

# The Quiet-Sun Photosphere and Chromosphere

BY ROBERT J. RUTTEN

*Sterrekundig Instituut, Utrecht University, Postbus 80 000, NL–3508 TA Utrecht,  
The Netherlands*

*Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029, Blindern,  
N–0315 Oslo, Norway*

*Lockheed-Martin Solar and Astrophysics Laboratory, 3251 Hanover Street, Palo Alto,  
CA 94304, USA*

The overall structure and the fine structure of the solar photosphere outside active regions are largely understood, except possibly important roles of a turbulent near-surface dynamo at its bottom, internal gravity waves at its top, and small-scale vorticity. Classical 1D static radiation-escape modelling has been replaced by 3D time-dependent MHD simulations that come closer to reality.

The solar chromosphere, in contrast, remains ill-understood although its pivotal role in coronal mass and energy loading makes it a principal research area. Its fine structure defines its overall structure, so that hard-to-observe and hard-to-model small-scale dynamical processes are the key to understanding. However, both chromospheric observation and chromospheric simulation presently mature towards the required sophistication. The open-field features seem of greater interest than the easier-to-see closed-field features.

**Keywords:** Sun, photosphere, chromosphere

## 1. Introduction

Solar photosphere–chromosphere–corona coupling is presently a premier research topic in trying to understand our star’s regulation of our environment. Large strides forward are made thanks to three methodological advances: (1) real-time and post-detection wavefront correction enabling 0.1'' resolution from meter-class optical telescopes, (2) continuous multi-wavelength high-cadence monitoring from space, (3) increasing realism of numerical simulations of solar-atmosphere fine structure.

This brief overview summarises the status, issues, and prospects in studying the lower solar atmosphere away from active regions. More detailed recent reviews of relevance are those of solar magnetism by Solanki et al. (2006)<sup>†</sup>, chromosphere observations by Judge (2006) and me (Rutten 2007), chromosphere modelling by Carlsson (2007), stellar chromospheres by Hall (2008), solar convection simulations by Nordlund et al. (2009), small-scale photospheric magnetism by De Wijn et al. (2009), magnetic photosphere-chromosphere coupling by Steiner (2010), and of supergranulation by Rieutord & Rincon (2010).

*Quiet Sun* denotes those areas of the solar atmosphere where magnetic activity is not obvious on the solar surface in wide-band optical continuum images.

*Photosphere* is a better descriptor than ‘surface’ for the thin near-spherical shell where the visible and infrared solar continua originate. It extends a few hundred km from the

<sup>†</sup> On-screen readers of the ArXiv pdf preprint may click on the year in a citation to open the corresponding ADS abstract page in a browser.

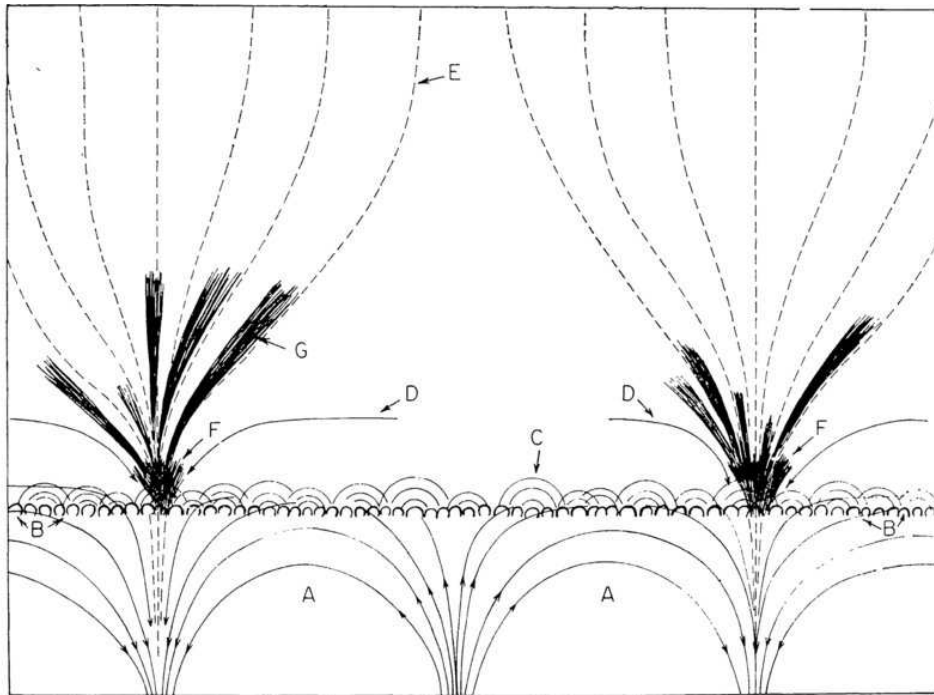


Figure 1. Sketch of the granulation-supergranulation-spicule complex in cross-section. A: flow lines of a supergranulation cell. B: photospheric granules. C: wave motions. D: large-scale chromospheric flow field seen in  $H\alpha$ . E: [magnetic] lines of force, pictured as uniform in the corona but concentrated at the boundaries of the supergranules in the photosphere and chromosphere. F: base of a spicule 'bush' or 'rosette', visible as a region of enhanced emission in the  $H\alpha$  and K-line cores. G: spicules. [...] The distance between the bushes is 30 000 km. Taken from Noyes (1967), including this caption.

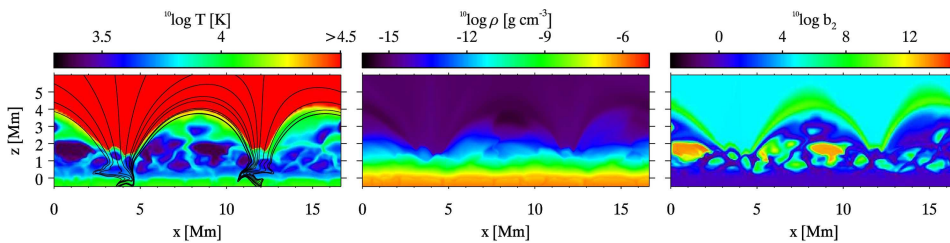


Figure 2. Cross-sections through a snapshot of a time-dependent 2D MHD simulation. The computational domain includes the top of the convection zone and reaches up to the corona. First panel: temperature, with superimposed field lines that are selected to chart the two magnetic concentrations. Second panel: gas density. Third panel: NLTE overpopulation of the  $n=2$  level of hydrogen, setting the  $H\alpha$  opacity. A movie, available at <http://www.astro.uu.nl/~rutten/rrweb/rjr-movies>, of the temporal variation of these cross-sections demonstrates that the narrow blue-green fronts in the clapotisphere under the internetwork canopy in the first panel represent shocks that travel upwards, mostly at a slant and with much mutual interference. They delimit very cool clouds (blue-black in the first panel) with gigantic HI  $n=2$  overpopulation (green-orange in the third panel). Taken from Leenaarts et al. (2007).

$\tau_{500} = 1$  Eddington-Barbier depth at which the radially emergent continuous intensity at  $\lambda = 500$  nm is approximately given by the continuum source function, which is dominated by bound-free  $H^-$  transitions. These contribute so much opacity that sunlight escapes only at much lower atmospheric gas density than that of the transparent air surrounding us. Slightly deeper continuum escape occurs in the opacity minima near  $\lambda = 400$  nm (with shortward onset of important metal ionisation edges that provide the  $H^-$  electrons) and  $\lambda = 1.6 \mu\text{m}$  ( $H^-$  bound-free threshold, with longward increase of the  $H^-$  free-free contribution).

Yet deeper escape, about 100–200 km, takes place within slender magnetic concentrations of kilogauss strength. In these, the magnetic pressure contribution to hydrostatic balancing reduces the gas density. Such fluxtubes constitute network as loose ‘filigree’ alignments along intergranular lanes at supergranular boundaries. At larger activity, they constitute plage in the form of denser clusters that inhibit normal granulation.

In addition, there appears to be abundant magnetism at much lower strength. Other quiet-photosphere ingredients are the ubiquitous granulation due to turbulent convection, overshoot phenomena including internal gravity waves, the supergranulation, and copious acoustics that are dominated by global  $p$ -mode standing-wave interference but also contain outward propagating waves from local excitation at granular scales.

*Chromosphere* does not stand for a spherical shell but for a thin, very warped and highly dynamic interface surface that comes down deep in and near kilogauss concentrations but rides high on acoustic shocks in otherwise cool internetwork (cell interior) gas. I call the latter domain the ‘clapotsphere’ (Rutten 1995) and reserve ‘chromosphere’ for the fibrillar canopies seen in  $H\alpha$ . These appear to be structured by the fields that extend from network and plage. The fibrils correspond to the off-limb spicule forest whose pink Balmer-line emission gave the chromosphere its name (Lockyer 1868). The transition region to the corona is likely a thin envelope to the fibrillar chromosphere. The principal ingredients defining chromospheric structure and dynamics are, for decreasing activity, magnetic reconnection, current heating, Alfvén waves, magnetically guided and/or converted acoustic waves, possibly gravity waves and torsional waves, and photon losses in strong lines.

In terms of physics, the principal quiet-Sun photospheric agents are gas dynamics and near-LTE radiation loss outside magnetic concentrations, magnetohydrodynamics (MHD) within the latter. These processes are presently emulated well in 3D time-dependent simulations of photospheric fine structure. The spatial simulation extent is still too small to contain full-fledged active regions, but sunspots (*e.g.*, Rempel 2011) and supergranules (Ustyugov 2008; Stein et al. 2009) come into reach. Higher up, the radiation losses become severely non-equilibrium (NLTE, PRD, time-dependent population rates) and the magnetogasdynamics becomes multi-fluid. These complexities constitute a challenging but promising modelling frontier.

## 2. The scene

Figure 1 sets the quiet-Sun scene for this overview. This sketch comes from the outstanding discussion by Noyes (1967) of the ingenious Doppler imaging first described in the seminal ‘Preliminary report’ of Leighton et al. (1962). The latter contained the discovery of the supergranulation, reversed granulation, five-minute oscillation, upward-propagating chromospheric waves, and rapidly changing chromospheric flows, all in a single paper! The various symbols in Noyes’s sketch define characteristic fine structure of the solar photosphere and chromosphere. The photospheric granulation, waves, and strong-field concentrations

are now largely understood<sup>†</sup> The photospheric supergranulation and the chromospheric structures and flows are not.

Figure 2 from Leenaarts et al. (2007) is not a cartoon but a snapshot from a time-dependent simulation representing state-of-the-art numerical implementation of the physics of MHD and radiative transfer in the solar atmosphere. The code of Hansteen et al. (2007) was used; other codes are described by Freytag et al. (2002), Schaffenberger et al. (2006), Vögler et al. (2005), Gudiksen & Nordlund (2005) and Gudiksen et al. (2011). In this case, one spatial dimension was sacrificed to make non-equilibrium evaluation of hydrogen population rates tractable (cf. Kneer & Nakagawa 1976; Carlsson & Stein 1992, 2002; Rammacher & Ulmschneider 2003). This is essential above the photosphere where shocks abound. The slowness of H ionisation/recombination balancing in the cool post-shock aftermaths makes hydrogen a much less effective internal energy buffer than it would be for instantaneous statistical equilibrium or LTE, and strongly affects the thermodynamics. The slow post-shock balancing also causes huge NLTE over-opacities of H $\alpha$  (third panel).

The two figures have much similarity. Each contains granules, oscillations, flows, and two magnetic concentrations in the photosphere (unipolar in figure 1, bipolar in figure 2) whose fields spread out at larger height.

There are also dissimilarities. A key one concerns the ‘chromospheric flow field seen in H $\alpha$ ’ marked by D in figure 1 that describes flows along cell-covering fibrils. In H $\alpha$  filtergrams such long internetwork fibrils appear ubiquitously, constituting an opaque chromospheric blanket all over the Sun except in extremely quiet areas. At the limb these fibril canopies provide an opaque floor to the H $\alpha$  spicule forest, *i.e.*, much of Lockyer’s chromosphere. However, the simulation snapshot (figure 2) does not contain such internetwork fibrils. The green arches in the third panel look suggestively as such, but these remain optically thin in H $\alpha$  even while marking H $\alpha$  opacities as much as  $10^8$  in excess of LTE.

Underneath these fibrils the sketch specifies wave motions; correspondingly, under the arches the simulation snapshot has large clapotospheric clouds of cool gas that are permeated by repetitive shocks. The latter push the chromospheric interface with the corona up to heights around 3–4 Mm, as high as the flow-mapping H $\alpha$  fibrils in the sketch. Near the magnetic concentrations the shocks are field-guided and jut out with repetitive extension and retraction to 2–3 Mm height (figure 3 of Leenaarts et al. 2007). More on these dynamic fibrils below, and also on straws/spicules-II/RBEs and weak fields which do not figure in these diagrams.

### 3. Photosphere

#### (a) Overall structure

*1D modelling.* Schwarzschild (1906) wrote, in Loeser’s translation in the compilation by Menzel (1962): “*the sun’s surface displays changing conditions and stormy variations [...] It is customary, as first approximation, to substitute mean steady-state conditions for these spatial and temporal variations, thus obtaining a mechanical or ‘hydrostatic equilibrium’ of the solar atmosphere*” and established that “*the equilibrium conditions of the solar atmosphere correspond generally to those of radiative equilibrium*”. In cool-

<sup>†</sup> Understood in terms of their structural physics and how their observational diagnostics arise. The unsolved riddles of how network fields come, assemble, cancel, disperse, and go are outside the scope of this article, as are *a fortiori* the structure, formation, evolution, and decay of active regions and filaments and their outbursts. The dynamo and activity cycle remain grand questions (cf. Spruit 2011).

star abundance studies, stellar-atmosphere modellers usually assume these equilibria plus mixing-length convection at the bottom of the photosphere.

In contrast, solar abundance determiners have typically used empirical spectrum-fitting models, in particular the HOLMUL update by Holweger & Müller (1974) of the LTE line-fitting model of Holweger (1967). They preferred this over the much more sophisticated NLTE continuum-fitting FALC model of Fontenla et al. (1993) because HOLMUL has no chromospheric temperature rise which would produce self-reversals in LTE-computed strong lines that are not observed. The mid-photosphere parts of these empirical models are so similar and so close to radiative-equilibrium predictions that LTE and RE seem reasonable first approximations where  $H^-$  radiation loss is the major stratification agent.

*NLTE masking.* FALC's classic VAL3C predecessor, formulated in the three monumental papers of Vernazza, Avrett & Loeser (1973, 1976, 1981), had a significantly cooler upper photosphere than HOLMUL. Such a steeper temperature gradient produces deeper lines, but also appreciable near-ultraviolet overionisation of species such as Fe I (Lites 1972). The resulting NLTE reduction of Fe I opacities offsets the line strengthening; Rutten & Kostik (1982) called this fortuitous cancellation 'NLTE masking'. Avrett's subsequent and most recent (Avrett & Loeser 2008) modelling includes a large number of ultraviolet lines to provide a quasi-continuous line haze (e.g., Greve & Zwaan 1980; Kurucz 2009) that resulted in a less steep, HOLMUL-like photosphere which was copied into FALC. All these lines are set to share an ad-hoc transition from LTE to pure scattering to avoid core reversals (see Rutten 1988). This NLTE opacity issue crops up again in modelling photospheric fine structure with steep temperature gradients (Shchukina & Trujillo Bueno 2001).

*Microturbulence.* All 1D modelling uses Struve's microturbulence as a free adjustment factor to account for ignored fine structure in matching observed spectral lines. It is the most arbitrary of the four classical stellar-atmosphere parameters (effective temperature, surface gravity, metallicity, turbulence) – Chandrasekhar (1949) quoted Russell's attribution "*to the direct intervention of the Deity*". In 1D solar modelling it became a bag of fudge parameters. Macroturbulence and height dependence were added, de Jager & Vermue (1977) defined functional kinetic-energy spectrum filters, Gray (1977) added anisotropy. VAL3C and FALC shared sizable microturbulence with large variation with height (figure 11 of Vernazza et al. 1981). The underlying assumption that the unresolved fine structure and dynamics can be described as a Gaussian convolution (of the extinction coefficient for micro, of the emergent intensity profile for macro, respectively) appears untenable (Uitenbroek & Criscuoli 2011).

#### (b) Fine structure

*Granulation.* The granulation became initially understood by Nordlund's early simulations (e.g., Nordlund 1982, 1984) and more so when he teamed up with Stein (e.g., Stein & Nordlund 1989, 1998; Nordlund & Stein 1990; Nordlund et al. 2009) and with the identification of radiative surface cooling as the major driver (Rast 1995). Current granulation research targets small vortices (Bonet et al. 2008, 2010; Steiner et al. 2010; Kitiashvili et al. 2011; Shelyag et al. 2011), supersonic flows (Bellot Rubio 2009; Vitas et al. 2011), flow bending (Khomenko et al. 2010), and intergranular jets (Goode et al. 2010; Yurchyshyn et al. 2011).

*Abundances.* The use of 3D Nordlund-Stein granulation simulations instead of 1D modelling with ad-hoc turbulence resulted in substantial downward revisions of key abundances, upsetting helioseismology and stellar evolution theory (e.g., Asplund et al. 2004,

2005; Pereira et al. 2009b, 2009a; Nordlund et al. 2009, Asplund et al. 2009). However, Caffau et al. (2009, 2011) report only small changes from the 1D to 3D paradigm shift and do not confirm such drastic revision. Fabbian et al. (2010) found that adding moderate magnetic flux has appreciable influence on iron abundance determination. These issues remain open.

*Reversed granulation.* In the mid-photosphere the granular intensity contrast reverses. The observations of Rutten et al. (2004) were well reproduced by the simulation of Leenaarts & Wedemeyer-Böhm (2005). Cheung et al. (2007) provided detailed explanation using the MHD code of Vögler et al. (2005). The phenomenon comes from overturning flows and produces marked imaging asymmetry between the wings of Na I D<sub>1</sub> (Rutten et al. 2011).

*Acoustic oscillations.* The simulations have self-excited acoustic box modes that are not too dissimilar from global *p*-modes (Nordlund & Stein 2001; Stein & Nordlund 2001). They serve to study stochastic mode excitation in near-surface convection for the Sun and other stars (*e.g.*, Samadi et al. 2003, 2007). Earlier, Goode and coworkers searched for identifiable *p*-mode exciters (*e.g.*, Restaino et al. 1993; Rimmele et al. 1995; Goode et al. 1998; Strous et al. 2000) for which the collapsars (small vanishing granules) of Rast (1999) and Skartlien et al. (2000) became the principal candidate. These indeed generate excess acoustics (Hoekzema et al. 2002).

*Magnetic concentrations.* Figure 1 is from before the identification of magnetic network elements as kilogauss fluxtubes by Frazier & Stenflo (1978) with Stenflo's (1973) line ratio technique. In the magnetostatic thin-fluxtube model of Spruit (1976) following ideas of Zwaan (1967), the inside magnetic pressure balances part of the outside gas pressure; the latter's outward drop makes the fluxtube expand with height. This paradigm was put on firm observational footing by Solanki and coworkers through best-fit modelling of the spatially unresolved signature of small kilogauss concentrations in multi-line spectropolarimetry (see the extensive review by Solanki 1993), and subsequently confirmed with MHD simulations, first in 2D (*e.g.*, Grossmann-Doerth et al. 1994, 1998; Steiner et al. 1998; Gadun et al. 2001; see also the two examples in figure 2), then in 3D (*e.g.*, Carlsson et al. 2004; Vögler et al. 2005; Yelles Chaouche et al. 2009). Newer research addresses wave excitation and diagnostics (Khomenko et al. 2008; Vigeesh et al. 2009, 2011; Kato et al. 2011).

*Magnetic bright points.* Many studies of small strong-field concentrations employ their alter-ego as network bright points (or magnetic knots, filigree grains, facular points, *etc.*) which are easier to observe, easiest in the G band of CH lines around  $\lambda = 430.5$  nm following Muller & Roudier (1984) but also in the wings of strong lines (Leenaarts et al. 2006a). They are not points, becoming flowers and ribbons with much substructure at high resolution (Berger et al. 2004; Abramenko et al. 2010). The upshot of the extended literature reviewed by De Wijn et al. (2009) is that they are useful indicators of magnetic concentrations in imaging 'proxy' magnetometry, but without precise one-to-one correspondence to the actual fields. Their brightness was explained by Spruit (1976) and Spruit & Zwaan (1981). It is not due to magnetic energy dissipation but comes from the hot walls that fluxtubes have below the outside surface because the viewing depth inside is 100–200 km deeper from the partial evacuation. In molecular bands dissociation increases the contrast with the outside granulation, as does ionisation for atomic lines and smaller collisional damping for strong-line wings. Towards the limb facular brightening results because viewing along a slanted line of sight penetrates through the tube into the granule behind it.

Detailed MHD simulations give good bright-point and facular agreement with observations (*e.g.*, Keller et al. 2004; Shelyag et al. 2004; Carlsson et al. 2004; Steiner 2005; Leenaarts et al. 2006b; Vitas et al. 2009; Wedemeyer-Böhm & Rouppe van der Voort 2009a). Irradiance modelling must cope with the inherently 3D nature of limbward facular brightening (Unruh et al. 2009).

*Weak and horizontal fields.* Neither figure 1 nor figure 2 shows the weak tangled inter-network fields detected with sensitive spectropolarimetry (Khomenko et al. 2003; Trujillo Bueno et al. 2004; Lites et al. 2007; Martínez González et al. 2010) and predicted by near-surface convective dynamo simulations (Cattaneo 1999; Vögler & Schüssler 2007). They seem to close on granular scales in the mid-photosphere, appearing there as relatively strong horizontal field (Lites et al. 2008; Steiner et al. 2008; Schüssler & Vögler 2008).

*Inversion modelling.* The La Laguna inversion school initiated by Ruiz-Cobo et al. (1990, 1992) has produced multiple codes that emulate HOLMUL-like empirical model construction by best-fit stratification modelling per observed pixel (*e.g.*, Socas-Navarro et al. 2001, 2008; Asensio Ramos et al. 2008; de la Cruz Rodríguez et al. 2010; Borrero et al. 2010). They serve especially to map flows and magnetic fields from full-Stokes line profiles. Many use the Milne-Eddington approximation of constant line/continuum opacity ratio; some use slab geometry. Many fit spline functions with height through a few anchor points. The approach generally works well in the photosphere where most radial behaviour is smooth.

## 4. Clapotisphere

### (a) Overall structure

*1D modelling.* The six VAL3 models of Vernazza et al. (1981) representing quiet-Sun conditions were made by fitting bins of different observed ultraviolet intensities with different temperature stratifications, all sharing the basic structure of photospheric decline, temperature minimum, extended raised chromospheric plateau, and a steep rise to coronal values called the transition region. Brighter spectra were reproduced by models that are slightly hotter throughout their upper parts and have a deeper-located transition region. With these models the term ‘chromosphere’ became to mean the raised-temperature plateau between the VAL3C temperature minimum at  $h = 500$  km and transition region at  $h = 2100$  km, rather than  $H\alpha$  fine structure.

However, collapsing the internetwork parts and network parts, respectively, of figures 1 and 2 to column averages would make sense only if the spatiotemporal fluctuations were small, but they are not at heights where the atmosphere suffers frequent shocks. The slight differences between the different VAL3 models (and for the similar grids of Fontenla et al. (1993, 2002, 2006, 2007, 2009) should be contrasted with the much larger temporal variations along columns in figure 2. In a movie<sup>†</sup> of this behaviour, the internetwork clapotisphere consists of very cool gas that is every few minutes ridden through by shocks. That such shocks invalidate static modelling was established already with the beautiful Ca II  $H_{2V}$  grain simulation by Carlsson & Stein (1994, 1995, 1997).

The existence of cool clouds that are incompatible with static 1D modelling was long before advocated by Ayres on the basis of deep CO line cores (*e.g.*, Ayres 1981; Ayres & Rabin 1996; Ayres 2002). In simulations the clapotispheric gas gets as cool as 2000 K.

<sup>†</sup> [http://www.astro.uu.nl/~ruttten/rrweb/rjr-movies/hion2\\_fig2\\_movie.mov](http://www.astro.uu.nl/~ruttten/rrweb/rjr-movies/hion2_fig2_movie.mov)

Leenaarts et al. (2011) conclude that such low temperatures are unavoidable unless there is weak-field heating not present in such simulations.

ALMA may deliver direct mm-radiation diagnostics of the spatiotemporal temperature behaviour (*e.g.*, Loukitcheva et al. 2004, 2006.)

### (b) Fine structure

*Acoustic shocks.* Many shocks in the movie companion to Figure 2 run at a slant, which explains why Carlsson & Stein (1997) found only a few locations in the observations of Lites et al. (1993) with well-defined  $H_{2V}$  grain sequences that they could faithfully reproduce one-dimensionally. The grains obtain their characteristic violet/red asymmetry from the presence of both a hot shock and higher-up post-shock downdraft along the line of sight; grain sequences imply vertical shock propagation. The slanted-shock interaction patterns indeed resemble clapotis (wild wave interference on rivers and oceans).

*Gravity waves.* Gravity waves should be copiously excited in the convective overshoot above the granulation (*e.g.*, Whitaker 1963; Stein 1967; Lighthill 1967; Mihalas & Toomre 1981, 1982), but are hard to diagnose (*e.g.*, Brown & Harrison 1980; Deubner & Fleck 1989; Rutten & Krijger 2003). Recent estimates combining Fourier observations with simulations, but applying linear theory, suggest that the gravity-wave energy flux into the upper chromosphere is comparable to the acoustic flux (Straus et al. 2008; Kneer & Bello González 2011). These waves remain understudied.

*Quietest Sun.* In the quietest areas  $H\alpha$  line-centre images show no cover-all fibril carpet but only network rosettes consisting of short mottles, and very dynamic cell interior between these. A fast-cadence  $H\alpha$  movie<sup>†</sup> of the latter from the data of Rouppe van der Voort et al. (2007) shows mushrooming three-minute oscillation blobs that break up into very narrow, fast-moving, probably hot, filamentary structures. Possibly these mark shock interference, or conversion into weak-field canopy waves, or tiny magnetic filaments as described by Schaffenberger et al. (2006), or shock-excited high-frequency oscillations as proposed by Reardon et al. (2008). Wedemeyer-Böhm & Rouppe van der Voort (2009b) reported swirl motions in such areas. These quiet-Sun phenomena also need further study, but require exceedingly high spatial and temporal resolution.

*Wave-field interaction.* The shocks push the clapotispheric transition region to large height because magnetic refraction and mode conversion become important only at low plasma-beta (Bogdan et al. 2002; Rosenthal et al. 2002). The ubiquitous presence of shock waves in both the observations and MHD simulations suggests that weak fields play no large role in the clapotispheric (cf. Steiner 2010), nor the multi-scale magnetic carpet proposed by Schrijver & Title (2003). Gravity waves convert easier into Afvén waves than acoustic waves (Lighthill 1967); their amplitude may be a canopy mapper (figure 5 of Rutten 2010).

## 5. Chromosphere

### (a) Overall structure

*1D modelling.* In the magnetic network shocks arise even deeper. The fluxtube simulation by Steiner et al. (1998) already suggested that photospheric shocks frequently arise in and near magnetic concentrations, excited by strong adjacent downflows driven by radiative

<sup>†</sup> <http://www.astro.uu.nl/~rutten/rrweb/rjr-movies/2006-06-18-quiet-ca+hawr.avi>



cooling through the tube walls. Recently, Kato et al. (2011) elaborated the mechanism, calling it magnetic pumping. The movie version of figure 2 also shows much shock activity in and near the magnetic concentrations. In the simulation of Leenaarts et al. (2010) magnetic-concentration shocks occur as low as  $h = 300$  km and affect the core of Na I D<sub>1</sub>. The Na I D<sub>1</sub> observations of Jess et al. (2010) and Rutten et al. (2011) confirm such shock sensitivity. It makes Na I D<sub>1</sub> Dopplergrams effective proxy-magnetograms by marking magnetic concentrations through the resulting core asymmetry. This ubiquity of deep-seated shocks invalidates static 1D modelling even more for network than for internetwork.

*Chromospheric heating.* Classically, the chromospheric heating budget was determined by evaluating the net radiative cooling in a standard model (figure 49 of Vernazza et al. 1981) or determining the amount of excess heating over radiative equilibrium that is needed to obtain such models (Anderson & Athay 1989). However, Carlsson & Stein (1995) demonstrated that a cool but shock-ridden clapotisphere delivers the hot VAL3C chromosphere when fitting ultraviolet continua, due to the non-linear Planck sensitivity to the hottest phases. In addition, the enhanced network brightness in these continua (in which network appears as in Ca II H & K filtergrams, bright but without fibrils as in H $\alpha$ ) is a mix of scattered photospheric fluxtube-wall radiation, brightness from Joule heating (Carlsson et al. 2010), and a haze of unresolved high-reaching spicules-II (see below). Modelling these diverse contributions as radiation loss at the height of 1D non-fluxtube continuum formation is a severe simplification.

The long debate whether acoustic waves provide important ubiquitous chromosphere heating has ‘no’ as the present answer (Fossum & Carlsson 2005).

#### (b) *Fine structure*

*Internetwork fibrils.* The long H $\alpha$  fibrils that cover (parts of) cell interiors were called ‘flow mappers’ by Noyes in figure 1. However, flows along them have been studied only scarcely for quiet-Sun conditions (Contarino et al. 2009). Watching H $\alpha$  movies gives a strong impression that the fibrils constitute canopies that ride on the clapotisphere. Rutten et al. (2008) found that they partake in shocks coming up underneath, as also evident in the Doppler timeslices of Cauzzi et al. (2009). The co-aligned image mosaics at <http://www.arcetri.astro.it/science/solare/IBIS/gallery> indicate that the transition region morphology seen in He II 304 Å follows the H $\alpha$  fibril pattern.

So far, the MHD simulations do not produce these long fibrils. Why not is not clear, perhaps a lack of resolution, extent, radiation physics, magnetic complexity, and/or history.

The long H $\alpha$  fibrils are often taken to outline chromospheric fields. Indeed, their filamentary patterns give a vivid impression of magnetic connectivity. However, direct correspondence remains unproven (de la Cruz Rodríguez & Socas-Navarro 2011), and the thermal and dynamic fine structure evidenced by the fibrils may be more complex than the field structure (Judge 2006). Since Ca II 854.2 nm responds to higher temperature with larger brightness while H $\alpha$  does not (Cauzzi et al. 2009), H $\alpha$  brightness may be the better field mapper if Ca II 854.2 nm brightness shows non-aligned features along heating sites. Also, the fibril canopies have less opacity in Ca II 854.2 nm so that this line instead shows clapotispheric acoustics in internetwork hearts (Vecchio et al. 2009).

If H $\alpha$  fibrils do map chromospheric fields, then extrapolation using the observed H $\alpha$  fibril connectivity as a constraint may help in nonlinear force-free field prediction of the shape and free-energy loading of coronal fields from photospheric magnetograms (Bobra et al. 2008; Wiegelmann et al. 2008). If so, space-weather prediction will eventually need

continuous high-resolution full-disk  $H\alpha$  imaging, best done from space with large detector mosaics. Direct polarimetric measurement of chromospheric fields is an important driver for large solar telescopes, but reaching quiet-Sun fibril mapping is a daunting challenge.

*Dynamic fibrils.* Near network and plage shorter fibrils are seen in  $H\alpha$  as extending and contracting stalks with abrupt transition-region caps (Suematsu et al. 1995), and similarly in  $Ly\alpha$  (Koza et al. 2009). These became a chromospheric success story with the work of Hansteen et al. (2006) and De Pontieu et al. (2007a), who identified them as  $p$ -mode-driven field-guided shocks that slant up from network and plage. The slant helps the waves to propagate by reducing the effective gravity (Michalitsanos 1973; Bel & Leroy 1977; Suematsu 1990). They are more upright than the long cell-covering fibrils and seem to stick out as regular ('type-I') spicules above the dense carpet made by those at the limb.

*Spicules-II/straws/RBEs.* These features (respectively off-limb/near-limb/on-disk) also border network and plage but they are yet more upright, slenderer, more dynamic, and reach higher. They were found in Ca II H near the limb and called 'straws' by me (Rutten 2006), observed as 'type-II spicules' in Ca II H off the limb by De Pontieu et al. (2007b, 2007c), and identified on the disk as dark 'rapid blue excursions' (RBEs) in the blue wings of Ca II 854.2 nm and  $H\alpha$  by Langangen et al. (2008) and Rouppe van der Voort et al. (2009). They may also be diagnosed from EUV line asymmetries (McIntosh et al. 2008; Hara et al. 2008; Hansteen et al. 2010; Martínez-Sykora et al. 2011a; Tian et al. 2011). They are probably a key player in providing mass and energy to the corona outside active regions (De Pontieu et al. 2009). Recently, De Pontieu et al. (2011) traced RBEs as coronal heating events in ultraviolet images. They appear as jets that send up bullets of hot gas with precursor fronts at coronal temperatures which continue up and out while the bullets drop back. These dynamic features occur near network and plage all over the Sun, not preferentially in bipolar areas or coronal holes. At the limb they appear as long spicules (up to 10 Mm, as in figure 1) that sway rapidly, likely from Alfvén waves (De Pontieu et al. 2007c).

The recent MHD simulation of a spicule-II-like event by Martínez-Sykora et al. (2011b) suggests a tangential field discontinuity in the chromosphere due to small-scale flux emergence as the principal ingredient, reminiscent of the squeezed tubes of Babcock & Babcock (1955), "*exciting upward travelling waves [...] with tenuous clouds of ions and electrons squeezed ahead*". Perhaps with helical motion as suggested by Beck & Rezaei (2011).

*Data inversion.* Spline-function inversion techniques lose credibility where chromospheric and chromospheric fluctuations are too wild for smooth 1D fitting. Fibrils are like overlying Schuster-Schwarzschild slabs, and so the filamentary nature of the chromosphere suggests cloud modelling. Inversion techniques using multi-parameter cloud profile synthesis have been reviewed by Tziotziou (2007); cloud modelling presently reaches its highest sophistication in filament-thread analysis (e.g., Gouttebroze & Labrosse 2009). The slowness of hydrogen (and worse for helium) ionisation/recombination balancing in post-shock gas plus the ubiquity of frequent shocking requires knowledge of the local history, if not the wide-area history including the field topography. Presently, grasping the physics processes via forward modelling by simulation with line synthesis has higher priority.

## 6. Conclusion

The overall and the fine structure of the quiet photosphere are largely understood. The structure of the clapotisphere is reasonably understood. The fine structure of the quiet chromosphere (of which the spatiotemporal mean is not of interest) is not understood excepting dynamic fibrils, but holds the key to the mass and energy loading of the quiet-Sun outer atmosphere. The upcoming large groundbased telescopes, ultraviolet space missions and increased realism of MHD simulations should combine into substantial progress in this premier solar physics frontier.

Because open fields (in a local sense) harbour more upward connectivity than closed fields, they are the ones to concentrate on even though the corresponding fine structure is harder to observe. In the quiet-Sun photosphere these are the kilogauss field concentrations, in the quiet-Sun chromosphere spicules-II/straws/RBEs.  $H\alpha$  mapping of closed fields (within the chromosphere) appears especially useful for eruptivity prediction.

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