Chromospheric Structure and Dynamics—Observations

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Abstract. I discuss the general problem of the Sun’s chromosphere, its structure and dynamics. I illustrate key aspects using space/time maps of the solar surface obtained recently with SOHO SUMER.

1. Introduction

The chromosphere is a highly structured dynamic region of the solar outer atmosphere. Here, not only are the effects of mechanical heating first evident (moving upward in altitude from the deep photosphere), but also the amount of nonradiative energy deposited is far greater than in the albeit much hotter overlying transition zone and corona. Further, the chromosphere is by far the thickest “layer” of the solar atmosphere with respect to the pressure scale height. A major goal of solar/stellar astrophysics is to understand how the chromosphere is heated and why it adopts its peculiar structure.

2. Contrasting Pictures of the Solar Outer Atmosphere

Fig. 1 illustrates two conceptual views of the solar outer atmosphere. The classical picture is one of “layers,” whereas the alternative view is one of “structures.” Moving upward from the deep photosphere, where the layered view is somewhat realistic, the classical view becomes progressively less tenable. The final insult is the corona; not the thick isothermal $\sim 1 \times 10^6$ K layer of the classical model, but instead a tangled spaghetti plate of loops and explosions covering the full range in $T$ from spicules ($\sim 10^4$ K) to flares ($\sim 10^7$ K).

The chromosphere has been a pivotal battleground between the two pictures. It is here that the fundamental structures—magnetic loops—are promoted from their minor role in the middle photosphere to their dominant position in the “canopy,” forming what conventionally we would have called the upper chromosphere. A major departure between the two views occurs at the base of the classical chromosphere, which now is replaced by a new zone—the “COmospHERE”—whose structure is not completely understood, but contemporary evidence (based on carbon monoxide spectra: see Ayres & Rabin 1996, and references therein) points to pervasive cool gas ($T \sim 3500$ K), a thousand degrees colder than the $T_{\text{min}}$ region of the classical picture.

As discussed by Gene Avrett in this workshop, spatially-averaged ultraviolet spectra can be modelled tolerably well in the layered paradigm, explaining
its popularity over the past several decades. The CO infrared spectra provide the “fly in the ointment,” however. One might be tempted to dismiss the CO evidence as a curious anomaly, but one is hardpressed to ignore the robustness of the molecular line formation (essentially in LTE), the ideal tracer for low-temperature gas. Let’s revisit, then, the ultraviolet side; examining how it fits (or doesn’t) into the new paradigm of “structures.”

2.1. New views from SUMER

The SUMER spectrometer (Wilhelm et al. 1997) on the Solar and Heliospheric Observatory (SOHO), is capable of taking long-slit spectrograms of the Sun, on the disk and off-limb, from below the Lyman edge out to beyond the C IV λ1549 doublet. Some of the first results from SUMER have dealt, not surprisingly, with chromospheric structure and dynamics. Two excellent recent papers are those by Judge, Carlsson & Wilhelm (1997) and Carlsson, Judge & Wilhelm (1997), based on rapid-cadence time series obtained during the instrument commissioning phase in early 1996. The two papers emphasize how dynamic the “quiet” Sun is, not only in phenomena analogous to the “K grains” in the supergranulation cell interiors (e.g., Rutten & Uitenbroek 1991), but also in the continual flickering of transition-zone emissions in the network itself.

The experiment I will describe below was conducted in May 1997. SUMER slit No. 2 (300″ in length, 1″ in width), oriented N/S, was placed +700″ west of the central meridian (μ ~ 0.7). Fig. 2 illustrates the geometry. Even with a fixed slit, solar rotation carries the surface westward across it at a rate of 1 slit-width per 10 minutes (at μ = 0.7). One thus samples the temporal history
of a $1'' \times 300''$ strip of the Sun for a period of several minutes, as solar rotation slowly replaces it with a new strip; building up a "drift-scan" image of transient and persistent surface features over several hours.

Fig. 3 illustrates the target wavelength interval, containing the O I $\lambda 1305$ and C II $\lambda 1335$ resonance multiplets, areas of clean continuum (e.g., $\lambda 1321$), and a sharp Si II chromospheric emission at $\lambda 1309$. We observed with the bright O I and C II multiplets on the reduced-sensitivity bare portions of the MCP sensor, and 1308–1329 Å on the KBr photocathode. The quiet-Sun peak count rates thus were $\sim 1$–2 s$^{-1}$ for the O I and C II lines. We recorded O I $\lambda 1302$, Si II $\lambda 1309$, $\lambda 1321$ continuum, and C II $\lambda 1334$ in $50 \times 360$ pixel$^2$ windows consistent with the 60 s integration time and the available telemetry slots. We geometrically-corrected, flatfielded, and "fluxed" the subimages using standard procedures from the SUMER Analysis Facility at NASA Goddard Space Flight Center.

The new observations are similar to those described by Judge, Carlsson, & Wilhelm, except that the $3 \times$ longer exposure time here allowed all four spectral "windows" to be read down from each image, instead of recorded sequentially in $\sim 1$ hour blocks as in the earlier work. We thus have a collection of simultaneous, cospatial measurements of the four diagnostics, covering a longer period of time—and thus a broader swath of the solar surface—than the temporally-separated frames of the previous study.

According to the layered models of Vernazza, Avrett & Loeser (1981), the $\lambda 1321$ continuum forms on the high side of the initial temperature rise out of the $T_{\text{min}}$ region. O I $\lambda 1304$ forms in the upper chromosphere (Carlsson & Judge
Figure 3. Key “chromospheric” wavelength interval for drift scanning (from SUMER Atlas, courtesy P. Judge).

1993), and C II in the low transition zone (Lites, Shine & Chipman 1978). The three diagnostics thus span the full height range of the chromosphere.

Fig. 4 illustrates a space/time diagram for the $\lambda$1321 continuum, from a sequence of 350 exposures (5h50m total duration). The lefthand frame depicts the result of concatenating the individual $1'' \times 300''$ continuum intensity traces. The grey scale is linear over the intensity range from 30% (light shading) of the sample median to 300% (dark shading).

The image is peppered with short vertical streaks representing transient brightenings, and horizontally-elongated features representing long-lived bright structures of significant E/W spatial extent. The central frame is a spatial map of persistent features obtained by filtering the space/time diagram to suppress the short-lived intensity fluctuations. The depiction is reversed with respect to normal convention, with W to the left and E to the right (to maintain proper orientation with respect to the space/time diagram).

The righthand panel illustrates masks derived from high-frequency and low-frequency filterings of the space/time diagram, emphasizing the upper portions of the respective intensity histograms. The dark areas indicate stable surface features, probably mostly network lanes. The lighter streaks, narrow along the time axis, mark the brightest of the transient events. Most of the rapid brightenings at this level of the atmosphere undoubtedly are related to the short-lived points seen in Ca K$_{2v}$ filtergrams and CN $\lambda$3883 pictures (Sheeley 1969).

The upper panel illustrates a histogram of brightness temperatures for the space/time diagram, derived from the calibrated intensities. The black and grey shaded areas correspond to the network and transient-point masks discussed above. Note that while the intensities in the image span more than a decade, the temperature range is remarkably narrow, with an rms of only about 80 K. In the ultraviolet, in the Wien limit, a great deal of intensity contrast can be produced by even a rather bland temperature field.

The histogram is nearly symmetric, with only a weak tail on the hot side. The network elements are systematically 100–200 K warmer than the dominant temperature of the map, while the transient points cover a wide range of tem-
perature in the upper half of the distribution. In the masks, the bright network occupies about 9% of the scene, while the brightest of the transient points fill another 13%, or so. Notice also that the minimum temperature of the $\lambda$1321 map is about 4400 K, a thousand degrees hotter than the putative COmosphere that is thought to exist at the same heights at which the far-ultraviolet continuum forms in the layered view. Owing to NLTE effects, the recorded $\lambda$1321 temperatures very likely are lower than the true kinetic temperatures in the continuum-forming gas. Where, then, is the cool material that shows up so well in the anomalous extreme-limb darkening of the strong 4.7 $\mu$m CO lines, and in their off-limb emissions? I will defer the question to later, noting only that far-ultraviolet continuum maps like that illustrated here provide—at least superficially—a strong argument against cool material at high altitudes.

Cursory examination of the $\lambda$1321 intensity image reveals apparent groupings of the transient streaks, suggestive of repetitive behavior. Cross-correlation of the map against itself along the time axis yields broad peaks at about 3 minutes, and multiples of that period. The transient intensity oscillations have the same character as those seen at high altitudes in the photosphere in molecular diagnostics like OH (Deming et al. 1988) and CO (Ayres & Brault 1990),

Figure 4. Space/time diagram for $\lambda$1321 continuum.
Figure 5.  Space/time diagram for O I λ1302.

namely a shift to higher frequencies from the 5 minute modes dominant in the lower atmosphere. That also is a property of the Ca II “cell flashes.”

Fig. 5 illustrates a space/time diagram for the emission core of the strong chromospheric O I λ1302 feature. The horizontal banding of the intensity frame is due to flatfield “noise.” (Not as obvious in the λ1321 map, because 30 spectral bins were combined to yield the continuum intensity, whereas only 5 bins contributed to the O I line core, with correspondingly less statistical mitigation of residual fixed patterns).

The O I scene is qualitatively similar to that of the λ1321 continuum, showing again substantial point-to-point intensity contrasts and dominated by the small-scale bright network elements. Here, however, discernable transient events are rare (note the masks in the righthand panel), and repetitive intensity structure is less evident. The temperature histogram is distinctly broader, and has a
more pronounced tail on the hot side. The network elements appear somewhat fuzzier and more extended spatially than their counterparts in the continuum image, and there is a distinct haze of emission surrounding them, roughly where the brightest continuum flashes occur. The bright network covers about 14% of the scene.

Fig. 6 illustrates a space/time diagram for the low-transition-zone feature C II λ1334. It is similar to the O I image, although one can identify places where C II is bright but O I is dim (rarely the reverse, however). Again, the spatial morphology is dominated by small-scale bright network lanes, occupying about 14% of the map, surrounded by a haze of less-intense emission. The temperature histogram is broader still, and strongly skewed to the hot side.

Fig. 7 illustrates a space/time diagram based on the combined intensities in the red and blue wings of C II λ1334. It highlights locations where the C II
profile was anomalously broad, blueshifted, or redshifted; signatures of the TZ "explosive events" (see Innes et al. 1997 for a recent discussion based on SUMER raster scans of TZ lines, and references to previous work). The explosive-event map shares some similarities with the previous diagrams, but there are significant differences as well. While explosive activity occurs commonly in the bright network, there are many isolated events well away from the network lanes. They do not appear to be associated with any chromospheric wave excitations, but instead likely represent magnetic reconnection episodes (Innes et al. 1997), perhaps in ephemeral bipolar regions. It also is worth noting that many of the highly active points, as measured by the excess Doppler broadening, are not especially bright in terms of integrated core intensity. The disconnections between the C II explosive events, morphology of the O I emissions, and the continuum cell flashes reinforce the picture of an active atmosphere dominated by a mixture of isolated structures at different heights.

2.2. Infrared thermal maps

Although the present discussion focusses on the far ultraviolet, it would be remiss of me not to show at least one diagram based on the CO lines from the
Figure 8. Velocity and temperature histograms for 4.7 μm CO lines.

thermal infrared. A broader discussion of the CO diagnostics can be found in Ayres (1997). Fig. 8 depicts velocity and temperature histograms derived from repeated scanning of a 40″×40″ area of the quiet Sun, near disk center, on 9 May 1996. At normal incidence in the strong CO lines one sees into the layers of the upper photosphere. (The “COMosphere” is visible in CO only near the extreme limb, or off-limb, and thus presumably is at even higher altitudes.) The velocity displacements are characteristic of p-mode excitations high in the photosphere, and the temperature rms is consistent with compressions and rarefactions associated with the nearly adiabatic waves in those layers. Note that unlike the ultraviolet temperature histograms, the CO distributions are slightly skewed to the cold side. The rms temperature width of the CO distribution is very similar to that of the λ1321 continuum, although the dominant temperature is several hundred degrees lower. Owing to NLTE effects in the Si I continuum, however, the similarity between the ultraviolet and infrared temperature distributions probably is merely coincidental.

3. Discussion

Before discussing a possible synthesis of the ultraviolet and infrared pictures, I will summarize my view of the SUMER space/time diagrams.

At the (presumably low) levels of the chromosphere probed by the λ1321 continuum, we see pervasive warm temperatures (T > 4400 K), ubiquitous oscillations, and a sprinkling of persistent bright structures, undoubtedly network fragments. In the upper chromosphere, probed by the O I resonance line, we
again find the bright network, somewhat more diffuse than in the $\lambda 1321$ map. There are few signs of intensity oscillations, however, but perhaps some fuzzy emission patches surrounding the bright network lanes. In the low transition zone, probed by the C II resonance line, we have essentially the same picture as in O I, although there is even greater contrast between the network fragments and the ambient background emission. In the C II wings, we see many more small-scale transient (line-broadening) episodes than are evident in the C II intensity map. These "explosive events" do not appear to be connected with the $\lambda 1321$ "flashes" and very likely are produced completely differently (Judge, Carlsson & Wilhelm 1997). Together, the space/time diagrams demonstrate that the chromosphere at all levels is highly dynamic and highly structured.

Can the (hot) ultraviolet and (cool) infrared pictures be reconciled? I believe they can. The fundamental issue is, where does the $\lambda 1321$ continuum form? According to Vernazza, Avrett & Loeser (1981), the background opacity at that wavelength is dominated by the ground-state photoionization continuum of atomic silicon. In the layered models, the continuum arises just above the $T_{\text{min}}$, and thus is a diagnostic of the initial temperature inversion.

The fact that the $\lambda 1321$ map shows warm temperatures everywhere would seem to imply that the classical chromospheric inversion is pervasive, and consequently there is "no room" for a cold COmospheric layer. In the structured model, the Si I continuum would become optically thick in the cold COmosphere itself, owing to the increased population of neutral silicon. Nevertheless, the thermal emissivity of a 3500 K gas at 1321 Å is several hundred thousand times less than at 6000 K. At the top of the COmosphere, there is a transition from the cool gas to the hot canopy, a "postponed" chromospheric inversion if you will. The Si I continuum would be optically thin in that warm interface, but the contribution function of the emergent intensity undoubtedly would be driven to those higher altitudes by the low emissivity of the cool COmosphere; the radiation field would never "see" the cold gas (see, e.g., Vernazza, Avrett & Loeser 1981, their Fig. 36, panel for 1318 Å).

In this picture, the Si I continuum would be a diagnostic for the underside of the chromospheric canopy—immediately above the COmosphere—several hundred kilometers higher than its formation height in the layered models. The morphological similarities between the $\lambda 1321$ map and Ca II filtergrams (flashes and network) would thus be a natural consequence of similar formation heights.

The core of the O I line arises much higher in the canopy, apparently where the influence of the cell flashes is minimal. That suggests that the disturbances responsible for the flashes (as seen in $K_2\nu$ and $\lambda 1321$) occur under the canopy. Significantly, the shock formation height in the 1-D radiation-hydro simulations of Carlsson & Stein (1997) is near 1000 km, about the altitude proposed for the base of the canopy (e.g., Solanki & Steiner 1990). The O I intensities are highest in the network lanes, but there is a halo of emission surrounding the bright points, presumably representing hot gas loading the diverging field lines that interconnect the fragments and form the canopy. The pervasive hot gas in the canopy, with temperature, density, and velocity contrasts from point to
point, yields the highly-structured Hα\(^1\) filtergrams that give the impression of a wide-spread chromosphere (which it is, after all, at those altitudes; but probably isn’t immediately below the canopy).

Finally, the hot transition-zone gas appears to be mostly confined to the network cores, although the enigmatic explosive events show a broader distribution. These emissions likely form in loops rising out of the canopy, tied to the network lanes, or out of ephemeral regions in the cell interiors.

4. Conclusions

The space/time diagrams from SUMER reinforce the view that much of the chromospheric “action” must be occurring on fine spatial scales and short times; particularly in the cell-interior transient brightenings, but also in the longer-lived network fragments. That regime of investigation is far removed from what one usually associates with the subject of this workshop, namely “synoptic” measurements. Nevertheless, long-term systematic records of chromospheric indices, filtergrams, and globally-averaged profile parameters (e.g., for Ca II) not only can provide important insights concerning the crucial roles of the cycle-variable and cycle-free parts of the solar magnetic field (see Karen Harvey’s presentation at the workshop), but they also can forge a key link with optical and ultraviolet “synoptic” measurements of stars. There, activity-related phenomena often are significantly exaggerated compared with the solar case, but high–spatial-resolution reconnaissance is not even a remote possibility.

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References


\(^1\)Note that although Balmer alpha falls in the red part of the optical spectrum, it behaves more like a highly-temperature-sensitive ultraviolet diagnostic, owing to the 10 eV excitation required to populate the n = 2 level of atomic hydrogen from which the Hα line arises.

Group Discussion

_November_: Is there direct observational evidence for a true $10^4$ degree corona or are cool corona structures really just high limb extensions into a fairly uniformly filled $10^6$ degree corona, as I think prominences and spicules are?

_Ayres_: The “corona” is composed of magnetic structures of various sorts; high up, most of the loops with significant gas densities are hot; lower down, the “loaded” loops can be hot, warm, or cool. Examples of the latter are prominences. An important point is that not all of the coronal magnetic field is populated by hot gas all of the time. The heating of the loops, and their “loading” by hot gas, is highly intermittent in time and space.

_van Ballegooijen_: What is the argument for believing that the CObmosphere is a uniformly cool layer and not a patchy, time-dependent structure with small filling factor of cool material? The limb extent of CO emission would seem to be consistent with either model.

_Ayres_: There are two arguments in favor of the pervasive model: (1) the off-limb extensions are sensitive to the tangential column density of cool material, itself related to the filling factor. The existing small-filling factor models show limb extensions that are too small compared with the observations. (2) The small filling factor model requires the presence of ultra cold regions, which should appear as a ~ 20% population of dark spots in a disk center map. No such features are seen in the existing maps of CO lines. It might be a question of poor temporal and spatial resolution of the existing CO maps; so we have to make improvements in the observations in order to address the issue more definitively.

_Canfield_: I found the Innes et al. (Nature) paper about bi-directional jets in explosive events interesting in the framework of magnetic reconnection. You have told us that explosive events are common in both network and inter-network sites, whereas I would expect them to be more common in the network. How do you explain these in terms of magnetic topology that encourages reconnection, yet is common in the inter-network?

_Ayres_: The “internetwork” explosive events undoubtedly occur in interacting small-scale bipoles newly emerged and not yet advected to the super granulation boundaries. The internetwork events appear isolated, whereas the network counterparts overlap strongly, giving the impression of a near-continuous
process. The internetwork explosive events are much less common than the continuum “grains” (cell flashes) and show very little spatial overlap; thus the explosive events very likely are the result of a different mechanism than the cell flashes.

H. Wang: Is there any comparison/identification between explosive events and Hα spicules and confirmation that they are due to magnetic reconnection?

Ayres: The recent paper in Nature by Innes et al. demonstrates that the explosive events are associated with X-type reconnections in magnetic flux concentrations. The correspondence of explosive events and spicules is under investigation by a number of groups. I’m not sure what the final answer is, but I suspect that only a fraction of the explosive events leads to ejections of cool material seen as spicules.

Schrijver: (in response to H. Wang’s question) I believe K. Dere has made a comparison of number densities of spicules and TR explosive events based on HRTS data, and found these to be significantly different.