The Solar Chromosphere: Old Challenges, New Frontiers

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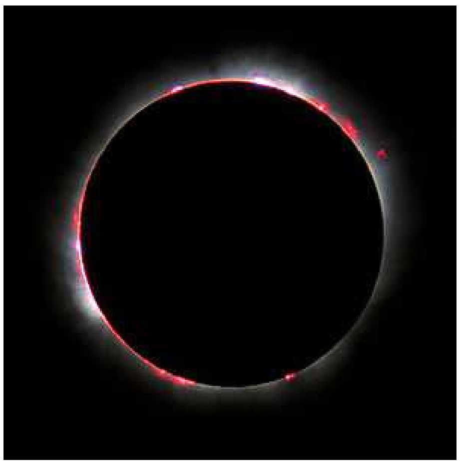
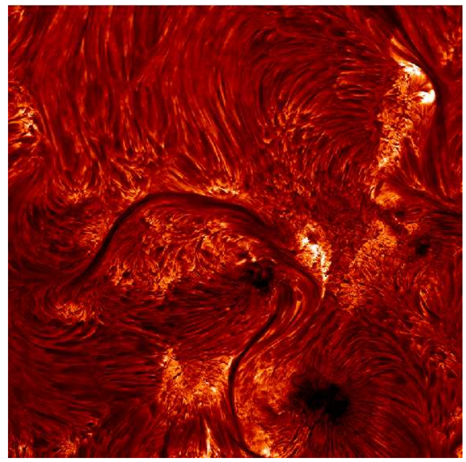
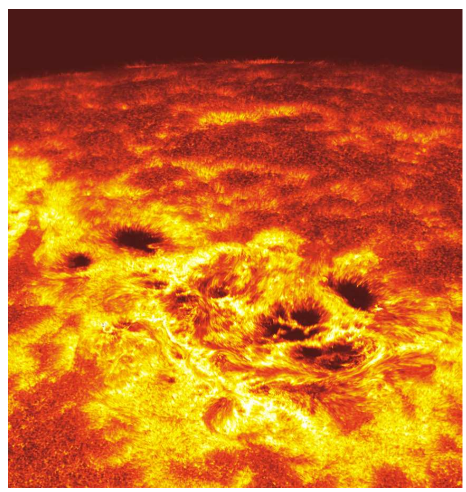
Chromosphere at eclipse



Hα filtergram of chromosphere



Photospheric spots & bright points



Same area in chromospheric Ca^+

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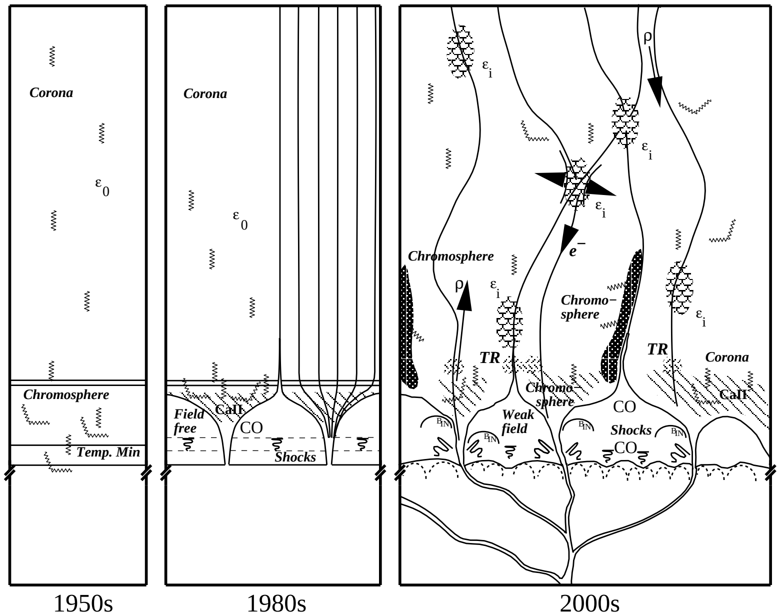

Figure 1: Cartoon evolution of solar chromosphere (C. J. Schrijver). It has grown from a simple stationary 'layer' of the 1950's; to topologically more diverse view of the 1980's, mixing cool ("CO") and hot gas at similar altitudes, pervaded by magnetic flux ropes, albeit still largely static; to contemporary highly dynamic and spatially chaotic "Magnetic Complexity Zone." This messy region now is speculated to have a major influence on the overlying corona, contrary to the historical view that the coronal "tail" to some extent wagged the chromospheric "dog."

SUMMARY. As in the history of photospheric granular convection, the judicious combination of high resolution multi-wavelength imaging and polarimetry with detailed numerical simulations offers the promise to elucidate the profound interactions of plasma and magnetic fields that give rise to the enigmatic, dynamic, phenomena-rich *chromosphere*. The Sun allows a sharp focus on principal physical effects, and not in some averaged fashion as is the reality for most other astronomical objects. Understanding the solar chromosphere will pave a path to more remote cosmic environments, also shaped by the forces of "magnetic complexity." New instrumental and facility developments, however, are needed to fully exploit the truly four-dimensional observations possible on our cosmic neighbor. Luckily, several pivotal groundbased initiatives (ATST, ALMA, EVLA) are expected to be operating in the next decade, to help shed light on this fundamental solar-stellar enigma.

Introduction

From ancient times, the Sun's chromosphere has been a subject of fascination. With the naked eye, it is seen only at eclipse, as a string of brilliant rosy beads above the solar limb, a bright and colorful contrast to the rather pale visage of the white light corona.

In the modern era of telescopes and astrophysics, the chromosphere retains its fascination,[1] but now as a key boundary region in the solar outer atmosphere. Here the near equilibrium,

[1] A search of the NASA Astrophysics Data System abstract server for "chromosphere" yielded 14,279 hits.

generally placid upper photosphere (above the convective overshoot layer) has given way to the highly nonequilibrium, dynamic, mechanically heated, forced temperature inversion of the higher altitudes; a segue into the equally enigmatic super-hot (few MK) corona. Like many boundaries in the cosmos, the transition is messy. The chromosphere at once hosts some of the coldest material in the whole solar atmosphere—$T \sim 3500$ K—as seen in off-limb emissions of 4660 nm CO lines (Solanki et al. 1994),[2] and very warm gas—$T > 10^4$ K—associated with ionizing shocks. There even is speculation that the upper chromosphere is site of the *coronal* heating outside of active regions, thanks to the uniquely contorted magnetic field topology, prone to sporadic energy release (Aschwanden et al. 2007).

In fact, it is fair to call the chromosphere the "Magnetic Complexity Zone," because the magnetic fields that pervade this region are highly twisted and tangled as a consequence of the shift from gas dominance in the deep photosphere (field lines frozen to the plasma, dragged about by surface flows) to field dominance in the corona (ionized plasma forced to flow along the field lines, bottled up in coherent large scale structures). At either extreme, the field takes on relatively simple forms: small scale intense flux tubes in the high-β photosphere,[3] and delicate near-potential loop-like structures in the low-β corona. Paradoxically, the field in the intervening $\beta \sim 1$ zone adopts a chaotic topology, reconnecting willy-nilly, and blossoming out into an overarching "canopy," the conspicuous source of the meandering striations seen in Hα filtergrams. Underscoring the complexity, long Ca^+ imaging sequences at the solar limb recorded by the *Hinode* satellite reveal an incredibly rich, relentlessly dynamic, and highly structured environment, with heating events switching on and off much faster than the underlying photosphere is seen to evolve (De Pontieu et al. 2007).

The Sun is not alone in hosting a chromosphere; virtually all late-type stars (F-types and later) possess them. The properties can vary wildly from object to object, depending on the degree of magnetic dynamo activity. There are two main systemic behaviors. One is the so-called rotation-activity connection (Skumanich 1972): chromospheres strengthen as stellar spin increases (and dynamo action intensifies). The second is codified in the "Wilson-Bappu Effect" (Wilson & Bappu 1957), a steady broadening of the chromospheric emission cores in the bottom of the Ca^+ H and K features (393, 396 nm) with increasing absolute visual luminosity, extending over a remarkable 15 stellar magnitudes.

The signature property of the chromosphere is its enormous thickness (some ten, or so, pressure scale heights). The prime suspect is the ionization of its dominant constituent, hydrogen. Given the large FIP,[4] hydrogen ionization acts as a sponge to soak up energy, buffering the gas somewhat from local heating spikes (like acoustic shocks), moderating the temperatures. More importantly, ionization frees electrons to fuel steady cooling by collisional excitation of abundant species such as Fe^+, Mg^+, and Ca^+. This "ionization valve" works effectively because of the large dynamic range of the electron fraction, n_e/n_H. It is only 10^{-4} at the base of the chromosphere (where the electrons are from singly ionized metals), but at the top approaches unity (hydrogen mostly ionized). This allows considerable leeway for the gas to balance heating even while the overall density falls outward (Ayres 1979).

[2] Abbreviated citations in text are linked to full citations inline.

[3] The plasma β is the ratio of gas pressure to magnetic pressure.

[4] First Ionization Potential.

However, once the reservoir of neutral hydrogen is exhausted, the valve cannot continue to hold the heating in check, and a thermal runaway ensues. Next stop: *coronal* temperatures.

Although this simple picture is appealing, it obscures the deep complexity of the solar example by sweeping a whole range of poorly understood phenomena into the slim rubric of "mechanical heating." A major thrust of contemporary solar physics, then, is to dig deeper into this enigmatic boundary layer. Fundamental unresolved issues:

How is the atmosphere heated? How is energy transported into and across the boundary? What is the source of the conspicuous structure, both long-lived and transient? What is the role of the chromosphere as a reservoir of mass and energy to feed the overlying corona (whose heating and mass loading requirements are but a small fraction of those of the chromosphere itself)?

The Sun, understandably, plays a key role in the effort because it is a few hundred thousand times closer than even the nearest other stars, allowing proximate scrutiny by earthbound and space telescopes.

In fact, the chromosphere was fertile ground in the 1950's and 1960's for the early development of specialized treatments of radiation transport and spectral line formation to confront the extreme departures from classical Local Thermodynamic Equilibrium (LTE) at the very low densities and high temperatures of this region. "Scattering" in strong resonance transitions on the one hand becomes a dominant transport mechanism, but on the other hand, the induced nonlocality of the radiation fields creates serious challenges for remote sensing.

In recent years, the near-equilibrium *photosphere* has served as an important laboratory to vet our understanding of kinetic transport, culminating in the sterling success of modern 3D convection models (e.g., Stein & Nordlund 2000; Vögler et al. 2005). The important lesson is the pivotal role played by small scale phenomena in controlling transport processes. Solar granular convection is a highly nonlocal phenomenon, driven from a thin surface thermal boundary layer. Here, radiative cooling produces low entropy gas that, in turn, forms strong downdrafts concentrated in the narrow intergranular lanes, smaller than 100 km in size (less than a tenth the diameter of the parent granule). Most of the buoyancy work occurs in such tiny structures. Similar comparisons currently underway for the more complex physical situation of magneto-convection show that dynamical control by small scale elements holds generally: in magnetic fibrils of the quiet Sun (e.g., Stein & Nordlund 2006), sunspot umbrae (Schüssler & Vögler 2006; Rimmele 2008), and the surrounding penumbral fans (Scharmer et al. 2008; Rempel et al. 2009).

Now, it is the chromosphere that stands as a new frontier for the palpably more challenging radiation-magnetohydrodynamic (R-MHD) simulations required when the classical transport processes begin to break down, and the magnetic field and nonlinear acoustic disturbances take over (e.g., Wedemeyer-Böhm et al. 2004; Abbett 2007; Martínez-Sykora et al. 2008). Most of the mass and nonradiative energy that sustain the outer atmosphere reside in the chromosphere, and from here are channeled upwards, thanks mainly to the magnetic field. (As one aficionado put it, "You ignore the chromosphere at your own peril!") However, it still is far from clear how the transport and heating are accomplished, and in particular the roles of the copious small and rapid phenomena, routinely observed in different guises as spicules, mottles, jets, Ellerman bombs, and other events with similarly evocative tags.

Some of these phenomena have tentative explanations, for example the creation of dynamic fibrils and mottles by means of magneto-acoustic shocks (De Pontieu et al. 2007; Rouppe van der Voort et al. 2007). But, for the most part, a complete description of the link between the photospheric drivers and the resulting hot outer atmosphere remains elusive. Fully 3D, R-MHD numerical simulations spanning from the upper convection zone through the corona—treated as a coherent system—are only now starting to appear, but cannot yet address all of the salient physical ingredients. Thus, a close collaboration between observers and theorists, similar to the successful model for photospheric processes, is essential to make progress in the chromospheric arena.

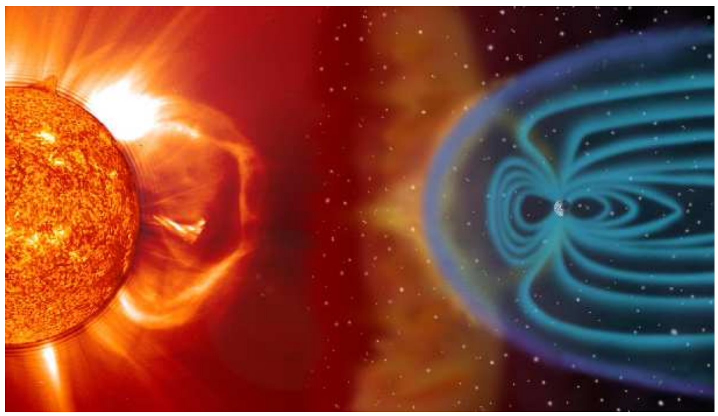

Figure 2: Popularized depiction of "Space Weather;" grossly out of scale, but nicely illustrating impacts of wind, UV radiation, and mass ejections on Earth.

Relevance of the Chromosphere

First and foremost, the chromosphere is source of most of the Sun's ultraviolet ionizing flux, a key input to terrestrial modeling (think "ionosphere"); not only in the short term to separate solar from human influences, but also in the longer term to establish the effect of evolving magnetic activity on the Sun's habitable zone (and those of other stars).

In fact, judging by G dwarfs in young Galactic clusters, the Sun was considerably more magnetically active in its extreme youth. The erosive effects of intense solar UV radiation and wind are thought to have played a key role in stripping volatiles from the primitive atmosphere of Mars (e.g., Luhmann 1992). The tormenting of newly formed planetary systems by their young and hyperactive suns undoubtedly is common in the cosmos.

Direct measurements of photospheric magnetic fields on distant, unresolved stars, either by polarimetry or in unpolarized light, are technically very challenging. Consequently, our main knowledge of stellar surface magnetism depends largely on the emission signatures carried by the chromospheric Ca^+ H and K lines. A better understanding of the solar mechanisms underlying the proxy would strengthen its value in ferreting out the broad properties of stellar magnetic dynamos, beyond the singular example of the Sun.

The chromosphere also is the seat of the acceleration mechanism of the solar wind, another key process whose physical origins remain elusive. The wind not only is relevant in a practical sense to Space Weather (Figure 2), but also is an accessible example of the vastly more powerful outflows that occur at the extremes of stellar evolution; in the earliest stages (T-Tauri phase) and the terminal episodes (asymptotic red giants).

Coronal modelers rely on photospheric vector field measurements to extrapolate the force lines into the corona, and typically fail miserably (DeRosa et al. 2009). The prime suspect: the Lorentz forces that act on the field in the photosphere. They are so large that the inferred electrical currents are not field-aligned, and either never make it into the corona, or are deflected to very different positions before they enter the corona. A remedy would be to measure the vector field directly in the upper chromosphere, and extrapolate from there.

Finally, the solar chromosphere is an excellent venue to explore the intricate interplay between plasma and magnetic fields in a regime where both are relevant and alternately dominant. Here, numerical simulations can be tested in great detail against observations, and important decisions can be made as to the essential physics and the most suitable algorithms. Success in this endeavor would benefit modeling of other astrophysical plasmas that operate in similar regimes, like magnetized accretion disks around young stars, or their more exotic cousins circling massive black holes in Active Galactic Nuclei.

Obstacles to Progress

Four effects mainly set the chromosphere apart from the much denser, near equilibrium photosphere. Each of these presents barriers to numerical simulations of chromospheric structure and physical processes; these also are potential obstacles to remote sensing.

(1) The chromosphere encompasses the domain in which magnetic fields begin to gain dominance over purely hydrodynamic forces. It contains intermixed regions where the plasma β is greater than and less than unity, with substantial spatial and temporal fluctuations. Strong gradients can develop in the chromospheric field owing to the small magnetic diffusivity.

(2) The chromosphere is optically thin at most visible wavelengths, apart from a few strong spectral lines. Because these same lines also dominate the transport of radiative energy, they must be handled with so-called non-LTE formation: challenging to formulate, dependent on often poorly known atomic physics, and costly to compute.

(3) Recombination time scales of hydrogen—the heart of the "ionization valve" noted earlier—can be much longer than dynamical time scales. Consequently, the ionization state at any instant depends on the previous history of the plasma. Chemical equilibrium time scales also are long compared with the dynamics. This can affect key species like CO, instigator of "molecular cooling catastrophes" in places where mechanical heating has temporarily abated (Ayres 1981). As with the magnetic field, strong gradients in ionization and chemistry can develop, with consequences for the plasma cooling and energy balance.

(4) There also is mounting evidence that the partial ionization leads to multi-fluid effects, very different from single-fluid MHD (e.g., Arber et al. 2007). This has clear consequences for wave propagation and mode couplings, but also might affect the outcomes when Lorentz forces act during, say, flux emergence, fibril dynamics, or filament disruption.

The severe departures from the equilibrium state make it distinctly trickier to model the chromosphere at a level of realism approaching what has been achieved for the photosphere.

New Opportunities

To achieve a successful close comparison between solar chromospheric observations and theory, much work is needed on both sides. For example, despite the Sun's proximity, the necessary polarimetric accuracy to capture chromospheric vector fields still is not achievable—at the desired fine spatial and temporal scales—with present instrumentation and telescopes (dividing up the photons into space, time, frequency, and polarization states quickly exhausts the supply). Innovations in both areas are actively being pursued, especially telescope aperture. Notably, the 4 m Advanced Technology Solar Telescope (ATST: Keil et al. 2001) is slated to be the flagship international facility in the coming decade to carry out pioneering high resolution studies of the solar atmosphere. On the instrumental front, designers are attempting to address several fundamental, sometimes conflicting, requirements. First, recording multiple spectral lines is necessary to probe the many scale heights spanned by the chromosphere. Second, the measurements must be obtained over a sizable field of view (e.g., $1' \times 1'$, containing several cells of the supergranulation "network"), to adequately trace the 3D interconnectivity forced by the magnetic field. Third, it is essential to capture the multi-line diagnostics *simultaneously,* to avoid ambiguities introduced by fast structure evolution and solar surface kinematics. Prototype instruments are IBIS at Sacramento Peak and CRISP at the Swedish Solar Telescope on La Palma. Continued technical innovations will fully exploit ATST's powerful capabilities when it comes on line circa 2016.

Deployment of high performance instruments with advanced capabilities, and operating at solar telescopes of large aperture, is a priority for the coming decade.

A related issue is the need to achieve high spatial resolution, of order $0.1''$ (~ 70 km) or better, over the extended fields of view, to resolve the fine scale structures in which much of the magnetic "action" likely takes place. Deployment of a large aperture solar telescope in space is one possibility, but a more realistic near-term option is Multi-Conjugate Adaptive Optics at a groundbased observatory (MCAO provides simultaneous correction of seeing caused by different layers in Earth's atmosphere). Parallel work on MCAO for nighttime telescopes offers opportunities for synergism.

Development of wide-field Adaptive Optics systems should be strongly supported.

In terms of theory, efforts to simulate the structure and dynamics of the photosphere, chromosphere, and corona as one coherent system are underway, as mentioned earlier. To approach realism, such "forward modeling" will require the inclusion of time-dependent hydrogen ionization, nonequilibrium radiation transport, multi-fluid behavior, and diverse magnetic field configurations, to mention a few key components; all challenging to implement and very costly to compute. Forward modeling not only is a key to sort out the most relevant physical effects, but also a tool for vetting measurement techniques: model intensities can be subjected to a simulated observation to judge how much of the original physical information is recovered by that procedure.

Continue to advance the state-of-the-art of forward modeling, not only to achieve physical insight, but also to validate and enhance observational strategies. A necessary adjunct is access to diverse and accurate atomic physics data.

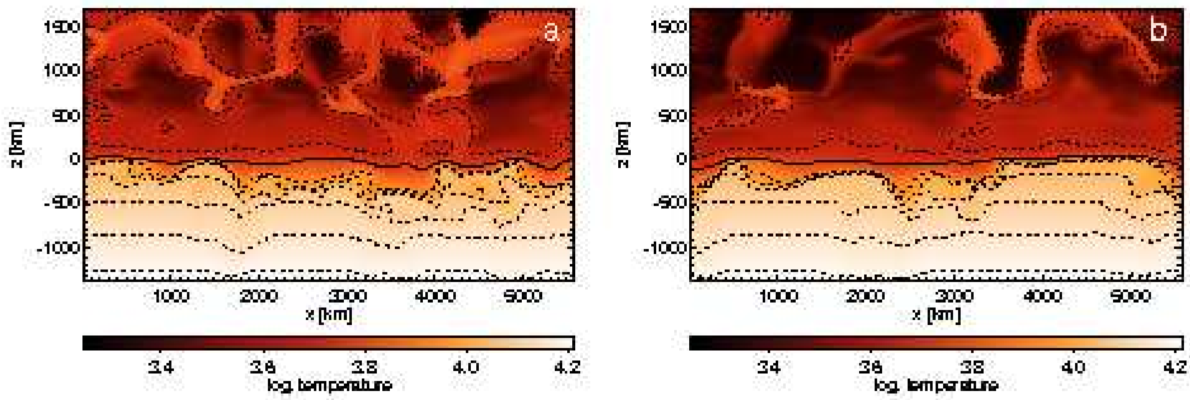

Figure 3: Pair of independent 2D temperature ($\log T$) slices through a 3D simulation of (nonmagnetic) chromospheric shock structure (Wedemeyer-Böhm et al.). Height scale, z, is relative to $\tau_{500\ \mathrm{nm}} = 1$ (solar "see level"): 500 km roughly marks the base of chromosphere. Note that very cold gas and hot filamented shocks are intermixed at high altitudes. Incorporating 3D R-MHD is a future—and immensely challenging—step.

As a final remark, the chromosphere presents a difficult remote-sensing target, because it is mostly transparent in the visible, aside from the cores of a few strong resonance lines. At the same time, the chromosphere is very opaque below the Lyman continuum edge at 91 nm (many solar space imagers and spectrometers operate in the EUV around 20-30 nm, and thus cannot directly probe this region). Finding new windows into the state of the chromospheric gas thus is both a major challenge and an opportunity. Coordinating space-based UV, visible, and X-ray imaging (say, from *Hinode*) with groundbased spectroscopy continues to be a mainstay of contemporary solar astronomy. An important new capability is the Atacama Large Millimeter Array (ALMA), currently under construction in northern Chile. The microwave interferometer will be able to achieve unprecedented high spatial resolution (0.1″, or better) on the Sun, into the depths of the chromosphere. Prototype 3D radiation-hydrodynamic simulations (Figure 3, above) suggest that ALMA multi-band imaging will provide stringent tests of these—and later R-MHD—models of the solar outer layers (Wedemeyer-Böhm et al. 2007). Furthermore, ALMA's exquisite mm polarization sensitivity should provide a completely new and unique probe of the chromospheric field. Similarly, the Expanded Very Large Array (EVLA) will have enhanced capabilities to probe explosive activity and particle acceleration at the top of the chromosphere in centimetric light, at the crucial level where magnetic complexity might evolve into coronal heating.

Innovative use, where feasible, of nighttime-oriented astronomy facilities to provide new windows into the Sun's outer atmosphere should be encouraged. The unique capabilities of space platforms also should continue to be exploited in coordination with groundbased instruments. But, special emphasis should be placed on UV imaging and spectroscopy longward of the LyC edge, necessary to actually "see" deep into the chromosphere itself.

Luckily, several of the pivotal groundbased initiatives (ATST, ALMA, EVLA) are expected to be operating in the next decade. The future of solar chromospheric exploration appears as rosy as its trademark Hα.