SUN-AS-A-STAR LINE FORMATION

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ABSTRACT. Spectral line formation in the solar photosphere is reviewed emphasizing stellar-like 1D standard modeling. A surprising result is that the classical LTE-RE assumption works very well for the spatially-averaged upper photosphere. True understanding, however, requires detailed study of inhomogeneities with much NLTE complexity.

1 INTRODUCTION

Spectral lines are used in three broad stellar research areas: *(i)* for abundance determination, studying stellar and galactic evolution; *(ii)* as diagnostics of stellar interiors (seismology), convection (bisectors), dynamos (Zeeman broadening) and atmospheric structure including activity (emission features); *(iii)* as cooling and heating agents in energy budgets. Solar line formation studies provide insights in everyone of these.

In this review I discuss line formation in the upper photosphere and temperature minimum region. My themes are the pitfalls of spatially-averaged modeling (Section 2) and its successes (Section 3). Both topics are of interest to stellar applications and have implications for the modeling of real-sun fine structure which is the frontier in solar physics now (Section 4).

Other reviews on line formation are by Avrett (1989) and Rutten (1988) for the solar photosphere, by Lites (1985) for the solar chromosphere and by Judge (1990) for stellar chromospheres. The proceedings of the Kiev IAU Symposium (Stenflo 1989) contain many reviews on solar surface fine structure.

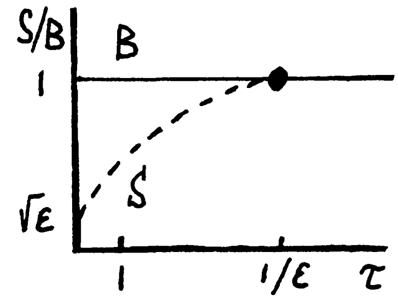
2 NLTE LINE FORMATION

In spatially-averaged '1D' modeling one assumes plane-parallel homogeneity, fudging fine structure away with ad-hoc spectral line fitting parameters as 'turbulence' and 'collisional damping enhancements'. Similarly, in '1.5D' modeling one assumes that the source function along a ray is not influenced by neighbouring structures with different state parameters. The complications of NLTE radiative transfer remain, however, and have traditionally received much attention. Mihalas' (1978) book remains the bible of the field, Athay's (1972) book remains its best source of numerical demonstrations, the VAL3 paper (Vernazza, Avrett and Loeser 1981) remains its outstanding 1D (actually 1.5D) application.

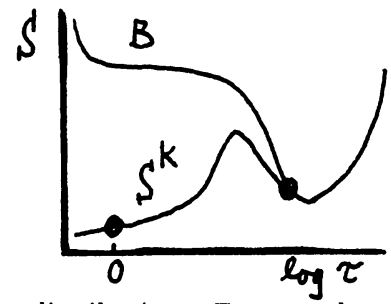
New numerical methods and modern computers now lead to a revival in which complex model atoms are investigated. Also, NLTE radiative transfer is now included in large-scale multi-dimensional simulations: the field evolves from 1D demonstration to realistic 3D application. The problems encountered before crop up again in new circumstances; I present them here in the form of a pictorial NLTE obstacle course, with ascending complexity in atomic representation following Athay's (1972) example.

2.1 Two Levels

Even the two-level atom poses complex NLTE problems. Surface photon loss tends to lower the line source function; scattering increases the depth over which the loss is felt.



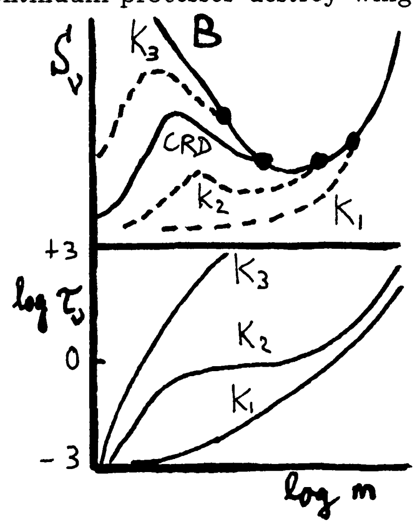
The two-level line source function is $S = (1-\varepsilon)\,\overline{J} + \varepsilon B$. For resonance lines the photon destruction probability ε is often so small (10^{-4}) that the dethermalising effects of photon losses propagate deeply into the atmosphere, reaching optical depth $\tau \approx 1/\varepsilon$ or more. The textbook example of a homogeneous halfspace has $S \approx \sqrt{\varepsilon}\,B$ at the surface with correspondingly small emergent intensity: $I(\tau{=}0) \approx S(\tau{=}1) \approx (1+\sqrt{3})\sqrt{\varepsilon}\,B$ for scattering with small ε (*e.g.* Rybicki and Lightman 1979, p. 320; see Hubený 1987 for an illuminating interpretation).



Thus, the source function of a resonance line falls below the Planck function already at large depth; the emergent intensity is *controlled* at a much deeper location than the $\tau = 1$ depth where it is *formed.* For example, the K_3 core of the Ca II K line is formed at the top of the chromosphere (VAL3 p. 637), but its intensity response to atmospheric variations is actually set at the bottom of the chromosphere.

Additional complexity arises from partial frequency redistribution. For complete redistribution the mean intensity is weighted by the extinction profile ($\overline{J} = \int J_\nu \varphi_\nu \, d\nu$), while strict coherency has $\overline{J} = J_\nu$. In the latter case, core and wing photons are not mixed together so that the core photons have smaller chance of escape while the wing photons are less tightly confined than for complete redistribution; coherency shifts the thermalisation point outward for line center radiation and inward for line wing radiation.

In reality, however, redistribution functions are required to admit partial collisional and Doppler redistribution, and sometimes 'cross' redistribution via other levels. The formalisms are known (*e.g.* Hummer 1962, Omont *et al.* 1972, Mihalas 1978, Heinzel and Hubený 1982, Hubený 1982) and fast codes exist (Ayres 1985, Gouttebroze 1986, Uitenbroek 1989b), but an old unsolved problem is posed by the increased sensitivity to the two classical fudge parameters: the microturbulence, which sets the Doppler width and therefore the transition between redistributed core photons and coherently scattering wing photons as well as the amount of crosstalk ('Doppler drifting') between these photon ensembles, and the damping enhancement factor, which determines to what extents collisions destroy wing coherence and continuum processes destroy wing photons.



These fudge parameters influence the line source function structure as well as the optical depth scaling. For example, the outward rise of the standard VAL3 turbulence produces a plateau in the Ca II K_2 τ_ν scale because a given wavelength shifts into the Doppler core; it affects the source function because wing photons from below are trapped higher up by the widening core. Recent results of Uitenbroek (1989a) show that the effects are dramatic: the whole chromosphere is imaged as a thick or as a thin slab in the K_2 peaks depending on the ad-hoc choice of microturbulence. Similarly, the mean free paths of K-core photons can be smaller or larger than the diameter of a typical fluxtube in the upper photosphere depending on this choice.

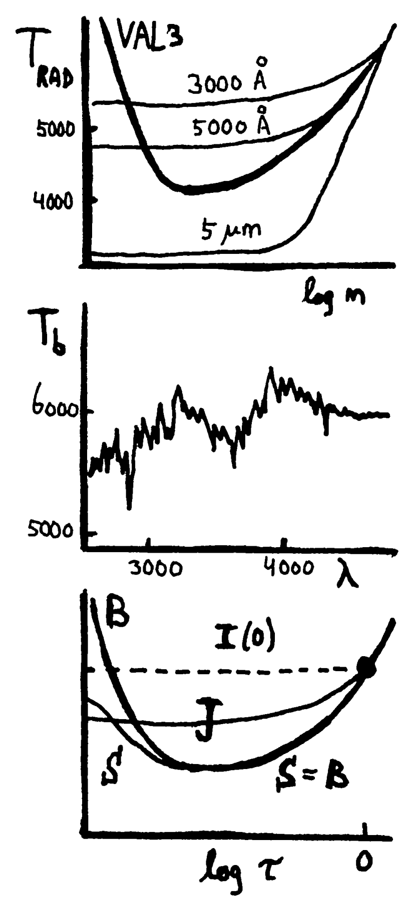
Also, it is not at all clear to what extent actual nonthermal velocities contribute to Doppler redistribution. Carlsson and Scharmer (1985) found that meso-scale velocity fields cannot be represented as a combination of microturbulence and macroturbulence; observed p-mode oscillations and predicted gravity waves are highly anisotropic; observed redistribution phenomena require small 'horizontal' microturbulence (Rutten and Milkey 1979). Worst of all, fitting microturbulence serves to 'correct' the neglect of structural inhomogeneities as granules and fluxtubes, of which the true signatures obviously differ from random velocity broadening. It is naive to fudge their structuring of the real atmosphere with a 'turbulent pressure' term, and similarly wrong to enter them simply as Doppler redistribution here.

Thus, the formation of resonance lines including effects of scattering and partial frequency redistribution is formally well understood, but in practice these effects make 1D modeling more suspect. Take the Ca II K line. Reproducing its spatially-averaged K_2 emission peaks and K_1 dips and their limb darkening was a triumph of plane-parallel partial redistribution modeling (Shine *et al.* 1975), but actually most if not all of the K_2 emission originates from tiny magnetic flux concentrations (Schrijver *et al.* 1989). Clearly, the 1D modeling was worthwhile in proving the importance of redistribution effects but is yet far from a definitive explanation.

2.2 One Level + Continuum

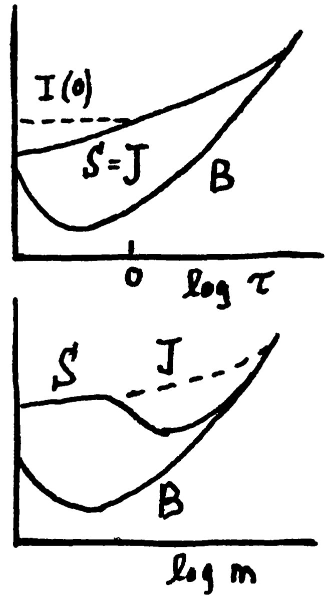
Adding bound-free processes brings in the continuous radiation fields throughout the spectrum. Comparing their radiation temperatures $T_{\rm RAD}$ where $J_\nu \equiv B_\nu(T_{\rm RAD})$ with the VAL3C temperature illustrates an important VAL3 NLTE characteristic: $J_\nu > B_\nu$ in the blue and ultraviolet while $J_\nu < B_\nu$ in the infrared.

Why? A first estimate $J(\tau=0) \approx (1/2)\, I(\tau=0) \approx (1/2)\, S(\tau=1) \approx (1/2)\, B(\tau=1)$ is accurate in the infrared. It specifies the limit value of J_ν; whether B_ν drops below that or not depends on the run of the temperature for $\tau_\nu < 1$. At shorter wavelengths B_ν falls much steeper for a given temperature decline due to the larger temperature sensitivity; B_ν drops below J_ν in the blue and ultraviolet for steep enough temperature gradients. The solar atmosphere (as any radiative-equilibrium photosphere) has inwardly steepening temperature gradients and the solar opacity has a broad minimum between 5000 Å and 3000 Å (Vernazza, Avrett and Loeser 1976, Fig. 6); therefore, blue, violet and near-ultraviolet radiation emerges from deep layers and exceeds the VAL3 Planck function appreciably in the upper photosphere (VAL3, Fig. 36 panels 500–300 nm).

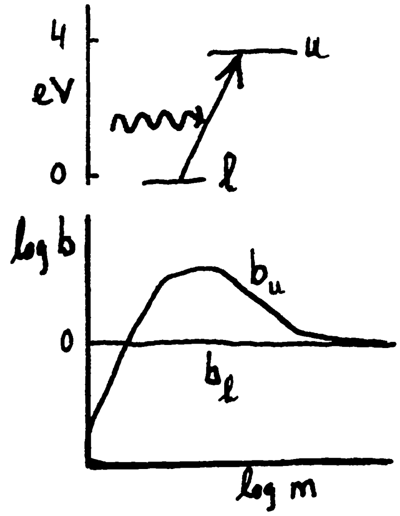


Ultraviolet radiation is also energetic, at 3–5 eV per photon exceeding the typical thermal collision energy of 1 eV. Collisional destruction is therefore rare and scattering important in the bf edges which make up the ultraviolet continua. These are narrow enough to behave just like resonance lines: their scattering (with complete redistribution over the edge profile) again shifts the thermalization to a point deep in the photosphere, far up the ever steeper temperature gradient. As a result, both S_ν and J_ν exceed B_ν appreciably in the upper photosphere in the ultraviolet continua even though their $\tau = 1$ depth lies near the temperature minimum (VAL3, Fig. 36 panels 200–130 nm).

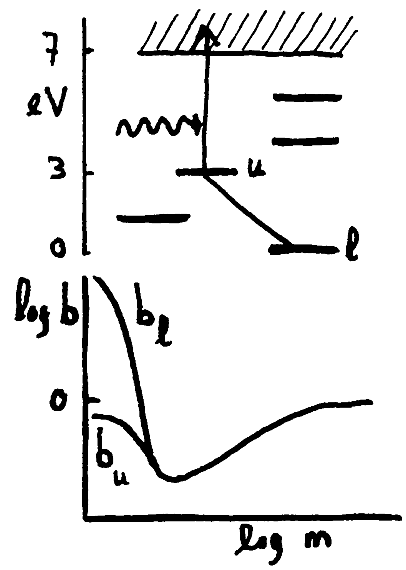
The same applies to line source functions of very weak resonance lines and to coherent far-wing source function components which also feel the steep temperature gradient in the deep photosphere, resulting in observed emission features inside the solar limb (Canfield 1971, Rutten and Milkey 1979, Rutten and Stencel 1980).



The $J_\nu^{\rm UV} > B_\nu^{\rm UV}$ imbalance affects any transition of about 4 eV. In bb transitions it causes 'optical pumping', for example of Fe II (Cram *et al.* 1980, Watanabe and Steenbock 1986) in which the upper levels of the resonance lines are overpopulated in the temperature minimum: $b_u > 1$ with $b_i \equiv n_i/n_i^{\rm SB}$ the NLTE population departure coefficient (here normalized to the Saha-Boltzmann population $n_i^{\rm SB}$, see Wijbenga and Zwaan 1972). Such pumping affects the line source function which scales with the ratio of the upper and lower level departures ($S \approx (b_u/b_l)\, B_\nu$) but not the line opacity which scales with the lower level departure: ($\kappa \approx b_l\, \kappa^{\rm SB}$; these relations are exact for negligible stimulated emission).

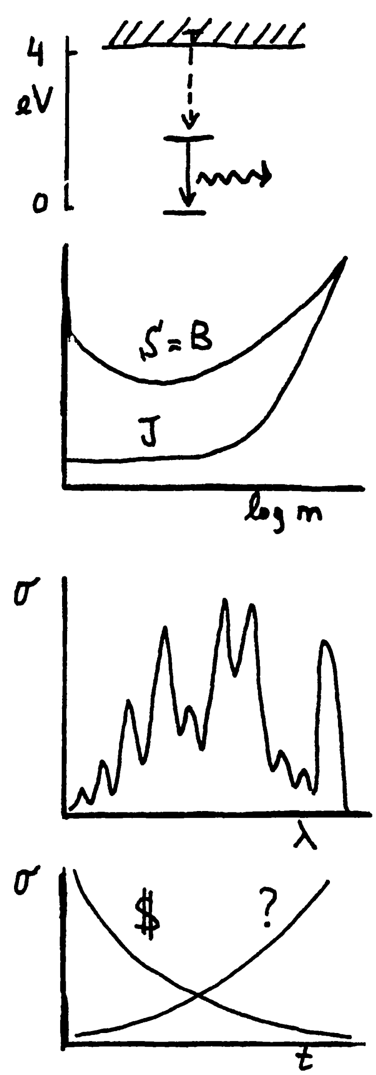


In bf transitions the $J_\nu^{\rm UV}$–$B_\nu^{\rm UV}$ imbalance causes overionization of atoms with well-populated levels 4 eV below the ionization limit. The classical example is Fe I (Lites 1972, Athay and Lites 1972, Rutten 1988). Its higher levels are coupled well enough by collisions and its lower levels are coupled well enough by the many strong lines that all populations generally obey Boltzmann statistics throughout the photosphere. However, they are all jointly out of LTE in VAL3-like models because they are 'photoionization dominated' (Thomas 1957): overionization due to the ultraviolet Fe I edges produces an overall underpopulation in the temperature minimum region which is shared by all levels and which affects the opacities of all photospheric lines ($b_l < 1$) but not their source functions ($b_u = b_l$).



In the chromosphere the Fe I departure coefficients rise steeply because $J_\nu^{\rm UV}$ remains constant while B_ν follows the temperature rise, and the departure coefficients diverge due to photon losses where the strongest lines become optically thin.

This Fe I pattern applies also to such other electron donors and opacity contributors as Si, Mg and Al. The pattern does not apply to the alkalis although they have about 4 eV ionization energy, because these happen to combine small bf cross-sections with large collision cross-sections. In fact, K I is overpopulated due to 'photon suction' by resonance-line photon losses which bring atoms down from the K II reservoir via collisional recombination to a lower than thermal state (Bruls *et al.*, in preparation).



The reverse imbalance, $J_\nu < B_\nu$ in the infrared, has less effect due to the much larger competition from collisions. They make photon destruction frequent and scattering unimportant so that $S_\nu = B_\nu$ even where J_ν is very low (VAL3, Fig. 36 panels 3 cm—500 nm).

Thus, the first obstacle met when including continua is that evaluating bound-free or bound-bound rates in the ultraviolet always requires full NLTE solving of the Si, Fe, Mg and Al ionization equilibria, taking care to admit scattering in their edges.

The second obstacle is that bf cross-sections rarely follow the Kramers hydrogenic ν^{-3} dependence but may instead show resonances as in Fe I (Hansen *et al.* 1977). These should be included in detail, but reliable data are scarce. More generally, this is the unfortunate conservation problem of the 'Sveneric Johansson Index' (the product of the astrophysical need for atomic data and the funding of atomic spectroscopy in physics) which applies to all cross-sections of astrophysical interest (see Smith 1989). Another example is the universal neglect of inelastic collisions with neutral hydrogen atoms (Holweger 1979) although they may well be important (Steenbock and Holweger 1984). Perhaps the compiling must shift from physics to astrophysics, which is the course taken by Kurucz and by the international 'Opacity Project' (Seaton 1990).

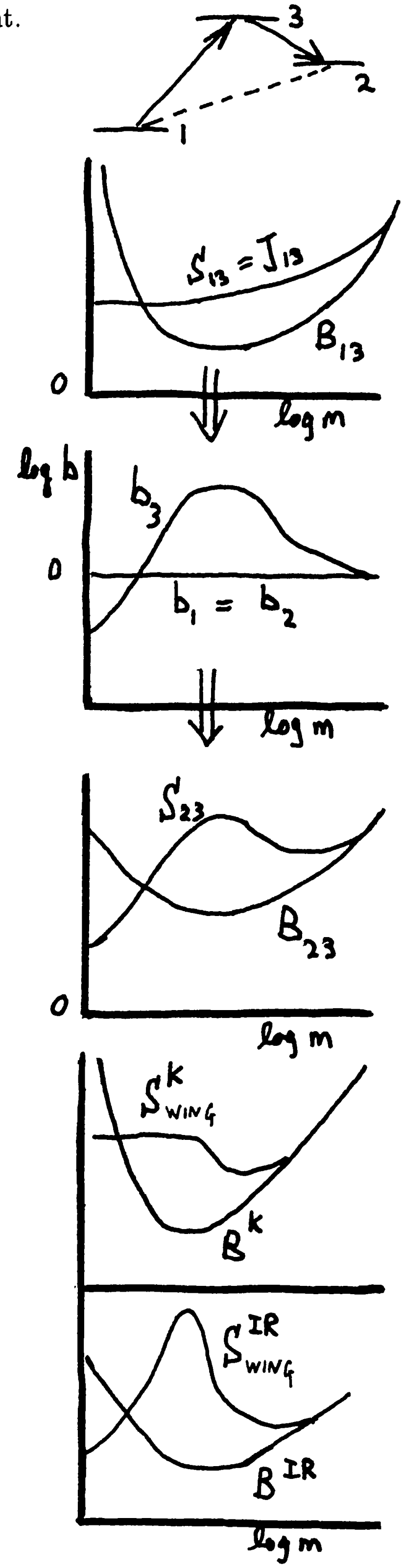
The third obstacle is the major problem of the near-ultraviolet 'line haze' which represents a quasi-continuum largely made up of Fe I and Fe II lines (Johansson 1990). All these lines can have NLTE source functions and/or NLTE opacities depending on their photon losses, individually and collectively, and on the $J_\nu^{\rm uv} - B_\nu^{\rm uv}$ imbalance which they help determine. For example, a steep temperature gradient produces $J_\nu^{\rm uv} > B_\nu^{\rm uv}$; the resulting overionization of Fe I and overexcitation of Fe II affect Fe I opacities and Fe II source functions and lessen the line haze blanketing. Instead, a shallow temperature gradient keeps both Fe I and Fe II closer to LTE in the upper photosphere and maximizes the line haze efficiency.

2.3 Three Levels

Adding a third bound level adds the possibility of photon conversion, with NLTE interlocking effects akin to the Zanstra planetary nebulae mechanism which imparts hot-star Lyman characteristics to cool-nebula Balmer lines. Photon conversion (up in one line, down in another) is a process like scattering, but very inelastic. It may even use another species as photon source ('coincidence conversion'), as the Ly$_\beta$ pump in the Bowen mechanism for O I.

Photon conversion brings Zanstra-like transcription of temperature sensitivity across the spectrum. For example, if $b_3 \neq b_1$ while $b_1 = b_2$ there is source function equality in the 1-3 and 2-3 lines in the sense that their source function departure factors b_u/b_l are equal. These will usually be set by the shorter-wavelength 1-3 line because that is the stronger one, but their effects are larger for the subordinate 2-3 line due to the change in Planck function sensitivity to a temperature gradient.

For example, if S_{13} follows a flat J_{13} rather than a deep minimum in B_{13}, the resulting hump in b_3 produces a prominent peak in S_{23} for subordinate lines in the red or infrared. This happens in Fe II (Cram *et al.* 1980) and explains why optical Fe II lines go into emission well inside the solar limb as observed (Van Dessel 1975). The enhancement is larger where stimulated emission is important; the most sensitive way of studying population departures set in the ultraviolet is to study resulting limb emission features in the infrared.



Such photon conversion processes often appear negligible at disk center because the larger opacity of the pumped 1-3 line keeps the subordinate 2-3 line thermalized up to above the latter's formation height. However, this situation changes in structures with larger surface to volume ratio such as slabs, be it dense slabs such as chromospheric prominences or embedded tenuous slabs such as photospheric flux concentrations. The longer free paths of the subordinate photons may then provide important lateral escape routes and figure heavily in the energy balance, not only producing radiative cooling through 3-2 photon escape but also producing local heating when a 3-2 escape is followed by collisional 2-1 deexcitation. The latter is probable when level 2 is metastable as for Ca II and Fe II.

A tricky point here is the amount of 'cross redistribution' in the conversion process, with complete redistribution in the 3-2 reemission as one extreme and coherent conversion, with the 3-2 photon precisely retaining the separation from line center of the 1-3 excitation, as the other extreme. Let us again take the Ca II K line as example. The frequency dependence of the K line source function propagates in enhanced form through coherent conversion to the 8542 Å infrared line. For example, the far-wing source function components of the K line follow the hot violet J_ν continuum (with an initial dip due to collisional redistribution), and this structure is again transformed into high peaks for the corresponding source function components of the infrared line. Profiles of the 8542 Å line computed for disk center from 1D modeling are not disturbed by these peaks because the line is formed too deep: reverse conversion keeps it thermalised by the K line. The reverse effect of coherent conversion on the disk-center K profile is larger, the less opaque infrared line contributing an extra photon escape channel (Uitenbroek, these proceedings).

How does this change for slab geometry? In an important paper Owocki and Auer (1980) computed that lateral transfer is not important in slab geometries for the Ca II K wings while it does smooth out horizontal contrast in the Mg II k wings. Owocki and Auer attributed the difference to the presence of metastable levels in Ca II. They did not include these nor the infrared lines in their computations, but simply assumed that their existence provides an incoherent channel from the K wing to the K core set by the branching ratio. This channel then keeps the K wing source function close to LTE for any spatial structure within which the K core is still thermalised at the wing formation depth $\tau^K_{wing} = 1$.

However, coherent conversion may actually accomplish the reverse, coupling K wing components not via the opaque infrared core to the very opaque K core with $\tau^K_{core} \approx 10^6\, \tau^K_{wing}$ but to corresponding infrared wing components of much smaller opacity, typically $\tau^{IR}_\nu \approx 10^{-4}\, \tau^K_\nu$. These far-reaching photons provide a channel with large escape probability which informs the K wing of spatial inhomogeneity.

This may bear on an old problem with the Fe II resonance lines (Athay and Lites 1972). These should be similar to the Si II 1808 Å and Mg II h and k lines (similar abundances, ionization energies and ionization stages), but their observed disk-center profiles show very weak or no reversals. Since the Mg II and Si II emission features originate exclusively from areas of enhanced magnetic field with slab or tube geometry, it may well be that lateral photon losses in the multitude of subordinate Fe II lines take away the sensitivity of the Fe II resonance lines to local temperature enhancements (Rutten 1988).

2.4 Many Levels

All of the above NLTE mechanisms can take place with real atoms and ions of larger complexity. In addition, there are other complications such as dielectronic processes, charge exchange reactions *etc.*

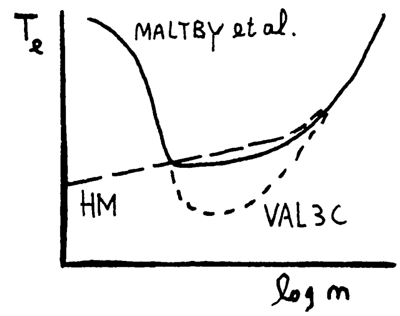
Take lines between high-lying levels as an example. Theory had it that such levels should be collisionally coupled to the continuum and therefore obey LTE if the next ion is the dominant ionization stage (*e.g.* Jefferies 1968 p. 284). The identification by Chang and Noyes (1983) of the 12 μm emission lines discovered by Murcray *et al.* (1981) and Brault and Noyes (1983) as high-level lines of Mg I and Al I came therefore as a surprise. These NLTE lines have large diagnostic potential because their Zeeman patterns are much wider, relative to their Doppler width, than for visible-wavelength lines and so their formation has been scrutinized—but without success; even their sphere of formation is uncertain. Brault and Noyes put them in the chromosphere, while Lemke and Holweger (1987) in the most detailed analysis so far conclude that the lines are photospheric. Zirin and Bopp (1989) argue forcefully for the chromosphere, while Deming *et al.* (1988) locate the lines in the temperature minimum because they oscillate with 276 s period. This is a sobering dispute in view of the NLTE sophistication paraded above!

Most of these NLTE issues have been around since the pioneering age of numerical radiative transfer in the sixties and early seventies. New methods and fast computers now bring a revival by permitting large model atoms with hundreds of levels and lines. The new methods are well presented in two books edited by Kalkofen (1984, 1987). Especially the two approximate operator techniques of Scharmer (1981) have proven successful, the first in the hands of the Kiel group (Werner and Husfeld 1985, Werner 1986, Hamann 1985, 1986) and the second in Carlsson's implementation (Scharmer and Calsson 1985), whose program MULTI (Carlsson 1986) is rapidly replacing LINEAR (Auer *et al.* 1972) and its derivatives as standard NLTE workhorse.

Pioneering is still to be done as well. One example is the difficult field of polarized radiation transfer (*e.g.* Streater *et al.* 1988, Faurobert 1987, 1988, Domke and Hubeny 1988, Lites *et al.* 1988; also Rees' 'Gentle Introduction' and other chapters in Kalkofen 1987). Another example constitutes also a final warning. The large-scale computer modeling now possible requires development of sophisticated diagnostics to understand what is going on within the computer. The two and three level simplifications above can help in such interpretation, as shown by Skumanich and Lites (1985, 1986) who develop a valuable scheme to interpret multilevel results.

3 ONE-DIMENSIONAL MODELING

Solar spatially-averaged modeling is obviously of interest to analysts of stellar photospheres; most 1D synthesis of optical solar lines is actually done by stellar spectroscopists as an intermediate calibration step in stellar abundance determination. They often adopt LTE to evade the above obstacles; surprisingly, elaborate 1D modeling of the upper photosphere now supports this shortcut, at least for the Sun. The chromosphere, however, is another matter.



The classical empirical LTE model is the HM photosphere by Holweger and Müller (1974) which is an improvement on Holweger (1967) and was derived from observed continuum intensities for the deep photosphere and observed intensities of optical Fe I lines for the upper photosphere. It has proven remarkably successful in explaining many other optical lines as well (*e.g.* Gurtovenko *et al.* 1989). One reason why it does so is that it has no chromospheric temperature rise.

The Harvard model sequence HSRA (Gingerich *et al.* 1971), VAL2M (Vernazza, Avrett and Loeser 1976) and VAL3C was constructed in similar but much more elaborate fashion, using not observed line cores but observed ultraviolet and infrared continua to derive brightness temperatures for the upper photosphere and low chromosphere. The NLTE formation of the ultraviolet edges discussed above then requires extensive NLTE solving, both to obtain the $J_\nu - B_\nu$ correction for each brightness temperature and to obtain the NLTE opacity correction necessary to locate its $\tau = 1$ formation height. These corrections were large because this Harvard sequence had much steeper temperature gradients in the upper photosphere than HM, producing large $J_\nu^{\rm UV} - B_\nu^{\rm UV}$ imbalances and therefore large overionization of Fe I and other opacity and electron donors.

There was no conflict with the LTE HM modeling of Fe I lines because employing a cool model with the corresponding NLTE departures produces nearly identical line fits as adopting HM and LTE does, throughout the optical spectrum and for many species (Rutten and Kostik 1982). See Rutten and Kostik (1988) for a demonstration of this 'NLTE-masking' using all 376 clean solar Fe I and Fe II lines measured by Rutten and Van der Zalm (1984).

However, the Harvard modeling has come about by flattening the temperature gradient in the upper photosphere (Avrett 1985); the latest Harvard model (Maltby *et al.* 1986) nearly reproduces the HM below the temperature minimum. The main reason is the inclusion of many more Kurucz lines in the ultraviolet. Their additional opacity shifts the $\tau = 1$ formation heights in the ultraviolet further out, so that a plot of the observed brightness temperatures (still the same as before) against height produces a flatter gradient. That results in smaller $J_\nu^{\rm UV} - B_\nu^{\rm UV}$ imbalances and smaller NLTE source function and opacity corrections, further flattening the fitted gradient; the end result is recovery of the HM model and validation of its LTE assumptions.

However, there are hidden NLTE snags. The Kurucz lines are entered into the computation with ad-hoc NLTE source functions, being told to go into full scattering near the temperature minimum because otherwise the chromospheric temperature rise would produce unobserved emission cores. Their opacities are assumed to be in LTE. Thus, a hidden HM-like model is adopted for the formation of the ultraviolet lines which then determine the model in these layers; a hidden steep-gradient model would require large opacity corrections and then produce a steeper model. Clearly, additional evidence is required to choose between a hot or a cool upper photosphere.

Observational evidence supporting a hot temperature minimum comes from balloon observations of the far-infrared continuum at 50, 80 and 200 μm (Degiacomi *et al.* 1985), from the limb darkening of ultraviolet continua (Samain 1980) and from the wings of the Ca II H and K lines (Ayres and Linsky 1976, Ayres 1977). However, the wings of the Mg II h and k lines require a yet hotter minimum (Ayres and Linsky 1976) while a cooler minimum is indicated by the wings of the Na D lines and high-excitation lines of C I (Shchukina *et al.* 1989).

Theoretical radiative-equilibrium (RE) modeling also supports a hot upper photosphere. The Bell *et al.* 1976 LTE-RE model resembles HM; Kurucz finds that his current 57 million lines result in much better LTE-RE HM-like reproduction of the solar spectrum than his 16 million lines did before (Kurucz 1990); strong evidence comes from the recent NLTE-RE analysis by Anderson (1989). He constructs representative model atoms to take account of the Kurucz lines (*i.e.* the previous list with 16 million), fully admitting NLTE departures in source functions and opacities. Anderson so produces an upper photosphere again close to HM, and also close to LTE up to the VAL3 temperature minimum, with significant divergence between LTE and NLTE blanketing only in the low chromosphere.

Thus, observed brightness temperatures throughout the spectrum, limb darkening, weak optical lines, strong-line wings and theoretical modeling all more or less agree; the spatially averaged solar photosphere seems to obey LTE and RE to quite a high degree.

Of course, LTE-RE must break down at some height even for spatially averaged diagnostics. Ayres' dark CO lines indicate the presence of substantial amounts of cool matter in the low chromosphere (Ayres *et al.* 1986), possibly cooled by the CO lines where and when they become optically thin (*e.g.* Ayres, these proceedings). This important observation shows that 1D breaks surely down at about the VAL3 temperature minimum. It also breaks down in the deep photosphere where convection penetrates. Does the upper photosphere present the only homogeneous layer of the entire solar envelope?

4 THE REAL SUN

Observing the Sun not as a star but with high spatial resolution (see reviews in Rutten and Severino 1989) immediately leads to doubting the validity of homogeneity or 1D LTE-RE line formation anywhere. The actual atmosphere is highly dynamic, affected by overshooting convection in the lower photosphere, by *p*-mode oscillations and other waves in the upper photosphere, by expanding fluxtubes and shocks in the lower chromosphere and by magnetic loops in the upper chromosphere. Steep temperature gradients are often realised in such structures, making the NLTE effects of Section 2 important; even if it seems that NLTE obstacles don't complicate 1D modeling anymore, they are an integral part of understanding solar fine structure.

This review hits the page limit here and cannot pay tribute to studies of non-plane parallel photospheric line formation (*e.g.* Lites *et al.* 1989, Grossmann-Doerth *et al.* 1989); let me conclude by proposing that the solar photosphere is actually far from LTE-RE but contrives to look like it for convenience (Rutten 1989) and not for perversity

(Anderson 1989): its spatial average seems to provide an incorrect but exact modeling convenience similar to the close correspondence between Newtonian gravitation and GRT in numerical results but not in conception. Whether other stars act likewise remains to be seen.

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