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# Observations of the Solar Chromosphere

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**Abstract.** I summarize observational properties of the solar chromosphere with emphasis on some of Bob Stein's continuing interests, with an historical slant. Bob's interests always concern basic physical processes, so I try to identify some basic facts about the chromosphere from the myriads of observations from radio to UV wavelengths. The observations suggest a simple demarcation between the "low" chromosphere and "high" chromosphere which depends on the local plasma-$\beta$. Relatively simple properties are exhibited in high-$\beta$ regions (hydrostatic equilibrium, three-minute compressive oscillations), and obviously complex thermal properties of the "fine structure" observed for many decades, arise in low-$\beta$ chromospheric regions. The latter appears to share properties more in common with the intermingled lower corona, where the energetically dominant magnetic structure is arguably simpler than the high-$\beta$ regions. But like the coronal heating problem, the thermal structure of the upper chromosphere is far more complex and is manifested as fine structure.

## 1. A simple picture of an apparently complex region

The chromosphere is often perceived to be one of the most challenging regions of the Sun. The Sun produces spectral features associated with chromospheric plasma (such as near the center of the H $\alpha$ line) in a wide variety of structures, with such names as bushes, fibrils, fibrules, flocculi, grains, mottles, prominences, rosettes, spicules. The bewildering structure and nomenclature can give the impression of complexity beyond our current understanding (see Figure 1). This impression is deepened when one considers the theoretical machinery needed to understand chromospheric thermodynamics (Thomas & Athay 1961), suitable heating mechanisms, and recent data which show the complex chromosphere/corona interface. My purpose here is to dispel the myth that the structure of the chromosphere is too messy to understand – with the understanding that by "structure" I refer mostly to the average *force* balance. The fine-scaled *thermal* structure of the upper chromosphere probably relates to the difficult coronal heating problem in ways that are very poorly understood, if at all. I will nevertheless argue that, at least qualitatively, many salient observations can be comprehended when one attributes to the chromosphere several simple properties, whose factual bases will form the bulk of discussion below:

- The bulk of the chromosphere is the partially ionized magneto-fluid immediately above the photosphere, spanning seven to ten pressure scale heights[1] (0.5 – 2 Mm) under almost isothermal conditions.

- The chromosphere is essentially isothermal because it is a natural thermostat: dissipated mechanical energy is taken up by latent heat of ionization, and is rapidly lost by radiation (typical radiative cooling times are just $\approx 80$ seconds above 0.7 Mm, Anderson & Athay 1989).

- The chromosphere typically requires $100\times$ more power than the corona.

- The lower chromosphere, below $\approx 1.3$ Mm above the visible photosphere, is nearly hydrostatically stratified, and the behavior is largely hydrodynamic. This region's behavior is recognizable as a natural extension of observable photospheric dynamics. The elements here are well-mixed by rapid collisions and a variety of dynamical processes inferred by observations.

- Above 1.3 Mm, the observed properties change as typical values of the plasma $\beta$ (gas/magnetic pressure) fall below 1. Both quiet and active chromosphere contain the $\beta = 1$ surface, which serves as a "magnetic transition region" in the solar atmosphere. The "upper chromosphere" appears more similar to the corona than the photosphere, in that the thermal structure (both bright and dark) is dominated by fine loop-like structures. Most of the emission seen 1.5 Mm and higher above the limb comes from "spicules" (Suemoto & Hiei 1962), whose structure and dynamics indicate the dominance of the Lorentz force. The elements here may not be well-mixed.

- Thus, the spectacular fine structure seen in the upper chromosphere is related more to the complexity of the gas *thermodynamics* – related to the difficult problem of coronal heating – than it is to the magnetic structure. The latter must be relatively simple, being almost force-free, because $\beta \ll 1$.

Below, I will argue that it is our *understanding of the chromosphere that has developed in a messy way*, not that the chromosphere *per se* is a mess, keeping in mind that the fundamental problem of the energization of the chromosphere remains with us. This situation arose because there is an uncomfortable but unavoidable symbiosis between models and observations (Thomas & Athay 1961, Chapter 1). It has taken decades to iron out some difficulties, and some still remain, but along the way the resolution led to important advances in 20th century physics and astrophysics, as we'll see below.

The above picture is appealing but incomplete, because the chromosphere is threaded by inhomogeneous magnetic fields, determined by the non-steady processes of magneto-convection, flux emergence and reconnection (see Keller (2006) and Khomenko (2006), in this volume). The $\beta = 1$ "surface" is morphologically

[1] All heights are relative to vertical optical depth unity for the 500 nm continuum.

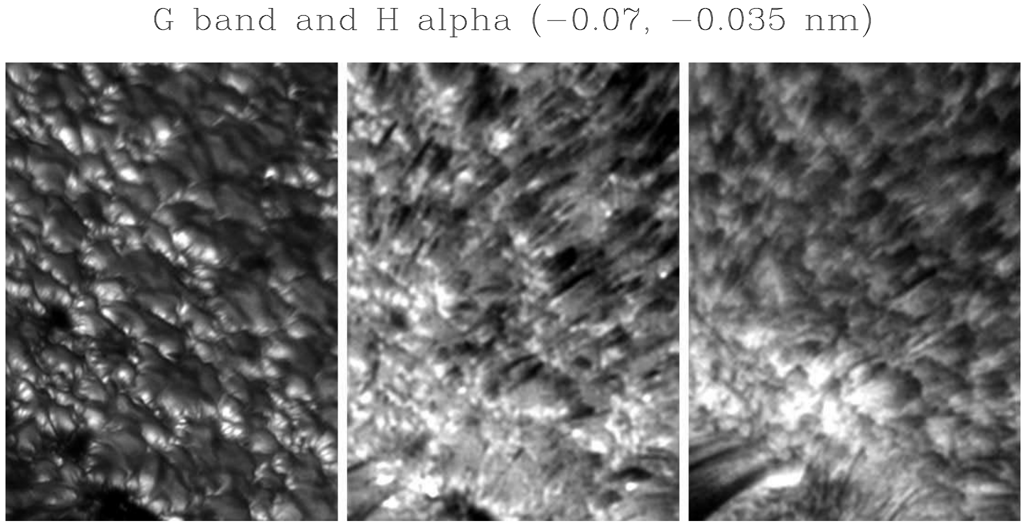


Figure 1. Modern G-band and H $\alpha$ images covering $\approx 40'' \times 55''$ near a small sunspot group at $\mu = 0.6$, highlighting the change in morphology between photospheric faculae (left image) and fine structure seen in the middle-upper chromosphere. Low chromospheric spectral features (bright areas in H $\alpha$) are morphologically more similar to the photosphere than the upper chromosphere (dark areas in H $\alpha$). Data obtained using the Swedish Solar Telescope by B. de Pontieu on 16 June 2003. The SST is operated by the Institute for Solar Physics of the Royal Swedish Academy of Sciences in the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

more complex than the above picture suggests. Additional challenges include the still unsolved problem of the origin of spicules and the nature of the upper chromosphere, and the problems of non-LTE and ionization non-equilibrium. It is also probable that it cannot be entirely described even as a single fluid. Nevertheless, I will continue undaunted.

## 2. A List of Spectral Features Formed in the Chromosphere

Here I list, with their advantages/disadvantages, spectral features which originate in the chromosphere. The list applies to observations of the solar disk. The limb as seen at eclipse or otherwise reveals weaker chromospheric emission features which are otherwise swamped by unattenuated disk light at near-UV, visible and IR wavelengths, an example being the helium spectrum. For a quantitative discussion of formation heights in 1D stratified models refer to Athay (1976); Vernazza et al. (1981).

The cores of strong visible/IR Fraunhofer lines (*e.g.* of Fe I, Mg I, Na I) are formed in the lower chromosphere (below $\approx 1.3$ Mm). The strongest Fraunhofer lines (Ca II H & K and infrared triplet, H $\alpha$) sample higher layers. Being readily accessible, visible lines have advantages over other wavelengths, including the use of sophisticated instruments (with adaptive optics, for example), relatively large telescopes, and a large accompanying literature. Both the Zeeman and Hanle effects have been used to explore chromospheric magnetism. Disadvantages are that they are subject to strong non-LTE effects, significant photon scattering, and to mixed intensity/Doppler signals, particularly in filtergrams.

Between the atmospheric cutoff near 320 nm and $\approx$ 152 nm the "continuum" is formed in the upper photosphere (below 0.5 Mm), and nearly all chromospheric spectral lines are swamped by disk continuum emission. The Mg II h and k lines near 280 nm, with cores formed even higher than H or K, have been commonly observed from balloons, rockets, and spacecraft.

Shorter UV wavelengths include photoionization continua and lines formed in the chromosphere. Continua below 152 nm form above 0.5 Mm, and many emission lines are superimposed on them. Continua have the advantage of reflecting local heating without confusion from the Doppler effect. Advantages of the UV lines below $\approx$ 170 nm are that collectively they form throughout the chromosphere, transition region and corona, and they arise from a variety of elements. They sample a wide range of optical depth, including spin-forbidden and forbidden lines unaffected by photon scattering. Disadvantages are that all features are formed under non-LTE conditions, although only certain resonance lines (of H and neutral He, C, O for example) suffer from difficulties introduced by partially coherent scattering in the source functions.

Sub-mm and mm continua are formed in the chromosphere, and have the advantages of being formed under pure LTE conditions, with opacities set by electron densities $n_e$ determined by the ionization of hydrogen. The intensities are linear in the electron temperature $T_e$. Disadvantages are that mm observations have relatively low angular resolution, and image contrasts are small. Chromospheric features are not isolated sources, they change on time scales $<$ five minutes, making images difficult to reconstruct using interferometry. The difficulties are exacerbated for dim areas such as the "internetwork" regions which lie in the interiors of the bright chromospheric "network cells" (see below).

## 3. Early Qualitative Work

Reports of phenomena seen during eclipse, which we would now call "chromospheric" emission from prominences, date from medieval times (in Russian monastic chronicles, (Pannekoek 1961, p. 406)). However, the first documented observation of what is certainly chromospheric emission (the "flash") outside of prominences, is an account from the 18th century (Young 1892): *"Captain Stannyan, in a report on the eclipse of 1706, observed by him at Berne, noticed that the emersion of the Sun was preceded by a blood-red streak of light, visible for six or seven seconds on the western limb."* So Bob Stein, like all of us, is still a relative newcomer to the field. Young's (1892) account continues: *"…This outer envelope.. seems to be made up not of overlying strata of different density, but rather of flames, beams and streamers, as transient as those of our own aurora borealis. It is divided into two portions… the outer portion… may almost, without exaggeration, be likened to 'the stuff that dreams are made of', since it is chiefly due to the 'corona'… At its base, and in contact with the photosphere, is what resembles a sheet of scarlet fire… This is the 'chromosphere', a name first proposed by Frankland and Lockyer in 1869… in allusion to the vivid redness of the stratum, caused by the predominance of hydrogen in these flames* *and clouds. It was called the "sierra" by Airy in 1842."* Secchi (1877) made spectroscopic visual observations out of eclipse, his drawings showing the ubiquitous hair-like structures typically of 10 arcseconds length pointing largely away from the solar surface (later named "jets" by Lyot and "spicules" by Roberts 1945). By the 1880s, observations had already revealed the chromosphere as a super-photospheric layer, overlaid and mixed with the fine-structured spicules.

Following an idea of Janssen, between 1890 and 1893 Hale and Deslandres independently developed the spectroheliograph, permitting photographs ("spectroheliograms") of prominences in the violet light of the H and K lines, to which early photographic plates were especially sensitive. Hale & Ellerman's (1904) spectroheliograms of the disk chromosphere revealed the "chromospheric network" at various wavelengths in the H and K lines and in H $\beta$, and showed that enhanced chromospheric emission occurs in "clouds" or "flocculi" above photospheric faculae. Hale (1908b) obtained the first spectroheliograms of the disk in H $\alpha$, using plates sensitized to red light. The data dramatically confirmed a peculiarity suggested to Hale in earlier data which *"... is clearly visible on the hydrogen photographs. It is a decided definiteness of structure indicated by radial or curving lines, or as some such distribution of the minor flocculi as iron filings present in a magnetic field."*. With the discovery of the Zeeman effect in sunspots (Hale 1908a), the vortex-like structure seen in H $\alpha$, thought by some to be giant fluid vortices analogous to hurricanes, might instead have a magnetic origin.

Already in 1877, Secchi noted that the limb chromosphere seen in H $\alpha$ (dominated by spicules) is organized on large spatial scales, and that this organization also changes with sunspot numbers. At Arcetri, Frascatoro (1948) measured between 1922 and 1946 a remarkable anti-correlation between sunspot number and the latitude-dependent thickness of the H $\alpha$ chromosphere: it is typically symmetric near solar maximum, and is $2''$ thicker at the pole than at the equator under minimum conditions. This behavior is reminiscent of the corona. Inventions of the coronagraph (Lyot 1930) and birefringent filter (Lyot 1933; Öhman 1938) permitted more frequent spicule and coronal observations, showing that the spicules are often aligned with overlying and magnetically structured coronal features (Van de Hulst 1953, for example). Kiepenheuer (1953) concluded that "The cause of the elongation of the segments and their alignment [*i.e.* the fine structure] cannot be purely hydrodynamic. Instead magnetic fields must play a major role, as the alignment of prominences (filaments) by spot fields." So, by the middle of the 20th century, magnetism was suspected to be a dominant structural influence in the upper chromosphere of the entire Sun.

## 4. The "Classical Chromospheric Problems"

Chromospheric work prior to the symbiosis of the non-LTE formalism with improved chromospheric data (Thomas & Athay 1961), notably from the 1952 eclipse, was in a state of disarray. Quantitative studies prior to the 1960s mostly used eclipse data, augmented with radio measurements. This was because, although early empirical evidence showed that the cores of the strongest Fraunhofer lines were formed in the chromosphere (Hale & Ellerman 1904, for example), the foundations of the non-LTE theory needed to interpret such data were not built until the late 1940s. Based on eclipse data then, much early work concerned the *three "classical" anomalies* (Pagel 1964): (1) Why does the chromosphere appear to be so physically extended? (2) Why are lines of relatively "high" ionization states seen, when radiative equilibrium would suggest very low temperatures? (3) Why were certain lines, especially of helium, so prominent in flash spectra when they were almost unobservable on the disk? To these we may add the questions: (4) are the elements fully mixed or fractionated in the chromosphere, and (5) is the typical kinetic temperature in excess of 10,000 K (related to 1)?

The process of trying to resolve these problems has occupied researchers from the 1920s onwards. Along the way, some remarkable advances in both physics and astrophysics were spurred on by the chromospheric data. For the "low" chromosphere, anomalies (1), (2) and (5) were essentially resolved by the 1950s (Van de Hulst 1953; Thomas & Athay 1961). However anomaly (3) remains with us, after 60+ year search for excitation mechanisms (from Goldberg 1939 to Pietarila & Judge 2004). The structure of the "upper" chromosphere, with spicules being a conspicuous component, remains a challenging problem, as are the associated subjects of elemental abundances, chromospheric fractionation processes, and how the chromosphere interfaces with the corona.

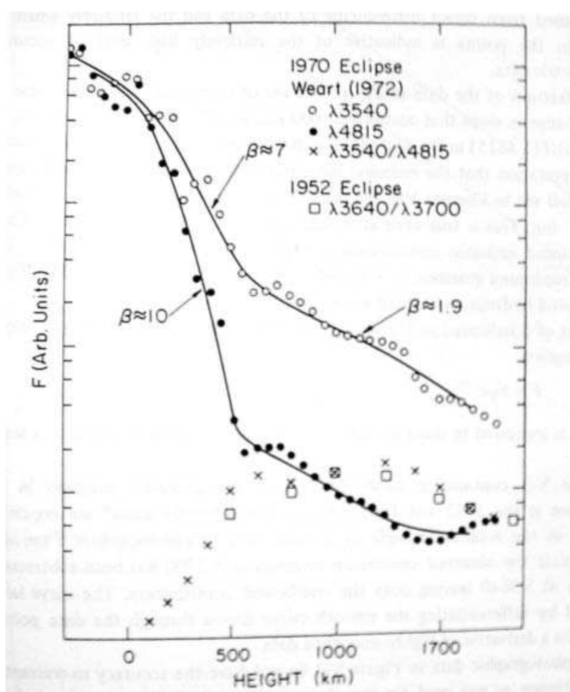


Figure 2. Continuum intensities from slitless observations of the chromosphere during total eclipses. The Balmer continuum edge is at λ3648. Note the different "scale heights" $\beta^{-1}$ in the photosphere and chromosphere (heights above 500 km). From Athay (1976).

Data relevant to anomaly (1) were documented even before a basic understanding of the solar atmosphere was developed. For example, Respighi (1869) observed H $\alpha$ emission extended to typically 9,000 km above the visible limb. Mitchell (1913) found emission from $Ca^+$ ions out to 14,000 km above the limb. Later measurements of photometrically calibrated eclipse spectra further quantified the problem. Scale heights of emission from lines and continua were found to increase dramatically from hydrostatic values $\approx$ 100 km in the photosphere, to much larger values in the chromosphere (see, for example, the data for the Balmer continuum shown in Figure 2). This anomaly prompted Milne (1924, "The equilibrium of the calcium chromosphere", and several more papers in MNRAS) to develop a widely discussed radiation pressure gradient support model, and McCrea (1929) to propose a competing "turbulent" support model of the chromosphere. McCrea added a turbulent component to the pressure tensor via an "effective" temperature in addition to the kinetic temperature. The subsequent debate laid the foundations for modern stellar atmosphere theory, including non-LTE efects, supersonic gas dynamics and the beginnings of radiation hydrodynamics (Menzel 1931; Chandrasekhar 1933; McCrea 1934; Van de Hulst 1953). The large scale heights for the low chromosphere were later understood in terms of the thermodynamics of ionization: "... we find no anomaly at all in the density gradient of the chromosphere in this region 500 km $< h <$ 1000 km. A distribution of material under hydrostatic equilibrium represents quite adequately the [limb] observations made in the continuum" – Thomas & Athay (1961, p. 207). Nevertheless, some workers remained confused (Zirin 1996).

The second anomaly served as inspiration for and was resolved by Saha's 1920 landmark paper "Ionisation in the solar chromosphere". The dependence of LTE ionization equilibrium on electron pressure showed that stratification naturally leads to higher ionization stages higher in the atmosphere. Non-LTE effects do not qualitatively change this conclusion (Thomas & Athay 1961).

The resolution of the fifth question is particularly interesting. Redman (1942) analyzed the first high resolution chromospheric eclipse slit spectra obtained under exceptionally favorable conditions. Broad line profiles of hydrogen lines versus metals suggested that the line widths have a *kinetic* origin, and that the chromosphere may have kinetic temperatures up to $35,000$ K. This value was supported by Wildt's (1947) analysis of Mitchell's eclipse data, based on LTE ionization equilibrium. Wildt found that the hydrogen density gradient was compatible with a hydrostatically supported atmosphere at $35,000$ K. This temperature was therefore adopted in Thomas' pioneering non-LTE chromospheric studies (Thomas 1948, 1949), who also cited anomaly (3) (enhanced helium emission) in support of this high temperature. However, such high temperatures were shown to be incompatible with several other types of data. For example, Wurm (1948) argued from the absence of forbidden line emission that the kinetic temperature cannot exceed 10,000 K. Miyamoto & Kawaguchi (1950) made similar arguments from a curve-of-growth analysis of the $Ca^+$ lines. Radio emission at 3 and 10 cm had also indicated brightness temperatures a factor of 2 lower (Southworth 1945). Woolley & Allen (1950) deduced that the EUV radiation expected from a chromosphere near 30,000 K was 10 $\times$ higher than is compatible with the known state of ionization of the Earth's ionosphere. Later, Redman & Suemoto (1954) demonstrated that widths of hydrogen lines were influenced by self-absorption and the Stark effect, concluding that all the observed lines were formed below $10^4$ K. Thus, what appeared to be the more "direct" measure of temperature – line widths – turned out to be subject to a different interpretation.

An example of confusion resulting from the symbiosis of observations with incomplete modeling is found in the analysis of Wildt (1947), who concluded that the chromosphere is not just extended, but that the abundances of different elements changes systematically with height, related to question (4). This result stood in sharp contrast to the conclusions of Menzel (1931) and Mitchell & Williams (1933). Thomas & Athay (1961) showed that many of these discrepancies are understood as artefacts of poor assumptions (LTE ionization equilibrium, in particular) in the treatments of the gas thermodynamics. Thus, in spite of the fact that even in 1957, some still believed that the elements were not well mixed (Abetti 1957), Van de Hulst (1953) concludes: "It thus seems much better to postulate a constant abundance ratio of hydrogen to metals and to derive on this basis the values of $N_e N_p / N_H$ through the lower chromosphere. It is found ... that this approach leads to a very plausible density and temperature distribution for the low chromosphere."

Pagel (1964, p. 292) concluded "... the classical problem of support of the chromosphere no longer exists. The problems are rather: (*a*) Why does the temperature in the low chromosphere (up to, say, 1000 km) rise to 6000° or 7000°? (*b*) Why does the chromosphere shoot forth spicules at about this height? (*c*) why is the corona hot?" The essentially hydrostatic stratification of the lower chromosphere (below 1500 km) has survived a variety of observational tests (Praderie & Thomas 1976, for example). However, while rightly focussing attention on the (still unresolved) issues of heating and spicules, there remained the nagging question of the unknown nature of the force balance and resulting stratification, as it changes from lower to upper chromosphere.

## 5. Chromospheric Problems Today

Since the 1950s, significant progress has been made both through purely observational advances, and through the continued symbiosis of observations and models. Yet, our understanding of chromospheric physics remains quite poor, with the possible exception of the internetwork chromosphere. Because of the huge volume of work, here I can only give a scanty, subjective overview.

In the 1950s and 1960s, important observational breakthroughs included development of the "magnetograph" (Babcock 1953; Leighton 1959) and the related "velocity cancelled Dopplergram" technique (Leighton et al. 1962). Both techniques provided vital information on photospheric conditions immediately below the chromosphere. New observations of the chromosphere itself were made as new wavelengths became accessible, both in the UV region from space (Tousey 1953), and at mm wavelengths (Tolbert & Straiton 1961). Connections to the corona became possible with observations providing spectral and imaging data both below the Lyman edge (Burton & Ridgeley 1970; Dupree & Reeves 1971) and in X-rays (Paolini et al. 1968; van Speybroeck et al. 1970). Later technical developments of particular importance to the chromosphere include the use of two dimensional electronic detectors, narrow band filters, polarimeters for the measurement of vector magnetic fields using the Zeeman effect, low polarization, high resolution telescopes, the ability to measure spectra at several wavelengths simultaneously, video-rate frame selection, image reconstruction techniques, adaptive optics, expansion of spectropolarimetric work into the infrared regions, and measurements of high polarimetric sensitivity permitting application of the Hanle effect.

Theoretical landmarks included the treatment of partial redistribution in resonance lines (such as Ca II H and K), the use of inverse methods applied to Zeeman-polarized lines, the development of *ab-initio* models of wave generation and dissipation, the development of non-LTE (and ionization non-equilibrium) radiation hydrodynamic calculations, tentative steps towards describing the dissipation of magnetic energy in the chromosphere (Goodman 2000), and development of the theory necessary to infer magnetic fields using the Hanle effect.

*Fine Structure* Chromospheric fine structure is visible in Ca II spectroheliograms but is seen most clearly from the ground in H $\alpha$. The fine structure suggested to Hale (1908b) that magnetic fields greatly influence the upper chromosphere. This is seen particularly clearly in d'Azambuja's H $\alpha$ data (Kiepenheuer 1953). The fine structure has been intensively studied ever since (Gaizauskas 1985; Grossmann-Doerth & Schmidt 1992; De Pontieu et al. 2003, for example). Several problems known to the pioneers remain with us today. For example, neither the causes of chromospheric fine thermal structure or the nature of spicules (Secchi 1877; Roberts 1945) are clearly understood. Nevertheless, some significant progress has been made.

A key advance was made when photospheric Dopplergrams revealed clearly the largely horizontal "supergranular flow" (Simon & Leighton 1963), detected earlier by Hart (1956). The flows were suspected by Leighton et al. (1962) to be directly related to the bright Ca II network (and associated dark H $\alpha$ wing downflows), called "course calcium flocculi" by Hale. With photospheric magnetograms and earlier observations by Howard, Simon & Leighton (1963, 1964) showed that the Ca II network overlies measurable photospheric magnetic field concentrations clustered in downflow lanes at the supergranular cell boundaries. Leighton imagined the magnetic fields being "diffused" (advected) by the turbulent granular motions to the longer-lived downflow lanes where, being buoyant, they bobbed, like flotsam and jetsam, in the converging supergranular velocity field. The fine structure seen at various wavelengths across the H $\alpha$ line is clearly linked to these magnetic fields – not only are the wing downflows rooted in these photospheric flux concentrations, appearing in clusters called "rosettes" or "bushes", but the outflowing spicules appear to originate there as well. Thus, Hale's intuition was correct. These magnetic fields are important for at least three reasons: the entire chromosphere is much *brighter* immediately overlying them than in the internetwork (Skumanich et al. 1975), the Sun's Ca II emission varies significantly with the solar sunspot cycle (White & Livingston 1981), and much of the *dynamics and structure of the upper chromosphere* is obviously controlled by magnetic fields rooted in supergranular downflow lanes.

UV images in Ly $\alpha$ and other upper chromospheric/ transition region lines (Feldman et al. 2003, for example) are morphologically similar to H $\alpha$. Why is the fine structure so clear in these particular features? Balmer lines are most sensitive to the $n = 2$ level populations of hydrogen. Unlike other Fraunhofer lines they are formed from photosphere (far wings) to the upper chromosphere (core) (Athay 1976, see his Figure II-2). Near line center, H $\alpha$ therefore shows fine structure in great detail. Those quiet regions with higher magnetic fluxes show more extensive fine structure (Gaizauskas 1985). The UV fine structure arises for different reasons related to the (unknown) magnetic heating mechanism(s). Since UV line emission requires relatively high $T_e$ values, and high temperatures cannot be sustained without a great deal of power throughout most of the chromosphere, UV emission is generally biased towards plasma which is both hotter and more tenuous than the middle chromosphere. Thus, most UV lines form above the $\beta = 1$ surface in the quiet Sun.

If fundamental progress in our understanding of some chromospheric phenomena has slowed since the 1960s, it is because of the importance of magnetic fields, and the far greater physical complexity thich they introduce. In a largely unipolar region, Figure 3 sketches some of the complications introduced by magnetic fields. These include the entrainment of the highly conducting, partially ionized plasmas to the field lines, the changing of the force balance within the chromosphere marked by the "$\beta = 1$ surface", which itself leads to drastic changes in field morphology and wave mode propagation. Magnetoplasma theory says that the magnetic field dramatically changes the ways energy can be transported and dissipated, compared with the field-free case. In particular, the turbulent nature of the underlying photosphere will inevitably lead to magnetic free energy (current systems) throughout the entire atmosphere which most likely consists of very fine-scaled current sheets and dissipation regions which are currently below the observable scales (Parker 1994, for example).

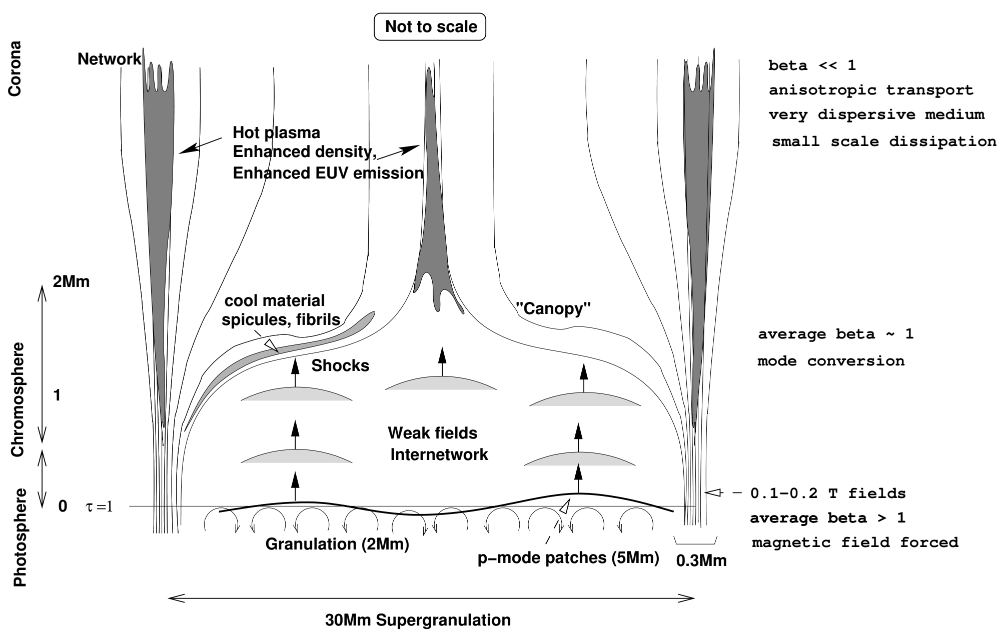


Figure 3. A sketch of the structure of the solar chromosphere in a reqion of quiet Sun predominantly covered with unipolar magnetic field. No granular magnetic fields of mixed polarity (Livingston & Harvey 1971) are shown.

*Chromospheric Oscillations* Dopplergrams showed that the quiescent solar photosphere oscillates with rms velocities $\approx 0.2-0.3$ km s$^{-1}$, in patches a few Mm across with a period of five minutes (Leighton et al. 1962; Noyes & Leighton 1963). Evans & Michard (1962), Jensen & Orrall (1963) and Noyes & Leighton (1963) explored the vertical velocity oscillations as they extend into the chromosphere using strong Fraunhofer lines. In internetwork regions, chromospheric lines oscillate with periods closer to three than five minutes, with rms amplitudes exceeding 1 km s$^{-1}$ (Noyes 1967). At cell boundaries, the network oscillates in a less periodic fashion and with longer periods (Orrall 1966; Lites et al. 1993). The work prior to 1972 is nicely summarized by Gibson (1973, Chapter 5), but the nature of the photospheric oscillations only became clear with the discovery of the "$k-\omega$ ridges" by Deubner (1975). Deubner's discovery followed predictions of Ulrich (1970) and Leibacher & Stein (1971) based upon the idea that the oscillations are acoustic eigenmodes trapped in the Sun between steep gradients in sound speed present in the sub-photosphere and deep in the solar interior. Here again is an example of the symbiosis between observation and theory. It might be thought that these "$p$-mode" oscillations are unimportant in the chromosphere, because the waves are largely reflected in lower layers (the five minute waves are evanescent), and because the *upper* chromosphere at least appears to be controlled by magnetic fields. These fields, while rooted in the photosphere, clearly lead to a complicated thermal structure in the upper chromosphere which is not obviously related to the $p$-mode oscillation patches beneath. However, observations showed a clear connection between the photospheric and *lower* chromospheric oscillations (Noyes & Leighton 1963; Lites et al. 1982).

In parallel, a related property of the H and K line profiles described as "minute bright calcium flocculi" by Hale & Ellerman (1904) seen in spectroheliograms was being studied. These "$H_{2V}$ and $K_{2V}$ cell grains", thoroughly reviewed by Rutten & Uitenbroek (1991), are a manifestation of the upward propagation of three minute compressive waves (Carlsson & Stein 1997) seen in spectroheliograms taken in the violet peaks of the Ca II lines (hence the "$V$s"). Their small spatial extent results not from the smallness of the wave sources or from magnetic fields (Lites et al. 1999), but from the interplay between interacting shock waves, the optical depth, largely determined by Doppler shifts associated with the waves, and the source function (Rutten 1999, for example).

The observed three-minute oscillations and cell grains have received a remarkably satisfactory explanation from radiation hydrodynamic simulations (Carlsson & Stein 1995; Carlsson & Stein 1997). Their 1D internetwork chromosphere is driven by a piston calculated to match observations of a photospheric line. The piston thus contains the global $p$ modes as well as more local sources of wave energy. Waves of three-minute period develop and shock near 1000 km, producing the grains. This work has received support from observations at UV and, more recently, mm wavelengths (*e.g.* Loukitcheva et al. (2004)). UV continuum observations reveal the waves and their coupling to the underlying $p$-mode oscillations in a particularly simple fashion, being sensitive primarily to the temperature (*i.e.* compression) of the chromospheric plasma (Judge et al. 2001). The internetwork chromosphere below $\approx 1300$ km oscillates in response to the $p$ modes, in patches whose horizontal scale, determined by the $p$ modes, exceeds the chromospheric depth, explaining why the 1D approximation may be acceptable. Infrared CO data, previously presenting difficulties for static models of the low chromosphere, may also be adequately described by such models, although further work is needed (Asensio Ramos et al. 2003; Wedemeyer-Böhm et al. 2005).

The range of conditions under which these shock models apply are beginning to become clear. Judge et al. (2003) compared simulated data of UV continua and the C II resonance lines at 133.5 nm with internetwork observations, finding that the model, while capturing the essential dynamics below 1300 km, fails to explain almost any property of the internetwork upper chromosphere sampled by the C II lines, which are observed to be a factor of several brighter than computed. Judge et al. (2001); McIntosh & Judge (2001) identified magnetic "shadows" in internetwork regions, close to network elements, where UV oscillations are absent and the average chromospheric emission is much darker. Magnetograms indicated that such regions are influenced by small magnetic loops connecting from the network into the neighboring cell.

What is the fate of the three minute oscillations as they propagate upwards? The answer may lie in mode conversion near $\beta = 1$. Internetwork UV continua data below 133 nm, formed between 0.8 and 1.2 Mm, oscillate clearly (Carlsson et al. 1997). Other internetwork observations show coherent oscillations of chromospheric intensity oscillations ($\beta > 1$) and Doppler shifts of UV lines formed in the upper chromosphere/transition region ($\beta \ll 1$) (Wikstøl et al. 2000; Pietarila & Judge 2004). The latter show little intensity oscillation. This behavior is expected from fast MHD waves above the $\beta = 1$ surface. The Doppler variations are often coherent over many arcsecond$^2$ areas, in spite of the fine thermal structure present when $\beta \ll 1$. This observation can be qualitatively reconciled with the fine structure, noting that the Alfvén speed $v_A \propto |B|/\sqrt{\rho}$ but the intensity of the UV emission scales with density $\rho$ as $\rho^2 f(T_e)$. Thus, if the magnetic field is quite uniform because $\beta \ll 1$, then, in the presence of density variations, surfaces of constant Alfvén speed should be much less structured than surfaces of constant UV emission.

*A Convergence of Ideas?* The above discussion, based on a wide variety of data from eclipses to oscillatory behavior, suggests that we are converging on an acceptable physical picture of one region of the chromosphere. The internetwork chromosphere below 1300 km or so might be adequately described in terms of the *p*-mode driven oscillation modeled by (Carlsson & Stein 1997). It is equally clear that outside this region, magnetic fields greatly complicate things. This dichotomy arises from the fundamentally different hydrodynamic and magnetohydrodynamic regimes of the two regions, separated by the $\beta = 1$ surface. In the MHD dominated region ($\beta \ll 1$), we have barely a qualitative understanding of the essential structure and no real clue as to the important physical processes. In the region $\beta \ll 1$, force balance ($\approx$ force-free) dictates that the magnetic field structure should be very simple. Yet we see in images of the upper chromosphere, transition region and corona, exquisite fine structure and dynamics. The reason must be that the mechanisms (momentum and energy deposition) which load the field lines with mass and heat the plasmas are intermittent in nature. Thus, I view these $\beta \ll 1$ plasmas as having a complex, intermittent *thermal* structure, embedded in a simpler *magnetic* structure.

*Outstanding Questions* The role of magnetism in the cell interiors is only beginning to be explored. Oscillation data indicate that such internetwork magnetic fields must not greatly influence three-minute wave motions below about 1300 km.

Not all researchers agree on the above picture of the internetwork chromosphere. Debate continues concerning the role of high frequency (say 10 – 50 mHz) acoustic-gravity waves, versus the pseudo $p$-mode three-minute (5 mHz) waves. For example, waves to 25 mHz, difficult to study from the ground, were detected and analyzed by Fossum & Carlsson (2005) using 160 nm continua observed with the TRACE spacecraft. Comparing intensity fluctuations with simulations, and knowing wave energy fluxes of the simulations, they concluded that acoustic waves fail to balance chromospheric energy losses by a factor greater than ten. This work extends a well-known result of Athay & White (1978, 1979), which applied to the upper chromosphere and corona, downwards to span the *entire* chromosphere. The significance of this work is that "…acoustic heating can not sustain a temperature structure like that in static, semi-empirical models…the neglect of high frequency waves in the simulations by Carlsson & Stein (1995, 1997) is not an important omission" (Fossum 2005). Dynamic simulations driven primarily by three-minute oscillations remain valid for the lower internetwork chromosphere. By implication, higher regions are heated by magnetic processes.

Some workers claim to have found chromospheric standing waves from strong Fraunhofer lines, after wave reflection from the transition region (Deubner 1998). Fleck & Deubner (1989) designated 800 – 1200 km as a "magic height" in quiet Sun conditions, from cross-power Fourier analysis of the Ca II IR triplet and photospheric data. However, Carlsson & Stein (1998) applied Deubner's analysis to simulated data, finding that the propagating shock models produce similar results. Another explanation might be that the "magic" behavior is another manifestation of waves encountering the $\beta = 1$ surface. In any case, it would be surprising to observe three-minute standing waves in the chromosphere resulting from reflection, because the chromosphere is a lossy medium, with radiative decay times of $\approx$ a minute.

Are elements fractionated within the chromosphere? The coupling between elements was studied by Milne, Menzel and others during the 1930s, in the context of the old problem of the chromospheric geometric extent. The question has resurfaced, in a different guise, because the corona and solar wind have abundances dependent on their first ionization potential which vary significantly according to the type of structure in which they are measured (Feldman & Laming 2000). This issue raises a second question of how rapidly the elements might be mixed in the chromosphere, which harks back to the work of McCrae. For example, calculations by Hansteen et al. (1997) showed that almost no helium is present in the solar wind unless helium is well mixed with hydrogen in the chromosphere. Turbulent mixing might also have implications for force balance: Van de Hulst (1953, p. 255) suggests that "…in a loose sense all this motion of the chromospheric gases may be called 'turbulence', and in the same loose sense we may talk of 'turbulent pressure'". The question of the "turbulent support" of the chromosphere remains with us.

A perennial puzzle is how the network chromosphere is heated and how the spicules are driven (Pagel 1964). Before these problems can be properly attempted, new sensitive observations should be made which measure properties of the controlling magnetic field at photospheric layers. A long-standing and controversial issue concerns the magnetic structure of the upper chromosphere – is it more like the cartoon shown in Figure 3, or, as proposed by Dowdy et al. (1986), a "junkyard" of closed magnetic structures at sub-supergranular scales?

*Promising new Developments and Directions* Measurements of the chromospheric magnetic field will address some of the outstanding problems today. Following pioneering studies of Livingston & Harvey (1974, unpublished) and Giovanelli (1980), several groups have extended Zeeman spectropolarimetry to chromospheric lines, in spite of challenges from non-LTE radiative transfer and velocity fields. Metcalf et al. (1995) inferred that a sunspot's magnetic field becomes force-free in the low chromosphere, compatible with the reduced height of the $\beta = 1$ surface in strong fields. Higher angular resolution data from the new SPINOR visible/IR polarimeter were analyzed via non-LTE inversion, by Socas-Navarro (2005b). He found however a sunspot in which fields were decidedly not force-free out to heights of 1700 km, which is surprising given the lower expected height of the $\beta = 1$ surface. Furthermore, Socas-Navarro (2005a) concluded that the measurable currents do not lie in hotter regions with enhanced chromospheric heating. Socas-Navarro argues that this discounts steady Ohmic heating and reconnection as viable mechanisms, leaving MHD waves. These provocative results deserve further attention. The Hanle effect has been applied to low chromospheric lines for some time (Faurobert-Scholl 1994), but has recently found application to spicules (Trujillo Bueno et al. 2005; López Ariste & Casini 2005). Recent work with mm arrays has begun to study the thermodynamics of the chromosphere (Loukitcheva et al. 2004; White et al. 2005). Very high angular resolution measurements at the diffraction limits of telescopes new (the DOT, SST) and old (the DST) are beginning to disentangle some of the messier aspects of chromospheric fine structure. Using time series of H $\alpha$ data obtained at very high angular resolution, De Pontieu et al. (2004) suggested that propagation of five-minute oscillations along tilted fields can explain spicules as the result of the formation of slow shocks, akin to the three-minute internetwork oscillations. We can anticipate continued progress with these and new and upcoming facilities including the SOLIS synoptic program (Keller et al. 2003), which includes chromospheric magnetograms (Ca II IR lines), *Solar*-B, ATST, and the proposed mm wavelength observatories CARMA and ALMA.

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