TEMPERATURE DIAGNOSTICS OF THE UPPER PHOTOSPHERE

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ABSTRACT. We use NLTE modelling of the alkali resonance lines and of C I and O I high-excitation multiplets to test their quality as temperature diagnostics of the upper photosphere, in the context of Avrett's NLTE recovery of the LTE Holweger-Müller model below the temperature minimum and Ayres' bifurcation into hot and cool components above the temperature minimum.

1. The two temperature issues

The two arrows in Figure 1 mark recent developments in spatially-averaged modelling of the upper solar photosphere. The arrow near $h = 500$ km marks an appreciable shift in the empirical NLTE continuum modelling by Avrett and coworkers, from the cool temperature minimum which characterised the earlier HSRA and VAL models (Vernazza *et al.* 1981) to the hotter minimum specified in the MACKKL model (Maltby *et al.* 1986). The primary diagnostics used are the infrared and ultraviolet continuum intensities; the change results from new, higher-intensity infrared data and from the outward shift in the computed height of formation of the near-ultraviolet continua due to the inclusion of more line blocking (Avrett, these proceedings).

The change brings the formation of the ultraviolet continua and of most optical metal lines close to LTE (Rutten 1988). The photospheric part of the new model is indeed much closer to the classical empirical LTE model of Holweger and Müller (1974), and also to theoretical radiative-equilibrium models (Bell *et al.* 1976, Anderson 1989). This similarity indicates that plane-parallel homogeneity, LTE and RE are reasonable assumptions for the upper photosphere, in conflict with the 3D granulation simulations of Nordlund (these proceedings) which predict spatial variations of large amplitude throughout the photosphere.

The arrow near $h = 900$ km marks the bifurcation into hot and cool components proposed by Ayres (these proceedings). His primary diagnostics are the Ca II K line for the hot component and the limb darkening of the infrared CO bands for the cool component, with CO molecules contributing strongly to the cooling wherever (or whenever) they associate—presumably in field-free medium between fluxtubes.

These two issues separated in height only recently. Originally Ayres (1981) started the bifurcation below the temperature minimum in order to reproduce the Ayres and
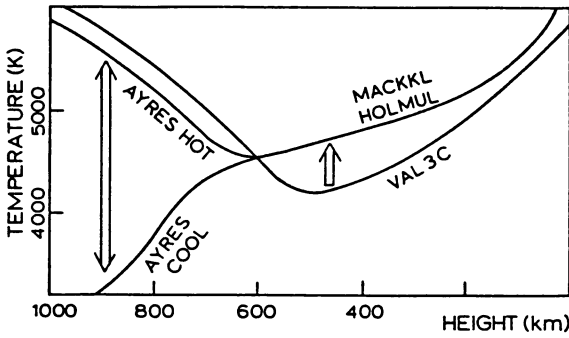
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Figure 1. Two issues in current photospheric modelling. Schematic electron temperatures against height for various models of the solar photosphere. The righthand arrow marks the change below the temperature minimum in the modelling of Avrett *et al.*, from VAL3C to MACKKL. The lefthand arrow marks the bifurcation into hot and cool components proposed by Ayres.
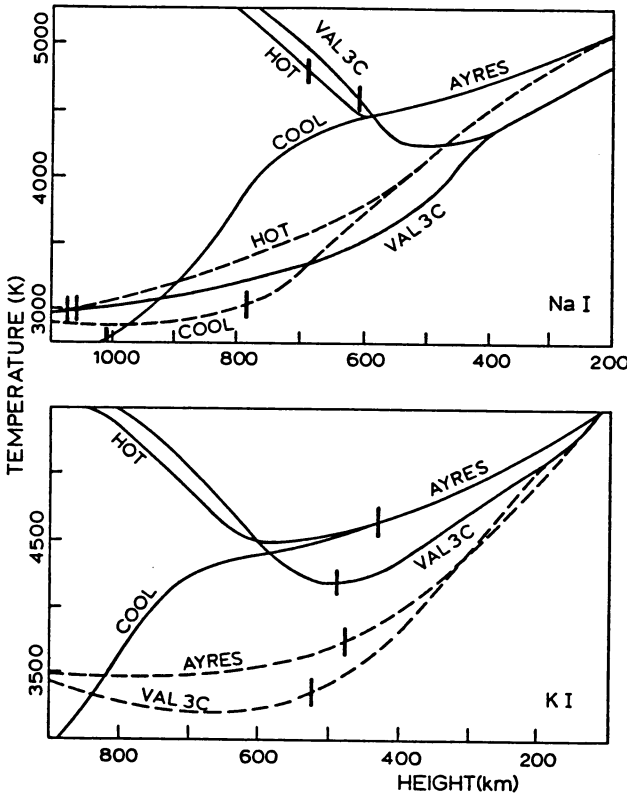

Figure 2. Formation of the Na D_1 line (*upper panel*) and the K I 770 nm line (*lower panel*).
Solid: electron temperature for the VAL3C model and for a model from Ayres which equals the hotter MACKKL model in the temperature minimum and splits into hot and cool components higher up.
Dashed: corresponding NLTE excitation temperatures.
Tick marks: $\tau = 1$ heights for viewing angle $\mu = 0.3$, respectively for LTE and NLTE line formation.

Linsky (1976) modelling of the Ca II line wings with the hot component. When the VAL to MACKKL change brought the continuum modelling into agreement with that, Ayres *et al.* (1986) shifted the split to higher layers. Avrett's criticism (these proceedings) that Ayres has overestimated the CO radiative cooling by using an inappropriate fixed radiation field is less pertinent there, but the criticism that the cool "CO clouds" are not seen in other data remains of interest.

Are there other observational diagnostics of these two temperature issues? Not from optical metal spectra such as Fe I and Fe II because their lines can be modelled as well with a hot as with a cool photosphere (Rutten and Kostik 1982). Which other lines might do? We have selected low-ionization and high-excitation lines as cool and hot diagnostics, respectively: the K I and Na I resonance lines which are from minority ionization stages with very low ionization energy and which should be enhanced in cool matter, and the C I and O I multiplets of about 8 eV excitation energy which should be enhanced in hot matter.

2. Low-ionization lines

Figure 2 shows results for the Na I and K I resonance lines; computational details will be given in Bruls *et al.* (in preparation). The line source functions (shown as excitation temperatures, dashed) decouple from the electron temperature (solid) in the upper and lower photosphere, respectively, and display typical scattering behaviour.

The computed heights of formation shift outward from LTE line formation ($\tau = 1$ ticks on solid curves) to NLTE line formation ($\tau = 1$ ticks on dashed curves). For K I this shift is due to photon losses in the resonance lines. These cause extra recombination from the ion reservoir which is not fully compensated by ultraviolet overionization in the temperature minimum region. For Na I the shift is very large for models with a chromospheric temperature rise because the rise is not followed by the ionising radiation originating from the photosphere. For Ayres' cool model, however, the ionising radiation is hotter than the electron temperature, resulting in radiative overionization and a reversed LTE–to–NLTE shift.

Figure 3 shows observed and computed cores for the Na D_1 line at two viewing angles. The differences between the various models are too small to be significant; the scattering behaviour makes the source function rather insensitive to the two temperature issues. The same holds for the K I resonance lines.

The inner wings of the Na I lines show better response. Figure 4 shows that these are sensitive to the temperature minimum region; the difference between the hot model (AYRES) and the cool model (VAL3C) is significant and exceeds the variations obtained by changing the microturbulent or collisional damping parameters within a reasonable range.

3. High-excitation lines

Figure 5 shows results for the infrared C I multiplet near 1070 nm; details are given elsewhere (Shchukina and Shcherbina 1989). The source function again displays photon-loss character, but with some sensitivity to the presence of a chromospheric temperature rise.
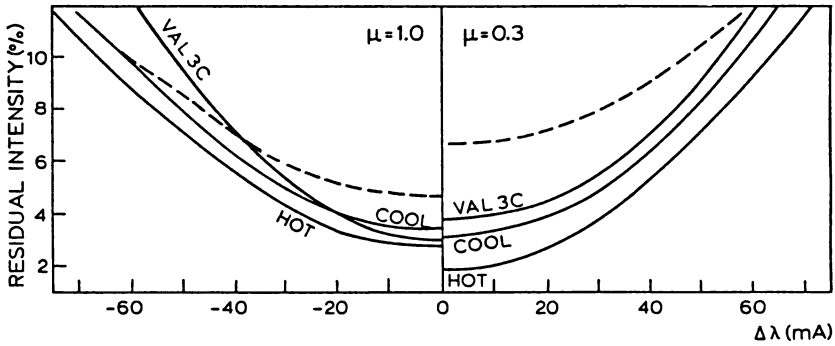
Figure 3. Computed (*solid*) and observed (*dashed*) line cores of the Na D_1 line. Viewing angles $\mu = 1.0$ (left) and $\mu = 0.3$ (right).
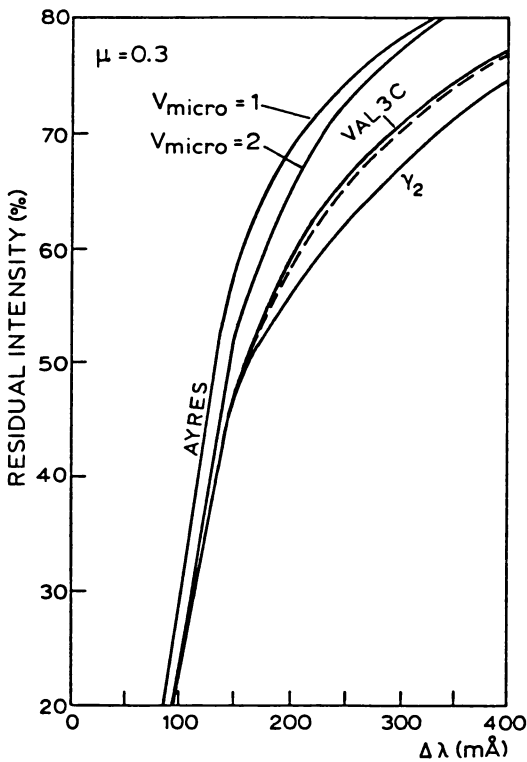

Figure 4. Computed (*solid*) and observed (*dashed*) inner wings of the Na D_1 line at viewing angle $\mu = 0.3$. The hot and cool components of model AYRES produce the same line wings. The AYRES model has been used with two microturbulence values (1 and 2 km/s). The VAL3C model has been used with two formalisms for collisional broadening. The effective damping parameter γ is larger by about 40% for the curve marked γ_2.
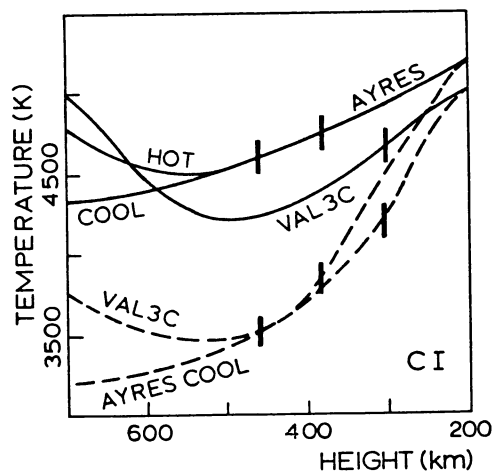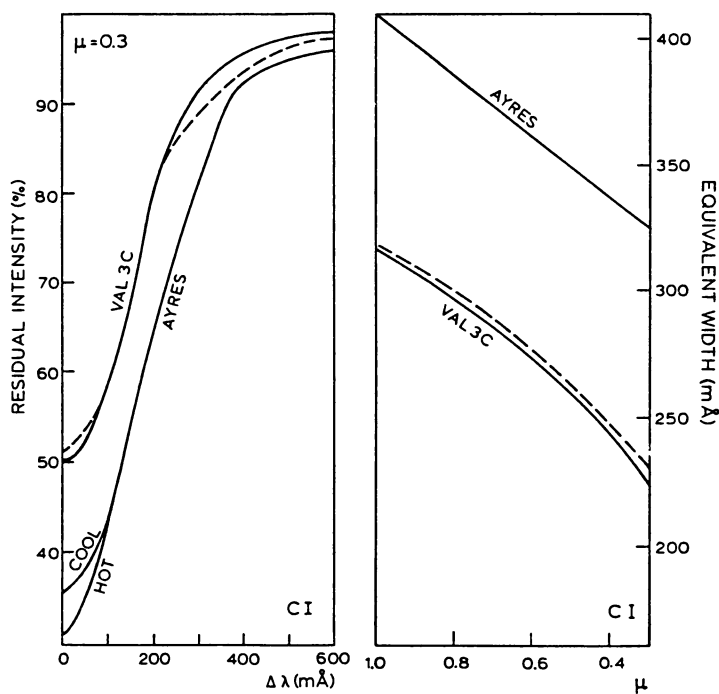
Figure 5. Formation of the C I triplet near 1070 nm.
Solid: model electron temperatures.
Dashed: C I excitation temperatures.
Ticks: $\tau = 1$ heights for $\mu = 0.3$, respectively for LTE line formation (solid curves) and NLTE line formation (dashed curves).

Figure 6. Computed (*solid*) and observed (*dashed*) line profiles (*left*) and equivalent widths (*right*) of the C I 1070 nm line.

The line opacity scaling is about the same in LTE and NLTE. This equality results for models with a cool temperature minimum from the fortuitous cancellation between the overpopulation due to ultraviolet pumping in the resonance lines and the depopulation through pumped near-ultraviolet lines that connect the lower levels of the multiplet to levels close to the continuum.

However, the line opacity scaling does depend on the temperature structure. It causes the separation between the $\tau = 1$ ticks for the AYRES-hot (outermost tick), AYRES-cool (middle) and VAL3C (innermost) models and results in appreciable line profile sensitivity, as evident in Figure 6a in which the difference between a hot and a cool temperature minimum is again significant. There is even some sensitivity to Ayres' bifurcation in the line core, which is deeper for the hot model because that produces more opacity. This is surprising because one tends to think of such high-excitation lines as very deeply formed; the contribution function is doubly peaked, however, and feels the chromospheric temperature rise also.

Figure 6b shows that the difference between hot and cool minima is markedly present even in the integrated profiles, here shown center to limb. Similar results were obtained for the 777 nm triplet of O I (Shchukina 1987).

Conclusion

All lines discussed here require detailed NLTE modelling. None of the lines provides a good diagnostic of Ayres' bifurcation above $h = 700$ km, but the inner wings of the Na D lines and the C I 1070 nm and O I 777 nm multiplets are sensitive to the temperature around $h = 400$ km. The observations, both of the "cool" Na D wings and the "hot" C I multiplet, are better reproduced with the old VAL3C model than with the new MACKKL model. This contradicts the current trend towards a hot temperature minimum.

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