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EPSILON

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Episodes

A small subset of Dick's research interests suffices to keep me busy a lifetime. Having found myself to be a pointillist, adding minute points to local detail that only belong to a bigger picture when the viewer (not the pointillist) steps back, I admire the more daring spirits who with bold strokes paint far horizons on bigger canvas. Dick was of course the archetype of these in stellar atmosphere research, stepping in large strides over much terrain. Strides that impressed with their sense of purpose and direction, blazing a trail to follow. But in small steps for me; it seems I remain stuck near trail head. I'll detail that below taking the collisional photon destruction parameter epsilon as example — back to the sixties therefore.

NLTE was a magic word at Utrecht when I was a student. Or rather a shout, from Ann Underhill who became professor at Utrecht when I started on the more advanced courses. She was the first female astronomer of that rank in Holland (sofar followed by just one other, Ewine van Dishoeck). She shouted often during colloquia that something was bound to be NLTE and the reported work therefore bound to be all wrong. We gathered that that mysterious condition upset most people's work and made life awfully difficult. It was explained to us by professor Kees de Jager in the course that I now give myself. NLTE line formation, something affecting the magic source function that therefore goes funny and is no longer given by the Planck function. De Jager worked on it with Jean-Claude Pecker. Tony Hearn, a postdoc at Utrecht long before that type of position became institutional in Holland, worked on it with Ann Underhill. Kees Zwaan suggested to Jaap Houtgast to go to eclipses to study solar NLTE effects near the limb — effectively defining my eventual thesis subject, career and teaching.

Thomas, Athay and Jefferies, the Boulder school, were the gurus of the field. I met the latter two in de Jager's Bilderberg Study Week, where I operated the slide projector and tried to catch the gist of the debates. Often hot, although not as heated as the reported fights between Thomas and Underhill at international meetings. Long before meeting Dick in person, I had a vivid image of somebody you wouldn't ever want to argue with.

A major issue at De Bilderberg was the nature and behavior of solar microturbulence. That infamous quantity led to a non-confrontation with Dick the first time I met him, at the ESMOC meeting which started the Solar Physics Section of the European Physical Society, in the early spring of 1975 in Florence. Kees de Jager had suggested, noting that I dabbled with numerical Fourier analysis for eclipse data reduction, that the shape of the transform of line profiles might constrain the amplitude distribution of wave modes making up microturbulence. In the first talk of that meeting this work was cited by Peter Ulmschneider as support for his chromospheric wave heating. Peter was attacked by Dick and so wondered aloud, searching around, whether there wasn't anybody from Utrecht to elaborate in his defense. Kees de Jager hadn't arrived yet so I should have stood up, but I chickened out. The two, one looking fearsomely Teutonic, the other living up to his reputation as well as being impressively eggheaded and loudvoiced in an English dialect that I didn't fully grasp at the time, made up a pair of contestants that I did not dare to join.

Dick looked amazingly like my father, a geologist who was well known for contempt of conventions, authorities and university behavior codes, and who was rather feared for sarcasm in the face of incompetence. But also well appreciated by his students when working along with him "in the field", on Europe-wide geology expeditions. Still in Florence, I found that Dick was not only a look-alike to my father but displayed his character as well. I befriended Lawrence Cram and Chris Cannon during the meeting and sat in on their lengthy discussions with Dick, learning the agressive but fruitful American style of debate that is so different from the polite conversations that tend to be the norm in continental Europe, and recognizing that interest and appreciation lay at their root, with partner equality a self-evident and unquestionable base.

So, my fear of Dick abated. And over the years, I have gotten the knack of no-nonsense arguing and even a habit of asking questions at conferences myself. (And have come to appreciate Peter Ulmschneider as a non-Teutonic but gentle and hospitable colleague.)

Then of course came the episode of the orange books. Dick involved me through Lawrence Cram. We were both at Sac Peak with our families. Lawrence taught us the art of feeding Dick when he visited on book business: "Easy! A steak and a coke and he is all done!". In return, we got a much more elegant dinner from Stu Jordan in Washington on the way back to Utrecht. For the books, Dick wanted overview that I didn't possess; I ended up going for eloquence rather than content in the introduction to *The Sun as a Star*. The only informative item was a copy of the famous SOT space-time plot. I still use that diagram, now on reversed scales so that small and fast is to the upper right where out-of-reach goals belong (Figure 1). Fortunately, the usefulness of *The Sun as a Star* sits in the other chapters. They remain a very good introduction for students who start on solar research projects.

Later, Dick tried also to involve me in the FGK book. I went to Paris and spent an enjoyable week with the Spites, reading up on FGK issues. But nothing came from it, it was too far from my own work and I did not make the switch from the sun to solar-like stars that was made so succesfully by Kees Zwaan and others at that time. In fact, only recently have I taken up Spite-type interests again, being puzzled by the apparent spread

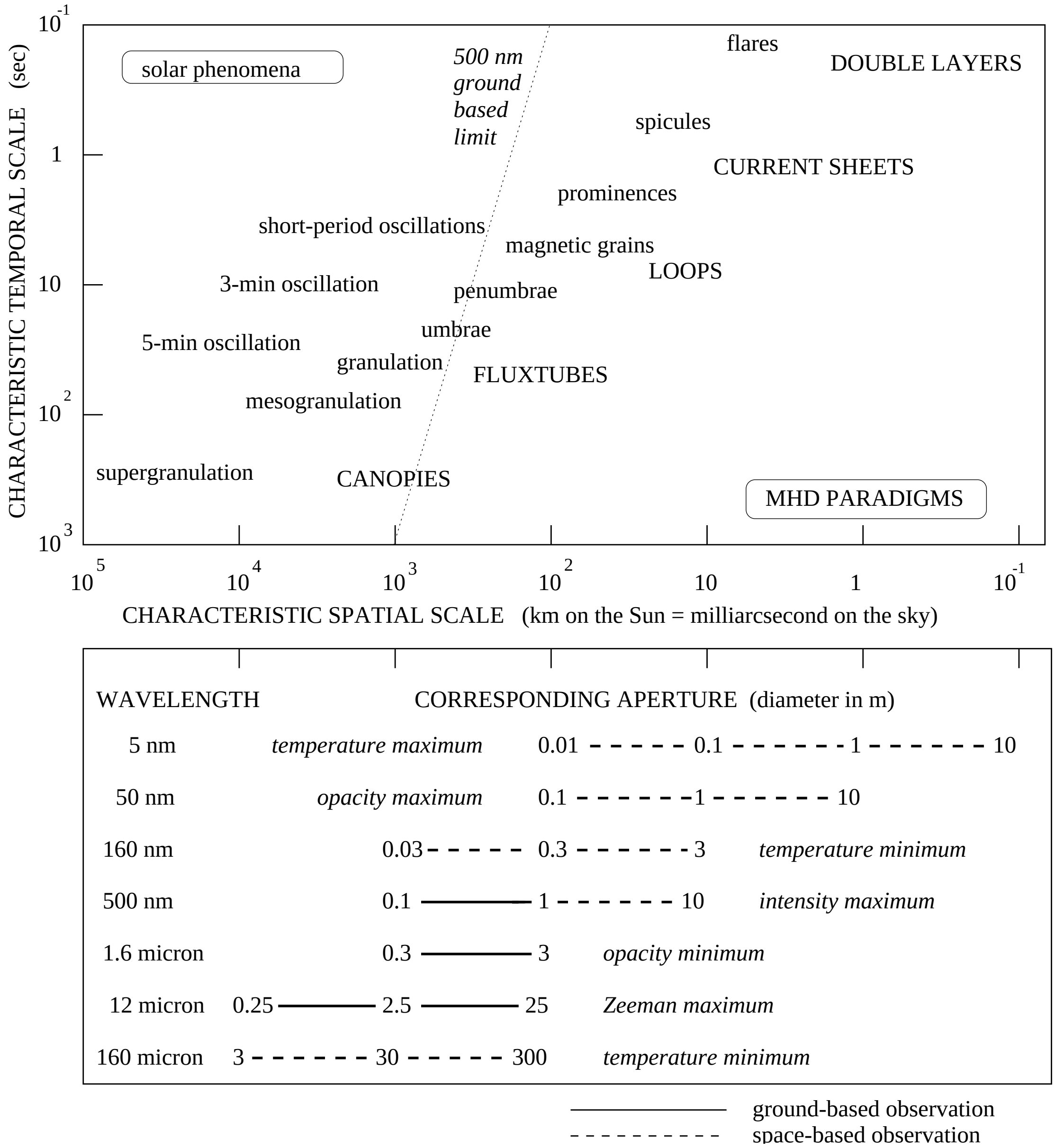

Figure 1: A solar space-time diagram, after the original SOT (Solar Optical Telescope) diagram by Dick Dunn, Jack Harvey and Bob Milkey. The lower panel plots corresponding aperture sizes at various wavelengths of interest. The highest angular resolution is still obtained from the ground although the dashed segments in the lower panel indicate that it should be reached from space. The biggest advances in solar physics since the SOT era have come from two resolutions not plotted here — Fourier resolution from long data sequences and numerical resolution from fast computers. From Rutten (1993).

in lithium content of the cool Pleiades (Stuik *et al.* 1997).

The last time I saw Dick was in Seattle at the sixth Cool Star Workshop, my first one. We walked up through the campus debating mass loss. I was nervous, going to give a naïve review on NLTE line formation with the whole big-shot Boulder school in the front row. Naïve, in fact cartoon-wise, because I wanted to convey the basic principles that had taken me so long to understand to those less steepened in the various Thomas–Athay–Jefferies–Mihalas books (Rutten 1990). But Grant nodded consent when I said something right, Andy thanked me for mentioning recent work, Jeff Linsky had an interesting comment and I don't remember Dick shooting me down. Of course, there was no mass loss in my talk, only photon losses; only now am I getting into mass transfer. But first the pointillist example.

Back to epsilon

During the past decade I have told my Utrecht classes every year that "epsilon is small" is the T-shirt slogan of NLTE line formation[1]. That is true, but I gave them the wrong definition all the time, defining the collisional destruction probability per extinction as

$$\varepsilon_{\nu_0} \equiv \frac{\alpha^{\rm a}_{\nu_0}}{\alpha^{\rm a}_{\nu_0} + \alpha^{\rm s}_{\nu_0}} = \frac{C_{ul}}{A_{ul} + B_{ul}\overline{J}_{\nu_0} + C_{ul}}, \tag{1}$$

with $\alpha^{\rm s}$ the scattering part and $\alpha^{\rm a}$ the true absorption part of the volume extinction coefficient due to a bound-bound transition with line-center frequency ν_0. The first version is general and is correct, no wonder since I took it from Rybicki and Lightman (1979) whose first chapter forms the backbone of my course on basic radiative transfer, but the second version is wrong. I thought it should apply to two-level atoms with complete redistribution and I obtained it by splitting the extinction into

$$\alpha^{\rm a}_{\nu_0} = \alpha^{l}_{\nu_0} \frac{C_{ul}}{A_{ul} + B_{ul}\overline{J}_{\nu_0} + C_{ul}} \tag{2}$$

$$\alpha^{\rm s}_{\nu_0} = \alpha^{l}_{\nu_0} \frac{A_{ul} + B_{ul}J_{\nu_0}}{A_{ul} + B_{ul}\overline{J}_{\nu_0} + C_{ul}}, \tag{3}$$

aiming to divide $\alpha^{l}_{\nu_0}$ into thermal and scattering components by asking whether the subsequent deexcitation is collisional or radiative. I included the term $B_{ul}\overline{J}$ to describe stimulated emission. At the time (1988), I did note that $\overline{J}_\nu$ enters in (1) where the standard textbooks have the Planck function B_ν instead, but I thought that due to an approximation—usually, the whole stimulated-emission term is neglected anyhow, and if it isn't, it is often accounted for adopting LTE. Mihalas (1978) gives the derivation as a problem (page 337) but I was too lazy to work it out, the more so since Jefferies (1968) said non-invitingly "after some algebra" in his description (page 37).

Wrong! My mistake was that $\alpha^{l}_{\nu_0}$ already contains a negative correction for induced emission. The negatively counted induced photons may themselves, depending on the nature of the preceding excitation, be of thermal or of radiative origin. Their presence in $\alpha^{l}_{\nu_0}$ upsets the above split.

[1] Hoping to get a T-shirt from them. No success sofar.

I never noticed this error until I started wondering about the presence of stimulated emission in Thomson scattering. I read in Mihalas (1978) that in a continuum scattering process there is no analogue of the stimulated emission that occurs in absorption processes, and textbook expressions for Thomson opacity do indeed not include a $[1 - \exp(-h\nu/kT)]$ correction factor. I understood this on the ground that an isolated electron does not possess the excitation energy, to be released upon suitable triggering, that an excited valence electron in a Bohr atom possesses. However, graduate student Han Uitenbroek taught me that in quantum mechanics a coherently scattered photon does not lose its identity and is not stored Bohr-wise as internal excitation energy. The clincher came from a remark on page 8 of Shu (1991) that photons like to bunch up together, being bosons, and that that property explains stimulated emission. A photon property, therefore, not a process property, and implying that Thomson scattering is stimulatable as well. Finally, I learned from page 71 of Shu (1991) that stimulated scattering indeed takes place but that it is never accounted for because its effects cancel between extinction and emission.

Shu's treatment is too sophisticated for my students (second year undergraduates), but shouldn't I be able to illustrate this cancelation in two-level-atom scattering with Einstein coefficients? It sits hidden in the "some algebra" of the standard derivation for two-level statistical equilibrium, but not too clearly. I believe that I finally got it didactically right while teaching my more advanced class (third year undergraduates) last year, writing the following paragraphs in the course notes[2]:

Sharp-line atoms. Let us now express the partial extinction coefficients α_ν^{a} and α_ν^{s} and the destruction probability ε_ν for two-level atoms in the Einstein coefficients. Their definitions specify transition probabilities for the whole line, but for radiative transport we are interested in what happens at each frequency within the line. We already avoid cross-talk between different transitions by discussing the idealized case of a two-level-atom medium; we will now also avoid spectral cross-talk within the line, between frequencies across the line width, by further simplification to unrealistic two-level atoms with infinitely sharp upper and lower levels, having no line broadening whatsoever. Such *sharp-line atoms* have $\varphi(\nu-\nu_0) = \psi(\nu-\nu_0) = \chi(\nu-\nu_0) = \delta(\nu-\nu_0)$, with the required area normalization $\int \varphi(\nu-\nu_0)\,\mathrm{d}\nu = 1$ and the total radiation field in the line given by $J_{\nu_0} \equiv \int J_\nu\,\varphi(\nu-\nu_0)\,\mathrm{d}\nu = J(\nu=\nu_0)$. Their Einstein coefficients specify transition probabilities at the single frequency $\nu = \nu_0$. This case resembles coherent scattering in the sense that the transport equation concerns only a single frequency, without cross-talk to other frequencies. It also resembles complete redistribution because all transitions are spread over the full "profile", each process taking a fresh sample of the same probability distribution.

Up-down sequences. The line extinction may be split in thermal and scattering components depending on the nature of the two-level up-down sequences. The full set of up and down two-level process combinations involving photons consists of the following seven sequences, schematically shown in Fig. 2:

[2] These lecture notes are available at `http://www.astro.uu.nl/~rutten/`. You are welcome to pull them over. If you find other errors, please tell me (`R.J.Rutten@astro.uu.nl`).

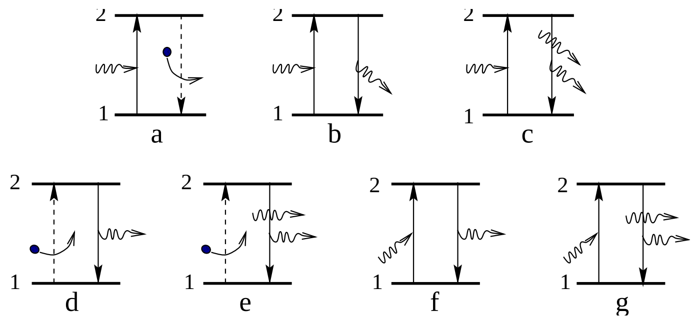

Figure 2: All up-down two-level-atom sequences involving photons in a given beam. The beam direction is to the right. The upper three pairs split the extinction of photons from the beam between collisional destruction and spontaneous and induced scattering. The lower four pairs split the emission of photons into the beam between spontaneous and induced thermal creation and scattering. The induced scattering pairs (c) and (g) both use a photon in the beam and one with arbitrary direction.

(a) thermal extinction = radiative excitation by a beam photon followed by collisional deexcitation,
(b) spontaneous scattering extinction = radiative excitation by a beam photon followed by spontaneous deexcitation,
(c) induced scattering extinction = radiative excitation by a beam photon followed by induced deexcitation,
(d) spontaneous thermal emission = collisional excitation followed by spontaneous emission of a photon into the beam,
(e) induced thermal emission = collisional excitation followed by induced emission of a photon into the beam,
(f) spontaneous scattering emission = radiative excitation followed by spontaneous emission of a photon into the beam,
(g) induced scattering emission = radiative excitation followed by induced emission of a photon into the beam.

Transport equation. For sharp-line two-level atoms the total deexcitation probability per particle in level 2 is given by:

$$P_{21} \equiv A_{21} + B_{21} J_{\nu_0} + C_{21}. \tag{4}$$

The seven-sequence transport equation at $\nu = \nu_0$ is, using $\int \varphi(\nu-\nu_0)\,\mathrm{d}\nu = \int \psi(\nu-\nu_0)\,\mathrm{d}\nu = \int \chi(\nu-\nu_0)\,\mathrm{d}\nu = 1$ and $\sigma^l_{\nu_0} = (h\nu_0/4\pi) B_{12}$:

$$\frac{\mathrm{d}I_{\nu_0}}{\mathrm{d}s} = \frac{h\nu_0}{4\pi}\, n_1 \Bigg[-\underbrace{B_{12} I_{\nu_0} \frac{C_{21}}{P_{21}}}_{\text{(a)}} - \underbrace{B_{12} I_{\nu_0} \frac{A_{21}}{P_{21}}}_{\text{(b)}} - \underbrace{B_{12} I_{\nu_0} \frac{B_{21} J_{\nu_0}}{P_{21}}}_{\text{(c)}}$$
$$+ \underbrace{C_{12} \frac{A_{21}}{P_{21}}}_{(d)} + \underbrace{C_{12} \frac{B_{21} I_{\nu_0}}{P_{21}}}_{(e)} + \underbrace{B_{12} J_{\nu_0} \frac{A_{21}}{P_{21}}}_{(f)} + \underbrace{B_{12} J_{\nu_0} \frac{B_{21} I_{\nu_0}}{P_{21}}}_{(g)} \Bigg]. \tag{5}$$

The three negative contributions (a) – (c) make up the total extinction of photons from the beam per centimeter path length. The four positive contributions (d) – (g) make up the total emission of photons into the beam. The intensity I_{ν_0} enters (e) and (g) because the stimulating photon has to be in the beam under consideration in order to induce photon emission along the beam.

Extinction. Conventionally, the volume extinction coefficient $\alpha^l_{\nu_0}$ corrects for induced emissions. The sharp-line extinction coefficient is therefore obtained by subtracting contributions (e) and (g) from the summed extinction terms (a), (b) and (c):

$$\begin{aligned}\alpha^l_{\nu_0} &= \frac{(\mathrm{a})-(\mathrm{e})+(\mathrm{b})+(\mathrm{c})-(\mathrm{g})}{I_{\nu_0}} \\ &= \frac{h\nu_0}{4\pi}\,n_1\left[B_{12}\frac{C_{21}}{P_{21}} - C_{12}\frac{B_{21}}{P_{21}} \right. \\ &\qquad \left. + B_{12}\frac{A_{21}}{P_{21}} + B_{12}\frac{B_{21}J_{\nu_0}}{P_{21}} - B_{12}J_{\nu_0}\frac{B_{21}}{P_{21}}\right] \\ &\equiv \alpha^{\rm a}_{\nu_0} + \alpha^{\rm s}_{\nu_0}. \end{aligned} \tag{6}$$

The thermal part $\alpha^{\rm a}_{\nu_0}$ consists of $(\mathrm{a})-(\mathrm{e})$ with

$$\begin{aligned}\alpha^{\rm a}_{\nu_0} &= \frac{h\nu_0}{4\pi}\,n_1\,B_{12}\frac{C_{21}}{P_{21}}\left[1-\frac{C_{12}B_{21}}{C_{21}B_{12}}\right] \\ &= \frac{h\nu_0}{4\pi}\,n_1\,B_{12}\frac{C_{21}}{P_{21}}\left[1-\mathrm{e}^{-h\nu_0/kT}\right], \end{aligned} \tag{7}$$

using the Einstein relations. The resulting TE correction factor $[1-\exp(-h\nu_0/kT)]$ befits the thermal origin of the induced photons. In the absence of any scattering, so that $\alpha^{\rm s}_{\nu_0}=0$ and $C_{21}/P_{21}=1$, this expression recovers the LTE version of the line extinction coefficient.

The scattering part $\alpha^{\rm s}_{\nu_0}$ of $\alpha^l_{\nu_0}$ consists of $(\mathrm{b})+(\mathrm{c})-(\mathrm{g})$ and has

$$\begin{aligned}\alpha^{s}_{\nu_0} &= \frac{h\nu_0}{4\pi}\,n_1\,B_{12}\left[\frac{A_{21}}{P_{21}}+\frac{B_{21}J_{\nu_0}}{P_{21}}-J_{\nu_0}\frac{B_{21}}{P_{21}}\right] \\ &= \frac{h\nu_0}{4\pi}\,n_1\,B_{12}\frac{A_{21}}{P_{21}}, \end{aligned} \tag{8}$$

where contributions (c) and (g) cancel because both sequences require one photon from the beam (I_{ν_0}) and another one with arbitrary direction (J_{ν_0}) so that their probabilities are identical. Only the spontaneous part of the scattering remains.

Destruction probability. The profile-summed photon destruction probability for these sharp-line two-level atoms follows from (7)–(8):

$$\varepsilon_{\nu_0} \equiv \frac{\alpha^{\rm a}_{\nu_0}}{\alpha^{\rm a}_{\nu_0}+\alpha^{\rm s}_{\nu_0}} \tag{9}$$

$$= \frac{C_{21}\,[1-\exp(-h\nu_0/kT)]}{C_{21}\,[1-\exp(-h\nu_0/kT)]+A_{21}} \tag{10}$$

$$= \frac{C_{21}}{C_{21}+A_{21}/[1-\exp(-h\nu_0/kT)]} \tag{11}$$

$$= \frac{C_{21}}{C_{21}+A_{21}+B_{21}B_{\nu_0}}. \tag{12}$$

Another form often used in the literature (Jefferies 1968 p. 37, Mihalas 1970 p. 355, 1978 p. 337) is the thermal-to-scattering extinction ratio:

$$\varepsilon'_{\nu_0} \equiv \alpha^{\rm a}_{\nu_0}/\alpha^{\rm s}_{\nu_0} \tag{13}$$

$$= \frac{\varepsilon_{\nu_0}}{1-\varepsilon_{\nu_0}} \tag{14}$$

$$= \frac{C_{21}}{A_{21}}\,[1-\,{\rm e}^{-h\nu_0/kT}]. \tag{15}$$

Interpretation. The $(\mathrm{c}) - (\mathrm{g})$ cancelation of (8) is implicitly achieved by including the stimulated emission as negative correction to the line extinction. Contribution (c) counts no longer in the volume extinction coefficient, nor does (g) count in the volume emission coefficient. This cancelation is desirable because, if one would instead add (c) to the extinction and (e) to the emission, the non-corrected extinction coefficient would overestimate the actual attenuation of the beam across the volume, so that the optical depth scaling would not measure the actual opacity of the medium.

Version (11) for the destruction probability is the standard definition seen in the literature, often in the approximation $\varepsilon_{\nu_0} \approx C_{21}/(C_{21}+A_{21})$ neglecting stimulated emission (or as $\varepsilon'_{\nu_0} \approx C_{21}/A_{21}$). The Planck function B_{ν_0} appears in the B_{21} term in the numerator of (12), rather than the actual induced rate $B_{21}J_{\nu_0}$, due to the cancelation of induced scatterings in $\alpha^l_{\nu_0}$. In version (10) the thermal remainder of the induced deexcitations shows up as correction of the destruction term C_{21} for induced photon creation.

Thomson and Rayleigh scattering. Coherent Thomson and Rayleigh scattering may be seen as special sharp-line scattering, without contributions (a), (d) or (e). The classical Thomson cross-section, as derived from the harmonic oscillator, corresponds to the spontaneous scattering sequence in contribution (b). This is the right measure for the volume extinction since addition of contribution (c) would again add unwanted extinction due to the exact cancelation by contribution (g). Thus, $\alpha^{\rm T} = \sigma^{\rm T} N_{\rm e}$ and $j^{\rm T}_\nu = \alpha^{\rm T} J_\nu$, ignoring the stimulated scatterings.

In hot-star atmospheres, where thermal Dopplershifts are substantial, the corresponding J_ν differences are yet small so that induced scattering may still be neglected as is always done (*e.g.,* Rybicki and Hummer 1992). Only when the photons lose their identity through large frequency shifts must the induced continuum scattering processes be included, as in the Kompaneets version of the Fokker-Planck approximation (Sect. 7.6 of Rybicki and Lightman 1979).

Sofar the lecture notes. They continue with the standard derivation for two-level atoms with complete redistribution, writing out all the steps of the "some algebra" in detail because I do not expect my students to do what I wouldn't do. That derivation starts with writing down two-level statistical equilibrium and eventually produces the same expression for ε_{ν_0}.

What is the moral of this story? It took me a decade to grasp a basic equation of the field that I am supposed to teach expertly, defining a key parameter in its development by Athay, Thomas, Hummer and Jefferies at Boulder and Avrett at Harvard over thirty years ago. My major error was that I didn't heed the writings of these giants but tried to re-invent the wheel by myself. The first book that I studied in detail, Jefferies' (1968)

Spectral Line Formation as well as my bible in later years (Mihalas 1970, 1978) define epsilon correctly. I should have hesitated to think their epsilons approximate.

It is even worse than that. Jefferies' discussion (pages 36–37) should long ago have brought me to the original paper by Milne (1928) but I confess that I have looked it up only just now, while writing this, for the very first time. I completed the above segment of lecture notes last year without knowledge of this paper—and find now that I was re-thinking Milne's work seventy years late. Milne circumvented the profile functions by assuming the angle-averaged intensity J_ν to be constant over the line profile, essentially the same trick as making the line profile infinitesimally narrow. That is laid out clearly in Dick's landmark 1957 paper, where he redid Milne's derivation as the first step "along an expository approach" to the general case including higher levels and the continuum and then went on to his famous (calling it "gross" in the paper) division between collisional and photoelectric source function control.

Having finally returned to these original sources, the next version of my course will not only refer to them but integrate them as a natural step in the development, a matter of course in the supposedly linear development of insight. That's the way teachers falsify their presentation and hide their own convoluted ways of getting at the truth, stealing left and right to glibly improve their material on the run to the classroom. Enough reason to maintain my lecture notes as easily-updatable non-pretentious WWW files with a request for error notification.

The positive side of this story is that I eventually got back on the right track, and that the right track is actually well defined by the literature. Thus, it may take decades before the literature is properly appreciated by slow types like me, but eventually it is. This brings me back to Dick. I don't understand many of the points and claims in *Stellar Atmospheric Structural Patterns* but that may well change as time goes by. In that book, Dick talks to us aloud, alive and well. I have no notion of what Milne looked like, but Milne's work remains available and inspirational. By choosing to leave Nebraska for science, Dick chose a career in which his voice remains present and his ideas remain accessible in his writings. In science, good ideas survive. That is as close to eternity as one may get.

On publishing

Master's voices will survive even better in coming years. At present, students learn from lecture notes which are popularizations compressing long developments into student-ready condensations. My WWW lecture notes are primarily a simplifying popularization of Mihalas (1970), while Mihalas' book itself is a condensation of many hundreds of research papers. Mihalas faithfully recorded which treatment comes from where, and I faithfully list the book pages where my lecture notes come from, but no student goes back to the original sources. In my institute, that means a time-consuming hunt in the dark dungeons where journals from before 1970 are stacked. But with the upcoming format of hypertext textbooks and lecture notes, a click should provide the original passage or diagram side by side. Old texts will come alive again in scanned form, much like ancient records have come alive in CD re-issue—such as Casals performing the Bach suites. A click on my home page now gets you a copy of my lecture notes; clicking within the notes themselves should get you to the pertinent originals. This upcoming revolution is one to enjoy. I am sure Dick would have done so. His persistent push to publish pro- and con arguments, in the form of orange books but also conference discussions such as the rich ones in the *Aerodynamic Phenomena* proceedings, would have been gratified and inspired by the cross-linking feasible in hypertext.

The FIP flip

My last item concerns solar mass loss. Photon losses have been enough to keep me busy sofar, following tracks laid by Dick decades ago. I listened to his mass loss issues without taking much direct interest. Similarly, I have never felt the ambition to take part in the shift from solar MHD to nonsolar plasma physics that my Utrecht colleagues performed, finding greener pastures (at least less observationally constrained ones) in the glamorous topic of accretion disks. I regard magnetism in MHD disguise already too hard to fathom and radiation hydrodynamics as my tackling limit. After all, Dick skirted magnetism too, didn't he?

But recently, I stumbled over an intriguing phenomenon that combines mass loss and MHD and nevertheless seems to sit in the low solar atmosphere where I feel most comfortable. This is the FIP flip summarized in Fig. 3. The vertical axis measures relative abundance on a logarithmic scale with arbitrary zero point. It says that elements with FIP < 10 eV are four times overabundant compared with elements with FIP > 10 eV. FIP stands for the First Ionization Potential. The flip is a well-established deviation of the coronal and solar wind abundances from the composition of the solar photosphere. It is also prsent in solar energetic particles and even, astonishingly, in galactic cosmic rays (see reviews by Meyer 1985, 1991, 1993).

This amazing segregation must obviously occur in circumstances where difference in FIP makes a difference, so well before the high-FIP atoms loose their outer electrons and are accelerated into the solar wind. Therefore, the outer-atmosphere low-FIP excess must be due to some neutral-ion separation process in the chromosphere where hydrogen and C, N and O are still predominantly neutral. In this regime, the charged low-FIP particles (which are predominantly once-ionized even throughout the photosphere) are presumably line-tied to magnetic fields while the high-FIP neutrals may flow or diffuse transversely across field lines. The segregation must be sensitive to the topology of the magnetic field since it is much smaller or absent in the fast wind streams that emanate from the open-field regions.

There are various FIP-flip scenarios in the literature and I have suggested a cartoon one myself (Rutten 1997). The flip seems a direct diagnostic of solar mass loss physics in the boundary-condition regime where I would have thought mass transfer unmeasurable. It would be worthwhile to discuss it with Dick—and fun.

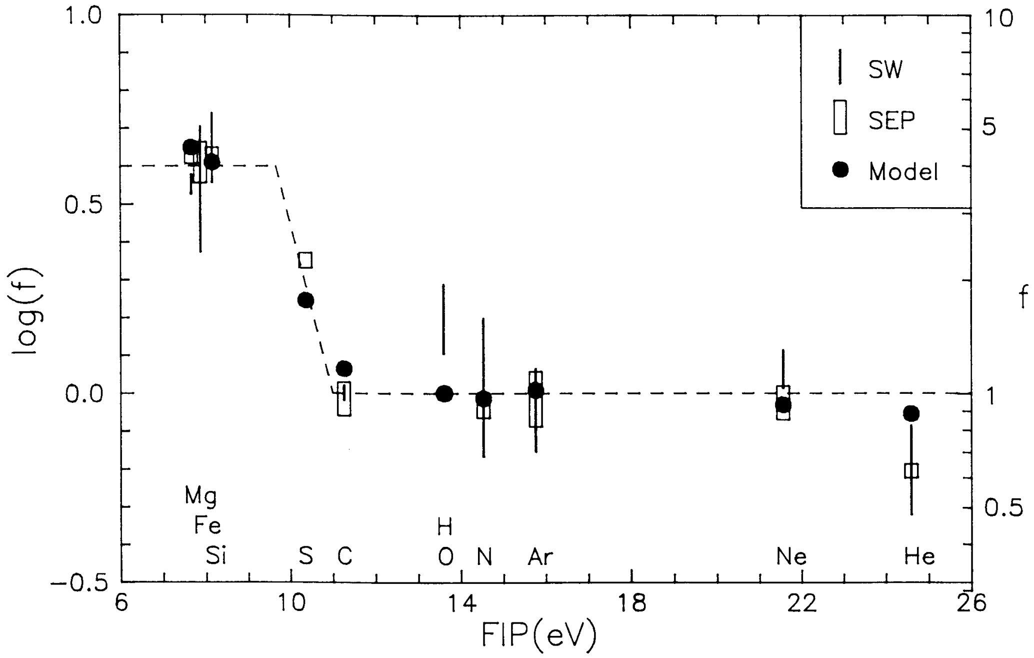

Figure 3: The FIP effect. The quantity f measures elemental abundance normalized by the photospheric value, on a relative scale with $\log f = 0$ assigned to oxygen. Bars (SW) are from in-situ slow solar wind sampling, rectangles (SEP) for solar energetic particles. The dots follow from a diffusion model. From Von Steiger and Geiss (1989).

References

Jefferies, J. T.: 1968, *Spectral Line Formation,* Blaisdell, Waltham, Mass.

Meyer, J. P.: 1985, “Solar-stellar outer atmospheres and energetic particles, and galactic cosmic rays”, *ApJS* **57**, 173

Meyer, J.-P.: 1991, “Diagnostic methods for coronal abundances”, *Advances in Space Research* **11**, 269

Meyer, J.-P.: 1993, “Elemental abundances in active regions, flares and interplanetary medium”, *Advances in Space Research* **13**, 377

Mihalas, D.: 1970, *Stellar Atmospheres,* W. H. Freeman and Co., San Francisco (first edition)

Mihalas, D.: 1978, *Stellar Atmospheres,* W. H. Freeman and Co., San Francisco (second edition)

Milne, E. A.: 1928, “The Effect of Collisions on Monochromatic Radiative Equilibrium”, *Mon. Not. R. Astron. Soc.* **88**, 493

Rutten, R. J.: 1990, “Sun-as-a-Star Line Formation”, in G. Wallerstein (Ed.), *Cool Stars, Stellar Systems and the Sun*, Proc. Sixth Cambridge Workshop, Astron. Soc. Pac. Conf. Series 9, p. 91

Rutten, R. J.: 1993, "High Resolution Solar Physics", in C. Mattok (Ed.), *Targets for Space-Based Interferometry*, Proc. ESA Coll. (Beaulieu), ESA SP-354, ESA Publ. Div., ESTEC, Noordwijk, p. 163

Rutten, R. J.: 1997, "Chromospheric Dynamics and the FIP flip", in B. Schmieder, J. C. T. del Iniesta, and M. Vázquez (Eds.), *Advances in the physics of sunspots*, Procs. ASPE 1996, Astron. Soc. Pac. Conf. Series, in press

Rybicki, G. B. and Hummer, D. G.: 1992, "An accelerated lambda iteration method for multilevel radiative transfer II. Overlapping transitions with full continuum", *Astron. Astrophys.* **262**, 209

Rybicki, G. B. and Lightman, A. P.: 1979, *Radiative Processes in Astrophysics*, John Wiley & Sons, Inc., New York

Shu, F. H.: 1991, *The Physics of Astrophysics I. Radiation*, University Science Books, Mill Valley

Stuik, R., Bruls, J. H. M. J., and Rutten, R. J.: 1997, "Modeling Li I and K I sensitivity to Pleiades activity", *Astron. Astrophys.* in press

Thomas, R. N.: 1957, "The Source Function in a Non-Equilibrium Atmosphere. I. The Resonance Lines", *Astrophys. J.* **125**, 260

Von Steiger, R. and Geiss, J.: 1989, "Supply of fractionated gases to the corona", *A&A* **225**, 222