ABSTRACT

We address the sensitivity of the Ni I 676.78 nm GONG line and the K I 769.9 nm resonance line to the temperature fluctuations present in the solar granulation. The temperature contrasts due to granulation are probably small in the upper photosphere where the cores of these two helioseismology lines are formed. However, the cores are sensitive also to the granulation temperature contrasts in the deep photosphere, through non-local NLTE effects in their formation. The largest effects are due to the ultraviolet radiation field, which is strongly modulated by the granulation in the deep layers where it escapes and carries these contrasts upwards to the line formation height. We discuss the resulting NLTE mechanisms and their influence on the two lines.

Keywords: Helioseismology, NLTE Line Formation, Solar Photosphere, Granulation, Ni I Lines, K I Lines, Fe I lines.

1. INTRODUCTION

A matter of concern in the helioseismological use of solar Fraunhofer lines is to what extent they are influenced by solar noise from other dynamic phenomena than oscillations. A prime source of noise is the solar granulation. We discuss the sensitivity of Fraunhofer lines to the temperature fluctuations imposed on the solar photosphere by the granulation, concentrating on the GONG Ni I 676.78 nm line and the K I 769.9 nm resonance line.

The reason to study temperature variations specifically is that these have a large influence on the emergent continuous radiation field, which through its non-local nature may affect line formation in unexpected manners.

We have performed detailed NLTE syntheses for granular models, respectively for the K I line at Naples and for the Ni I line at Utrecht. In both cases, model atoms of sufficient detail were constructed and used as input to the Carlsson (1986) NLTE radiative transfer code (which implements the particularly efficient method of Scharmer and Carlsson 1985), for different components of a granulation model taken from the literature. The effects that we find in this "1.5-D"-type computation are indicative of what happens with these lines above real granules and real intergranular lanes.

In this contribution we skip the details of the computations, which will be published elsewhere. Instead, we employ the results to provide a general explanation of the NLTE effects that may be expected in helioseismology lines.

2. GRANULATION MODELS

A first issue is to which height the granulation actually penetrates. Nordlund's well-known anelastic simulation (*e.g.* Nordlund 1984, 1985b) predicts that the contrast between granules and intergranular lanes remains very large all the way up to the upper photosphere (righthand panel of Figure 1). Nordlund explains this high penetration as due to the large amount of radiative heating that the rising granules undergo by absorbing ultraviolet photons from below, in the numerous iron lines that together make up the socalled line haze (see also Rutten 1988). In contrast, Steffen's 2-D simulation (see Steffen and Muchmore 1988) produces granules of which the temperature contrast quickly vanishes with height, and even reverses in the middle photosphere (lefthand panel of Figure 1). Observations indicate that this reversal indeed exists (Evans and Catalano 1972, Suemoto *et al.* 1987, Holweger and Kneer, in press), and therefore that this description may be closer to reality for upper photosphere than Nordlund's results, although the latter are based on a more sophisticated treatment of the radiative heating than the grey approximation used by Steffen.

We discuss experiments here for granules that vanish quickly with height, like Steffen's. We do this because this type of granule most clearly demonstrates the non-local effects that we describe below. These effects exist for Nordlund-type granules as well, but then act in addition to the large temperature contrast already locally present. It is more illustrative to show that granules affect lines formed in the middle and upper photosphere even if no granule persists to that height.

3. NLTE EFFECTS

There are three specific NLTE effects to be explained in this context. All three have to do with the differences between the mean continuous intensity J_ν and the Planck function B_ν as shown in Figure 2 for a standard model atmosphere. (They are shown in the form of radiation temperatures rather than energies in order to have a single curve for B_ν at the three wavelengths.) The height of escape at the three wavelengths shown is about the same, and the surface value of J_ν is therefore similarly set by $J_\nu \approx 0.3 B_\nu(\tau_\nu = 1)$ at the same geometrical depth for the three wavelengths. However, the changes in the temperature sensitivity of the Planck function throughout the spectrum cause J_ν to exceed B_ν appreciably in the upper photosphere in the blue and ultraviolet, while $J_\nu < B_\nu$ at longer wavelengths. Thus, radiative bb and bf transitions that use 300–400 nm photons (corresponding to 4–3 eV transitions) can feed on a strong NLTE radiation field in the upper photosphere, whereas NLTE imbalances can also occur for transitions of 1.5 eV or less from insufficient photoexcitation and photoionization. In the first case, overpopulation of the upper state follows; in the second case, overpopulation of the lower state.

The first NLTE effect discussed here is that of ultraviolet overionization, which typically occurs for minority species with sufficient atoms in levels that are about 4 eV from the continuum. (It is not important for majority species, because ionization imbalances do not affect their overall populations unless the balance is completely upset.) Ultraviolet overionization has been extensively studied for the case of Fe I (Lites 1972, Rutten and Kostik 1982, Nordlund 1984; see also Rutten 1988). Figure 3 contains a simplified Fe I Grotrian diagram which demonstrates that there are numerous levels from which ultraviolet overionization can take place. As a result, Fe I is appreciably underpopulated in the upper photosphere wherever there is a strong ultraviolet radiation field.

The second NLTE effect is that of ultraviolet overexcitation of lines near 300 nm. Such pumping has been studied mainly for Fe II (Cram *et al.* 1980, Watanabe and Steenbock 1986). Overpopulations of the upper levels of 300 nm lines (which are typically resonance lines in neutral and singly ionized metals) can lead to large effects in the source functions of lines at longer wavelengths that share upper levels with these pumping lines. The source function changes are large at longer wavelengths because there the fractional change of a line source function as specified by the upper level population departure is much larger when measured in terms of the local temperature sensitivity of the Planck function (see Rutten 1988, p. 196). For example, pumped long-wavelength lines may turn into emission while the ultraviolet pumping line itself remains in absorption.

The third NLTE effect is that of overrecombination at long wavelengths. This can be important for those minority species that have well-populated levels at about 1 eV from the continuum. The photoionization from such levels is insufficient to balance the LTE recombination because of the $J_\nu - B_\nu$ deficit shown in Figure 2.

How do these NLTE processes depend on the solar granulation? A granule is (in any model) considerably hotter in the deep photosphere than the intergranular lanes are. Therefore, ultraviolet overionization and overexcitation are enhanced above a granule by the extra-hot radiation from below. Pumping phenomena are also enhanced. Red and infrared overrecombination occur less than for the averaged atmosphere, however. Above an intergranular lane, the three effects are reversed.

4. NLTE EFFECTS FOR Fe I

Figures 3–5 show Grotrian diagrams for Fe I, Ni I and K I. Their vertical scales are identical to enable comparison. The Fe I diagram is the simplified basic diagram of Lites (1972), while the Ni I and K I diagrams are reasonably complete.

The Fe I diagram is given here as a reference. An extensive and illuminating discussion of Fe I line formation within the solar granulation has been presented by Nordlund (1984, 1985a). In summary, the line opacities are sensitive to the ionization equilibrium. Since this depends sensitively on the ultraviolet radiation field coming from below, the line opacities vary across granules with the temperature in deeper layers. Thus, Fe I is strongly affected by NLTE effect 1 above.

In addition, one may expect pumping to take place, for example in the 1–14–3 and 1–15–3 triangles of Figure 1. Such phenomena have not been studied yet. However, since there are many more levels and lines present in Fe I than shown in Figure 3, pumped overpopulations may well be washed out by collisional redistribution over neighbouring levels and by crosstalk in lines, so that the populations are effectively equalized.

Thus, for Fe I lines to be used as diagnostics one may well assume that the line source functions are locally in LTE. The opacities, however, will be out of LTE and very dependent on the ultraviolet radiation field from below.

5. NLTE EFFECTS FOR Ni I

Ni I is quite like Fe I except that there are far fewer levels and lines in the Grotrian diagram (Figure 4). The Ni I ionization energy is nearly equal to the Fe I ionization energy so that the ultraviolet overionization should be very similar. In addition, ultraviolet pumping may be expected. The GONG line, which connects levels 5 and 7, is a prime candidate for NLTE effect 2.

Our computations confirm these expectations. Figure 6 shows results. (Note that the abscissae measure column mass density and run reversedly from the height scales of Figures 1 and 2.) The top panel shows the input models, consisting of the standard HSRA plane-parallel model atmopshere and hot and cool components from Steffen's simulation. The middle panel shows NLTE departure coefficients of the levels of Figure 4 that result for the HSRA. Their pattern closely mimicks Lites' (1972) results for Fe I. Levels 13–15 drop away from the 1–6 curves deeper in the photosphere than levels 7–12 because their downward lines are weaker and become optically thin at lower height than the downward transitions from levels 7–12. Levels 1–6 do not experience photon losses at all, and simply follow the ultraviolet overionization which is produced through NLTE effect 1, primarily from levels 7–12.

The bottom panel shows the departure coefficients of the upper and lower levels of the GONG line, computed for Steffen's hot and cool granular components. The differences are large. The outward increasing split between the two lower-level curves (5) is due to the difference in ultraviolet overionization between the two granular components. The resulting opacity difference is given by the separation between the two tick marks which specify the locations of optical depth unity.

In the case of the cool component (dashed), the upper level departure coefficient (7) drops away in standard fashion from the lower-level departure coefficient due to photon losses. However, for the hot model this does not occur until $m = 0.6$ g cm^{-2}, and in fact there is a population inversion below that height. This is due to ultraviolet pumping in line 2–7.

In summary, the core of the GONG line is affected by the granular modulation of the ultraviolet radiation field in both its opacity and its source function. The effects combine: both the NLTE decrease of the line opacity and the reduction of the NLTE photon losses by the NLTE pumping increase the line core intensity above a hot granule.

Figure 6: *Results for the Ni I 676.78 nm GONG line.*
Top panel: models used.
Middle panel: NLTE departure coefficients of the Ni I levels shown in Figure 4 for the HSRA standard plane-parallel model atmosphere. There are three groups of curves, respectively for levels without downward radiative transitions (1–6), medium-energy levels with strong downward transitions that become optically thin in the upper photosphere (7–12), and high-energy levels with weaker downward transitions that cause photon losses already in the deep photosphere (13–15).
Bottom panel: population departures for the GONG line, above a hot granule (dot-dashed) and above a cool intergranular lane (dashed). Tick marks indicate the locations of optical depth unity at line center. The line optical depth scales with the lower-level departure coefficient, while the line source function scales with the ratio of the upper-level and lower-level departure coefficients. (Note that the abscissa is reversed from the abscissae of Figures 1 and 2: height runs to the left here.)

6. NLTE EFFECTS FOR K I

The Grotrian diagram for K I (Figure 5) differs from the other two, illustrating the difference between alkalids and metals. The ionization energy is much lower. Only the ground state ionizes by using the hot ultraviolet radiation field. Due to spin-orbit interaction, its ionization cross section is unusually small. Therefore, NLTE effect 1 is less important here.

There is a blue transition that is pumped, however, namely the 1–5 line in Figure 5. The pumped-up atoms cascade down along levels 3 and 4 to level 2 and back to the ground state. This pumping partially offsets photon losses in the resonance line.

The largest effect for K I is NLTE effect 3. It causes large over-recombination to level 4, which results in slight overpopulation of the K I atom in the deep photosphere and partially cancels the ultraviolet overionization higher up. As a result, the K I ground state is close to LTE throughout the photosphere for the HSRA—which is quite surprising for such a minority stage of ionization.

What happens above a hot granule? The ultraviolet ionization from level 1 increases and the long-wavelength recombination to level 4 decreases; both changes reduce the K I population. In fact, the ground state becomes underpopulated throughout the photosphere in our computation. In addition, the 1 to 5 pump is enhanced so that the resonance line photon losses are compensated somewhat more and the line source function increases. Both effects again produce a higher core intensity above a granule than there would be without NLTE phenomena.

6. CONCLUSION

The modulation that a granule imposes on the emergent radiation field affects the formation of helioseismology lines, even though their height of formation is above the layer of granular overshoot. Both the line opacity and the line source function can be affected.

For changes that are due to the ultraviolet radiation field, ultraviolet Planck function sensitivity is thus translated across the spectrum to the line wavelengths. This is a phenomenon similar to the Zanstra planetary nebulae mechanism, in which optical Balmer lines display ultraviolet radiation quality. An important difference between the Ni I line (and similar Fe I and Fe II lines) and the K I line is therefore that the former line displays ultraviolet sensitivity, while the latter line is dominated by recombination operating in the red. Thus, the granular signature in the core of the K I line should be less evident than in Ni or Fe lines that are formed at the same height in the photosphere.

ACKNOWLEDGEMENTS

We are indebted to Mats Carlsson for his helpfully spreading around of his efficient and elegant radiative transfer code, and to Matthias Steffen for emailing us results from his granulation simulation as computer-ready files immediately upon our request.

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Figure 1: *Models of the solar granulation. Results from Steffen's simulation (left) and Nordlund's simulation (right) are compared. For each, the temperature is plotted against height for a number of grid points covering the granulation. The scales are identical.*

Figure 2: *Radiation fields in the solar atmosphere at three wavelengths. The curve marked HSRA is the electron temperature of the standard HSRA model atmosphere. The other three curves represent the angle-averaged mean intensity* J_ν *in the form of corresponding radiation temperatures.*

Figure 3: *Grotrian diagram for Fe I. After Lites (1972).*

Figure 4: *Grotrian diagram for Ni I.*

Figure 5: *Grotrian diagram for K I, after Severino et al. (1986).*