taught many of us working today on stellar atmospheres through his masterly writings and research. So in closing, I would like to quote a saying that someone shared with me many years ago:

> The *purpose* of life is to *discover* your gift.
> The *meaning* of life is to *give* it,
> thus enriching the lives of all around you.

Thus, there is only one Itzhak Perlman in the world, but there are billions of us who can enjoy his mastery of the violin. Walter Stibbs is a man who found himself, by any standard, profoundly gifted in many areas. And what has made him such an extraordinary human is how *willingly, gracefully*, and *completely* he gives his gifts to all of us.

Walter, I salute you!

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