REVIEW

The quiet-Sun photosphere and chromosphere

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The overall structure and the fine structure of the solar photosphere outside active regions are largely understood, except possibly the important roles of a turbulent near-surface dynamo at its bottom, internal gravity waves at its top and small-scale vorticity. Classical one-dimensional static radiation-escape modelling has been replaced by three-dimensional time-dependent magneto-hydrodynamic simulations that come closer to reality. The solar chromosphere, in contrast, remains little 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 key to understanding. However, both chromospheric observation and chromospheric simulation presently mature towards the required sophistication. Open-field features seem of greater interest than 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 have been made owing to three methodological advances: (i) real-time and post-detection wavefront correction, enabling 0.1" resolution from metre-class optical telescopes, (ii) continuous multi-wavelength high-cadence monitoring from space, and (iii) increasing realism of numerical simulations of solar–atmosphere fine structure.

This brief overview summarizes the status, issues and prospects in studying the lower solar atmosphere away from active regions. More detailed recent reviews

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One contribution of 11 to a Theme Issue ‘Astrophysical processes on the Sun’. 
of relevance are those of solar magnetism by Solanki et al. [1], chromosphere observations by Judge [2] and Rutten [3], chromosphere modelling by Carlsson [4], stellar chromospheres by Hall [5], solar convection simulations by Nordlund et al. [6], small-scale photospheric magnetism by De Wijn et al. [7], magnetic photosphere–chromosphere coupling by Steiner [8], and of supergranulation by Rieutord & Rincon [9].

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 \( \tau_{500} = 1 \) Eddington–Barbier depth at which the radially emergent continuous intensity at \( \lambda = 500 \text{ nm} \) is approximately given by the continuum source function, which is dominated by bound-free H\(_{\alpha}\) transitions. These contribute so much opacity that sunlight escapes only at much lower atmospheric gas density than that of the transparent air surrounding us. A slightly deeper continuum escape occurs in the opacity minima near \( \lambda = 400 \text{ nm} \) (with shortward onset of important metal ionization edges that provide the H\(_{\alpha}\) electrons) and \( \lambda = 1.6 \mu\text{m} \) (H\(_{\alpha}\) bound-free threshold, with longward increase of the H\(_{\alpha}\) 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 flux tubes 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 that 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 an otherwise cool internetwork (cell interior) gas. I call the latter domain the ‘clapotisphere’ [10] and reserve ‘chromosphere’ for the fibrilar 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 [11]. The transition region to the corona is likely a thin envelope to the fibrilar 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.

\(^{1}\)On-screen readers of the ArXiv pdf preprint may click on the year in a citation to open the corresponding Astrophysics Data System abstract page in a browser, making the (overly page-consuming) reference list superfluous.
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 Hα. 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 Hα and K-line cores. G, Spicules. […] The distance between the bushes is 30,000 km. Reproduced with permission from Noyes [15], including this caption.

In terms of physics, the principal quiet-Sun photospheric agents are gas dynamics and near-local thermodynamic equilibrium (near-LTE) radiation loss outside magnetic concentrations, magnetohydrodynamics (MHD) within the latter. These processes are presently emulated well in three-dimensional time-dependent simulations of photospheric fine structure. The spatial simulation extent is still too small to contain full-fledged active regions, but sunspots [12] and supergranules [13,14] come into reach. Higher up, the radiation losses become severely non-equilibrium (non-local thermodynamic equilibrium (NLTE), partial redistribution, time-dependent population rates), and the magneto-gasdynamics 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 [15] of the ingenious Doppler imaging
Figure 2. Cross sections through a snapshot of a time-dependent two-dimensional MHD simulation. The computational domain includes the top of the convection zone and reaches up to the corona. (a) Temperature, with superimposed field lines that are selected to chart the two magnetic concentrations. (b) Gas density. (c) NLTE overpopulation of the \( n = 2 \) level of hydrogen, setting the H\( \alpha \) opacity. A movie, available at http://www.staff.science.uu.nl/~rutte101/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 (a) represent shocks that travel upwards, mostly at a slant and with much mutual interference. They delimit very cool clouds (blue–black in (a)) with gigantic H\( \text{I}\ n = 2 \) overpopulation (green–orange in (b)). Reproduced with permission from Leenaarts et al. [18]. (Online version in colour.)

The photospheric granulation, waves and strong-field concentrations are now largely understood.\(^2\) The photospheric supergranulation and the chromospheric structures and flows are not.

Figure 2 from Leenaarts et al. [18] 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. [19] was used; other codes are described by Freytag et al. [20], Schaffenberger et al. [21], Vögler et al. [22], Gudiksen & Nordlund [23] and Gudiksen et al. [24]. In this case, one spatial dimension was sacrificed to make non-equilibrium evaluation of hydrogen population rates tractable (cf. [25–28]). This is essential above the photosphere where shocks abound. The slowness of H ionization/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\( \alpha \) (figure 2c).

Figures 1 and 2 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 a larger height.

\(^2\)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. [17]).
There are also dissimilarities. A key one concerns the ‘chromospheric flow field seen in Hα’ marked by D in figure 1 that describes flows along cell-covering fibrils. In Hα, filtergrams such as 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 Hα spicule forest, i.e. much of Lockyer’s chromosphere. However, the simulation snapshot (figure 2) does not contain such internetwork fibrils. The high arches in figure 2c look suggestively as such, but these remain optically thin in Hα, even while marking Hα 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 clapotispheric 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 Hα 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 (fig. 3 of Leenaarts et al. [18]). More on these dynamic fibrils below, and also on straws/spicules-II/rapid blue excursions (RBEs) and weak fields, which do not figure in these diagrams.

3. Photosphere

(a) Overall structure

(i) One-dimensional modelling

Schwarzschild [29] wrote, in Loeser’s translation in the compilation by Menzel [30]: ‘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-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 [31] of the LTE line-fitting model of Holweger [32]. They preferred this over the much more sophisticated NLTE continuum-fitting FALC model of Fontenla et al. [33] 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 radiative equilibrium seem reasonable first approximations where H− radiation loss is the major stratification agent.

(ii) Non-local thermodynamic equilibrium masking

FALC’s classic VAL3C predecessor, formulated in the three monumental papers of Vernazza et al. [34–36], had a significantly cooler upper photosphere than HOLMUL. Such a steeper temperature gradient produces deeper lines,
but also appreciable near-ultraviolet overionization of species such as FeI [37]. The resulting NLTE reduction of FeI opacities offsets the line strengthening; Rutten & Kostik [38] called this fortuitous cancellation ‘NLTE masking’. Avrett’s subsequent and most recent [39] modelling includes a large number of ultraviolet lines to provide a quasi-continuous line haze [40,41] 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 [42]. This NLTE opacity issue crops up again in modelling photospheric fine structure with steep temperature gradients [43].

(iii) Microturbulence

All one-dimensional 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 [44] quoted Russell’s attribution ‘to the direct intervention of the Deity’. In one-dimensional solar modelling, it became a bag of fudge parameters. Macro turbulence and height dependence were added, de Jager & Vermue [45] defined functional kinetic-energy spectrum filters, Gray [46] added anisotropy. VAL3C and FALC shared sizable microturbulence with large variation with height (fig. 11 of Vernazza et al. [36]). 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 [47].

(b) Fine structure

(i) Granulation

The granulation became initially understood by Nordlund’s [48,49] early simulations and more so when he teamed up with Stein [6,50–52], with the identification of radiative surface cooling as the major driver [53]. Current granulation research targets small vortices [54–58], supersonic flows [59,60], flow bending [61] and intergranular jets [62,63].

(ii) Abundances

The use of three-dimensional Nordlund–Stein granulation simulations instead of one-dimensional modelling with ad hoc turbulence resulted in substantial downward revisions of key abundances, upsetting helioseismology and stellar evolution theory [6,64–68]. However, Caffau et al. [69,70] report only small changes from the one- to three-dimensional paradigm shift and do not confirm such drastic revision. Fabbian et al. [71] found that adding moderate magnetic flux has appreciable influence on iron abundance determination. These issues remain open.

(iii) Reversed granulation

In the mid-photosphere, the granular intensity contrast reverses. The observations of Rutten et al. [72] were well reproduced by the simulation of

Phil. Trans. R. Soc. A (2012)
Leenaarts & Wedemeyer-Böhm [73]. Cheung et al. [74] provided a detailed explanation using the MHD code of Vögler et al. [22]. The phenomenon comes from overturning flows and produces marked imaging asymmetry between the wings of Na I D$_1$ [75].

(iv) Acoustic oscillations

The simulations have self-excited acoustic box modes that are not too dissimilar from global $p$-modes [76,77]. They serve to study stochastic mode excitation in near-surface convection for the Sun and other stars (e.g. [78,79]). Earlier, Goode and co-workers [80–83] searched for identifiable $p$-mode exciters for which the collapsars (small vanishing granules) of Rast [84] and Skartlien et al. [85] became the principal candidate. These indeed generate excess acoustics [86].

(v) Magnetic concentrations

Figure 1 is from before the identification of magnetic network elements as kilogauss fluxtubes by Frazier & Stenflo [87] with Stenflo’s [88] line ratio technique. In the magneto-static thin-fluxtube model of Spruit [89] following ideas of Zwaan [90], 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 set on a firm observational footing by Solanki and co-workers through best-fit modelling of the spatially unresolved signature of small kilogauss concentrations in multi-line spectropolarimetry (see the extensive review by Solanki [91]), and subsequently confirmed with MHD simulations, first in two dimensions (e.g. [92–95]; see also the two examples in figure 2), then in three dimensions (e.g. [22,96,97]). Newer research addresses wave excitation and diagnostics [98–101].

(vi) 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.) that are easier to observe, easiest in the G band of CH lines around $\lambda = 430.5$nm, following Muller & Roudier [102], but also in the wings of strong lines [103]. They are not points, becoming flowers and ribbons with much substructure at high resolution [104,105]. The upshot of the extended literature review by De Wijn et al. [7] 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 [89] and Spruit & Zwaan [106]. 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 ionization 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. [96,107–112]). Irradiance modelling must cope with the inherently three-dimensional nature of limbward facular brightening [113].

(vii) Weak and horizontal fields

Neither figure 1 nor 2 shows the weak tangled internetwork fields detected with sensitive spectropolarimetry [114–117] and predicted by near-surface convective dynamo simulations [118,119]. They seem to close on granular scales in the mid-photosphere, appearing there as relatively strong horizontal fields [120–122].

(viii) Inversion modelling

The La Laguna inversion school initiated by Ruiz-Cobo et al. [123,124] has produced multiple codes that emulate HOLMUL-like empirical model construction by best-fit stratification modelling per observed pixel (e.g. [125–129]). 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

(i) One-dimensional modelling

The six VAL3 models of Vernazza et al. [36] representing quiet-Sun conditions were made by fitting bins of different observed ultraviolet intensities with different temperature stratifications, all sharing the basic structure of a photospheric decline, a temperature minimum, an 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 Hα fine structure.

However, collapsing the internetwork 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. [33,130–133]) should be contrasted with the much larger temporal variations along columns in figure 2. In a movie (http://www.staff.science.uu.nl/~rutte101/rrweb/rjr-movies) 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$_2$V grain simulation by Carlsson & Stein [134–136].
The existence of cool clouds that are incompatible with static one-dimensional modelling was long before advocated by Ayres on the basis of deep CO line cores [137–139]. In simulations, the clapotispheric gas gets as cool as 2000 K. Leenaarts et al. [140] conclude that such low temperatures are unavoidable unless there is weak-field heating not present in such simulations.

The Atacama large millimeter/submillimeter array may deliver direct mm-radiation diagnostics of the spatiotemporal temperature behaviour (e.g. [141,142]).

(b) Fine structure

(i) Acoustic shocks

Many shocks in the movie companion to figure 2 run at a slant, which explains why Carlsson & Stein [136] found only a few locations in the observations of Lites et al. [143], with well-defined \( \text{H}_2 \text{V} \) 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).

(ii) Gravity waves

Gravity waves should be copiously excited in the convective overshoot above the granulation (e.g. [144–148]), but are hard to diagnose (e.g. [149–151]). 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 [152,153]. These waves remain understudied.

(iii) Quietest Sun

In the quietest areas, \( \text{H} \alpha \) line-centre images show no cover-all fibril carpet, but only network rosettes consisting of short mottles, and a very dynamic cell interior between these. A fast-cadence \( \text{H} \alpha \) movie (http://www.staff.science.uu.nl/~rutte101/rrweb/rjr-movies) of the latter from the data of Rouppe van der Voort et al. [154] shows mushrooming 3 min 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. [21], or shock-excited high-frequency oscillations, as proposed by Reardon et al. [155]. Wedemeyer-Böhm & Rouppe van der Voort [156] reported swirl motions in such areas. These quiet-Sun phenomena also need further study, but require exceedingly high spatial and temporal resolution.

(iv) Wave–field interaction

The shocks push the clapotispheric transition region to large heights because magnetic refraction and mode conversion become important only at low plasma-beta [157,158]. The ubiquitous presence of shock waves in both the observations and MHD simulations suggests that weak fields play no large role
in the clapotisphere (cf. [8]), nor the multi-scale magnetic carpet proposed by Schrijver & Title [159]. Gravity waves convert easier into Alfvén waves then into acoustic waves [146]; their amplitude may be a canopy mapper (fig. 5 of Rutten [160]).

5. Chromosphere

(a) Overall structure

(i) One-dimensional modelling

In the magnetic network, shocks arise even deeper. The fluxtube simulation by Steiner et al. [94] already suggested that photospheric shocks frequently arise in and near magnetic concentrations, excited by strong adjacent downflows driven by radiative cooling through the tube walls. Recently, Kato et al. [101] 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. [161], magnetic-concentration shocks occur as low as $h = 300$ km and affect the core of Na I D$_1$. The Na I D$_1$ observations of Jess et al. [162] and Rutten et al. [75] confirm such shock sensitivity. It makes Na I D$_1$ Dopplergrams effective proxy-magnetograms by marking magnetic concentrations through the resulting core asymmetry. This ubiquity of deep-seated shocks invalidates static one-dimensional modelling even more for networks than for internetworks.

(ii) Chromospheric heating

Classically, the chromospheric heating budget was determined by evaluating the net radiative cooling in a standard model (fig. 49 of Vernazza et al. [36]) or determining the amount of excess heating over radiative equilibrium that is needed to obtain such models [163]. However, Carlsson & Stein [135] demonstrated that a cool but shock-ridden clapotisphere delivers the hot VAL3C chromosphere when fitting ultraviolet continua, due to the nonlinear 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 [164], and a haze of unresolved high-reaching spicules-II (see below). Modelling these diverse contributions as radiation loss at the height of one-dimensional 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 [165].

(b) Fine structure

(i) 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 [166]. Watching H$\alpha$ movies gives a strong impression that the fibrils constitute canopies that ride on the clapotisphere. Rutten et al. [167] found that they partake in shocks coming up underneath, as
also evident in the Doppler timeslices of Cauzzi et al. [168]. 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 Hα 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 Hα fibrils are often taken to outline chromospheric fields. Indeed, their filamentary patterns give a vivid impression of magnetic connectivity. However, direct correspondence remains unproved [169], and the thermal and dynamic fine structure evidenced by the fibrils may be more complex than the field structure [2]. Since Ca II 854.2 nm responds to higher temperature with larger brightness, while Hα does not [168], Hα 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 [170].

If Hα fibrils do map chromospheric fields, then extrapolation using the observed Hα 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 [171,172]. If so, space–weather prediction will eventually need continuous high-resolution full-disc Hα 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.

(ii) Dynamic fibrils

Near network and plage shorter fibrils are seen in Hα as extending and contracting stalks with abrupt transition-region caps [173], and similarly in Ly α [174]. These became a chromospheric success story with the work of Hansteen et al. [175] and De Pontieu et al. [176], 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 [177–179]. 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.

(iii) Spicules-II/straws/rapid blue excursions

These features (respectively, off-limb/near-limb/on-disc) also border network and plage, but they are yet more upright, more slender, more dynamic and reach higher. They were found in Ca II H near the limb and called ‘straws’ by Rutten [180], observed as ‘type-II spicules’ in Ca II H off the limb by De Pontieu et al. [181,182], and identified on the disc as dark RBEs in the blue wings of Ca II 854.2 nm and Hα by Langangen et al. [183] and Rouppe van der Voort et al. [184]. They may also be diagnosed from extreme ultraviolet line asymmetries [185–189]. They are probably a key player in providing mass and energy to the corona outside active regions [190]. Recently, De Pontieu et al. [191] 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 that continue up and out while the bullets drop back. These dynamic features occur near networks
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, probably from Alfvén waves [182].

The recent MHD simulation of a spicule-II-like event by Martínez-Sykora et al. [192] 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 [193], ‘exciting upward travelling waves […] with tenuous clouds of ions and electrons squeezed ahead’. Perhaps with helical motion, as suggested by Beck & Rezaei [194].

(iv) Data inversion

Spline-function inversion techniques lose credibility where clapotispheric and chromospheric fluctuations are too wild for smooth one-dimensional 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 [195]; cloud modelling presently reaches its highest sophistication in filament-thread analysis [196]. The slowness of hydrogen (and worse for helium) ionization/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 means 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 ground-based 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. Hα mapping of closed fields (within the chromosphere) appears especially useful for eruptivity prediction.

I thank J. Leenaarts and N. Vitas for assistance, the referees for making me rewrite an earlier draft, and the issue editor for allowing additional reference pages.

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*Phil. Trans. R. Soc. A* (2012)


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