STRUCTURE OF THE SOLAR PHOTOSPHERE

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Abstract. The majority of measured solar abundances refer to the solar photosphere. In general, when determining photospheric abundances a plane-parallel atmosphere and LTE are assumed. However, the photosphere is structured by granulation, magnetic fields and p-modes. They change line profiles by the thermal inhomogeneities and wavelength shifts they introduce. A brief description of the first two of these phenomena is given and some of the ways in which they influence abundances are pointed out. Departures from LTE also occur. The magnitude of the errors introduced into elemental abundances by neglecting such departures is also briefly discussed.

Key words: Solar Abundances, Solar Granulation, Solar Magnetic Fields, Radiative Transfer

1. Introduction

The photosphere of the sun is a comparatively thin layer (by solar standards), being only a few hundred km thick. Nevertheless, it is the most massive layer of the directly observable parts of the sun and contains some of the coolest solar gas. The most striking characteristic of the photosphere, however, is that it encompasses the visible surface of the sun, i.e. it is the layer in which the visible (and large parts of the UV and IR) solar spectrum is formed.

The richness of the photospheric spectrum and the relative simplicity with which it can be modelled are mainly responsible for our knowledge of such a large number of photospheric elemental abundances. Indeed, the photosphere is the solar layer for which the largest number of elemental abundances is known, so that in many cases the term "solar abundance" is synonymous with "photospheric abundance". The current status of photospheric abundance determinations is reviewed by Grevesse and Sauval (1998).

The solar photosphere is also special in another respect. It is the layer for which we possess the most sensitive diagnostics of temperature, velocity and magnetic field. Once again, this is largely due to the richness of the visible solar spectrum and the relative simplicity of line-formation physics in this layer. This means that we can actually test the assumptions underlying the determination of photospheric abundances. The availability of relatively realistic simulations of photospheric features and processes is also a significant asset.

The most important assumptions about the sun made when deriving abundances are:

1. Neglect of NLTE effects (i.e., departures from thermodynamic equilibrium),
2. Neglect of the horizontal structure of the photosphere.

Space Science Reviews **85**: 175–186, 1998.

Further simplifications are the description of solar velocity fields in terms of micro- and macroturbulence and the use of fudge factors to enhance the Van der Waals damping of spectral lines.

The aim of the present paper is to illustrate the validity (or otherwise) of these assumptions on the basis of examples taken from the literature. In Sect. 2 the influence of NLTE is discussed (while remaining within the framework of plane-parallel atmospheres). In Sects. 3 and 4 the influence of convection and magnetism, respectively, is assessed under the assumption of LTE.

2. NLTE Effects

The influence of NLTE on photospheric spectral lines has been studied in greatest detail for iron, so that I mainly discuss its behaviour here. One of the basic ingredients of every photospheric abundance analysis is the model atmosphere employed. Not only does the derived abundance directly (i.e. even in LTE) depend on the choice of atmosphere, but, as shown by Rutten and Kostik (1982), Steenbock (1985) and Holweger (1988), the magnitude of NLTE effects is also dictated by the model atmosphere.

In this context the empirical photospheric models can be divided into three classes, examples of each of which are plotted in Fig. 1.

1. LTE-based models: The most prominent example of this type of model is that of Holweger and Müller (1974, abbreviated here as HOLMUL), which is based on the model of Holweger (1967). Such models have a gentle $T(z)$ gradient in the photosphere and no chromospheric temperature rise, since the temperature must continue to follow the approximate source function of the stronger lines. These models look very similar to the radiative equilibrium models of Bell et al. (1976), Anderson (1989), Kurucz (1992a,b), etc. NLTE effects in such LTE models are very small in the photospheric layers, i.e. LTE provides an excellent description of the spectral lines when such HOLMUL-like models are used together with LTE; an effect referred to as LTE masking by Rutten and Kostik (1982).
2. Old NLTE-based models: The HSRA (Gingerich *et al.*, 1971) and the VAL models (Vernazza *et al.*, 1976, 1981) belong to this type. They are distinguished by a larger temperature gradient in the photosphere and a cool temperature minimum. Such models produce large departures from LTE.
3. New NLTE-based models: This is basically the model presented by Avrett (1985), as well as its derivates the MACKKL (Maltby *et al.*, 1986) and FAL-C (Fontenla *et al.*, 1993). These models are characterized by a high minimum temperature and a photospheric temperature stratification which is very similar to that of the HOLMUL model. As with that model, photospheric NLTE effects are relatively unimportant.

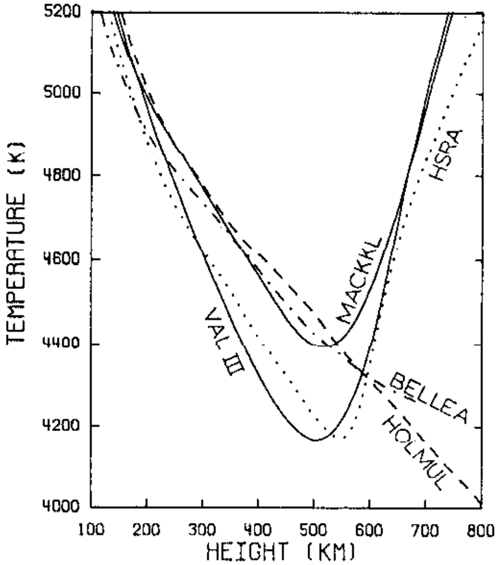

Figure 1. Temperature vs. height of 4 empirical and 1 radiative equilibrium model atmospheres. HOLMUL: Empirical, LTE-based model of Holweger and Müller (1974), HSRA: Empirical, NLTE-based model by Gingerich et al. (1971), VAL III: similar model by Vernazza et al. (1981), MACKKL: newer NLTE-based model due to Maltby et al. (1986), BELLEA: LTE-based radiative equilibrium model of Bell et al. (1976). Figure from Rutten (1988) by permission.

The residual NLTE effects for FE I and II (for the HOLMUL atmosphere) are plotted in Fig. 2. Note that for almost all lines the logarithmic abundance correction

$$\Delta \log \epsilon = \log \epsilon_{\rm NLTE} - \log \epsilon_{\rm LTE} < 0.05 \ ,$$

where ϵ is the derived elemental abundance relative to hydrogen. Departures of this magnitude are only exhibited by low excitation Fe I lines. For the majority ion, Fe II, $\Delta \log \epsilon < 0.005$ and is thus completely negligible.

In summary: Abundance determinations based on photospheric and 1-D models are only little affected by neglecting departures from LTE, if the plane-parallel assumption is correct.

3. Structuring the Photosphere: Convection

3.1. PROPERTIES OF SOLAR GRANULATION

Convection cells of different sizes are observed in the solar photosphere. They are generally divided into 3 classes. The smallest, the granules, are typically 1500 km

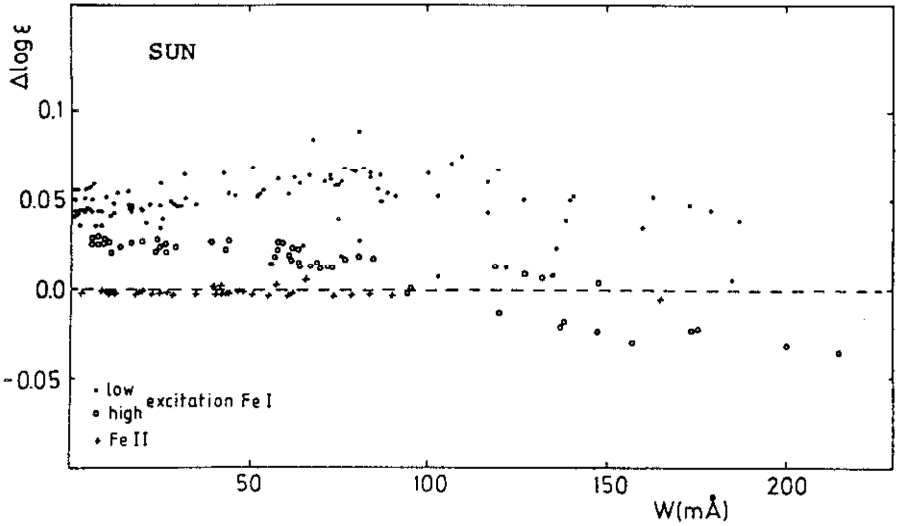

Figure 2. NLTE abundance correction $\Delta \log \epsilon = \log \epsilon_{\text{NLTE}} - \log \epsilon_{\text{LTE}}$ for Fe I and Fe II lines plotted vs. equivalent width (W_λ) for the HOLMUL model atmosphere. Each symbol represents a spectral line. Lines with different excitations or belonging to different ionization stages are distinguished by different types of symbols (from Holweger, 1988, by permission).

across, mesogranules are roughly 7000 km, while supergranules possess diameters of 20000–30000 km. There is, as for any highly dynamic fluid phenomenon, a large scatter around these values. As far as their influence on abundances is concerned granules are the most important and the further discussion is restricted to them.

Granules have mean lifetimes of 6–8 minutes, rms vertical velocities on the order of 1 km/s and horizontal rms velocities that are somewhat larger. Peak velocities are considerably larger and there is evidence for supersonic horizontal flows. Granulation is clearly visible in continuum images, exhibiting contrasts $(\delta I/I)_{\text{rms}}$ in the visible that can exceed 10% in the best images (here I is the intensity). Note that the contrast value is a strong function of spatial resolution and wavelength. Granulation also possesses a distinctive surface topology, being composed of isolated, bright granules, that correlate with upflows, and multiply connected, dark intergranular lanes, correlating with downflows. The narrow lanes cover a smaller part of the solar surface than the broad granules. The downflow velocities are also correspondingly higher than the upflows.

These and further observed properties of granulation are reviewed by Muller (1989), Title *et al.* (1990), Karpinsky (1990) and Spruit *et al.* (1990). References to the vast literature on observations of solar granulation may be found therein.

There is also a growing body of work on granule simulations, i.e. time-dependent solutions of the radiation-hydrodynamic equations on a two- or three-dimensional spatial grid. Modern 2-D (Steffen, 1990; Steffen and Freytag, 1991;

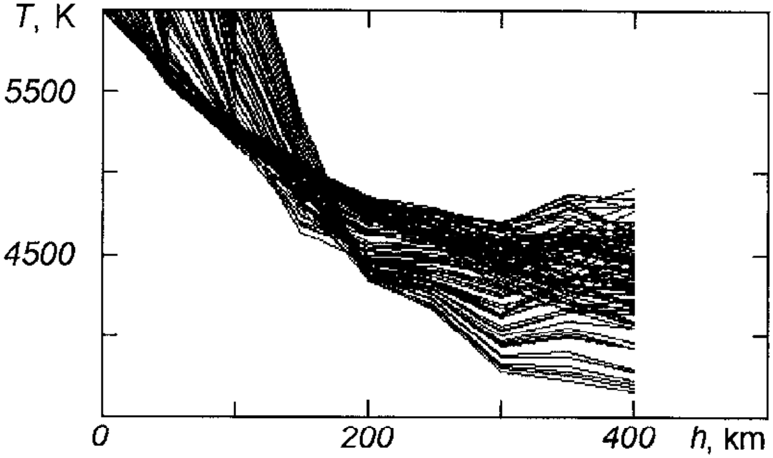

Figure 3. Temperature stratification (T vs. height h) along vertical rays passing through a 3-D simulation of granular convection. Note the large scatter. A careful inspection reveals a systematic correlation between the temperature in the lower photosphere and the temperature gradient (adapted from Atroshchenko and Gadun, 1994; figure kindly provided by A. Gadun).

Gadun *et al.*, 1997, 1998; Solanki *et al.*, 1996a) and in particular 3-D simulations (Nordlund, 1984, 1985; Stein and Nordlund, 1989; Lites *et al.*, 1989; Malagoli *et al.*, 1990; Atroshchenko and Gadun, 1994; Rast, 1995) reproduce a large number of observations, often with considerable quantitative accuracy. The remaining differences between the best simulations and the observations are partly caused by the need to introduce a numerical viscosity into the simulations and the consequently limited Reynolds numbers, but in part are also due to uncertainties in the magnitude and exact form of spatial distortions produced by the Earth's atmosphere.

3.2. GRANULATION AND CONVECTION

The main diagnostic of elemental abundances is spectral line equivalent width. The equivalent width is also strongly dependent on the temperature stratification and, to a lesser degree, on velocity.

Consider first the temperature. Figure 3 shows $T(z)$ at different horizontal positions of a set of the 3-D simulations of Atroshchenko and Gadun (1994). The scatter in temperatures is greater than 500 K in both the upper and lower photosphere. The 3-D models of Nordlund (1985) exhibit an even larger scatter (over 1000 K in the upper photosphere). Such a difference in temperature non-linearly affects line strengths of minor-ion lines (such as those of Fe I).

It is not just this scatter that is important, but also the correlation between the temperature near the continuum-forming layer (i.e. $h \approx 0$ in the figure) and the temperature gradient. Although perhaps not so well visible in the figure, regions that are hot in the lower layers are cooler in the upper layers (cf. Stein and Nordlund, 1989), in qualitative agreement with the observations, although these also indicate the importance of wave motions in determining the structure of the upper photosphere (e.g., Komm *et al.*, 1990).

This structure implies, however, that spectral lines are particularly deep over granules and particularly shallow over intergranular lanes. Since this dependence on temperature stratification is non-linear it is unlikely that the average of the profiles resulting from the individual atmospheres possesses the same W_λ as the profile resulting from the averaged atmosphere.

The influence of granulation on Fe abundances has been studied by Nordlund (1984) and Gadun and Pavlenko (1998) and on Li by Kiselman (1997), Uitenbroek (1998) and Gadun and Pavlenko (1998). The spate of work on Li followed an initial suggestion by Kurucz (1995) that convection could falsify the Li abundance by up to an order of magnitude.

The detailed calculations of Uitenbroek (2-D NLTE radiative transfer), Kiselman (1.5-D NLTE) and Gadun and Pavlenko (1.5-D LTE) showed that these fears are unfounded for the solar case. Of interest is the difference in A, the logarithmic abundance relative to hydrogen, between the multi-dimensional and the 1-D case. In the former case the radiative transfer is carried out along multiple rays passing through the simulation and the emerging profiles are then averaged. This average profile is compared with the observations (which have low spatial and temporal, but high spectral resolution and high S/N ratio). In the latter case in principle a plane-parallel reference model (e.g. HOLMUL) can be used, but in order to isolate the influence of spatial inhomogeneities it is better to use an atmosphere constructed by forming a horizontal average of the temperature stratifications of the granulation simulation. The average $T(\tau)$ looks rather similar to HOLMUL or RE models, although the seemingly small differences have a significant effect (see below).

For Li the abundance derived from 2-D and 3-D models relative to the plane-parallel case differs by 0.1–0.2 dex (Gadun and Pavlenko, 1998) and by 0.1 dex or less (Kiselman, 1997; Uitenbroek, 1998).

In the case of iron the difference is also small: 0.1 dex for Fe I and only 0.05 dex for Fe II (Gadun and Pavlenko, 1998). Earlier, Nordlund (1984) found a greater difference (0.3–0.4 dex), but ascribed that to shortcomings in his old, incompressible models. Gadun and Pavlenko (1997) did find an additional and more disturbing deviation from the HOLMUL results, however. Whereas for HOLMUL A(Fe II) = A(Fe I) the simulations imply a difference between the abundance derived from the two ions: A(Fe II) = A(Fe I) + 0.3.

The reason for this discrepancy is unclear. Due to the sensitivity of NLTE on the detailed temperature stratification, it is conceivable that NLTE effects need to be taken into account when using 2-D simulations to determine abundances. On the other hand, this discrepancy may be an artifact caused by (on average) somewhat incorrect temperature gradients in the granulation simulations due to a not sufficiently exact description of the UV radiation field (the opacities of Kurucz, 1979, are used, which do not yet include sufficient lines in the UV).

An empirical approach was taken by Kiselman (1994), who considered the variation of spectral line parameters across granules. He also concluded that the influence of convection on abundances should be small (cf. Holweger *et al.*, 1990).

Granular velocity fields also influence line profiles. Traditionally, spectral lines have been broadened using a mixture of micro- and macroturbulence. In reality, convective and wave-like or oscillatory motions dominate the solar velocity field; the former in the lower and mid photosphere, the latter in the higher layers. Note that in the above investigations these motions were consistently taken into account. They have strong horizontal and vertical gradients. The former is clearly visible in the wiggly line shapes along the slit in high resolution spectra. The latter can be deduced from line asymmetries in line profiles observed with high spatial resolution; e.g., Bonnacini (1989, see his Fig. 6). As illustrated by Fig. 4 the sum of these motions broadens the line profile sufficiently to match the observations without requiring additional micro- and macroturbulence (e.g., Nordlund, 1984; Lites *et al.*, 1989; Steffen and Freytag, 1991; Gadun *et al.*, 1998). Note that at disc centre horizontal gradients of the velocity produce no change in W_λ, i.e. to first order act like macroturbulence, while vertical gradients produce an enhancement of W_λ, i.e. act like microturbulence. The mixture of vertical and horizontal gradient, however, need not have the same influence on W_λ as the mixture of micro- and macroturbulence used to reproduce the line profile shape. Hence the velocity structure also affects the derived abundances, although the influence is expected to be smaller than of the thermal inhomogeneities (at least for not too strong spectral lines).

Finally, the wings of strong lines appear to be enhanced by granulation (Bruls and Rutten, 1992), which may provide an alternative to the generally used fudge-factors to the Van der Waals damping constants. How far this has an effect on the abundance is unclear, although the too strong wings produced by the simulations (Bruls and Rutten, 1992) might point to the need for lower abundances of the elements in question (Na and K), or alternatively to shortcomings of the simulations, although Stuik *et al.* (1997) question such a need.

4. Structuring the Photosphere: Magnetism

The main structuring agent of the solar photosphere besides convection is the magnetic field. Magnetic features range from the smallest magnetic elements (estimated diameters of approximately 50 km) to sunspots (diameters of up to 50000 km). Over the 6 orders of magnitude of flux per magnetic feature thus spanned the intrinsic field strength in the lower photospheric layers remains remarkably constant, lying between 1000 and 2000 G (averaged over the magnetic feature). A simulated magnetic element is illustrated in Fig. 5 (Steiner *et al.*, 1996). Due to the requirement of horizontal force balance (which for smaller magnetic features is basically horizontal pressure balance) and exponential decrease of gas pressure with height

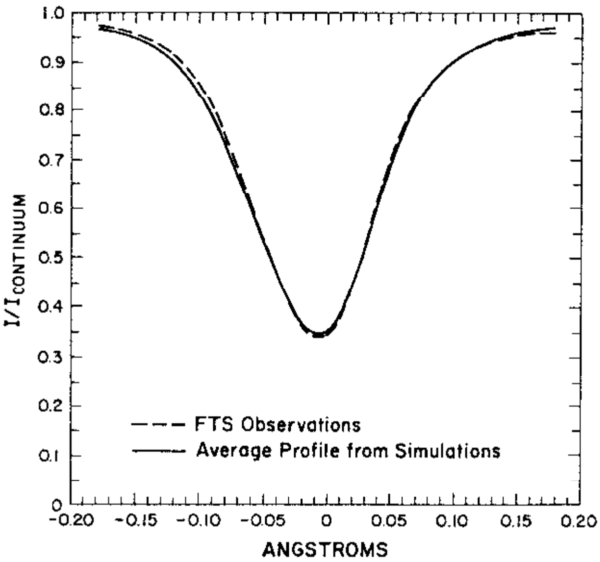

Figure 4. Spatially and temporally averaged profile of Fe I 630.25 nm observed at solar disc centre with an Fourier transform spectrometer (dashed curve) and synthesized from 3-D granular simulations (solid curve). Note the similarity between the two profiles (from Lites *et al.*, 1989, by permission).

the field strength also decreases rapidly with height. Magnetic flux conservation then requires that the magnetic field flares out with height.

Thus, although magnetic features cover at the most 1% of the solar surface in the lower photosphere they fill ever larger portions of the atmosphere with increasing height. In and above the middle-chromosphere the field occupies all available space.

In contrast to the field strength the thermal structure of magnetic features depends strongly on their size. Magnetic elements are brighter than the quiet sun, while sunspots are darker. The properties of magnetic elements and sunspots are reviewed in greater detail by Stenflo (1989), Spruit *et al.* (1990), Solanki (1993) and Schüssler (1993).

Sunspots are clearly visible and can be easily avoided when observing. Consequently, they mainly play a role for abundance determinations when molecular species provide the most reliable abundances (but see, e.g., Ritzenhoff *et al.*, 1997, who determine the Li abundance from atomic lines in sunspot spectra). Magnetic elements, on the other hand, are distributed all over the sun, including the quiet sun (at the supergranule boundaries). In the middle and upper layers of the photosphere they are considerably hotter than the average quiet sun (see Fig. 6), which leads to a considerable weakening of spectral lines, in particular of minor ions. If the enhanced temperature is not taken into account it can lead to over a factor of

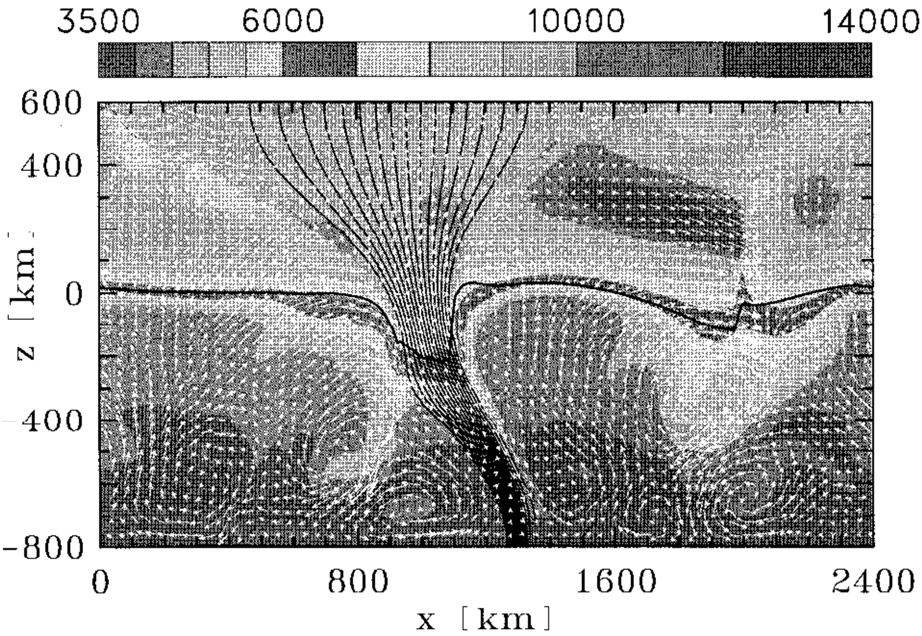

Figure 5. Snapshot of a 2-D simulation of a magnetic element (magnetic flux slab) lasting over a total period of 18.5 minutes real time. The nearly vertical solid lines near the centre of the frame are representative field lines (note their spreading with height). The thick nearly horizontal black curve marks unit continuum optical depth ($\tau_{5000} = 1$) for vertically incident lines of sight. The arrows indicate the strength and direction of the flow field, while the double grey scales indicate the temperature according to the bar at the top of the figure (from Steiner *et al.*, 1996, by permission).

2 error in the elemental abundance within the magnetic element. However, since outside active regions magnetic elements cover only 1% of the surface they have no practical implications for photospheric abundances.*

In addition to the highly visible kG fields discussed above, there is at least as much magnetic flux in weak fields, i.e. those with intrinsic field strengths of a few G to a few hundred G (Faurobert-Scholl *et al.*, 1995; Solanki *et al.*, 1996b; Meunier *et al.*, 1998). Only recently have new observing techniques made these fields amenable to study.

Due to their intrinsic weakness they cover a much larger portion of the solar surface than magnetic elements. Could they significantly affect abundance determinations?

Unfortunately, the thermal structure of these weak fields is unknown. However, theoretical arguments indicate that the temperature is not very different from that of

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* Velocities and in particular magnetic fields have a far smaller effect even than the temperature. Thus for most studies of the quiet sun it is much more important to select spectral lines according to their temperature sensitivity rather than to follow the common practice of choosing $g = 0$ lines in order to avoid undue influencing by magnetic features.

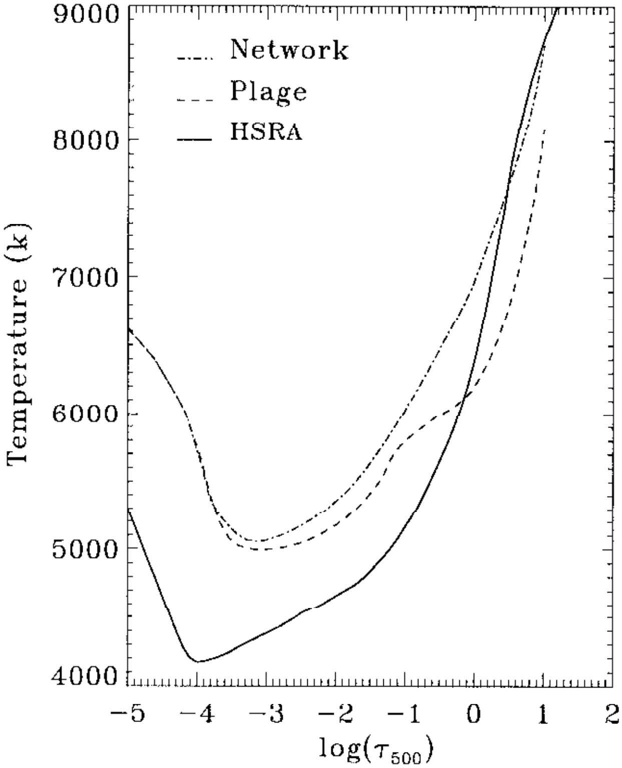

Figure 6. Temperature vs. logarithmic continuum optical depth ($\log \tau_{5000}$) of 3 empirical model atmospheres. Solid curve: Quiet sun model HSRA, dashed curve: model describing the magnetic elements found in active region plage, dot-dashed curve: magnetic elements forming the network (from Briand and Solanki, 1995).

the surrounding gas. Hence they probably play a smaller role than the granulation in affecting abundance determinations.

Can we therefore completely forget magnetic features when considering solar abundances? Although this may well be true it appears somewhat premature to draw this conclusion in its full generality. Recall that although magnetic elements cover less than 1% of the solar surface, their magnetic fields fill much of the chromosphere and all the corona and heliosphere. Hence the gas in which First Ionisation Potential (FIP) fractionation takes place (see Geiss, 1998; von Steiger, 1998) is connected to the magnetic features and not to the bulk of the photospheric material to which the photospheric abundances apply. In principle it is possible that abundances in magnetic elements are considerably different form those in the "field free" photosphere (e.g., photospheric magnetic elements could exhibit the FIP effect), without this being noticed, since no rigorous abundance determinations have been carried out so far. Although it appears unlikely on theoretical grounds, abundances in the photospheric layers of magnetic elements do provide a boundary condition for FIP theories and should be determined.

Acknowledgements

This paper is dedicated to H. Holweger, who has devoted a large part of his life to the topics covered here and who has been right more often than he admits. C. Briand, A. Gadun, R. Rutten, M. Schüssler and O. Steiner kindly provided original figures.

References

Anderson, L.S.: 1989, *Astrophys. J.* **339**, 558.

Avrett, E.H.: 1985, in *Chromospheric Diagnostics and Modelling*, B.W. Lites (Ed.), National Solar Obs., Sunspot, NM, p. 67.

Atroshchenko, I.N. and Gadun, A.S.: 1994, *Astron. Astrophys.* **291**, 635.

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

Bonnacini, D.: 1989, in *High Spatial Resolution Solar Observations*, O. von der Lühe (Ed.), National Solar Observatory, Sunspot, NM, p. 241.

Briand, C. and Solanki, S.K.: 1995, *Astron. Astrophys.* **299**, 596.

Bruls, J.H.M.J. and Rutten, R.J.: 1992, *Astron. Astrophys.* **265**, 257.

Faurobert-Scholl, M., Feautrier, N., Machefert, F., Petrovay, K., and Spielfiedel, A.: 1995, *Astron. Astrophys.* **298**, 289.

Fontenla, J.M., Avrett, E.H., and Loeser, R.: 1993, *Astrophys. J.* **406**, 319.

Gadun, A. and Pavlenko, YA. V.: 1997, *Astron. Astrophys.* **324**, 281.

Gadun, A.S., Hanslmeier, A., and Pikalov, K.N.: 1997, *Astron. Astrophys.* **320**, 1001.

Gadun, A., Solanki, S.K., and Johannesson, A.: 1998, *Astron. Astrophys.* , submitted.

Geiss, J.: 1998, *Space Sci. Rev.*, this volume.

Grevesse, N., and Sauval, A.J.: 1998, *Space Sci. Rev.*, this volume.

Holweger, H.: 1967, *Z. Astrophys.* **65**, 365.

Holweger, H.: 1988, in *The Impact of Very High S/N Spectroscopy on Stellar Physics*, G. Cayrel de Strobel, M. Spite (Eds.), Kluwer, Dordrecht *IAU Symp.* **132**, 411.

Holweger, H. and Müller, E.A.: 1974, *Solar Phys.* **39**, 19.

Holweger, H., Heise, C., and Kock, M.: 1990, *Astron. Astrophys.* **232**, 510.

Karpinsky, V.N.: 1990, in *Solar Photosphere: Structure, Convection and Magnetic Fields*, J.O. Stenflo (Ed.), *IAU Symp.* **138**, 67.

Kiselman, D.: 1994, *Astron. Astrophys. Suppl. Ser.* **104**, 23.

Kiselman, D.: 1997, *Astrophys. J.* **489**, L107,

Komm, R., Mattig, W., and Nesis, A.: 1990, *Astron. Astrophys.* **239**, 340.

Kurucz, R.L.: 1991, in *Precision Photometry: Astrophysics of the Galaxy*, A.G. Davis Philip, A.R. Upgren, K.A. Janes (Eds.), L. Davis Press, Schenectady.

Kurucz, R.L.: 1992, *Rev. Mexicana Astron. Astrof.* **23**, 181.

Kurucz, R.L.: 1995, *Astrophys. J.* **452**, 102.

Lites, B.W., Nordlund, Å., and Scharmer, G.B.: 1989, in *Solar and Stellar Granulation*, R.J. Rutten, G. Severino (Eds.), Reidel, Dordrecht, p. 349.

Malagoli, A., Cattaneo, F., and Brumell, N.H.: 1990, *Astrophys. J.* **361**, L33.

Maltby, P., *et al.*: 1986, *Astrophys. J.* **306**, 284.

Meunier, N., Solanki, S.K., and Livingston, W.C.: 1998, *Astron. Astrophys.* **331**, 771.

Muller, R.: 1989, in *Solar and Stellar Granulation*, R.J. Rutten, G. Severino (Eds.), Reidel, Dordrecht, p. 101.

Nordlund, Å.: 1984, in *Small–Scale Dynamical Processes in Quiet Stellar Atmospheres*, S.L. Keil (Ed.), National Solar Obs., Sunspot, NM, p. 181.

Nordlund, Å.: 1985, in *Theoretical Problems in High Resolution Solar Physics*, H.U. Schmidt (Ed.), Max-Planck-Inst. f. Astrophys., Munich, p. 1.

Rast, M.P., Nordlund, Å., Stein, R.F., and Toomre, J.: 1993, *Astrophys. J.* **408**, L53.

Rast, M.P.: 1995, *Astrophys. J.* **443**, 863.

Ritzenhoff, S., Schroter, E. H., and Schmidt, W.: 1997, *Astron. Astrophys.* **328**, 695.

Rutten, R.J.: 1988, in *Physics of Formation of Fe II Lines Outside LTE*, R. Viotti (Ed.), Reidel, Dordrecht *IAU Coll.* **94**, 185.

Rutten, R.J. and Kostik, R.I.: 1982, *Astron. Astrophys.* **115**, 104.

Schüssler, M.: 1992, in *The Sun — a Laboratory for Astrophysics*, J.T. Schmelz, J.C. Brown (Eds.), Kluwer, Dordrecht, p. 191.

Solanki, S.K.: 1993, *Space Science Rev.* 61, 1.

Solanki, S.K., Rüedi, I., Bianda, M., and Steffen, M.: 1996a, *Astron. Astrophys.* **308**, 623.

Solanki, S.K., Zuffrey, D., Lin, H., Rüedi, I., and Kuhn, J.: 1996b, *Astron. Astrophys.* **310**, L33.

Spruit, H.C., Nordlund, Å., and Title, A.M.: 1990, *Ann. Rev. Astron. Astrophys.* **28**, 263.

Spruit, H.C., Schüssler, M., and Solanki, S.K.: 1992, in *Solar Interior and Atmosphere*, A.N. Cox *et al.* (Eds.), University of Arizona press, Tucson, AZ, p. 890.

Steenbock, W.: 1985, in *Cool Stars with Excesses of Heavy Elements*, M. Jaschek, P.C. Keenan (Eds.), Reidel, Dordrecht, p. 231.

Steffen, M.: 1991, in *Stellar Atmospheres: Beyond Classical Models*, L. Crivellari *et al.* (Eds.), Kluwer, Dordrecht, p. 247.

Steffen, M. and Freytag, B.: 1991, *Rev. Mod. Astron.* **4**, 43.

Stein, R.F. and Nordlund Å.: 1989, *Astrophys. J.* **342**, L95.

Steiner, O., Grossmann-Doerth, U., Knölker, M., and Schüssler, M.: 1996, *Solar Phys.* **164**, 223.

Stenflo, J.O.: 1989, *Astron. Astrophys. Rev.* **1**, 3.

Stuik R., Bruls J.H.M.J., Rutten R.J., 1997, *Astron. Astrophys.* **322** 911

Title, A.M., *et al.*: 1990, in *Solar Photosphere: Structure, Convection, Magnetic Fields*, J.O. Stenflo (Ed.), Kluwer, Dordrecht *IAU Symp.* **138**, 49.

Vernazza, J.E., Avrett, E.H., and Loeser, R.: 1976, *Astrophys. J. Suppl. Ser.* **30**, 1.

Vernazza, J.E., Avrett, E.H., and Loeser, R.: 1981, *Astrophys. J. Suppl. Ser.* **45**, 635.

von Steiger, R.: 1998, *Space Sci. Rev.*, this volume.