THE NLTE FORMATION OF IRON LINES IN THE SOLAR PHOTOSPHERE

Robert J. Rutten
Sterrewacht "Sonnenborgh"
Zonnenburg 2
3512 NL Utrecht
The Netherlands

ABSTRACT. Solar iron lines provide extremely important diagnostics of the solar photosphere, including its deviations from LTE line formation in general. The NLTE effects in Fe I, Fe II and many other spectra are closely related because they are mainly determined by the amount of near-ultraviolet radiation present in the upper photosphere. The long-standing result that the ultraviolet is highly suprathermal, causing large overionization in minority species such as Fe I and overexcitation in majority species such as Fe II, is now challenged by Avrett on the basis of the ultraviolet blocking predicted from Kurucz's line compilations. Most of these blocking lines are from Fe I and Fe II, however, and since they set the temperature structure of the upper photosphere, the choice between LTE and NLTE Fe line formation can be self-fulfilling. The sun itself fulfills both choices all over its surface, according to Nordlund's simulation of the granulation, and the choice contributes also to Ayres' temperature bifurcation scenario. This issue is important in spatially-averaged atmospheric modeling as well as in modeling fine structure, for the sun and for other cool stars.

1. INTRODUCTION

1.1 IRON AS PROVIDER OF PHOTOSPHERIC DIAGNOSTICS

The literature on solar iron lines is quite large. It is roughly divided into three categories:

- stellar studies using solar lines to calibrate abundance determination and oscillator strengths;

- solar studies of (partially) resolved inhomogeneities, using a few specifically-chosen "magnetic" lines (large Landé factor g) or "velocity" lines (g=0);

- solar studies of unresolved inhomogeneities, using many iron lines

R. Viotti et al. (eds.), Physics of Formation of FeII Lines Outside LTE, 185–210.

simultaneously to obtain spatially-averaged signatures of photospheric fine structure.

There are recent advances for each category. In the abundance work, the solar iron spectrum remains the archetypical example of stellar photospheric line formation. The advent of reliable Fe I oscillator strengths (Blackwell et al. 1982 and references therein) represents the elimination of an important source of error that has caused much confusion in the past. Recent NLTE studies of this type are Steenbock (1985) and Saxner (1984).

The second category, studying inhomogeneities, constitutes most of the solar iron literature. It has now started to profit from the space age (NRL HRTS spectrograph, e.g. Dere et al. 1984). Groundbased observation generally suffers from much poorer resolution, with the exception of some data sets taken at Sacramento Peak (e.g. Zwaan et al. 1985). Basic fine-structure entities as granules and fluxtubes will only be fully resolved, however, when a sufficiently large telescope is put into orbit.

In the meantime, the third category of solar iron studies presents the most important advances. Dravins (e.g. 1982) has pioneered the use of precise wavelength shifts and profile bisectors of optical iron lines as gauges of the spatially-averaged effects of the solar granulation. Solanki and Stenflo (1984) have pioneered the study of solar fluxtubes from the same iron lines by extracting statistical properties from polarization spectra with very high spectral resolution obtained with the Kitt Peak FTS employed as a polarimeter. Since both of these techniques use spatially-averaged data and resolve only the solar center-to-limb variation, they supply promising diagnostics of stellar granules and stellar fluxtubes, respectively; in both cases, their pioneers have started stellar observations (Dravins and Lind 1984; Mathys and Stenflo 1986).

The reason why all these studies concentrate on iron lines is simply that iron provides the overwhelming majority of the diagnostics in the optical spectrum. In a compilation of unblended optical solar lines (Rutten and Van der Zalm 1984), Fe I provides 354 lines out of the total of 745, and Fe II is with 22 lines the only dominant stage of ionization present with more than 10 lines. In particular, Harvey (1973) and Sistla and Harvey (1970) list 18 good magnetic lines and 18 good velocity lines from Fe I respectively, more than all other species provide together. In addition, the iron lines are not spoiled by isotope and hyperfine splitting, in contrast to most other species; they are truly clean.

While Fe I supplies most of the useful lines, the majority of the iron atoms in the photosphere are ionized. One should therefore always include Fe II lines in any analysis using Fe I lines, to obtain complementary diagnostics and to avoid errors due to the large sensitivity of the Fe I opacities to the ionization equilibrium. This strategy has been adopted by Blackwell et al. (1980) in abundance determination, by Dravins and Larsson (1984) in spatially-averaged granulation analysis, and by Solanki and Stenflo (1985) in spatially-averaged fluxtube polarimetry.

1.2 IRON AS A SHAPER OF THE PHOTOSPHERE

The enormous line densities of the Fe I and Fe II spectra not only result in their diagnostic prominence in the optical but also in severe line crowding in the ultraviolet. It seems likely that most of the "missing opacity" between 2000 and 3000 Å is due to iron (Rudkjøbing 1986; Kurucz, these proceedings), and thus iron is the major provider of the ultraviolet line blocking which affects the temperature structure of the upper photosphere. In addition, the combination of high abundance and rather low ionization energy makes iron the major contributor to the electron density in the temperature minimum region where hydrogen is neutral (see Vernazza et al. 1981, Fig. 47. Henceforth, I abbreviate this important and informative paper to VALIII). Finally, the Fe I photoionization edges from a^5D at 1575 Å and a^5F at 1768 Å contribute significantly to the continuous opacity near these wavelengths (VALIII, Fig. 36) and cause significant radiative cooling in the upper photosphere (VALIII, Fig. 49 [1]).

1.3 IRON AND NLTE DEPARTURES IN THE PHOTOSPHERE

In none of the three classes of solar iron research listed above has much attention been paid to departures from LTE. Usually, LTE is simply adopted. For many diagnostic applications, the question simply doesn't matter; for example, a g=0 velocity line will serve to measure Doppler shifts in helioseismology irrespective of its formation details. However, the details including departures from LTE in the excitation and ionization balances do matter in abundance determination, in diagnostic usage where the height of formation or the geometry is important, and in studies that require evaluation of radiation losses to determine energy budgets.

This review is limited to the LTE-NLTE issue only, and only for the photosphere. The chromosphere, with its major and interesting NLTE problems (fluorescence, optically thin conditions etc.) is treated by Carole Jordan in these proceedings. Here I only discuss the general departures in the ionization and excitation balances, not details of specific lines. Even within these restrictions, there is good ground for a review at this time because the old (and heated) debate "LTE or NLTE" is flaring up again.

The old debate was never settled but has developed into an amazing schism between radiative transfer theoreticians and stellar abundance determiners. The first group, after completing the full theory of NLTE radiative transfer in the sixties and putting it into textbooks in the seventies (Jefferies 1968, Mihalas 1970, Athay 1972, Ivanov 1973), moved on to more complicated problems (partial frequency redistribution, expanding atmospheres, etc.). The second group simply continued Unsöld's trick of adopting LTE, sometimes "proving" its

---

[1] In VALIII the Fe II ground level is incorrectly adopted as parent term for ionization from a^5F. The actual parent is a^4F and the corresponding edges are near 1700 Å instead of 1768 Å.

validity from the good consistency of the results.

This split is most distinct in Fe I analyses. Lites' (1972) comprehensive study showed that ultraviolet overionization leads to large Fe I opacity deficits, which affect all strong and medium strong Fe I lines (section 2.3 below). On the other hand, Holweger (1967) built a very satisfactory model photosphere precisely from the medium-strong Fe I lines adopting LTE opacities. Although these two descriptions differ very much, both reproduce the observed iron lines quite well. Let me illustrate this split with two quotations. Athay wrote in 1972 (p. 181):

> "...somewhat to the surprise and consternation of those who have criticized the LTE analysis of Fraunhofer lines, Holweger does find, in fact, that a single model gives an acceptable representation of both the continuum and the lines..."

Holweger wrote in 1979:

> "...Among the problems that need further study are deviations from LTE. Unfortunately, these are easily arising in the computer if important collisional processes are neglected, or if radiative rates are not realistic. In cool stars, collisional excitation by hydrogen atoms is generally neglected; data on cross-sections are largely missing. However, in the Sun, hydrogen atoms outnumber the free electrons by a factor of 10000. The UV radiation field is complicated by a vast number of absorption lines..."

Holweger's model was succeeded by the very similar HOLMUL model (Holweger and Müller 1974) which is invariably the choice of LTE abundance determiners simply because it results in smaller spread than the elaborate semi-empirical NLTE models built in the meantime, most notably the HSRA (Gingerich et al. 1971) and the VALII (Vernazza et al. 1976) and VALIII models. These models are much cooler in the upper photosphere (Fig. 5), and it turns out that the LTE-or-NLTE formation issue is closely connected to the hot-or-cool upper photosphere issue (section 3.1 below).

There are two important recent papers concerning this issue, unfortunately both hidden in workshop proceedings. In the first, Avrett (1985) recovers Holweger's model by including ultraviolet line blocking in detail in a very comprehensive NLTE fit of the solar continua with a hot model (section 3.2 below). This indicates that photospheric overionization indeed arose artificially in the computer before, and that the actual solar photosphere does obey LTE. On the other hand, Nordlund (1984) shows from a very comprehensive simulation of the solar granulation that hot and cool photospheres are simultaneously present all over the sun (section 4.1 below). Nordlund finds that the spatial and temporal averaging over the granulation is so nonlinear due to the steep temperature sensitivity of the ionization equilibria that even the classical iron abundance determined from the standard models is quite wrong.

Thus, the NLTE-versus-LTE issue crops up again, now on the basis of comprehensive computer modeling. The issue is both controversial and important, being essential not only to the formation of Fe I but

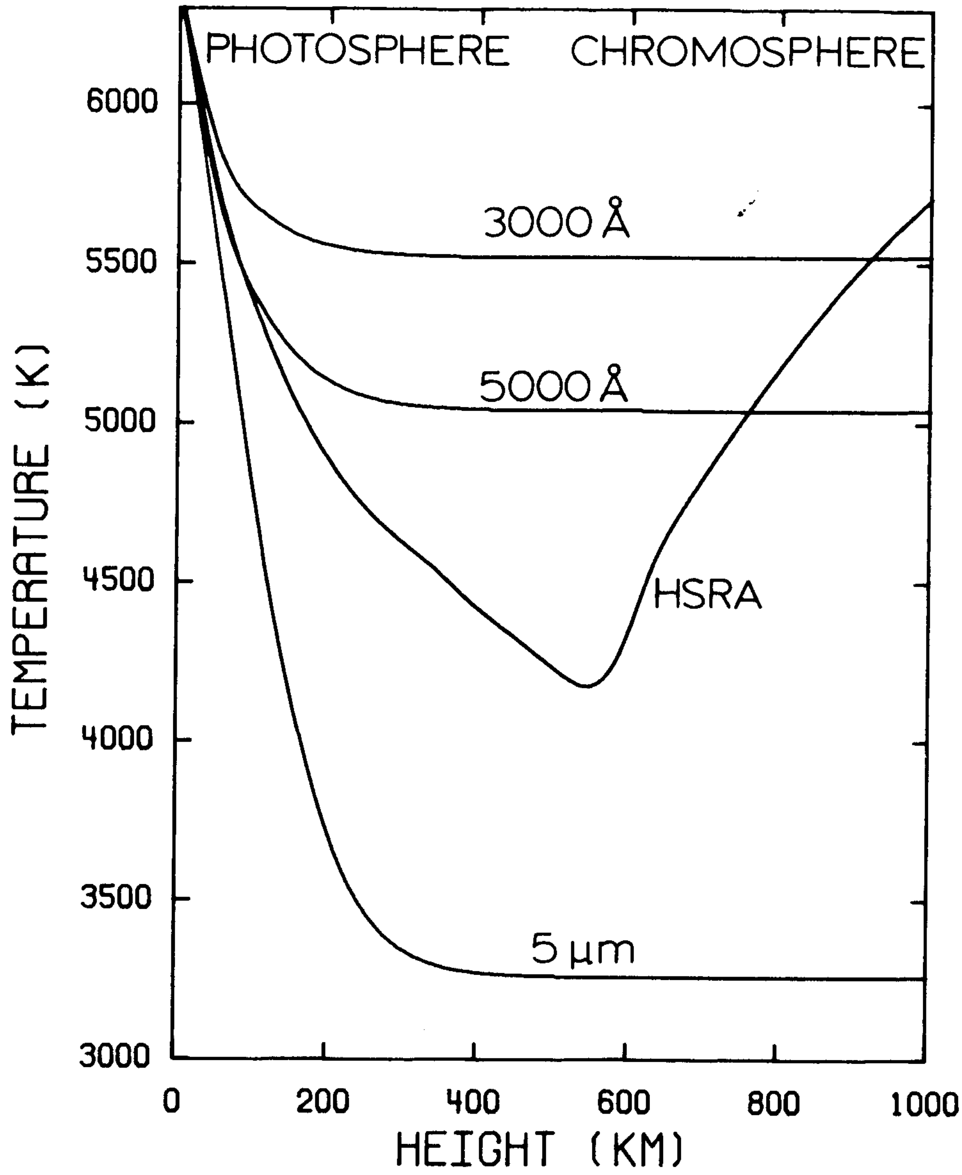

Fig. 1. Radiation fields in the solar atmosphere. The curve marked HSRA is the electron temperature of the HSRA model and represents the Planckian radiation field B_ν. The other curves represent the angle-averaged monochromatic continuous intensity $J_\nu(h)$ in the form of radiation temperatures, for the indicated wavelengths. The transition between photosphere and chromosphere is defined here as occurring at the temperature minimum.

also to the excitation balance in Fe II and the formation of lines of many other species. I will therefore mainly discuss the Fe I - Fe II ionization balance, and since Fe I lines are more sensitive to it than Fe II lines, I will pay much attention to Fe I line formation. I wish to apologize for this bad behaviour in a meeting devoted exclusively to Fe II!

2. NLTE IN PHOTOSPHERIC IRON LINES

2.1 NLTE MECHANISMS

Since this meeting brings together astrophysicists from widely different fields, it seems appropriate to outline the main points of photospheric NLTE departures even though detailed descriptions are available (e.g. Athay 1972, the VAL papers, Thomas 1983).

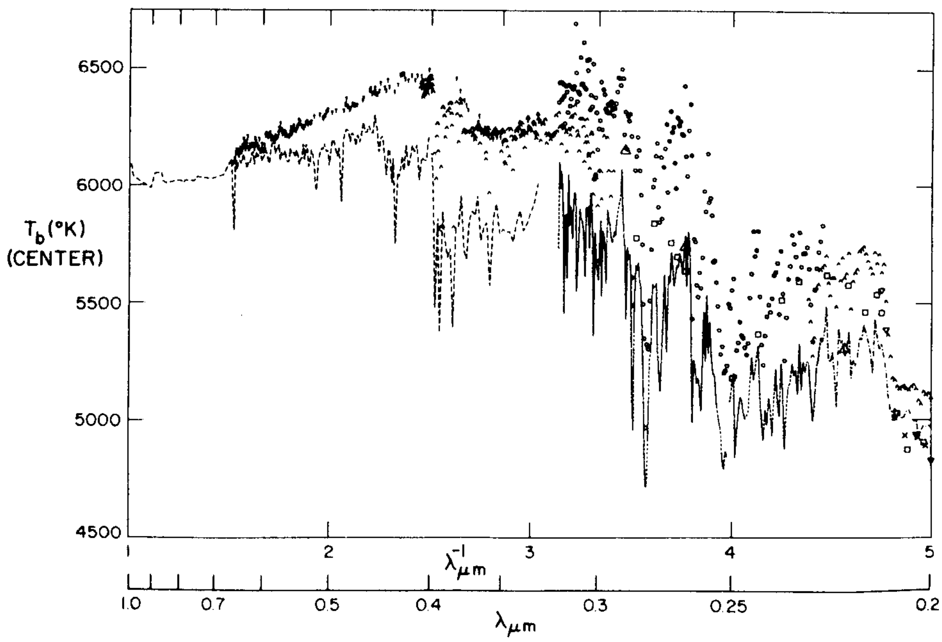

Fig. 2. Solar disk-center brightness temperatures against wavelength, from VALII. The brightness temperature corresponds with the observed disk-center monochromatic intensity. The upper values are for the highest continuum points between lines, the lower values are spectral averages including lines. From Vernazza et al. (1976), with permission from The Astrophysical Journal.

The reasons that most photospheric NLTE phenomena are set in the ultraviolet are that there the angle-averaged intensity J_ν exceeds the local Planck function B_ν, and that there the emergent radiation is both hot and energetic. Figs. 1 and 2 illustrate these points following Avrett (1985). Fig. 1 shows J_ν and B_ν in the form of radiation temperatures at three wavelengths for which the photon escape depth is about the same: the disk-center Eddington-Barbier depth $\tau_\nu = 1$ is near h = 0 km in each case. The surface value of J_ν is about 0.3 $B_\nu(\tau_\nu=1)$ at each wavelength, but because the temperature sensitivity of the Planck function decreases with wavelength, J_ν drops below B_ν toward the surface at long wavelengths whereas it exceeds B_ν at shorter wavelengths. Note that this difference occurs here in LTE ($S_\nu \approx B_\nu$ at $\tau_\nu = 1$; it also occurs in radiative equilibrium which requires only the integral equality $\int\kappa_\nu S_\nu d\nu = \int\kappa_\nu J_\nu d\nu$ to hold at all heights). If scattering contributes significantly to the continuous opacity, as it does in the Fe I ionization edges below 2000 Å, J_ν decouples from B_ν much deeper in the atmosphere than the depth where $\tau_\nu = 1$ (VALIII Fig. 36).

Fig. 2 (taken from VALII) shows the observed brightness temperature at disk center. It is quite high in the near ultraviolet, reaching 6500 K at 3000 Å between spectral lines. This graph is in shape the reverse of the wavelength dependence of the monochromatic opacity: a high brightness temperature corresponds to deep photon escape. Note, however, that the average brightness temperature is appreciably lower between 2000 and 4000 Å due to line crowding, and that even the observed maxima are far below the continua computed from model atmospheres if only the known bound-free and free-free opacities are included. Nevertheless, the near-ultraviolet radiation escapes rather deep, is therefore hot, and since it has a steep Planck function, it has $J_\nu > B_\nu$ in the temperature minimum by about 1000 K (Fig. 1).

It is also energetic, 4 eV per photon at 3000 Å. Which are the most important 4 eV radiative transitions? For Fe I, photoionizations from the intermediate levels; for Fe II, being the dominant stage of ionization, the resonance lines. For both types of transition, the photon destruction probability per extinction process ε is small, so that the source function $S_\nu = (1 - \varepsilon)\, J_\nu + \varepsilon\, B_\nu$ follows J_ν rather than B_ν, as shown in fig. 36 of VALIII for the a^5F polarization edge. The ultraviolet excess $J_\nu - B_\nu$ therefore results in over-ionization from the intermediate Fe I levels at the temperature minimum, and in overexcitation in the wings of the Fe II resonance lines formed there. Note that scattering in the cores of strong lines always results in $J_\nu < B_\nu$ even in the ultraviolet, because the additional line opacity makes the gradient $dB_\nu/d\tau_\nu$ much shallower than in the continuum. The cores of strong lines follow the textbook example of a homogeneous layer which has $S_\nu = \varepsilon^{\frac{1}{2}}\, B_\nu$ at its surface.

2.2 NLTE DESCRIPTION

Another preamble which seems useful here although it is textbook matter is to define the description of departures from LTE to be used here. In fact, the definition of LTE itself isn't always clear; for example, Bowers and Deeming (1984, p. 81) define weak, moderate and strong versions. The definition used here is Ivanov's (1973, p. 6):

LTE requires that the matter is in thermodynamic equilibrium with the local kinetic temperature (the Maxwell, Boltzmann and Saha distributions are valid), while the radiation is not. It then follows that $S_\nu^\ell = B_\nu$ (ib., p. 46) while I_ν and J_ν can depart from B_ν and the net flux from zero.

The usual way to measure departures from LTE is by specifying departure coefficients relative to the Saha-Boltzmann populations. But take care: their normalization differs among authors, and not all authors are aware that this can affect opacities. The original definition (Menzel and Cilliê 1937) is usually followed (e.g. Jefferies 1968, eq. 6.3; VALIII eq. 15):

$$n_i = b_i \left(\frac{h^2}{2\pi m_e kT}\right)^{3/2} \frac{g_i}{2\, U_k^*} e^{(E_k - E_i)/kT} n_k n_e \qquad (1)$$

or:

$$b_i = \frac{n_i/n_i^*}{n_k/n_k^*}$$

where n is the actual population and n^* the population computed from the Saha and Boltzmann distributions, respectively for a level i and the next higher ion k. This definition differs from what it is often taken to be:

$$\beta_i = \left(n_i/n_i^*\right) = \left(n_k/n_k^*\right) b_i \qquad (2)$$

which was introduced by Wijbenga and Zwaan (1972). This coefficient relates the population departure of a level to the total amount of the element rather than the population of the next higher ionization stage. When the latter is out of LTE the two definitions can differ appreciably. For example, photospheric hydrogen has (VALIII p. 663):

$$\beta_1 = 1/b_k = 1 \quad \text{while} \quad b_1 = {}^1/\beta_k \simeq \left({}^B/{}_J\right)_{LyC} \simeq 0.3$$

The departure coefficients are readily converted into corresponding temperatures (Wijbenga and Zwaan 1972). In particular, writing $\Theta = 5040/T$, the excitation temperature T_{exc} for a line between lower level ℓ and upper level u is given by:

$$\theta_{exc} = \theta_e - (E_u - E_\ell)^{-1} \log(\beta_u/\beta_\ell) \qquad (3)$$

It is the equivalent of the line source function; writing

$$\beta_u/\beta_\ell = 1 + \Delta\beta \quad \text{and} \quad h\nu/kT = \delta$$

one finds for the Wien approximation ($\delta > 1$):

$$S_\nu^\ell = B_\nu(T_{exc}) \simeq (1 + \Delta\beta)\, B_\nu(T_e) = \left({}^{\beta}u/\beta_\ell\right) B_\nu(T_e) \qquad (4)$$

and for the Rayleigh-Jeans approximation ($\delta < 1$):

$$S_\nu^\ell = B_\nu(T_{exc}) \simeq (1 + \Delta\beta/\delta)\, B_\nu(T_e) \qquad (5)$$

Finally, the lower-level departure coefficient affects the line extinction coefficient:

$$\kappa_\ell = \frac{\pi e^2}{mc} \frac{H(a,v)}{\sqrt{\pi}\Delta\nu_D} g_\ell f_{\ell u} \beta_\ell n_\ell^* [1 - (\beta_u/\beta_\ell)e^{-\delta}] \simeq \beta_\ell \kappa_\ell^* \qquad (6)$$

Many authors equate NLTE conceptually to $S_\nu \neq B_\nu$ but neglect the opacity dependence on β_ℓ (e.g. Cowley 1970, Chapt. 2-6).

2.3 PUBLISHED NLTE MODELING OF Fe I AND Fe II

Lites' outstanding thesis (Lites 1972, 1973; summary in Athay and Lites 1972; tables in Lites and White 1973) remains the only Fe I NLTE analysis published in detail so far. Fig. 3 summarizes its main results in the form of departure coefficients and excitation temperatures. The solid curves in Fig. 3a are for the a^3F and z^5G^o levels respectively, which are representative for low-lying levels and levels of intermediate excitation, respectively. Lites found that all such Fe I levels share the drop to log (β) = -0.7 at h = 500 km, which is the location of the temperature minimum. This drop is the result of ultraviolet overionization, mainly from rather high levels (~ 4 eV) due to the hot radiation near 3000 Å, but shared out over all Fe I levels through the strong radiative and collisional coupling that the line- and level-rich Fe I term diagram provides.

The result of this shared drop in β for the optical Fe I lines is that their excitation is thermal ($\beta_u \approx \beta_\ell$), but that their opacity, which scales with β_ℓ, is reduced by about 0.7 dex (abundanese jargon for 10-log units, see Allen 1976) at the heights where their cores are formed. This is a large effect! The line cores are shallower than in LTE since they are formed deeper in the atmosphere. However, the effect is much smaller for equivalent widths since these are not very sensitive to the higher layers; the drop results typically in only 0.1 dex reduction in equivalent width (Holweger 1973, Rutten and Zwaan 1983).

Above the temperature minimum, the departure coefficients rise sharply because the ionizing radiation does not follow the chromospheric temperature rise. The 4 eV (z^5G^o) departure coefficients drop away from the ground-level coefficient due to the photon losses in the resonance lines; these are strong enough that excitation departures only occur above the temperature minimum.

Lites did not include higher levels in his modeling, except for some trial computations. These show the same pattern of $\beta_u/\beta_\ell < 1$ at the heights where photon losses in the strongest downward transitions from these high levels occur, i.e. where they become optically thin, which is below the temperature minimum for these lines which are actually weak in the solar spectrum due to their small Boltzmann factor. Thus, the strongest optical lines at high excitation have source function deficits as well as opacity deficits compared to LTE estimates. These deficits compete in their effect on the observed line depth. The drop in the line source function produces deeper-than-LTE profiles, while the drop in the line opacity produces shallower-than-

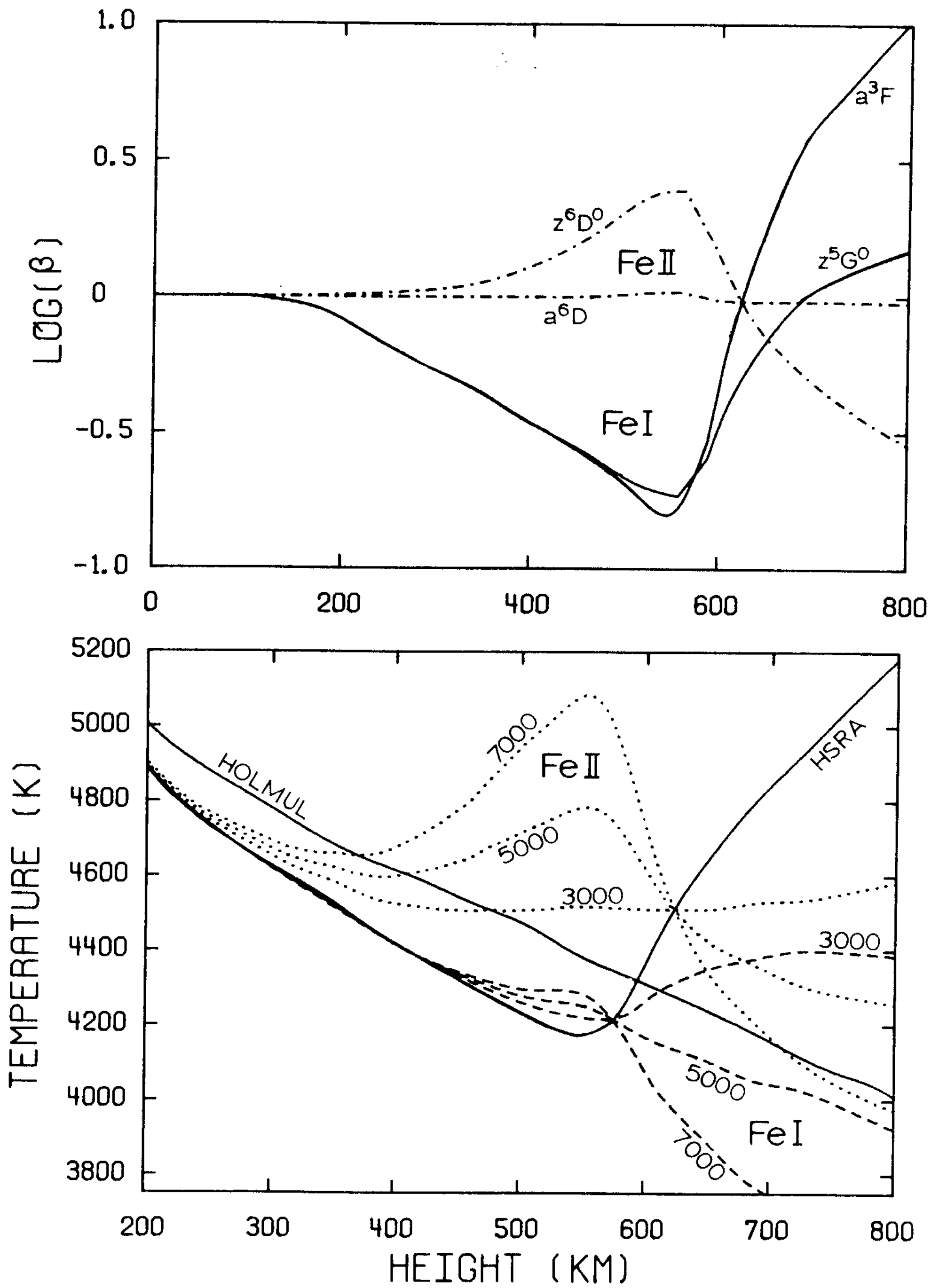

Fig. 3. Results of NLTE modeling of solar Fe I and Fe II, after Rutten and Kostik (1982). Top: representative departure coefficients against height, respectively for Fe I (solid) and Fe II (dot-dashed). The even-parity curves represent typical lower-level departures (β_ℓ). and the odd-parity curves typical upper-level departures (β_u).
Bottom: excitation temperatures against height, derived from the departure coefficients in the top panel with eq. 3, for λ = 3000 Å, 5000 Å and 7000 Å and for Fe I (dashed) and Fe II (dotted), respectively.

LTE profiles. The deficits may thus cancel, resulting in lines that look as if they were formed in LTE. This fortuitous cancellation of excitation and ionization departures is evident in Saxner's (1984) stellar model computations; it also seems confirmed by the actual photospheric high-excitation lines and their fitting by LTE abundance determiners (Rutten and Van der Zalm 1984). It is in conflict with the assertion (Jefferies 1968) that the high-excitation levels should have $\beta \approx 1$ through coupling to the reservoir of Fe II ground-level atoms, which have $\beta = 1$. If that were the case, the high-excitation Fe I lines would have $S_\nu^\ell > B_\nu$, since their lower level would still have the drop in β_ℓ shown by z^5G^o in Fig. 2a. The source function excess and the opacity deficit would then work together in producing lines much shallower than when computed in LTE. This is not seen; presumably, the collisional coupling to the continuum is not strong because the upper levels of the observable optical lines are yet about 1 eV from the continuum (Rutten and Zwaan 1983, Fig. 2), and the radiative coupling is small because most high levels ionize to excited Fe II parent terms.

The amount of collisional coupling between the levels isn't well known. Lites did not include neutral hydrogen collisions, but they should be taken into account as advocated by Holweger (see quote above). They were included by Steenbock (1985), but he has not yet published detailed rates. For small energy separations, these collisions must be as important as they are in producing collisional line broadening; and so one may expect that at any excitation energy all nearby levels will share their populations. This implies that a particular Fe I level will be in Boltzmann equilibrium with the low levels until the strongest downward transitions from the nearby levels become optically thin, further strengthening the general population sharing already found by Lites. The observed line-to-line differences should thus be small. This is indeed the case; although there is evidence for significant differences between specific multiplets (Blackwell et al. 1984), these are indeed very small, less than 0.1 dex. In any case, the basic NLTE effect, overionization by the suprathermal ultraviolet, is not sensitive to the amount of low-energy collisional coupling.

Let us now turn to Fe II. Fig. 3a specifies departure coefficients for the a^6D ground - level and the z^6D^o excited level, which is the upper level of the 13-line resonance multiplet near 2900 Å. The Fe II departure pattern is just the opposite of the Fe I pattern. The lower level population is in LTE; this holds for all the low levels in Fe II because they are all of even parity and only collisionally coupled, and Fe II is the dominant ionization stage. The upper level population peaks in the temperature minimum, and then drops in the chromosphere. The drop is simply due to photon losses in the resonance lines, but the peak has been controversial. Lites (1974) concluded that it is due to downward diffusion of photons out of the strong self-reversed emission cores he predicted for the resonance lines. Subsequently, Cram et al. (1980) concluded that the peak is due to the high value of J_ν near 2600 Å in the continuum (Fig. 2); it pumps the upper-level population via the wings of the resonance lines.

The presence of this peak is observationally required from the observed behaviour of the weak subordiante line at 3969.4 Å, which shares its z^6D^o upper level with the resonance lines and which is located in the wing of the Ca II H line between the H core and H_ε. This line is seen in emission inside the solar limb, with extraordinary spatial intensity variations (Canfield and Stencel 1976; Rutten and Stencel 1980). It is even seen in emission at the center of the solar disk within small-scale structures (Cram et al. 1980). These emission features, which require $S_\nu > B_\nu$ locally, are probably photospheric in origin because their spatial distribution is not correlated with the chromospheric features seen in the adjacent core of the H-line. They are so clearly observable in this weak line because the added H-wing opacity pushes its height of formation to the peak in β_u and the corresponding peak in the line source function (Fig. 3b). Their spatial intensity variation is so large because they have ultraviolet temperature sensitivity although they are seen in the optical, just as in the familiar Zanstra mechanism in which the optical Balmer lines from planetary nebulae exhibit the ultraviolet radiation temperature of the central star.

Cram et al. (1980) showed that the same departure pattern holds for other subordinate lines sharing z^6D^o upper levels (multiplets 1, 30 and 40). Similar patterns probably hold throughout the term diagram because Fe II typically has strong ultraviolet lines feeding odd-parity levels that are shared with optical transitions to the metastable even-parity levels. It follows that most optical Fe II lines will have suprathermal line source functions in the temperature minimum due to photospheric ultraviolet pumping. A direct consequence is that they should all turn into emission well inside the solar limb because the optical continua follow B_ν. This is indeed the case, as can be concluded from Pierce's (1968) compilation of solar limb emission lines. This list is not a list of the chromospheric spectrum, although its title says so - it is primarily a list of photospheric lines with suprathermal source functions near the temperature minimum (Rutten and Stencel 1980). Direct evidence from high-quality eclipse spectrograms has been given by Van Dessel (1975), who found that Fe II lines typically turn into emission already 1500 km inside the limb, while Fe I lines with their LTE source functions turn into emission much closer to the limb (Van Dessel 1974).

In conclusion, the overexcitation shown by the optical Fe II lines from the upper photosphere is set by the imbalance $J_\nu > B_\nu$ in the near ultraviolet. The Fe II overexcitation and the Fe I overionization are different manifestations of the same NLTE mechanism.

An important aspect of the equality of the upper-level population departures shared by the subordinate Fe II lines is that they result in enhanced effects toward longer wavelengths. This is illustrated by the excitation temperatures in Fig. 3b which are derived from the departure coefficients in Fig. 3a by eq. 3. The overexcitation set by J_ν below 3000 Å (which drops smoothly outward) results in a prominent peak in S_ν^ℓ at the temperature minimum for λ = 7000 Å. The peak is due to the decreasing temperature sensitivity of the Planck function. For example, in the Wien limit one can say that there is source function equality according to eq. 4, but doubling S_ν by $\beta_u/\beta_\ell = 2$ at the temperature minimum results sooner in emission for lines formed there when the inward increase of the Planck function toward the height of continuum formation is less steep. The effect is even larger for the Rayleigh-Jeans limit due to the magnification factor δ in eq. 5 (Mihalas 1978, p. 404). It implies that the best observational test of Fe II NLTE is to study limb emission lines in the infrared.

Optically thick emission is such a good NLTE diagnostic because it is direct evidence of a suprathermal source function. In the case of the Fe II resonance multiplet, however, the absence of intense chromospheric emission in the line cores may be an important diagnostic. This absence is surprising. At larger abundance than Mg and with similar ionization energy, one would expect Fe II reversals comparable to the prominent peaks in the Mg II h and k resonance lines (Athay and Lites 1972). Although the profiles computed by Cram et al. (1980) have negligible reversals, they were based on too small an iron abundance and on the erroneous assumption of complete frequency redistribution. When monochromatic scattering is taken into account, the line cores are coupled more closely to the chromospheric temperature rise, just as in the case of the Mg II and Ca II lines. The absence of chromospheric emission peaks thus remains unexplained; undoubtedly, the complexity of the Fe II term diagram over the otherwise similar Ca II term diagram plays a role.

3. IRON NLTE AND THE MEAN ATMOSPHERE

3.1 EMPIRICAL PLANE-PARALLEL MODELING FROM LINES

The NLTE results summarized above have large effects on optical Fe I and Fe II lines formed near the temperature minimum. The stronger photospheric Fe II lines have appreciable source function enhancements (Fig. 3b); the optical Fe I lines, while having LTE source functions, have large opacity deficits (Fig. 3a). How can it be that all these lines can be reproduced quite well assuming LTE, as is the case in numerous abundance-type analyses? This discrepancy was explained by Rutten and Kostik (1982) by showing that the Holweger and HOLMUL atmospheric models are "NLTE-masking": these departures from LTE are, if present, implicitly compensated by the temperature structure of these LTE models.

Fig. 4 schematically explains this masking by way of a thought experiment for Fe I. Suppose that the NLTE modeling by Lites and by Cram et al. using the HSRA is precisely correct. If one then neglects these NLTE departures and constructs an empirical model from the observed line-center brightness temperatures, a HOLMUL-like atmosphere will automatically result. Neglecting the effect of β_ℓ on the opacities (single arrows in Fig. 4) results in a spurious model height scale, stretched where $\beta_\ell < 1$ and compressed where $\beta_\ell > 1$. Neglecting the chromospheric source function departures (β_u/β_ℓ, double arrows) requires that the model is a representative excitation temperature

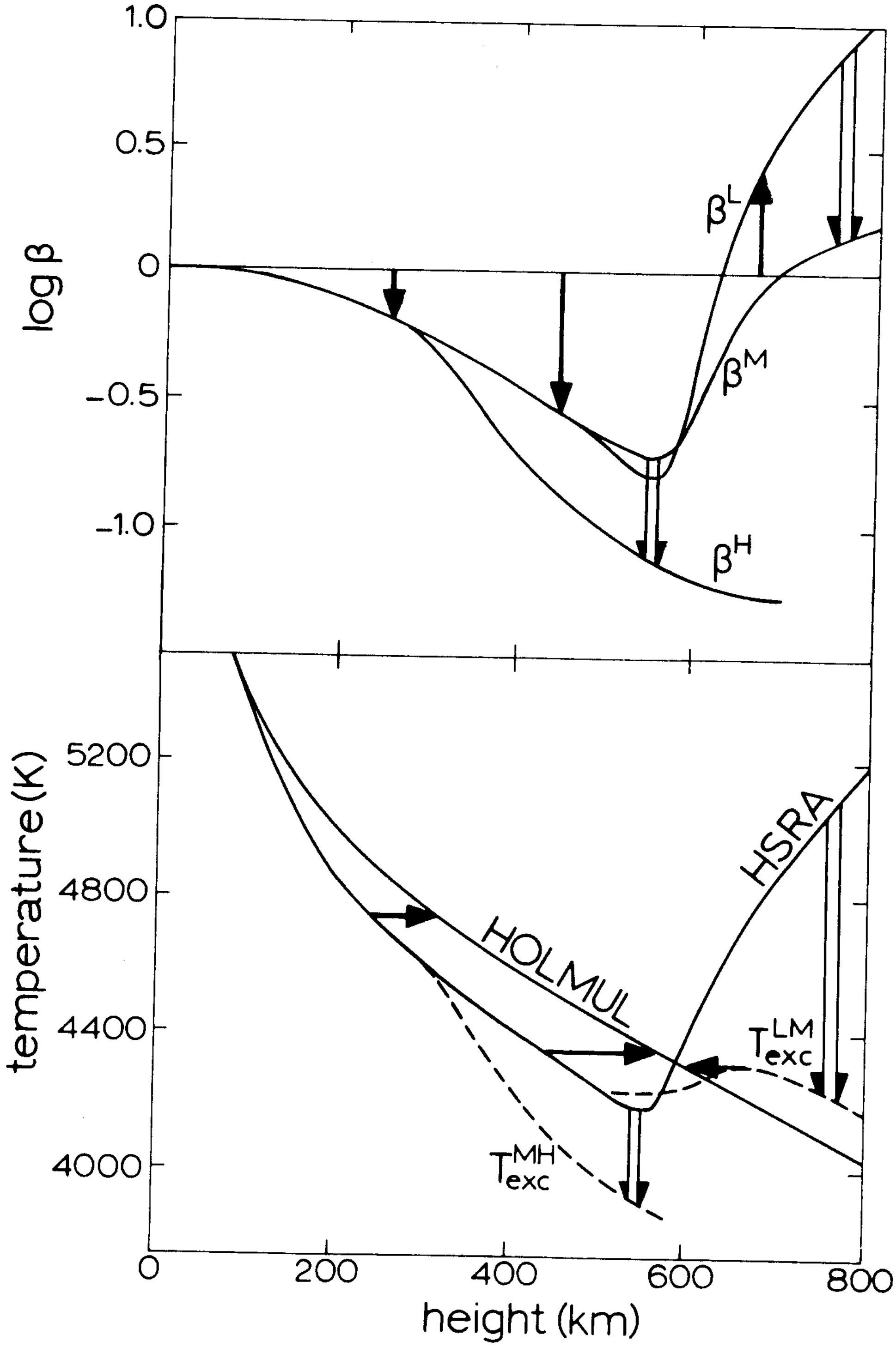

Fig.4. Schematic explanation of NLTE masking. The top panel shows typical Fe I departure coefficients computed for the HSRA model, respectively for low levels (L), intermediate levels (M) and high levels (H). The corresponding excitation temperatures (eq. 3) are shown in the bottom panel (dashed), together with the electron temperatures of the HSRA and HOLMUL models (solid). The double arrows

in both panels demonstrate the effect of the NLTE departures on the line source functions, set by the ratio β^M/β^L for low-excitation lines (LM) and by the ratio β^H/β^M for high-excitation lines (MH), respectively. The single arrows in both panels indicate the NLTE shift in height of formation, set by β^L and β^M, respectively. For LM lines the combined effect of these arrows is that the HSRA and NLTE together produce the same line formation as HOLMUL and LTE together. The strongest MH lines, however, are deeper in the first case.

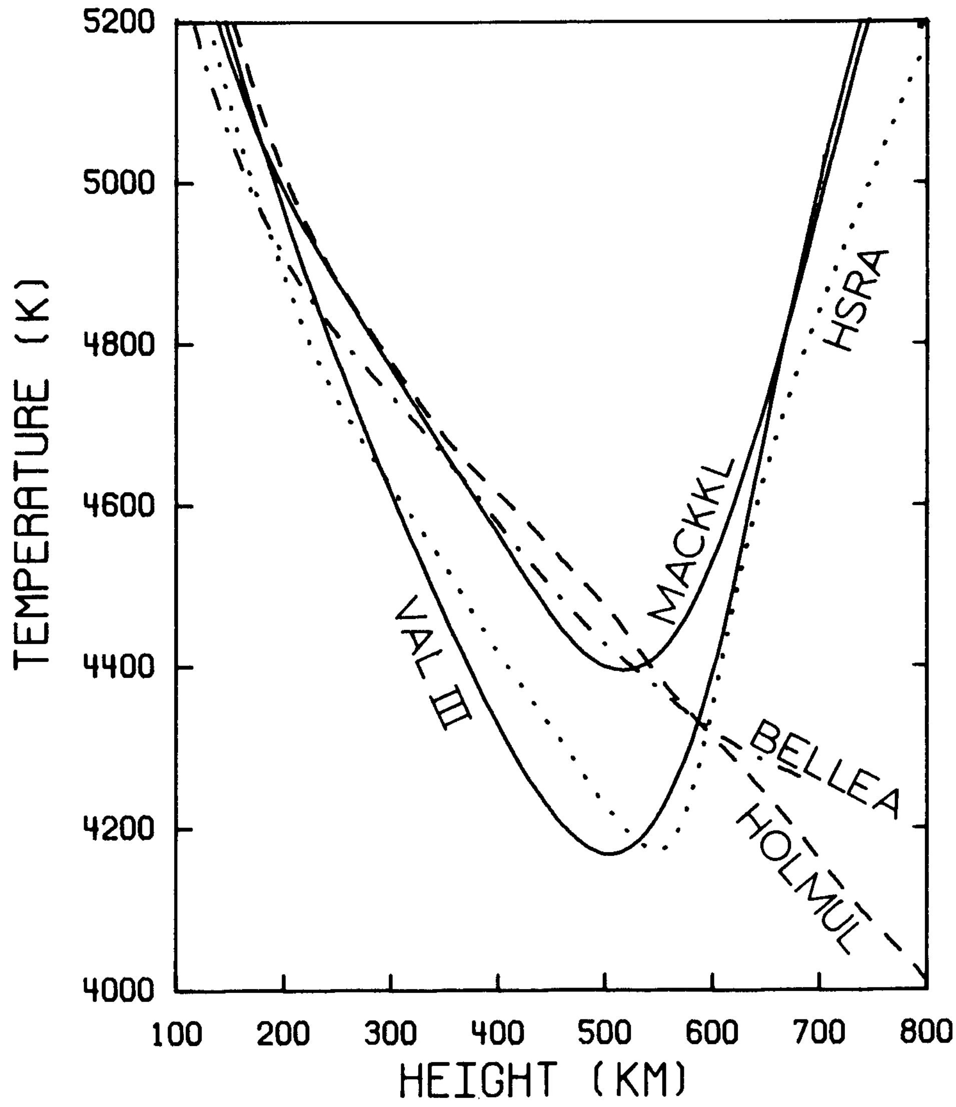

Fig. 5. Plane-parallel models of the solar atmosphere. BELLEA is a theoretical LTE radiative-equilibrium model, HOLMUL an empirical LTE model based on optical continua and lines, and HSRA, VALIII and MACKKL are semi-empirical models, based on NLTE fits of the solar continua throughout the spectrum.

instead of the kinetic temperature above the temperature minimum. The derived LTE model is hot in the upper photosphere to compensate for the opacity shifts and it follows the opacity-shifted Fe I excitation temperatures in the chromosphere. This NLTE masking works quite well for all optical Fe I lines. It also works for optical Fe II lines because their NLTE overexcitation is also set by the ultraviolet excess. A hot LTE model reproduces more or less the raised excitation temperatures shown in Fig. 3b, in this case without opacity shifts. It does not reproduce the observed emission features but one might argue that these are due to specific inhomogeneities anyhow.

Rutten and Kostik (1982) interpreted this explanation of the success of the HOLMUL model as a reconciliation with the HSRA which in roundabout fashion supports Lites' NLTE modeling. However, it is possible to reverse the sign and the arrows in this experiment, and to assume instead that the LTE modeling is precisely correct. One then concludes that the large NLTE departures found by Lites for Fe I and by Cram et al. for Fe II result artificially from their assumption of a too cool upper photosphere. If the actual upper photosphere is much hotter than the HSRA, the true ultraviolet overionization and over-excitation are small and the populations, Fe I opacities and Fe II source functions are close to LTE. The departures computed from the too cool model would be far too large, but just what is needed to reproduce the observed lines. The cool model would be "LTE-masking" in the photosphere.

In summary, we have an iron-line dilemma: one can model the observed Fe I and Fe II lines by either assuming (and believing) a HSRA-like cool model with a large excess of J_ν over B_ν in the ultraviolet, or by assuming (and believing) a HOLMUL-like hot model with a small ultraviolet excess and negligible departures from LTE up to the temperature minimum. The photospheric lines are well reproduced by each combination. Actual examples for many observed iron lines are given by Rutten and Kostik elsewhere in these proceedings.

3.2 EMPIRICAL PLANE-PARALLEL MODELING FROM CONTINUA

A similar quandary has recently appeared for the semi-empirical model atmospheres based on the observed solar continua. Traditionally, these had cool upper photospheres in order to fit the observed ultraviolet and infrared continua (HSRA, VALII, VALIII). However, Avrett (1985) has published results from a new model with a hot upper photosphere; the model itself has appeared very recently (Maltby et al. 1986, MACKKL model). It is shown in Fig. 5 together with the earlier models. The new model is similar in construction to the earlier VAL models. Its temperature-height relation was derived by fitting the observed continua with opacities computed from the statistical equilibrium and hydrostatic equilibrium equations taking full NLTE radiative transfer into account for all important opacity and electron sources. (The name of the computer code, PANDORA, seems aptly chosen).

The difference with the earlier models is that Kurucz's latest compilation with 17 million lines is used to predict the ultraviolet line blocking in a much more detailed manner than the opacity sampling functions employed before. The addition of all these lines results in increased effective ultraviolet opacity, thus in a higher height of formation of the emergent ultraviolet radiation. Fitting the observed ultraviolet brightness temperatures then requires a less steep temperature gradient, i.e. a hotter upper photosphere.

Avrett (1985) emphasizes that this new model unifies diverse diagnostics of the upper photosphere: the ultraviolet intensities, the spatially-averaged profiles of the inner wings of Ca II H and K, and the microwave continuum which shows the temperature minimum near 150 μm. They are all satisfactorily reproduced by the new model, in contrast to the VALII and VALIII models which predicted lower Ca II line-wing intensities than the empirical fit by Ayres and Linsky (1976) and lower microwave temperatures. The latter did agree with the older observations used in the VALII and VALIII modeling, but they are lower than the recent Swiss balloon data (Degiacomi et al. 1984). The computed ultraviolet intensities are about the same as before, and still fit the data already used by Lites (1972) to derive his ultraviolet radiation temperatures. The point of Avrett's addition of more line blocking is not that it results in lower ultraviolet intensities, but that the height of formation (photon escape) is now located higher in the atmosphere. This does affect the computed ultraviolet limb-darkening, which now agrees better with Samain's (1982) observations.

Thus, the difference with Lites' modeling is that J_ν departs from B_ν at about the same temperature but at larger height; the ultraviolet excess $J_\nu - B_\nu$ is therefore much smaller, and the iron excitation and ionization balances are much closer to LTE throughout the photosphere. The only remaining NLTE effect is the presence of photon losses in the most-probable lines at a given upper-level excitation energy. The only iron lines with NLTE source functions ($S_\nu^\ell < B_\nu$) in the photosphere are therefore the weak lines with large oscillator strengths at high excitation. All iron lines have LTE opacities throughout the photosphere. This holds for both Fe I and Fe II, and should hold also for H, Si, Mg, K, O and many other species that are sensitive to the ultraviolet radiation fields and that have NLTE imbalances when the HSRA is assumed.

With this new model Avrett more or less retrieves, proves and extends the LTE HOLMUL model. Fig. 5 shows that the photospheric parts of the MACKKL and HOLMUL models are quite similar. The combined assumptions of such a hot model, LTE opacities and LTE source functions therefore reproduce the optical lines and continua, the ultraviolet and infrared continua, and the Ca II line wings quite well. With enormous computational sophistication, plane-parallel modeling of the solar photosphere is back again to simple LTE!

One might conclude iron-ically that the whole NLTE issue has been a red herring, much ado about nothing, as far as photospheric line formation goes. I prefer to make two points instead. The first is that even if LTE modeling turns out to be not only an easy way out but in fact physically correct, the NLTE sophistication was necessary to prove it so. Obviously, LTE breaks down at some height in the atmosphere, and Avrett-like detailed modeling has to show where this breakdown occurs, in the photosphere or the chromosphere. In general, the only way a tractability assumption like LTE can be proven is by relaxing it and testing its validity in detail (see Rutten and Cram, 1981). The MACKKL model is clearly not the final truth yet, being empirical and having other tractability assumptions (like being plane-parallel with a specific microturbulence model).

Secondly, there is a hidden complexity. When taking all the ultraviolet blocking lines into account, it is necessary to specify both their height-dependent source functions and their height-dependent opacities. Initially, Avrett (private communication) assumed LTE for both, but when he found that these lines developed strong emission reversals in the chromosphere, he changed the line source functions by requiring them to follow a smooth transition between B_ν and J_ν in the upper photosphere, i.e. specifying them to become scattering lines with a source function without chromospheric rise, quite similar to the HOLMUL Planck function. The opacities are still added as derived from LTE. These two assumptions are ad-hoc and force a model fitted to the observed ultraviolet intensities at the computed height of formation to have a HOLMUL-like temperature-height relation. The upper photosphere is then quite hot, B_ν is close to J_ν, and the resulting Fe I and Fe II departures are small in the upper photosphere in agreement with the assumptions. The specified drop of S_ν below B_ν in the chromosphere is precisely what photon losses in strong lines should produce, and so the model is roughly self-consistent.

If on the contrary one would assume at the outset that the blocking lines behave as Fe I and Fe II lines (which constitute most of them) and that they follow the NLTE departure patterns shown in Fig. 3, then the opacities of the Fe I line cores would be smaller, resulting in deeper photon escape for the observed ultraviolet intensities, and the observed intensities would require corrections for Fe II excitation departures. A cooler model would result, and the large Fe I and Fe II NLTE departures predicted from it would agree with the assumed ones, again showing self-consistency.

In summary, the assumption of LTE or NLTE for the formation of the host of ultraviolet blocking lines is self-fulfilling: it results in empirical models which are respectively hot or cool, which produce the assumed line formation, and which reproduce the observations in either case. Just as with the optical iron lines, this is a dilemma that cannot be settled from the observed ultraviolet intensities although they are set by iron transitions. It is the new Swiss microwave data that really swing the balance to the MACKKL model, and therefore back to the classical LTE HOLMUL model, as the best representation of the solar photosphere within the constraints and assumptions of plane-parallel modeling.

3.3. RADIATIVE-EQUILIBRIUM MODELING

A third type of plane-parallel modeling is the one most often used in stellar physics: flux-constant modeling based on the assumptions of radiative equilibrium and LTE together. Solar examples are the solar controls of the model grids by Bell et al. (1976) and Kurucz (1979), and Kurucz's progress report in these proceedings.

Fig. 5 shows the Bell et al. (1976) solar model. It is close to the HOLMUL model in the upper photosphere but significantly cooler in deeper layers. Addition of yet more ultraviolet line-haze opacity may result in more backwarming and more and higher-located surface cooling, making it nearly identical to the HOLMUL model. It will therefore reproduce the observed optical iron lines assuming LTE quite well, just like the HOLMUL model.

The main difference with Avrett's modeling of the upper photosphere (the chromospheres are obviously different) is the latter's result that the optical H^- bound-free continuum has $J_\nu > B_\nu$ (Fig. 1) to such an extent that the total budget remains unbalanced, even for the new hot MACKKL model (Avrett 1985), thus requiring an unspecified energy sink. Although the empirical NLTE modeling and the radiative-equilibrium LTE modeling now produce about the same photosphere, the problem remains that a source of cooling rather than heating seems required just below the nonthermally heated chromosphere, at least in the context of plane-parallel modeling.

The main problem in radiative-equilibrium modeling is again to account for all the ultraviolet lines, and the problem of specifying their source functions and opacities arises again. Traditionally LTE is assumed for both in the construction of opacity distribution functions (e.g. Gustafsson et al. 1975, Kurucz 1979, Carbon 1979). Nordlund (1985b) has recently shown examples in which the line-haze source functions are changed from pure absorption to pure scattering. This results in a hotter upper photosphere because there is less surface cooling, just as if the ultraviolet lines were not present. The opacities of the haze lines are still assumed to be in LTE (Nordlund uses the term "scattering opacities" for opacity-binned averages over scattering source functions), but it is clear that departures from LTE in the ionization equilibria affect the location of the surface cooling and therefore affect the structuring of the upper layers, too.

4. IRON NLTE AND THE REAL SUN

4.1 GRANULATION

The real sun differs from the plane-parallel modeling discussed above in being highly inhomogeneous. The inhomogeneities are taken into account in the plane-parallel modeling by empirical adjustment of the micro- and macroturbulence parameters (often taken height-dependent and anisotropic as well) and also with collisional damping enhancement factors. Together these form a large set of ad-hoc fudge parameters. Although turbulence may be a reasonable description of motion fields as the 5-minute oscillation (which is certainly anisotropic), the scales of the latter are not well represented by the micro-macro separation (Carlsson and Scharmer 1985), and velocity broadening alone is clearly not a good physical description of the convective and magnetic small-scale structuring of the atmosphere (which are certainly height dependent).

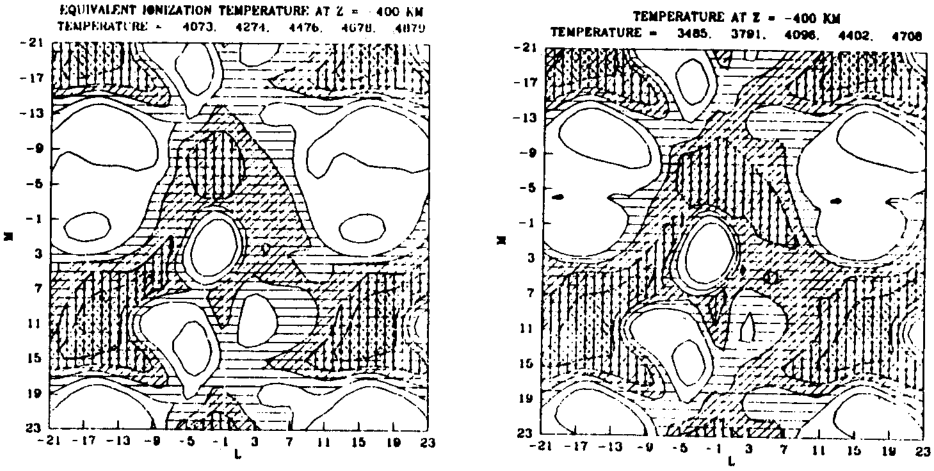

Fig. 6. A snapshot from Nordlund's numerical simulation of the solar granulation, taken from Nordlund (1984). The righthand panel shows the distribution of the electron temperature in a horizontal plane at a height of 400 km. The temperatures are shown as shaded contours defined on top. The lefthand panel shows the corresponding iron ionization temperature. It is much higher than the electron temperature where the latter is low, due to ultraviolet overionization.

The major source of inhomogeneity in the deep photosphere is the granulation. Nordlund (1984) has computed typical iron line formation from his extensive time-dependent theoretical simulation of the solar granulation. The spatial and temporal variations in his results are very large; the temperature variation is much larger than the difference between the hot and cold mean models discussed above. This implies that the concomitant small and large departures from LTE are actually present side by side all over the sun. Fig. 6 (taken from Nordlund 1984) illustrates this. The righthand panel is a snapshot of the kinetic temperature distribution in a horizontal plane. The lefthand panel is the corresponding iron ionization temperature (i.e. the temperature that reproduces the computed NLTE ionizaton fraction from the Saha equation, cf. eq. 3). Its variation is smaller but still large, and its average is much higher in agreement with the over-ionization in Lites' (1972) plane-parallel modeling.

The resulting iron line profiles vary spatially and temporally with very large amplitudes. Nevertheless, the averaged observed Fe I profiles are reproduced very well. The computed line cores are deeper than the profiles in the Jungfraujoch Atlas (Delbouille et al. 1973), but this can be due to the neglect of NLTE overexcitation. Nordlund (1985a) finds that overexcitation indeed occurs even for Fe I, in contrast to plane-parallel modeling. It is due to the extra absorption of continuum photons by Doppler-shifted atoms. Another difference with plane-parallel modeling is that the Fe II opacities are also out of LTE. Comparison of Figs. 6.1, 6.6 and 6.7 in Nordlund (1984) shows that Fe I would be the dominant ionization stage in large fractions of the upper photosphere if LTE were valid. The overionization there leads to large relative overabundance of iron ions.

It is important to note that Nordlund requires no microturbulence, no macroturbulence other than a small contribution by the 5-minute oscillation, and no damping enhancement factors to fit the iron lines, and that he used no free parameters in the simulation itself. His fits are the first reproductions of Fraunhofer lines without any free parameters other than the iron abundance; this is a remarkable achievement.

It is also important to note that Nordlund obtains a very small iron abundance (A_{12} = 7.18). While it is larger than the abundance he finds for LTE ionization (A_{12} = 7.00), it is much smaller than the standard LTE or NLTE plane-parallel result (A_{12} = 7.6, e.g. Allen 1976, Rutten and Van der Zalm 1984). This difference is due to the nonlinear averaging caused by the steep temperature sensitivity of the ionization equilibrium, which typically scales as T^{10} (Nordlund 1984, eq. 6.4 but with the ratio reversed). This result indicates that comprehensive modeling of the real atmosphere can lead to marked changes from standard plane-parallel modeling. Taking the sun as an example for stellar abundance determination in general, it leads to questioning the numerical results of much of the latter.

However, also in this dynamical modeling there is the issue of the formation of the ultraviolet line haze. Nordlund (1984) computed the NLTE iron ionization equilibria with line-haze opacities that were scaled to reproduce the observed radiation temperatures at the iron ionization edges assuming the height-dependence of the H^- opacity. For high-excitation Fe II lines this height-dependence is reasonable in the upper photosphere, but it fails for high-excitation Fe I lines if the ionization is thermal and it fails also deeper down and for low excitation lines (Rutten and Van der Zalm 1984, Fig. 3). Nordlund argues that these opacities are not dominated by the iron ionization but this may be incorrect in the near ultraviolet where Fe I contributes heavily to the line haze and its intermediate levels contribute strongly to ionization imbalances.

Another problem is that in the simulation itself LTE was assumed for both the opacities and the source functions in the opacity-binned line-haze distribution functions. The resulting spatially-averaged temperatures are similar to the HSRA, with a cool upper photosphere. Nordlund (1984) describes an experiment in which he obtains instead a HOLMUL-like hot mean upper photosphere by applying height-dependent opacity enhancement factors in the near ultraviolet that bring the computed source functions closer to J_ν. The factors are just the inverse of the Fe I departure coefficients of Fig. 3a, and can be interpreted as representing the effect of stronger line blocking. The resulting change in the height of escape of the near-ultraviolet radiation affects the granular dynamics and leads to a hotter mean. Nordlund has not computed iron ionization equilibria in this experiment, but a much higher iron abundance would clearly be required to fit the observed Fe I lines.

In another experiment, Nordlund (1985b) shows that assuming pure scattering for the line haze source functions leads to lower temperatures in the upper photosphere than when LTE source functions are adopted. This experiment illustrates a major difference between the dynamic modeling and the plane-parallel radiative-equilibrium modeling discussed above. The granules in the simulation penetrate very far into the upper photosphere, and provide expansion cooling which would be very large if they rose adiabatically, but which is offset by strong radiative heating in the line haze. This heating by optically thin lines contributes to the high penetration; without it, the granules would be cooler and denser, and stop sooner.

Thus, the iron ionization and excitation equilibria are closely coupled together with the inhomogeneous temperature structure of the upper photosphere, even more closely than in the plane-parallel modeling because of the steep temperature sensitivity of the ionization balance. It seems prudent not to worry too much about Nordlund's small iron abundance before the role of the line haze has been further clarified, including its NLTE departures.

4.2 FLUXTUBES AND BIFURCATIONS

The chromosphere seen in Ca II K filtergrams is highly inhomogeneous. Bright Ca II emission coincides with locations of much magnetic field (e.g. Zwaan 1981), and the question one faces for the upper photosphere is to which extent the magnetic fluxtubes affect spatially-averaged modeling.

Ayres has proposed and given evidence that the low chromosphere is bifurcated into two components, a hot one which shows up in Ca II emission and presumably consists of fluxtubes, and a cool one which consists of the plasma between the tubes and which shows up in the infrared CO lines (Ayres et al. 1986 and references therein). The latter lines would actually trigger the bifurcation by providing large energy sinks wherever the temperature drops below the CO dissociation limit. Since the fluxtubes expand with height (e.g. Spruit 1981), the hot tubes would cover a negligible fraction of the surface in the photosphere.

In such a scenario, the strong Fe II lines will predominantly come from the hot fluxtubes and the strongest Fe I lines from the cool chromosphere in between. An attractive possibility arises to explain the absence of bright emission cores in the Fe II resonance lines from fluxtube geometry. Such slender structures may well be optically thin in lateral directions for the many weaker lines that share upper levels with the resonance lines. Lateral photon losses in subordinate lines result in lower source functions and lower opacities for the Fe II resonance lines than for the Mg II and Ca II resonance lines, because the latter have far fewer subordinate lines and metastable levels (Mg II has none, and indeed appears hotter in the empirical modeling by Ayres and Linsky 1976). The subordinate lines would be seen in emission at the limb, with large spatial intensity variation.

Below the temperature minimum, the cool component of the modeling by Ayres et al. (1986) equals the hot MACKKL model, in order to reproduce the latter with a negligible fluxtube filling factor. Photospheric iron lines should thus be only marginally affected by fluxtubes, as indeed shown by Stenflo and Lindegren (1977), except for their polarization (Solanki and Stenflo 1984, 1985). Nevertheless, iron line formation can be important in the bifurcation itself because, again, the line haze may contribute to it. Nordlund (1985b) obtains a similar bifurcation into stable hot and cool states simply from adopting a scattering ultraviolet line haze in plane-parallel radiative-equilibrium modeling, without invoking fluxtubes. Just as in Ayres' empirical modeling, the cool equilibrium state is caused by CO cooling in the infrared, and appears quite high in the atmosphere, above the location of the temperature minimum in the standard models. Thus, the line haze strikes again, and the iron ionization equilibria may well influence this thermal bifurcation and its location.

5. CONCLUSION

Current interpretation of solar iron line formation is amazingly multifarious. The same optical lines are used as gauges of the granulation and, independently, as spatially-averaged diagnostics of fluxtubes. Their formation may be very close to LTE or very far from it. The photosphere may be in radiative equilibrium up to the temperature minimum, or quite far from it. The inhomogeneities may be so important that interpreting spatially-averaged data is of little value even for abundance determination, or so unimportant that the classical turbulent fudge parameters provide a satisfactory description. The aspect perhaps most amazing is that each of these conflicting descriptions produces good fits to the observed lines. Clearly, fitting observations doesn't guarantee validity of the assumptions.

There are three main avenues to clarify these dilemmas. First and foremost, it is important in all descriptions to account in detail for the ultraviolet line haze, the more so because it largely consists of iron lines. All modeling of photospheric radiative transfer, whether plane-parallel or time-dependent 3-D, now depends on Johansson and Kurucz for further specification of the haze lines. These will have to be put into the computer with binning schemes that permit location-dependent NLTE departures in both the radiation fields and the populations; an example is given by Anderson (1985). Such simplification schemes are required because combining full 3-D radiative transfer for thousands of frequencies with full hydrodynamics and hydromagnetics as well is computationally prohibitive, even with the new efficient radiative transfer codes (Carlsson, these proceedings).

Second, the infrared iron lines as well as the infrared and microwave continua can provide important diagnostics, especially when observed from the extreme solar limb.

Third, observations with high spatial, temporal and spectral resolution supplied by space instruments will permit detailed evaluation of the role of inhomogeneities.

Finally, I would like to conclude this review with a philosophical speculation. The apparent success of classical plane-parallel LTE modeling of the spatially-averaged solar spectrum is in utter contrast to the extraordinary complexity that solar physicists deem necessary to explain solar granulation, magnetic fluxtubes etc., including intricate details of NLTE line formation for thousands of iron lines. It seems as if the classical modeling is going to be as adequate a first-order description for the spatially-averaged solar spectrum as Newtonian theory is for gravitation and Maxwell theory for electrodynamics, even though the "real" Sun requires a much deeper level of understanding, as in general relativity and quantum electrodynamcis. This deeper understanding will be profoundly different from the simple approximation, not only in its degree of complexity but also conceptually, but nevertheless, the latter may suffice for many applications.

ACKNOWLEDGEMENT. I thank Roberto Viotti for permitting me to discuss solar Fe I as well as Fe II, the Leidsch Kerkhoven-Bosscha Fonds for a travel grant, Jo Bruls, Petr Heinzel and Han Uitenbroek for comments, and Evelyn Cockburn for typing this paper.

REFERENCES

Allen, C.W.: 1976, "Astrophysical Quantities", William Clowes & Sons, London

Anderson, L.S.: 1985, in "Progress in Stellar Spectral Line Formation Theory", J. Beckman and L. Crivellari (eds.), NATO Advanced Science Institutes Series, Reidel Publ. Co., Dordrecht, The Netherlands

Athay, R.G.: 1972, "Radiation Transport in Spectral Lines", Reidel Publ. Co., Dordrecht, The Netherlands

Athay, R.G., Lites, B.W.: 1972, Astrophys. J. 176, 809

Avrett, E.H.: 1985, in "Chromospheric Diagnostics and Modeling", B.W. Lites (ed.), National Solar Observatory Conference, Sacramento Peak, Sunspot, p. 67

Ayres, T.R., Linsky, J.L.: 1976, Astrophys. J. 205, 874

Ayres, T.R., Testerman, L., Brault, J.W.: 1986, Astrophys. J. 304, 542

Blackwell, D.E., Shallis, M.J., Simmons, G.J.: 1980, Astron. Astrophys. 81, 340

Blackwell, D.E., Petford, A.D., Shallis, M.J., Simmons, G.J.: 1982, Mon. Not. R. Astron. Soc. 199, 43

Blackwell, D.E., Booth, A.J., Petford, A.D.: 1984, Astron. Astrophys. 132, 236

Bell, R.A., Eriksson, K., Gustafsson, B., Nordlund, Å.: 1976, Astron. Astrophys. Suppl. 23, 37

Bowers, R., Deeming, T.: 1984, "Astrophysics I", Jones and Bartlett Publishers Inc., Boston

Canfield, R.C., Stencel, R.E.: 1976, Astrophys. J. 209, 618

Carbon, D.F.: 1979, Ann. Rev. Astron. Astrophys. 17, 513

Carlsson, M., Scharmer, G.B.: 1985, in "Chromospheric Diagnostics and Modeling" B.W. Lites (ed.), National Solar Observatory Conference, Sacramento Peak, Sunspot, New Mexico
Cram, L.E., Rutten, R.J., Lites, B.W.: 1980, Astrophys. J. 241, 374
Cowley, C.R.: 1970, "The Theory of Stellar Spectra", Gordon and Breach, New York
Degiacomi, K., Kneubühl, F.K., Huguenin, D., Müller, E.A.: 1984, Internat. J. Infrared Millimeter Waves, 5, 643
Delbouille, L., Roland, G., Neven, L.: 1973, "Photometric Atlas of the Solar Spectrum from λ 3000 to λ 10000", Institut d'Astrophysique, Liège
Dere, K.P., Bartoe, J.-D.F., Brueckner, G.E.: 1984, Astrophys. J. 281, 870
Van Dessel, E.L.: 1974, Solar Phys. 38, 351
Van Dessel, E.L.: 1975, Solar Phys. 44, 13
Dravins, D.: 1982, Ann. Rev. Astron. Astrophys. 20, 61
Dravins, D., Larsson, B.: 1984, in "Small-scale dynamical processes in quiet stellar atmospheres", S.L. Keil (ed.), National Solar Observatory Conference, Sacramento Peak, Sunspot, New Mexico, p. 306
Dravins, D., Lind, J.: 1984, in "Small-scale dynamical processes in quiet stellar atmospheres", S.L. Keil (ed.), National Solar Observatory Conference, Sacramento Peak, Sunspot, New Mexico, p. 414
Gingerich, O., Noyes, R.W., Kalkofen, W., Cuny, Y.: 1971, Solar Phys. 18, 347
Gustafsson, B., Bell, R.A., Eriksson, K., Nordlund Å.: 1975, Astron. Astrophys. 42, 407
Harvey, J.W.: 1973, Solar Phys. 28, 9
Holweger, H.: 1967, Zeitschr. f. Astrophysik 65, 365
Holweger, H.: 1973, Solar Phys. 30, 35
Holweger, H., Müller E.A.: 1974, Solar Phys. 39, 19
Holweger, H.: 1979, in "Les elements et leurs isotopes dans l'Univers", 22me Liège Colloquium, Université de Liège, Belgium
Ivanov, V.V.: 1973, "Transfer of Radiation in Spectral Lines", English Edition, National Bureau of Standards, Special Publication 385, U.S. Gov. Printing Office, Washington
Jefferies, J.T. 1968, "Spectral line formation", Blaisdell Publ. Co., Waltham, Mass.
Kurucz, R.L.: 1979, Astrophys. J. Suppl. 40, 1
Lites, B.W.: 1972, "Observations and Analysis of the Solar Neutral Iron Spectrum", NCAR Cooperative Thesis no. 28, University of Colorado, Boulder
Lites, B.W.: 1973, Solar Phys. 30, 283
Lites, B.W.: 1974, Astron. Astrophys. 33, 363
Lites, B.W., White, O.R.: 1973, High Altitude Research Memorandum no. 185, Boulder
Maltby, P., Avrett, E.H., Carlsson, M., Kjeldseth-Moe, O., Kurucz, R.L., Loeser, R.: 1986, Astrophys. J. 306, 284
Mathys, G. and Stenflo, J.O.: 1986, Astron. Astrophys., in press

Menzel, D.H., Cilliê, G.G., 1937: Astrophys. J. 85, 88
Mihalas, D.: 1970, "Stellar Atmospheres", 1st edition, Freeman and Co., San Francisco
Mihalas, D.: 1978, "Stellar Atmospheres", 2nd edition, Freeman and Co., San Francisco
Nordlund, Å.: 1984, in "Small-scale dynamical processes in quiet stellar atmospheres", S.L. Keil (ed), National Solar Observatory Conference, Sacramento Peak, Sunspot, New Mexico, p. 181
Nordlund, Å.: 1985a, in "Progress in Stellar Spectral Line Formation Theory", J.E. Beckman and L. Crivellari (eds.), NATO Advanced Science Institutes Series C 152, Reidel Publ. Co., Dordrecht, The Netherlands
Nordlund, Å.: 1985b, in "Theoretical Probelems in High-resolution Solar Physics", H.U. Schmidt (ed.), Proceedings of the MPA/LPARL Workshop 1985, Max-Planck-Institut für Astrophysik, München
Pierce, A.K.: 1968, Astrophys. J. Suppl. 17, 1
Rudkjøbing, M.: 1986, Astron. Astrophys. 160, 132
Rutten, R.J., Cram, L.E.: 1981, in "The Sun as a Star", S.D. Jordan (ed.), CNRS-NASA Monograph Series on Nonthermal Phenomena in Stellar Atmospheres, NASA SP-450, part IV.
Rutten, R.J., Kostik, R.I.: 1982, Astron. Astrophys. 115, 104
Rutten, R.J., Stencel, R.E.: 1980, Astron. Astrophys. Suppl. 39, 415
Rutten, R.J., Van der Zalm, E.B.J.: 1984, Astron. Astrophys. Suppl. 55, 143
Rutten, R.J., Zwaan, C.: 1983, Astron. Astrophys. 117, 21
Samain, D.: 1980, Astrophys. J. Suppl. 44, 273
Saxner, M.: 1984, "Some aspects of spectral lines in stellar atmospheres", thesis, Uppsala University
Sistla, G., Harvey, J.W.: 1970, Solar Phys. 12, 66
Solanki, S.K., Stenflo, J.O.: 1984, Astron. Astrophys. 140, 185
Solanki, S.K., Stenflo, J.O.: 1985, Astron. Astrophys. 148, 123
Spruit, H.C.: 1981, in "The Sun as a Star", S. Jordan (ed.), CNRS-NASA Monograph Series on Nonthermal Phenomena in Stellar Atmospheres, NASA-SP 450
Steenbock, W.: 1985, in "Cool stars with excesses of heavy elements" M. Jaschek, P.C. Keenan (eds.), Strasbourg Colloquium 1984, p. 231
Stenflo, J.O., Lindegren, L.: 1977, Astron. Astrophys. 59, 367
Thomas, R.N.: 1983, "Stellar Atmospheric Structural Patterns", NASA-CNRS Monograph Series on Non-thermal Phenomena in Stellar Atmospheres", NASA Special Publ. SP-471
Vernazza, J.E., Avrett, Loeser, R.: 1976: Astrophys. J. Suppl. 30, 1
Vernazza, J.E., Avrett, E.H., Loeser, R.: 1981, Astrophys. J. Suppl. 45, 350
Wijbenga, J.W., Zwaan, C.: 1972, Solar Phys. 23, 265
Zwaan, C.: 1981, in "The Sun as a Star", S.D. Jordan (ed.), CNRS-NASA Monograph Series on Nonthermal Phenomena in Stellar Atmospheres, NASA SP-450, p. 167
Zwaan, C., Brants, J.J., Cram, L.E.: 1985, Solar Phys. 95, 3