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Solar Atmosphere Models

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ABSTRACT

This contribution honoring Kees de Jager's 80th birthday is a review of "one-dimensional" solar atmosphere modeling that followed on the initial *"Utrecht Reference Photosphere"* of Heintze, Hubenet & de Jager (1964). My starting point is the Bilderberg conference, convened by De Jager in 1967 at the time when NLTE radiative transfer theory became mature. The resulting Bilderberg model was quickly superseded by the HSRA and later by the VAL–FAL sequence of increasingly sophisticated NLTE continuum-fitting models from Harvard. They became the "standard models" of solar atmosphere physics, but Holweger's relatively simple LTE line-fitting model still persists as a favorite of solar abundance determiners. After a brief model inventory I discuss subsequent work on the major modeling issues (coherency, NLTE, dynamics) listed as to-do items by De Jager in 1968. The present conclusion is that one-dimensional modeling recovers Schwarzschild's (1906) finding that the lower solar atmosphere is grosso modo in radiative equilibrium. This is a boon for applications regarding the solar atmosphere as one-dimensional stellar example — but the real sun, including all the intricate phenomena that now constitute the mainstay of solar physics, is vastly more interesting.

1. Introduction

The sun possesses an extended atmosphere in various respects. Firstly, any eclipse tourist[1] observes directly that the corona as seen in scattered white light extends well away from the sun, multiple solar radii out to the background set by the sky which isn't totally dark even at mid-eclipse. The LASCO coronagraph onboard SOHO, a highly successful ESA-initiated mission to whose conception Kees contributed (see Bonnet 1996) reaches much further out and shows CME's bursting out to the edge of its field, with the geo-effective ("humanity-challenging") ones beautifully showing rapid coronal expansion all around the occulting disk. Yet further out the solar atmosphere blows past us at 400 km s^{-1}, twice faster outside the ecliptic, and extends at least to the magnetopause beyond the planets. That the sun reaches the earth in more than just rays of photons and neutrinos is now heavily emphasized in space weather and climate forcing research, particularly in the US where these interests make NASA fund the "Living with a Star" program including SOHO's successor, the "Solar Diagnostics Observer".

Secondly, the solar atmosphere possesses an extended literature. By and large, all solar physics papers excepting dynamo theory, helioseismology and neutrino hunts are atmospheric in nature. So are all Kees' solar physics papers[2].

Thirdly, the solar atmosphere extends itself through transcending research boundaries. Many stellar physicists, in particular abundance determiners and cool-star activists, use the solar atmosphere as a Rosetta source of inspiration and calibration. Many plasma physicists view the solar atmosphere as the nearest laboratory displaying conditions they won't ever get in Tokamaks.

The sun's extended atmosphere vindicates the presence of a solar article in this SUA volume. It gives me the opportunity to review what happened to "standard" modeling of the least extended part of the solar atmosphere, the photosphere and low chromosphere, after Kees started the field and then left it for other endeavors. The subsequent developments are of interest to stellar atmosphere modeling in general, but represent refinements of a field of which the main foundations had been laid when Kees turned his attention to other things (such as coronal loops and solar flares).

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[1] A harmless addiction affecting both Kees and myself, although we shared our viewing location only once: during the annular eclipse on May 20, 1966 in Greece. A photograph of Kees and his wife Doetie on that occasion is available at http://www.astro.uu.nl/∼rutten.

[2] Bibliography in file http://www.astro.uu.nl/∼rutten/rrtex/bibfiles/publists/dejager.ps.

Starting new endeavors is a characteristic Kees habit. I remember his remark in a speech (I believe given when stepping down as director of Utrecht Space Research) that he had planned his career to have three phases, research, management, and research again. Three spans of fifteen years each, presumably 25–40, 40–55, 55–70 in terms of Kees age, or 1946–1961, 1961–1976, 1976–1991 on the calendar. So he should have stopped research about ten years ago which he didn't — while adding a fourth phase with popularization as major activity[3].

In his research, Kees pioneered in the radio, infrared, ultraviolet and X-ray domains, and he went from the sun via meteorites to the stars. He now lectures monthly about anything whatever wherever in astronomy and the universe. Outside astronomy his marathon running and ballroom dancing come to mind as start-up endeavor.

In comparison I feel very narrow-minded. No marathon running, no ballroom dancing, and solidly glued to the sun except for minor stellar excursions[4]. I still teach the course which I was taught by Kees (Rutten 2000) and I have slowly worked up my way from the solar photosphere to the chromosphere, expecting to finally reach the transition region when Hammerschlag finally installs Hα imaging on the Dutch Open Telescope[5].

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[3] Although he didn't neglect that duty to the general public even while he was managing the Utrecht observatory, Dutch space research, the IAU, COSPAR, and what not else, all at the same time. ADS doesn't list his popular-science articles, book prefaces etc. but the list must be about as long as his formal publication list (which has 361 ADS entries and 2140 ADS citations at the time of writing, a formidable record).

[4] The most boring paper I wrote so far was a stellar one (Carlsson et al. 1994), but even though boring it earns my co-authors and myself more citations than any other. That is because it addressed stellar lithium abundance determination. There seem to be more people doing just that than solar physicists in our combined fields. A situation I find disconcerting since, despite holy-grail big-bang overtones in some lithium issues, the sun offers a much wider range of much more intriguing problems in my view.

[5] See http://dot.astro.uu.nl. Also a Kees story, but principally a Kees Zwaan one since C. Zwaan came up with the idea of an open rather than a vacuum solar telescope and persuaded Hammerschlag to build one, a long-duration enterprise that now keeps me busy too. But also a Kees de Jager story since Kees took over the stewardship of JOSO, the "Joint European Organisation for Solar Observations", when Kiepenheuer died prematurely in 1975. Under De Jager as president and Zwaan as site-test leader, JOSO identified the Canary Islands as the best European location for optical solar telescopes and paved the way for half a dozen solar telescopes there (plus major nighttime telescopes which followed suit). The DOT is presently the sharpest solar telescope thanks to its location, open structure, and consistent speckle reconstruction. The US National Solar Observatory has put La Palma on its list of

I will narrow down this contribution even further and limit it to a review of "standard" modeling of the lower solar atmosphere, of the "one-dimensional" type in which the run of the temperature with height plus the assumption of hydrostatic equilibrium (HE) constitutes a complete "model" — given the chemical composition ("metallicity"), surface gravity, and Struve's fudge parameter "microturbulence" which sweeps actual fine structure and dynamics under a carpet of judicious Dopplerwidth adjustment[6]. De Jager was, with Pecker and others, a principal player in this game when it started, in 1964 leading to the "Utrecht Reference Model of the Photosphere and Low Chromosphere" (URP) by Heintze et al. (1964). That was before my time. I take up the story at Kees' Bilderberg meeting a few years later, briefly review the subsequent one-dimensional models of these layers, and then discuss various modeling issues in which I have been involved one way or other.

2. Overview of standard models

In the classical stellar atmosphere literature, the effective temperature plus the assumption of radiative equilibrium (RE) suffices to define a Kurucz-type model or a TLUSTY (Hubený & Lanz 1992) modeling run. In the solar literature, such models do generally not assume RE but are determined empirically from the observed spectrum.

2.1. The Bilderberg Study Week and the BCA model

My initiation in solar modeling came at the "International Study Week" which De Jager organized in April 1967 at the well-known Hotel De Bilderberg near Arnhem. The attendance was by invitation; the attendants were given

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sites to test for the future *Advanced Technology Solar Telescope*, aiming at 4-m aperture using the same open concept.

[6] Adding height dependence, anisotropy and macroturbulence to gain parameter space. Gray introduced a "radial-tangential" variation (e.g., Gray 1992) and Kees added "mesoscale" turbulence and defined "filters" to describe turbulent effects on different scales (de Jager 1972, de Jager & Vermue 1977, Vermue & de Jager 1979). These fudge parameters should vanish in correct numerical modeling including fine structure and dynamics. This has happened through realistic simulations for the solar granulation in the low photosphere but not yet for the waves in the low chromosphere (Section 3.3), while simulations of magnetically dominated behavior remain far from parameter-free realism. "Turbulence" diagnosed from non-thermal line widths remained a major ingredient in many susbequent de Jager papers on giant-star atmospheres.

Fig. 1.— Participants at the Bilderberg conference, April 1967. *Front row, left to right:* Jean-Claude Pecker, John T. Jefferies, Carla E. Boot (support staff), Marijke Burger, Robert W. Noyes, Edith A. Müller, Roger M. Bonnet, Simone Dumont, David L. Lambert, Yvette Cuny. *Second row:* Jacques E. Blamont, Jacob Houtgast, R. Grant Athay, Christiane Guillaume, Nicolas Grevesse, Osamu Namba, Cornelis de Jager. *Third row:* J. Paul Mutschlecner, Owen Gingerich, George Withbroe, Marcel G.J. Minnaert, Tom de Groot, Hartmut Holweger, Jacques Sauval, Hans Vesters (support staff), Pierre Souffrin, Hans Hubenet, Michel Herse, Robert J. Rutten, Pierre J. Léna, Andrew Skumanich, Philippe Delache, Jaap B. Vogel (support staff). From de Jager (1968).

homework already three months before the meeting; the idea was to come up with a definitive model of the solar photosphere. That materialized eventually as the "Bilderberg Continuum Atmosphere" shown in Fig. 2 (BCA, Gingerich & de Jager 1968).

It was an outstanding meeting. The participants (Fig. 1) where a well-selected mixture of big shots (Athay, Jefferies, Pecker), younger talent (Bonnet, Delache, Grevesse, Lambert, Léna, Noyes, Sauval), recent PhD's (Holweger, Souffrin, Withbroe), plus Utrecht staff and students[7]. In hindsight, the most noticeable absentee was Eugene H. Avrett who already had written nine papers

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[7] I operated the slide projector. No powerpoint or viewgraphs then, only a small easel-mounted blackboard plus projector. No Xerox copier but a mimeograph machine. Gingerich taught me how to trace his models by cutting into a mimeograph master sheet held against the window for backlighting, with corrections applied by filling wrong cuts with lacquer. The slide projector sat centrally within the U-shaped table configuration, a position that enabled me to take snapshot portraits of which some can be inspected under "Astronomer shots" at http://www.astro.uu.nl/∼rutten.

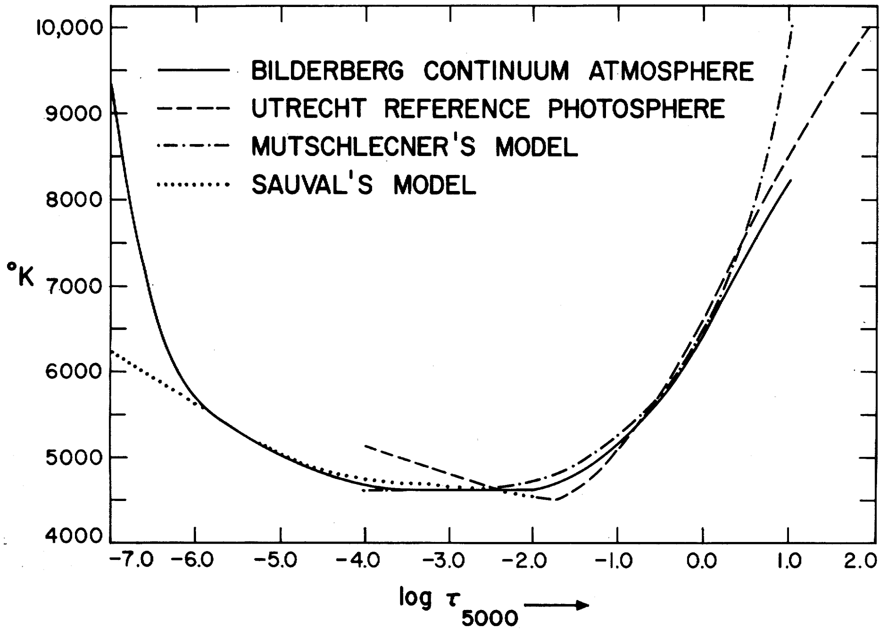

Fig. 2.— Solar atmosphere models in the Bilderberg era. Taken from Gingerich & de Jager (1968). All four are empirical and possess a chromospheric temperature rise.

on NLTE atmosphere modeling at the time.

The idea was to generate a consensus model. Gingerich came with stacks of CDC 6400 printout from which hydrostatic-equilibrium pressures could be evaluated for any temperature we might come up with, leaving only the temperature stratification and the microturbulence stratification(s) to be settled. Both became hot debates, especially whether the microturbulence increases or decreases with height and whether it varies with viewing angle or not. I remember Jefferies exasperatedly telling Pecker to for once listen to him explain a procedure how to derive the Dopplerwidth. In the end, the model assumed depth-independent and isotropic micro- and macroturbulence, and was admitted to be good for the continuum only, not for lines with chromospheric cores. The proceedings (de Jager 1968, a book which duplicates *Solar Physics* 3 issue 1, the very first conference published as journal issue in one of the Reidel journals founded by Kees) contains the resulting BCA model and additional contributions of which many make a good read even now. They vividly illustrate the beginning of the numerical modeling age. Some even dispute the resulting model next to the inputs.

2.2. The Holweger models

Shortly before the Bilderberg meeting Holweger had completed his thesis (Holweger 1967) which was announced by his adviser Unsöld to Minnaert as a breakthrough proof that LTE holds for nearly all Fraunhofer lines. In essence, Holweger's approach was to fit the observed line-center brightness temperatures of many iron lines. In contrast to the URP and BCA and other models, his model did not have a chromospheric temperature rise but declines outward just as a RE atmosphere. Holweger gauged the model success by comparing observed and predicted line strengths near the limb, finding that most come out very well.

I remember Edith Müller saying at the end of the Bilderberg meeting that although the meeting had been nice she would stick to the Holweger model. She thought the latter plus LTE a much better approach to explain both atomic and molecular lines than the combination of a model harboring a chromospheric temperature rise with the source-function departures from LTE which are then necessary to avoid non-observed central reversals in strong lines such as the Mg I b, Na I D, and Ca II infrared lines as well as the strongest violet Fe I lines modeled by Holweger and the strong infrared lines she was interested in herself. Six years later, she and Holweger revamped his model slightly in order to reproduce the solar Ba II lines better. This update, the Holweger-Müller model (1974, HOLMUL in Fig. 4a), became the favorite of solar abundance determiners (e.g., many papers by Blackwell and coworkers and by Grevesse and coworkers). They invariably chose this model because, combined with simple LTE line formation, it gave "the most self-consistent results", meaning small fitted-abundance spread between lines of a given species (after optimizing the turbulent and damping fudge factors). The fact that even the strongest CO lines, thought to be formed in LTE, also do not exhibit reversals but dark cores was taken up extensively by Ayres in later years to claim that at least some part of the chromosphere must be quite cool ("the chilling truth", e.g., Ayres 1981, Ayres & Wiedemann 1989, Ayres & Rabin 1996). This claim still stands; I return to it in Section 3.3 below.

2.3. RE models

The Holweger model and its HOLMUL update closely resemble radiative-equilibrium (RE) models (Fig. 4a). By definition, the latter also lack a chromospheric temperature rise, apart from a NLTE Cayrel rise as computed for hotter than solar stars (e.g., the classic hydrogen-atmosphere papers of Auer & Mihalas 1969a, 1969b). Kurucz (1974, 1979) initiated his LTE-RE stellar atmosphere modeling with a solar model. Major LTE-RE model production was (and still is) done at Uppsala (e.g., Gustafsson et al. 1975, Bell et al. 1976). The TLUSTY[8] code of Hubeny & Lanz (1995) computes RE models with much sophistication and without assuming LTE.

2.4. Harvard models

The principal successor to the BCA model was the HSRA model of Gingerich et al. (1971) which truly became a "reference" model used in hundreds of studies (425 ADS citations at the time of writing). Subsequently, Avrett took over from Gingerich (who turned from solar physics to the history of astronomy) as the main atmospheric model builder[9] in solar physics, with different co-workers from Argentina but always with programmer Rudolph Loeser. The three monumental VAL papers (Vernazza, Avrett & Loeser 1973, 1976, 1981) are a pinnacle of solar physics[10]. A modification of the structure around the temperature minimum between photosphere and chromosphere was discussed by Avrett (1985) and specified in Maltby et al. (1986). Later, Fontenla, Avrett & Loeser (1993) updated the temperature structure in the transition region toward the corona by accounting for ambipolar diffusion, and their most recent production[11] adds systematic flows as modeling ingredient.

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[8] TLUSTY means "thick" in Czech whereas Hubený means "thin". The pun is intended, and reminds me of Dick Dunn whose name translates as "Thick Thin" in Dutch.

[9] In a recent meeting I asked Gene whether or when he might retire. The answer was a forceful: "never ever!". I have found two role models for retirement. Either one doesn't retire but just keeps going, or one retires effectively well before the official date. My impression is that colleagues of the first type look forward to what they are going to do and age slowly or not at all, whereas colleagues of the second type are preoccupied by past achievements and age prematurely. Writing this back-looking review seems to put me in the second category, but I will rather take Kees and Gene as examples — which they indeed have been, admiredly, throughout their and my career so far.

[10] The third one, VALIII, has 733 ADS citations at present. The VALIII-C model is elevated to stellar status in my WWW lecture notes (Rutten 2000) by claiming that VALIIIC is a plane-parallel solar-like star which strictly obeys standard plane-parallel NLTE modeling theory as formulated by Avrett and programmed by Loeser. Students may trust standard line-formation theory to apply perfectly to this star, making any of the highly informative diagrams in the VALIII paper a candidate for examination questions.

[11] Preprint at http://cfa-www.harvard.edu/ avrett.

3. Modeling issues

In his preface to the Bilderberg proceedings, de Jager (1968) wrote:

> *. . . not everyone would agree about the model, and it became obvious too that future research is strongly needed, in particular in the field of line formation (coherence, or non-coherence; local thermodynamical equilibrium), while also the motion field of the photosphere and chromosphere is insufficiently known, and its influence on the formation of spectral lines hardly understood.*

In the remainder of this contribution I discuss subsequent work on these complexities, in the order of this statement. Much has happened in the meantime, but nevertheless each point remains valid.

3.1. Coherency

Background. In the same year that Kees wrote the above statement, Jefferies (1968) published his book on spectral line formation, "*A carefully written account of line formation theory at the time when numerical solutions began changing the field. It was superseded by Mihalas' book and is now partially outdated. Its clear formulation of NLTE basics remains valuable, though.*" (Rutten 2000). It devotes relatively much space to coherent scattering, a topic which Mihalas neglected in the 1970 edition of *Stellar Atmospheres* but gave much attention in the 1978 edition. No wonder, since Mihalas participated in the peak in partial redistribution papers in the 1970's.

Much earlier the coherency issue was succinctly put by Eddington as "*does the atom remember at which frequency it was excited when it falls back emitting a photon?*". At Utrecht, Houtgast (1942) had written a famous thesis on this question, applauded by Unsöld in his book[12] and by Spitzer (1944) in an ApJ editorial. Houtgast found empirically that complete redistribution matches Fraunhofer-line shapes better than coherent (monochromatic) scattering, a finding put later on a firmer footing by Jefferies & White (1960) and Hummer (1962) for the Doppler-redistributed core, and computed precisely for two-level atoms by Avrett & Hummer (1965).

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[12] *Physik der Sternatmosphären* (Unsöld 1955), a bible for German stellar spectroscopists which would have had more impact if it had appeared in English. It was actually translated by Hans A. Panofsky and Keith A. Pierce but publication was not authorized (there is a copy in the NSO library at Tucson).

Subsequently, Milkey & Mihalas (1973, 1974), Milkey, Shine & Mihalas (1975a) and Shine, Milkey & Mihalas (1975a,b) systematically investigated the effect of partial frequency redistribution on resonance line formation. Similar approaches are implemented for Lyα and other lines in Avrett's PANDORA. The upshot is that the line cores, the inner wings, and the outer wings of resonance lines possess independent source functions which each uncouple from the Planck function at their own thermalization depth. For example, the inner-wing Ca II K_1 dips do not measure the temperature minimum value, as was the case in the CRD resonance line modeling of Jefferies & Thomas (1959).

Ba II 4554 Å. During these years I stumbled over the coherency issue while analysing solar eclipse spectrograms containing the Ba II 4554 Å resonance line. The eclipse expedition (Mexico 1970) was the next to last one in the extensive Utrecht tradition[13]. I found that near the solar limb the Ba II 4554 Å line shows emission wings caused by inner-wing coherency, an empirical conclusion later validated by Rutten & Milkey (1979). The line is relatively weak but has larger coherency[14] than e.g., the Na I D lines, as shown later by my first two PhD students (Uitenbroek & Bruls 1992).

Status. Subsequent developments include methods to evaluate cross redistribution (via subordinate lines such as the infrared Ca II lines, cf. Uitenbroek 1989) and fast evaluation schemes (e.g., Paletou & Auer 1995). Nevertheless, partial redistribution (PRD) remains a somewhat off-mainstream issue not yet implemented in the major radiative hydrodynamics simulation and data inversion codes. For the moment it remains a rather esoteric problem lurking in the background, but eventually it must be addressed in detail in many applications.

At present, coherent scattering is popping up as a new topic in understanding the complex near-limb linear polarization patterns seen in the

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[13] Eighteen in total, from Sumatra 1901 to Mauritania 1973, the last one of nine led by Houtgast. I took part in three. Photographs including characteristic Houtgast portraits on http://www.astro.uu.nl/∼rutten.

[14] In addition, Ba II 4554 Å is a particularly sensitive Doppler diagnostic thanks to the large atomic mass. We have recently tested a narrow-band Lyot filter for this line that was built in Irkutsk in the 1970's. We brought it to the late Swedish Vacuum Solar Telescope on La Palma and took trial Dopplergrams including speckle restoration. They are extraordinary sharp (Sütterlin et al. 2001), motivating installation of the filter in the Dutch Open Telescope. The combination is likely to make Ba II 4554 Å an important high-resolution Doppler diagnostic.

"second solar spectrum" (e.g., Stenflo et al. 1997, 2001). The Ba II 4554 Å line also possesses the largest near-limb linear polarization of all Fraunhofer lines in the optical spectrum, making it a prime candidate for Hanle-depolarization measurement of weak fields in the upper photosphere.

3.2. Departures from LTE

De Jager & Neven analyses. After the Bilderberg meeting Kees continued his solar modeling efforts a few years, in a productive partnership with Neven at Ukkel (Royal Observatory of Belgium) which was based on Kees being part-time professor at the nearby Brussels Free University (where he effectively founded Flemish astrophysics). Every Friday, at the end of a full day of teaching, Kees would visit Neven and come up with suggestions for computations that were then completed under Neven's supervision by programmer Willy Nijs before Kees' next visit.

The corresponding sequence of papers in *Solar Physics* addressed various aspects of Fraunhofer line formation (De Jager & Neven 1968a,b; 1970; 1972a,b). In the first paper they fitted infrared line source functions to observed line center intensities, requiring NLTE source function behavior since the cores of their lines come from chromospheric heights but do not show the reversals that the URP and BCA predict in LTE. In the last paper they added evaluation of the lower-level population departure coefficient β_l. This addition resulted from a debate with Kees Zwaan[15] who pointed out that NLTE population departures affect the line source function through the upper-lower β_u/β_l ratio, the line opacity through the β_l value, and that these influences may be independent and must be determined independently. The point is important since opacity NLTE is often neglected while concentrating on source function NLTE[16]; I therefore

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[15] The debate must have taken place in 1969 since I remember the presence of Dick Canfield, then a postdoc at Utrecht, in the discussion. Zwaan wrote his departure coefficients as β to distinguish them from Menzel's b's. They are the same for minority stages of ionization but not for majority ones. This is carefully explained in the VALIII paper (Vernazza et al. 1981) but nevertheless, various authors have taken the b_1 plot for solar H I on p. 663 of that paper as evidence that the hydrogen ground state is underpopulated by a factor three in the solar temperature minimum region — which would be strange because all hydrogen sits in the ground state at such low temperature! Rather, the hydrogen continuum state (free protons) is overpopulated through radiative overionization by the Balmer continuum which has $J_\nu > B_\nu$.

[16] The definition of LTE is not that $S_\nu^l = B_\nu$ as is often stated, but that the level populations obey Saha-Boltzmann statistics, i.e., that the matter component follows the equilibrium

elaborate it didactically in the next paragraph, with equations taken from Rutten (2000).

Departure coefficients. Zwaan had at that time generalized Menzel's H I departure coefficients (Menzel & Cillié 1937, Wijbenga & Zwaan 1972):

$$\beta_l = n_l / n_l^{\rm LTE} \qquad\qquad \beta_u = n_u / n_u^{\rm LTE} \tag{1}$$

with n the actual population and $n^{\rm LTE}$ the Saha-Boltzmann values for the lower and upper level, respectively. With these, the general line source function is

$$S_\nu^l = \frac{2h\nu^3}{c^2} \frac{\psi/\varphi}{\dfrac{\beta_l}{\beta_u}\,{\rm e}^{h\nu/kT} - \dfrac{\chi}{\varphi}} \tag{2}$$

and for complete redistribution with $\chi_\nu = \psi_\nu = \varphi_\nu$

$$S_{\nu_0}^l = \frac{2h\nu_0^3}{c^2} \frac{1}{\dfrac{\beta_l}{\beta_u}\,{\rm e}^{h\nu_0/kT} - 1}, \tag{3}$$

where $S_{\nu_0}^l$ does not depend on frequency over the extent of a narrow line. In the Wien regime with $(\beta_l/\beta_u)\exp(h\nu/kT) \gg 1$ the fractional departure of the source function from the Planck function is given by the inverse fugacity ratio β_u/β_l:

$$S_{\nu_0}^l \approx \frac{\beta_u}{\beta_l} B_{\nu_0}. \tag{4}$$

The monochromatic line extinction coefficient per unit of length becomes:

$$\begin{aligned} \alpha_\nu^l &= \frac{h\nu}{4\pi}\,\beta_l\,n_l^{\rm LTE} B_{lu} \varphi(\nu - \nu_0) \left[1 - \frac{\beta_u\,n_u^{\rm LTE}\,B_{ul}\,\chi}{\beta_l\,n_l^{\rm LTE}\,B_{lu}\,\varphi}\right] && (5) \\ &= \frac{\pi e^2}{m_{\rm e} c}\,\beta_l\,n_l^{\rm LTE} f_{lu} \varphi(\nu - \nu_0) \left[1 - \frac{\beta_u}{\beta_l}\frac{\chi}{\varphi}\,{\rm e}^{-h\nu/kT}\right] && (6) \end{aligned}$$

with $\chi/\varphi = 1$ for complete redistribution. In the Wien approximation:

$$\alpha_\nu^l \approx \beta_l \left[\alpha_\nu^l\right]_{\rm LTE}. \tag{7}$$

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distributions exactly while the radiation may depart slightly (cf. Ivanov 1973). Validity of the Boltzmann distribution implies $S_\nu^l = B_\nu$ through $\beta_u = \beta_l = 1$ in Eq. 3. "Source function LTE" implies $\beta_u = \beta_l$ but even then "opacity NLTE" with $\beta_l \neq 1$ may yet occur.

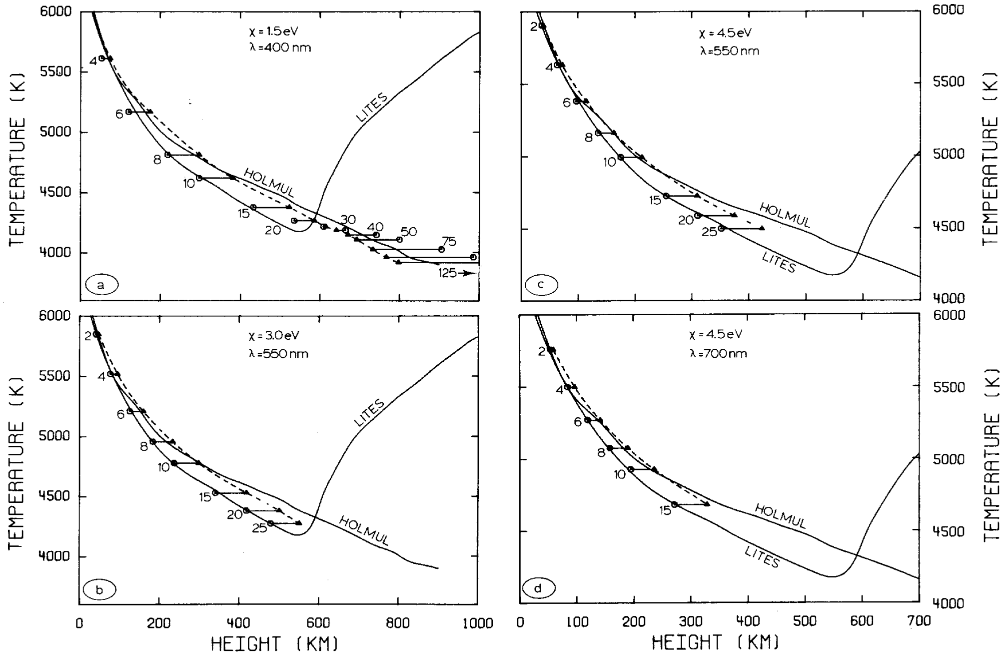

Fig. 3.— "NLTE masking" for Fe I lines at different excitation energy and wavelength. The circles denote line-center brightness temperatures of lines computed from Lites' (1972) NLTE modeling, plotted at their height of formation. The numbers specify their equivalent width in pm. The triangles show the same brightness temperature but at the height of formation found when assuming LTE opacities. The dashed curves connecting the triangles simulate Holweger's LTE model-building procedure. All four lie close to the actual HOLMUL model. This experiment shows that if the actual solar atmosphere obeys the LITES model with the concomitant NLTE departures, Holweger's procedure inevitably produces a HOLMUL-like shallow-gradient model. Reversely, if the actual solar atmosphere obeys the HOLMUL model but one adopts a steeper-gradient model, one needs the concomitant $J_\nu > B_\nu$ NLTE departures to explain the observed lines. Thus, flat–LTE and steep–NLTE modeling explain Fe I lines about equally well. This quandary also holds for Fe II lines, for most other metals, for multi-component modeling, and for modern inversion methods. From Rutten & Kostik (1982).

NLTE masking. I used Zwaan's point later to explain the success of the Holweger and Holweger-Müller models in explaining Fe I and Fe II line formation as due to "NLTE-masking" in an analysis (Rutten & Kostik 1982) based on Lites' ground-breaking thesis on Fe I NLTE (Lites 1972, Athay & Lites 1972). We showed that if one adopts Lites' HSRA-like model atmosphere with his corresponding NLTE populations (for Fe I, and with comparable NLTE populations for Fe II computed by Cram, Rutten & Lites 1980) to derive an empirical formation-temperature model from the computed iron lines in the same manner that Holweger applied to observed iron lines, one automatically

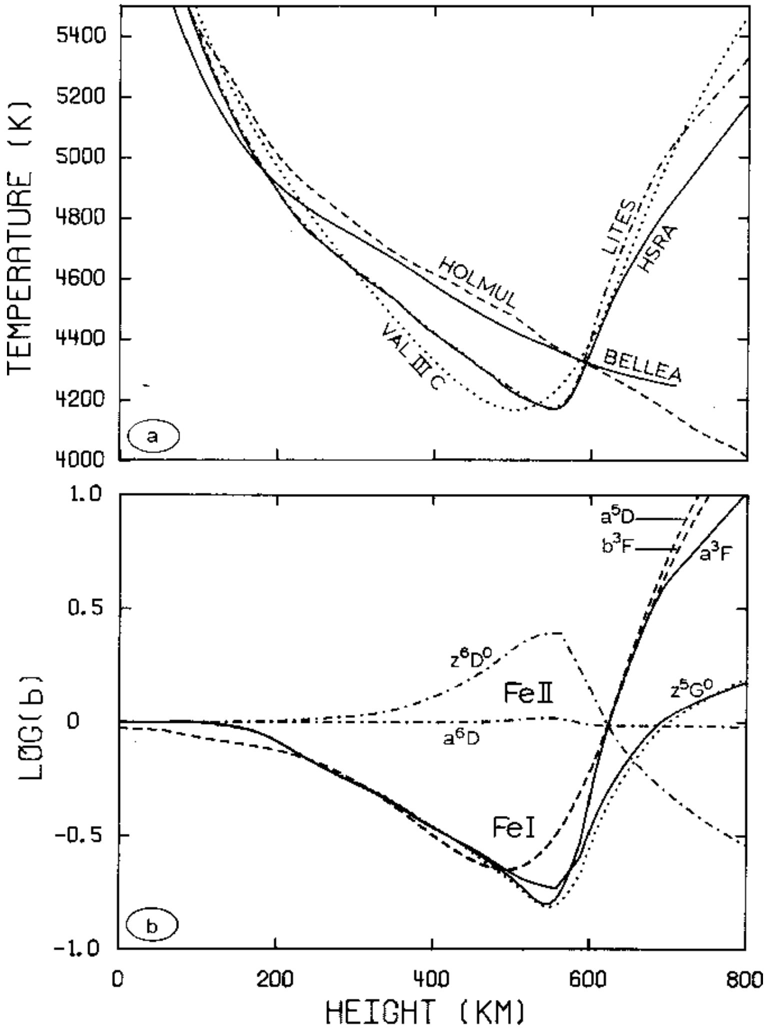

Fig. 4.— *Top:* selection of solar models. The HSRA (Gingerich et al. 1971) and VALIIIC (Vernazza et al. 1981) are NLTE continuum-fitting models from Harvard. LITES is a modification of the HSRA by Lites (1972). BELLEA (Bell et al. 1976) is a theoretical RE model from Uppsala. HOLMUL (Holweger & Müller 1974) is an update of Holweger's (1967) model fitting Fe I lines assuming LTE. Notice the close resemblance of the latter two and the low-temperature upper photosphere of the HSRA-LITES and VALIIIC models. *Bottom:* NLTE population departure coefficients b (in the Zwaan definition, written as β in Eqs. 1–7) for representative levels of Fe I and Fe II for the LITES model. The joint dip of the Fe I curves comes from radiative overionization in the near ultraviolet. The peak of the Fe II z$\,^6$D$^{\rm o}$ curve results from radiative overexcitation in Fe II resonance lines. The divergences at larger height, with higher-level curves dropping below lower-level curves, result from strong-line photon losses. Optical Fe I lines have LTE source functions but joint NLTE opacity depletion. Optical Fe II lines have LTE opacities but NLTE source function enhancements. Such departure behavior is characteristic for many metals when the upper-photosphere temperature gradient is steep enough to cause $J_\nu > B_\nu$ radiation excesses in the near ultraviolet. From Rutten & Kostik (1982).

ends up with a Holweger-like model. Figure 3 shows that the scheme works well throughout the optical spectrum. We therefore claimed that the HOLMUL model is a self-fulfilling prophecy, explaining most lines quite well assuming LTE because its derivation is based on such lines assuming LTE.

Figure 4 illustrates the physics. Most optical Fe I lines have LTE source functions in the photosphere but ultraviolet overionization causes joint opacity deficits for all Fe I levels. These cause the horizontal height-of-formation shifts in Fig. 3. The strongest lines have NLTE source function deficits from photon losses in the chromosphere, which cause the vertical offsets of the circles from the LITES model in Fig. 3 (line darkening, no central reversals). For Fe II the situation is the reverse: low Fe II levels have LTE populations because Fe II is the majority stage, but excited Fe II levels are overpopulated through overexcitation ("pumping") in the Fe II resonance lines at yet shorter wavelengths (Cram et al. 1980). The Fe II lines therefore weaken through source function NLTE.

For steeper temperature gradients the Fe I opacity deficits and the Fe II source function enhancements increase due to larger ultraviolet $J_\nu > B_\nu$ excesses. The resulting Fe I and Fe II line depths remain about the same. HOLMUL-like model stratifications will follow from LTE line fitting even if the actual temperature gradient is yet steeper than in the LITES (HSRA) model.

Inverse masking. Reversely, NLTE masking goes away if the actual photosphere possesses a temperature gradient as shallow as the HOLMUL model and the chromosphere is actually as cool as a RE model. One may also claim that the HSRA has artificially high ultraviolet $J_\nu > B_\nu$ excesses due to its overly steep gradient, and that the NLTE overionization computed in detail in Avrett's PANDORA code is overkill because it becomes negligible for non-steep temperature gradients. Thus, NLTE modeling may also be seen as a self-fulfilling prophecy. Holweger (1979) did so when writing: *"[...] deviations from LTE are easily arising in the computer if important collisional processes are neglected, or if radiative rates are not realistic. [...] The UV radiation field is complicated by a vast number of absorption lines"*.

The first point alludes to inelastic collisions with neutral hydrogen atoms. Holweger claims that these dominate metal transition rates and enforce Boltzmann population ratios, but without much proof so far.

The second point was made earlier for sunspot modeling by Zwaan (1975, cf. Greve & Zwaan 1980) and was taken up later by Avrett (1985) by including more and more of the millions of lines inventoried atomically by Kurucz in ever-increasing tabulations (from punch cards to reel tapes to CD-roms to WWW server). They constitute the “ultraviolet line haze”. Their effect in Avrett’s modeling is to reduce the ultraviolet $J_\nu > B_\nu$ excesses in the upper photosphere, so that the ultraviolet overionization diminishes, the bound-free opacities increase, and the empirical continuum-fitting model becomes less steep. The resulting Harvard model, tabulated in the Maltby et al. (1986) sunspot paper[17], is quite close to HOLMUL and BELLEA in the upper photosphere. Thus, *“with this new model, Avrett more or less retrieves, proves and extends the LTE HOLMUL model”* (Rutten 1988). The same masking story but sign-reversed: it wasn’t the LTE modeling that masked NLTE reality in the upper photosphere, but the actual NLTE departures had indeed been overestimated by not including enough line-haze lines.

Line haze scattering. The shallower temperature gradient produces a 200 K higher temperature minimum value at the onset of the chromospheric temperature rise. The presence of the latter maintains the need for source function departures in strong lines that do not show reversals. A hidden complexity is that also many of the line-haze lines possess reversals when computed in LTE. These are avoided in PANDORA through imposing an ad-hoc source function transition from pure absorption in deep layers to pure scattering above the temperature minimum. Overionization is neglected in the line haze opacities. Thus, the NLTE complexities affect the computation of the line haze which undoes them, an awkward inconsistency necessitating large-volume NLTE line-blanketing computation (Anderson 1989, cf. Anderson & Athay 1989).

NLTE masking in simulations and inversions. The NLTE masking quandary resurfaces in modern modeling. Even if the the one-dimensional mean has a sufficiently flat temperature gradient to avoid $J_\nu > B_\nu$ overionization and overexitation, actual stellar atmospheres must contain locations with steeper radial gradients. In simulations of solar and stellar granulation, spectral lines from such locations with steep temperature gradients may be reproduced quite well from too shallow computed gradients by assuming LTE, or may be badly reproduced from correct gradients by NLTE modeling underestimating the ultraviolet line haze.

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[17] MACKKL officially, mackerel unofficially.

Similarly, spectral-line inversion codes assuming LTE, which basically automate Holweger's modeling approach, may wrongly favor shallow-gradient models when based on LTE, or they may deliver too steep gradients from NLTE modeling when underestimating the ultraviolet line haze. It remains dangerous to rely on good correspondence between Fe I and Fe II line fitting as a proof of method validity since overionization and overexcitation may again affect the one and the other, respectively, with comparable results.

Both warnings come together when one-dimensional LTE inversions are gauged from LTE line formation computed from numerical simulations, as for example in the recent analysis by Allende Prieto et al. (2001) which combines the Holweger-like inversion method of with the granulation simulation of Asplund et al. (2000a). The result repudiates the rhetorical question asked at the end of Asplund et al. (2000b) why one would still want to apply classical modeling with lots of simplifications in the era of much more realistic simulations (a question expecting "stop that right now" as answer) by finding that simple inversions come a long way in producing reliable stellar abundances. I don't dispute this conclusion (see my own conclusion below), but at some height in the stellar atmosphere the good working of such inversions will at least partially be thanks to NLTE masking, and so will apparent consistency between computed Fe I and Fe II lines.

NLTE masking in fluxtube modeling. Another application where NLTE masking crops up as a suspect (at least in my suspicious mind) is empirical solar fluxtube modeling. The standard fluxtube models come from Solanki with coworkers (e.g., Solanki & Stenflo 1985, Solanki 1986, Solanki et al. 1991, Solanki & Brigljevic 1992, Bünte et al. 1993, Bruls & Solanki 1993, Briand & Solanki 1995). His "plage" fluxtube model at left in Fig. 5 is an example. It describes the temperature stratification along the axis of a magnetostatic fluxtube as constrained by Stokes V profiles of Fe I lines. Automated inversion modeling of such data delivers very similar results (Ruiz Cobo & Del Toro Iniesta 1992, Bellot Rubio et al. 1998). LTE is assumed both in Solanki's empirical modeling and in these inversions.

My suspicion concerns the flat gradient of the fluxtube model around the $\tau = 1$ radiation emergence depth. It is much flatter than for radiative equilibrium and implies considerable energy dissipation already at very low heights. An alternative scheme is that sideways irradiation of the fluxtube interior from the hot surrounding walls overionizes Fe I and other minority stages inside the tube radiatively. LTE interpretation of the observed Stokes V

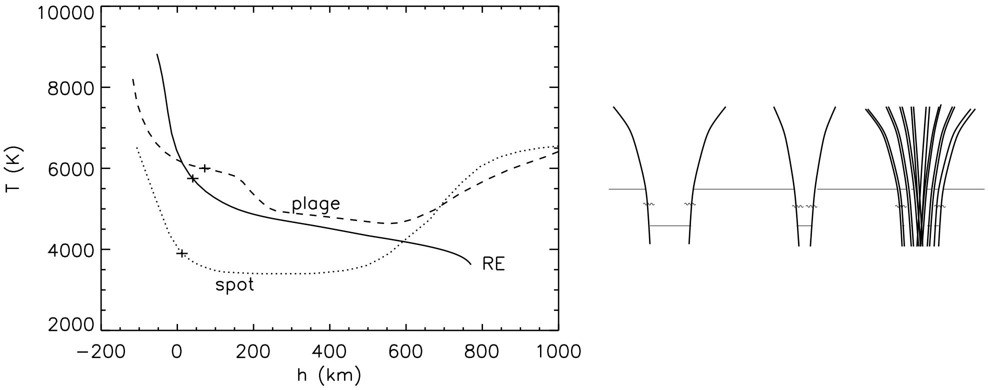

Fig. 5.— Fluxtube modeling. Graph at left: standard models from Stuik, Bruls & Rutten (1997). The plage model describes fluxtubes at 15% filling factor and comes from Bruls & Solanki (1993), the RE model for the solar photosphere comes from Uppsala, the sunspot model is from Maltby et al. (1986). Each model is shown on its own height scale having $\tau = 1$ at $h = 0$ km. The crosses mark the effective temperatures. Cartoon at right: schematic fluxtubes of different widths, respectively a wide tube in which hot-wall radiation does not penetrate far, a narrow tube in which the hot-wall radiation may upset ionization (and possibly dissociation) equilibria as proposed by Rutten (1999), and a micro-structured MISMA fluxtube (Sánchez Almeida et al. 1996) consisting of an assembly of numerous very thin transparent fluxtubes. From Rutten et al. (2001).

profiles will then model the resulting line weakness as due to high excitation temperature, again correcting NLTE opacity deficits by setting a shallower source function gradient through a shallower temperature gradient. This may happen while the actual gradient follows radial RE within the fluxtube. Consistency between Fe I line fits and Fe II line fits is again no proof since majority-stage source function NLTE may have similar effects[18] on Fe II.

The cartoon at right in Fig. 5 illustrates that such masking is likely to occur in fluxtubes that are not much wider than the mean free photon path (middle). Even at the resolution of the Dutch Open Telescope (0.2 arcsec or 150 km) the intergranular bright points that mark magnetic elements are not yet resolved; it will take larger-aperture adaptive optics to measure actual fluxtube diameters.

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[18] I have also proposed that the G band made up of CH lines around 4305 Å might gain its appreciable bright-point contrast, which makes the high-resolution images from the late Swedish telescope and the speckle-restored movies from the Dutch Open Telescope on La Palma so vividly dramatic, from similar irradiative CH overdissociation (Rutten 1999). However, the molecular radiative rates seem too slow (Sánchez Almeida et al. 2001) while LTE modeling does quite a good job in explaining the observed contrast (Rutten et al. 2001).

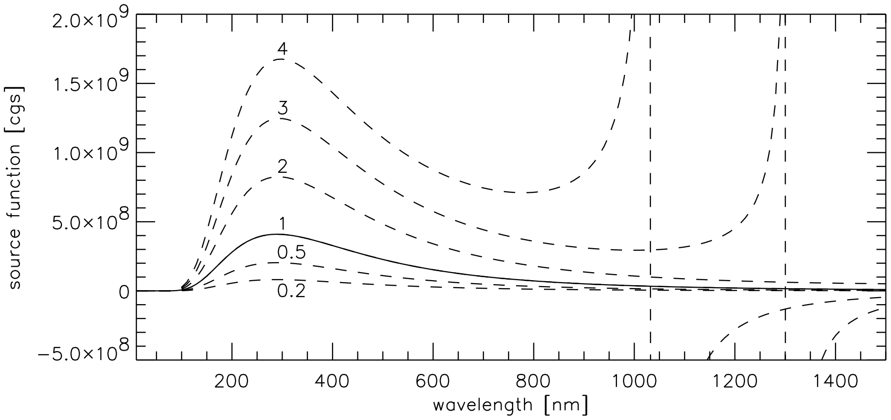

Fig. 6.— Wavelength variation of the general source function (3) for $T = 10\,000$ K and the specified ratios β_u/β_l, in cgs units with $\Delta\lambda = 1$ nm. The NLTE source function scales with the Planck function (solid curve) in the Wien part at left, but reaches the laser regime for large β_u/β_l in the Rayleigh-Jeans part at right. From Rutten (2000).

The MISMA tube at right embodies Sánchez Almeida's proposal (Sánchez Almeida et al. 1996, cf. van Ballegooijen 1985) that magnetic elements are inherently unresolvable since consisting of micro-structured clusters of very thin (10 km) tubes. The thin threads in such a cluster will share their temperature gradient with the interspersed and surrounding non-magnetic gas through radiative exchange. The evacuated threads will act as photon leaks to the ensemble, permitting collective photon escape from deep layers. It is of interest whether such a joint leak may explain the flat gradient of the plage model at left in Fig. 5 as an alternative to NLTE masking in monolithic tubes.

Source function NLTE in stimulated emission lines. The most outspoken example of source function NLTE in the solar spectrum concerns the case of the Mg I 12 micron emission lines. They were discovered by Murcray et al. (1981), after they had earlier been noticed by Testerman and Brault and had even been handmasked out of the spectrum atlas of Goldman et al. (1980) on the suspicion of being artifacts. Brault & Noyes (1983) were the first to study them in detail and showed that both lines contain strong emission peaks already at disk center. Subsequently, Chang & Noyes (1983) identified the lines as high-level transitions of Mg I.

Thanks to their long wavelength the lines have large Zeeman splitting, with fields of a few hundred Gauss already causing complete peak separation. Obviously, it is important to decide at which height the lines originate for diagnostic usage. The dilemma whether the emission peaks are photospheric or chromospheric was posed at the outset by Brault & Noyes (1983). It was the subject of a long and heated debate which is summarized in Carlsson, Rutten & Shchukina (1992). In that paper we identified the emission mechanism as being due to slight $\beta_u > \beta_l$ population divergence in the upper photosphere (we actually used an RE model without chromosphere). The divergence results from collisional cascade through high levels which maintains a diffusive recombination flow into lower levels that is driven by photon losses in strong lines and radiative overionization. The mechanism is explained in Rutten & Carlsson (1994).

The resulting population divergence is only a few percent but its effect on the emergent line profiles is large due to the β_u/β_l factor[19] in the correction for stimulated emission in Eq. 3. Reworking gives

$$\frac{S^l_{\nu_0}}{B_{\nu_0}} = \frac{1 - \, \mathrm{e}^{-h\nu_0/kT}}{(\beta_l/\beta_u)\,[1 - (\beta_u/\beta_l)\,\mathrm{e}^{-h\nu_0/kT}]}\,, \tag{8}$$

implying source function enhancement over the Planck function when $(\beta_u/\beta_l)\exp(-h\nu_0/kT)$ goes down to unity. Figure 6 illustrates this, showing that the source function blows up to large values before it goes negative in the lasering regime[20].

The Mg I 12 micron lines have since been used to identify superpenumbrae around sunspots (Bruls et al. 1995), but more extensive application as sensitive Zeeman diagnostics awaits higher-resolution infrared observing capability (as promised by the ATST which will combine large aperture with adaptive optics).

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[19] Zwaan did not include this factor in his original formulation of the population departure coefficients. It was added by Egidio Landi degl'Innocenti when he was as postdoc at Utrecht.

[20] This part of the explanation was correctly identified by Lemke & Holweger (1987) in their search for the Mg I emission mechanism, but they failed to properly model the collisional departure flow through the high levels by a lack of yet higher levels and by adopting erroneous collisional cross-sections. In this case, the NLTE phenomenon is actually dominated by collisions since only with sufficient level-to-level coupling the recombination flow passes through the pertinent high levels. Thus, Lemke & Holweger (1987) were qualitatively correct but quantitatively wrong. Their work was severely attacked by Zirin & Popp (1989) in a paper which wasn't quantitative at all and qualitatively wrong. When writing Carlsson, Rutten & Shchukina (1992) I made a point of pointing this out, which earned me esteem from Zirin (*“at last somebody daring to pick a fight with me”*).

3.3. Atmospheric dynamics and line formation

The third to-do issue listed by De Jager in his 1968 preface to the Bilderberg proceedings concerns the dynamics of the atmosphere and the influence of motions on line formation[21]. This is the main arena of current solar atmosphere modeling, the more so if we tacitly include magnetic fine structure in “dynamics”.

Photospheric granulation. Detailed radiation hydrodynamics simulation of the solar granulation, a field pioneered with great success by Nordlund (Nordlund 1982, Nordlund & Stein 1990, cf. Spruit et al. 1990), does indeed explain Fraunhofer line shapes without adding any ad-hoc turbulence (Nordlund 1984, Asplund et al. 2000). Even though simplistic plane-parallel inversion methods may produce reliable abundances (Section 3.2), true understanding requires such detailed application of the same physics equations as obeyed by the sun itself in a numerical simulation in which ideally only numerical resolution, numerical viscosity, and the imposed boundary conditions differ from the real thing. Turbulent convection has come a far way along this way, at least when assumed free of magnetism. Nordlund’s current frontier is adding and studying magnetic fields (e.g., Dorch & Nordlund 2001).

Chromospheric oscillations. Another simulation success story concerns acoustic shocks running up into the chromosphere. The story began already with Hale & Ellerman’s (1904) distinction between “minute bright” and “coarse” calcium flocculi seen on Ca II K spectroheliograms. The coarse ones are now called network grains, the minute ones K_{2V} grains (or more generally internetwork grains since they are also seen in e.g., 1700 Å filtergrams from TRACE as shown by Rutten et al. 1999 and analysed by Krijger et al. 2001).

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[21] The latter question led to my only collaboration with Kees (and with Peter Hoyng). After a presentation in which I discussed Fast Fourier Transform deconvolution of my Ba II 4554 Å eclipse spectra, Kees suggested that deconvolution of weak line profiles should identify the shape of the turbulent distribution causing nonthermal line broadening. The resulting paper (Rutten, Hoyng & de Jager 1974) was an early entry in what later became an industry in the hands of David Gray and Rich Robinson, respectively measuring stellar rotation and stellar magnetism by separating the rotational broadening, respectively Zeeman broadening, from the intrinsic and “turbulent” broadening. An important point that we overlooked is that Fourier-domain shape recognition is especially reliable for profile shapes with zeroes in their transform, since multiplication conserves zeroes whatever they are multiplied by.

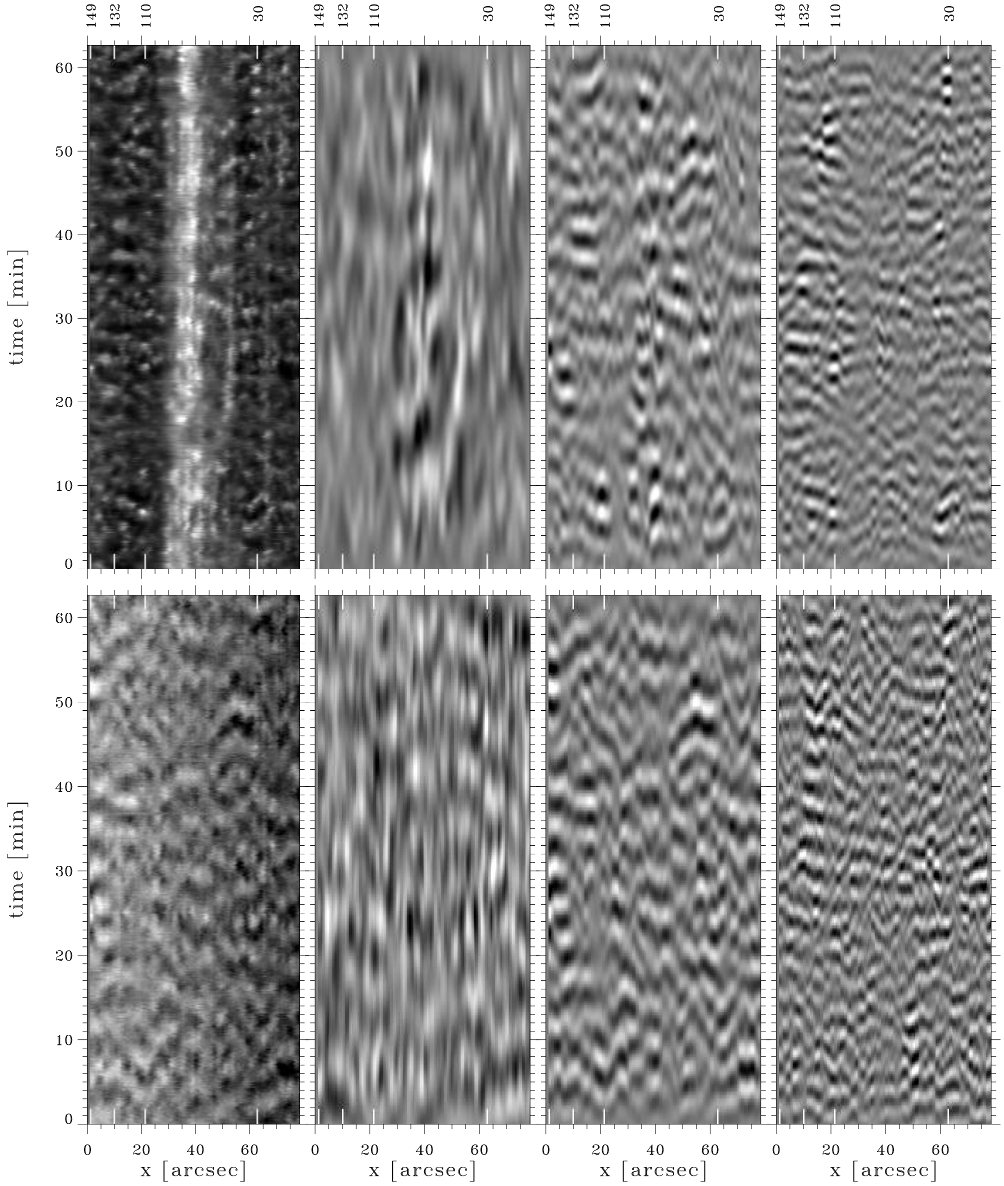

Fig. 7.— Fourier-decomposed space-time “slices” of the spectral data of Lites, Rutten & Kalkofen (1993). Upper panels: Ca II H_{2V} decomposition. The H_{2V} brightness slice at left shows network as bright vertical striping. The internetwork areas show sequences of H_{2V} “grains”. The other panels display its Fourier decomposition into low-frequency modulation, five-minute modulation and three-minute modulation, obtained by temporal filtering of the sequence for each spatial position along the slit. The greyscale is set to maximum contrast for each panel independently. Lower panels: similar decomposition for the Dopplershift of Fe I 3966.82 Å, the blend from which Carlsson & Stein (1997) derived a subsurface piston to simulate the intensity in the upper panels at the four locations marked along the top. From Krijger et al. (2001).

The observational side of this long story was reviewed[22] by Rutten & Uitenbroek (1991). Our conclusion was that the K_{2V} grains in internetwork regions are acoustic in nature, not marking magnetic elements but wave interference maxima[23] in the so-called three-minute chromospheric oscillation. Figure 7 illustrates this oscillatory character in the form of space-time modulation plots for two spectral features. The lower panels decompose the Dopplershift of the photospheric Fe I 3966.82 Å line into Fourier components. The second panel shows fish-bone granular evolution overlaid by slow oscillatory modulation. The wavy-curtain pattern in the third panel is due to the five-minute oscillation. The three-minute Dopplershift modulation (fourth panel) is clearly also oscillatory. The upper panels similarly decompose the simultaneously measured intensity of the Ca II H_{2V} feature (violet peak besides line center). The network (bright central stripe at left) shows slow modulation in the second panel. The internetwork is dominated by the three-minute oscillatory modulation in the fourth panel, but the slower modulations also contribute to "grain" appearance in intensity (first panel). Of the chromospheric panels in the upper row, only the five-minute modulation (third panel) corresponds fairly closely to the underlying modulation in the photosphere, illustrating that the

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[22] In a very long paper published in *Solar Physics*. The paper is long because the pertinent literature is large. When we started working on it we didn't appreciate how far back it goes and that it encompasses much of the chromospheric line formation literature and the non-seismological solar oscillation literature. At that time I asked Kees as *Solar Physics* editor — over our morning coffee, which was one of the great assets of Utrecht astronomy when we were still housed in the highly scenic Sterrewacht Sonnenborgh which is now being converted into an astronomy museum under Kees' enthousiastic guidance, while we are housed substandardly in an uninspiring concrete monstrosity — to invite me to write a review on the topic for *Solar Physics*. He did so on the spot. By the time it was ready, much later, Kees Zwaan thought it was far too long to be publishable in any journal, but fortunately Kees de Jager didn't object (although he must have forgotten the invitation in the meantime).

[23] This conclusion is still somewhat controversial. I think it stands, especially after the detailed investigation by Lites, Rutten & Berger (1999), and I feel that colleagues who persist in believing that most internetwork grains betray magnetic anchoring (e.g., Sivaraman et al. 2000) should take a better look at the literature, at TRACE near-UV movies such as the ones available at http://www.astro.uu.nl/∼rutten/trace1, and above all at their own data which I find very unconvincing. What I in the meantime have become convinced of is that there is another agent: not magnetic field elements but atmospheric gravity waves. The recent analysis by Krijger et al. (2001) of internetwork oscillations measured in ultraviolet brightness movies from TRACE establishes their presence. In an analysis I am presently pursuing I will demonstrate that internetwork grain appearance is set by interference between gravity waves and acoustic waves. I don't know yet whether atmospheric gravity waves have an important function to fill, but at least they seem to be all over the place in the upper photosphere as predicted by Mihalas & Toomre (1981, 1982).

five-minute waves are evanescent.

The theoretical side of the story consists of the radiative hydrodynamics simulation by Carlsson & Stein (1997) of the data in Fig. 7. The sophistication of their simulation which made it more realistic and successful than numerous attempts by others lies in the detailed treatment of time-dependent NLTE radiative transfer and the fact that they modeled our actual observations, permitting direct comparison with these. For the four spatial positions marked by column numbers along the top of Fig. 7 they derived subsurface piston excursions from the Fe I Dopplershifts shown in the leftmost lower panel, used that "observed" piston to excite acoustic waves at the bottom of their one-dimensional atmosphere, and found that the higher-frequency ones propagate up and steepen into weak shocks in the chromosphere, with much shock overtaking (cf. Rammacher & Ulmschneider 1992).

Carlsson & Stein then computed Ca II H line formation from the simulation in display formats that can be compared directly with our actual observations. The initial result for one location is shown in Fig. 8; the results for all four are similarly displayed in Carlsson & Stein (1997). The correspondence between the observed and computed spectral behavior of the Ca II H core is very good. Since the spectral evolution patterns are quite intricate, this correspondence ascertains beyond doubt that acoustic shock modulation is the major agent affecting the formation of Ca II H in the internetwork. Experiments with deleting specific frequency bands from the piston confirmed that grain appearance is set broad-band, as shown observationally in Fig. 7. The Ca II H line formation itself is highly complex but well understood — at least within the simulation context (and at some time will become part of my radiative transfer course).

However, the Carlsson-Stein wave modeling has not yet reached the parameter-free perfection established in Nordlund-Stein granulation simulations. There are severe assumptions which affect its outcome. First of all, the simulation is only one-dimensional so that the energy budget is unrealistic (no sideways sources and leaks). Second, the simulation assumes sizable microturbulence, partially as a hedge for the neglect of partially coherent scattering in Ca II H line formation — which itself is a third major limitation. The piston lacks high frequency power if actually present, since the response of the Fe I line diminishes with the wave period and wavelength (Theurer et al. 1997, cf. Ulmschneider 1999).

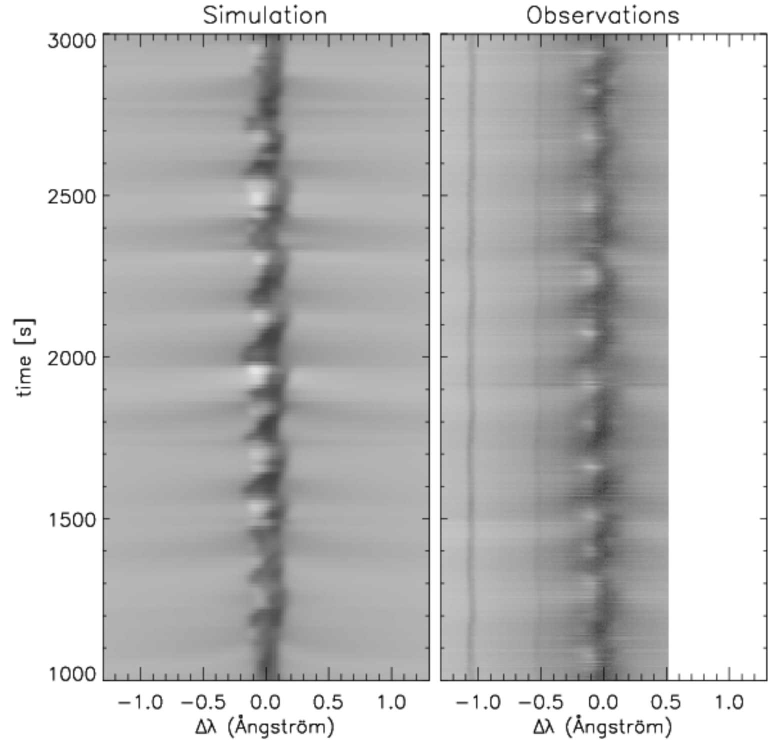

Fig. 8.— Ca II H profile evolution at one internetwork location, Right: data from Lites, Rutten & Kalkofen (1993). Left: corresponding Carlsson & Stein simulation results. Note the three-minute repetitivity, the inwards-shortening inner-wing "whiskers" (Beckers & Artzner 1974), the sawtooth Dopplershift changes of the Ca II H_3 center, and the appearance of bright H_{2V} grains on the violet side of line center. The simulation reproduces much of this complex behavior. From the cover of Carlsson (1994).

Chromospheric temperature rise. A controversial result from the Carlsson-Stein H_{2V} simulation is shown in Fig. 9. This experiment suggests that the actual internetwork (non-magnetic) chromosphere does not possess an outward temperature rise to heights of about $h = 1000$ km, but that the temperature rise of the HSRA, VAL and FAL models is an artifact due to non-linear averaging over the large temperature excursions present in the shocks running up in the atmosphere. This conclusion is still being debated (e.g., Kalkofen 2001) but strengthens Ayres' similar conclusion based on the dark cores of the strong infrared CO lines. The last word on this issue won't come in unless somebody achieves detailed time-dependent simulation including CO chemistry, which is nontrivial. For now, the hot-chromosphere camp points out one sees emission in ultraviolet lines all the time everywhere, whereas the cool camp points out that the CO cores are dark all the time everywhere. Myself, I am fairly convinced that the sun manages to keep both hot and cool, though perhaps not at a single time and place together at sufficiently high resolution, and expect that in the

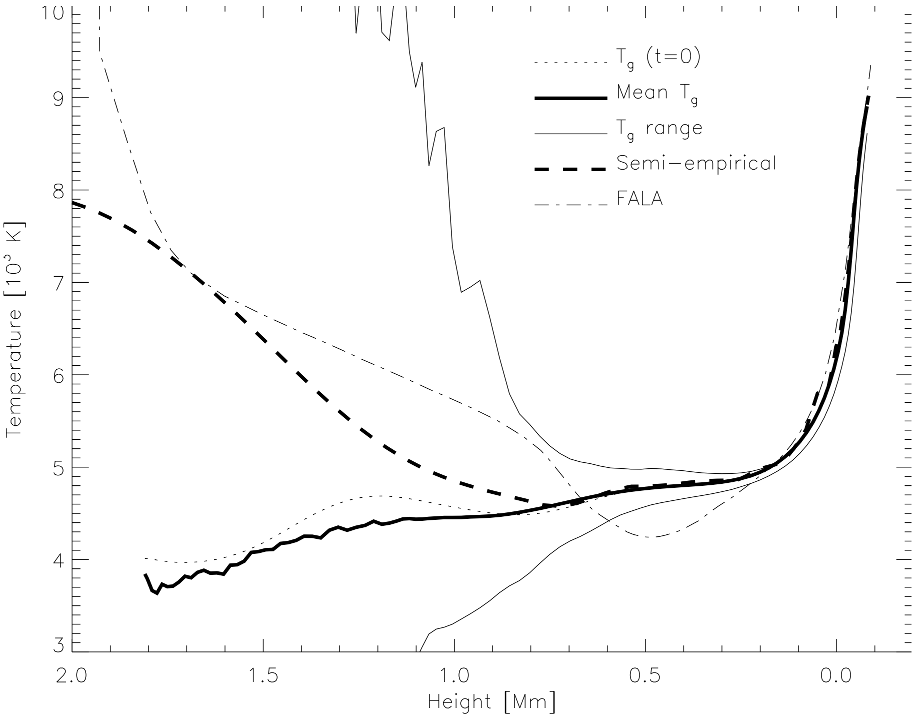

Fig. 9.— An experiment casting doubt on the existence of a ubiquitous chromospheric temperature rise below $h = 1000$ km. The thin dotted curve is the starting temperature in the dynamical Carlsson & Stein (1997) simulation, a RE stratification without outward temperature rise. The actual time-dependent simulation temperature oscillates (in shocks) between the two thin solid curves. The temporal mean is shown as the thick solid curve. It has no outward temperature rise either. However, if an empirical model would be constructed from the computed mean intensity of near-ultraviolet continua in the model-building procedure employed for the VAL and FAL models by Avrett and coworkers, one obtains the thick dashed curve. It does show an outward increase because the temperature peaks in the shocks are weighted non-linearly through the Planck function temperature sensitivity into the apparent brightness temperature. This curve is fairly close to the actual FALA quiet-sun model of Fontenla et al. (1993). From Carlsson & Stein (1994) (cf. Carlsson & Stein 1995).

end everybody will turn out right one way or another.

4. Conclusion

Within the narrow context of the one-dimensional modeling of the lower solar atmosphere reviewed here, one person who seems to be right to even larger height than before is Holweger. His 1967 LTE model represented an oldfashioned Unsöldian contender at the Bilderberg meeting which did not fit the Athay–Jefferies–Pecker dominated NLTE spirit. However, after I had so proudly demonstrated that its success is only apparent since due to erroneous NLTE masking (Fig. 3), I had to reverse the masking sign when Avrett desteepened his upper photosphere gradient and made it coincide nearly with the Holweger model. Later, the Carlsson-Stein simulation took away even the VAL/FAL chromospheric temperature rise (Fig. 9). At present, Holweger's model (or a RE model, nearly the same thing) seems to be the best zero-order approximation to the mean temperature stratification out to heights as high as 1000 km. Long live Schwarzschild's (1906) finding that the solar atmosphere obeys radiative equilibrium! (I bet it also holds reasonably within fluxtubes.)

This point has inadvertently and unknowingly been recognized all along by classical solar abundance determiners who, assuming plane-parallel modeling and LTE, always preferred the Holweger model in its HOLMUL reincarnation because "it gives the best results". They may have been more right than they knew, a point I have canonized in two dedicationally named equations (Rutten 1998):

$$\begin{array}{rl} \textit{Holweger:} & \mathrm{PPSA} + \mathrm{HOLMUL} + \mathrm{LTE} + \xi_\mu + E(\gamma) + gf \Longrightarrow A_{12}^{\odot} \\ \textit{Grevesse:} & A_{12}^{\odot} = A_{12}^{\mathrm{M}} - 0.004. \end{array}$$

Let me quote their description from Rutten (1998): *"The Holweger equation states that a good recipe to derive solar abundances is to assume a plane-parallel solar atmosphere obeying the HOLMUL temperature stratification hydrostatically and to assume LTE, a best-fit microturbulence value ξ_μ and a best-fit van der Waals damping enhancement factor $E(\gamma)$. The only remaining uncertainty is the transition probability gf (cf. Kostik, Shchukina & Rutten 1996). The point is proven by the Grevesse equation which states that for any element, excepting the lightest and carbon, the solar abundance determined Holweger-wise equals the value from carbonaceous chondrites, with a negligible correction for gravitational settling derived from fitting p-mode frequencies. These equations represent a great boon for stellar abundance determination. Forget about granules, waves, shocks, fluxtubes and NLTE complications in photospheric composition studies!"* The recent stellar inversion calibration of Allende Prieto et al. (2001) confirms this conclusion.

Of course, this has nothing to do with the real sun, not reviewed in this contribution. The real sun has granules, waves, shocks, fluxtubes, sunspots, filaments, loops, flares and what not, highly complex phenomena that inspire research by inquisitive scientists like Kees de Jager. His type isn't satisfied by precisely measuring abundances, but seeks insight in the awe-inspiring workings of Mother Nature, driven by curiosity as to how and why the universe operates. Most solar physicists take part in this general astronomy quest; within it, solar physics concerns the workings of the plethora of complex phenomena that our star chooses to put on display for the inhabitants of her third planet, as example of stellar astrophysics, to teach us MHD and plasma physics, or just for fun.

What role do one-dimensional simplifications as the modeling reviewed above have in actual-reality solar physics? In the end, having understood and simulated all the actual phenomena, we may quantify the grand-total verdict on how precise classical abundance determination really is. Such detailed and holistic simulation isn't feasible yet, but I won't be surprised if the ultimate result will produce optical spectral lines close to what a simple Holweger-like one-dimensional LTE-RE model predicts[24]. Anderson (1989) has called this notion *"perverse"* but I attribute it to the *"principle of solar communicativity"* (Rutten 1990).

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