Understanding the Thermal Structure of the Chromospheric and Coronal Plasmas

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The complex thermal structure of the solar chromosphere and corona is driven by, as yet unexplained, mechanisms transferring the emergent energy from the photosphere to the upper solar atmosphere.

There is a long list of short-lived, ubiquitous dynamic events that connect the chromosphere to the corona: spicules, explosive events, network jets, campfires, mini filament eruptions. All of these phenomena have been tied to the evolution of the magnetic field, but in 2020 observational solar physics is at an impasse because of our inability to simultaneously derive high resolution spectral, spatial, and temporal information on these sources.

The cartoon model that connects these phenomena is easy to outline Fig. 1. Magnetic fields in the photosphere are perturbed by convective flows. Some of the magnetic field in the photosphere expands into and populates the chromosphere. The force balance in the chromosphere is complicated as gravitational stratification takes a backseat to shock wave-driven expansion-contraction cycles. At the top of the chromosphere, the magnetic pressure dominates gas pressure, and the net Lorentz force is broadly reduced. The upper chromosphere and the corona are theoretically filled with smoothly distributed magnetic flux systems. To make an analogy, if photospheric flux tubes are the meat, and corona loops are the sausage, the chromosphere is a grinder. You don't know what is in the sausage until you understand what is happening inside the grinder.

The cartoon breaks down when we incorporate the fact that latent magnetic energy must be stored in the chromosphere or the corona, somewhere. This is the only way to generate the large X-ray flares we observe. The current state-of-the-art for numerical simulations are just starting to be able to capture the evolution of the coupled chromosphere-corona system. But thanks to numerical resistivity, the problem of magnetic energy storage is largely unaddressed.

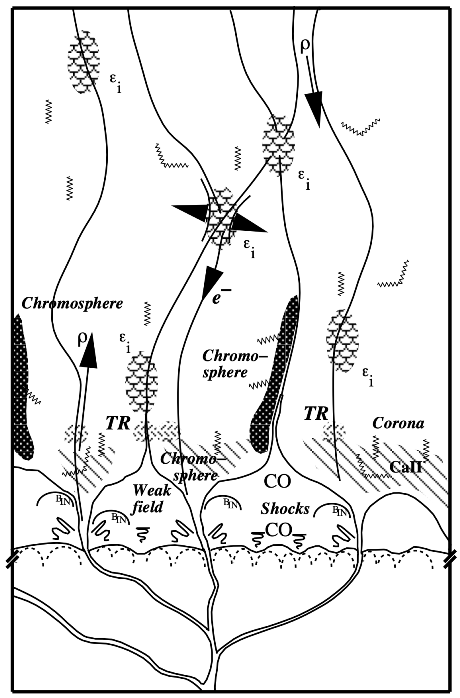

Figure 1: Cartoon concepts of the solar corona with a fully inhomogeneous mixing of photospheric, chromospheric, and coronal zones by dynamic processes such as heating and cooling mass flows (ρ), intermittent heating (ε), nonthermal electron beams (e), field line motions and reconnections, emission from hot plasma, absorption and scattering in cool plasma, acoustic waves, and shocks (From: M. Aschwanden's "Physics of the Solar Corona an Introduction" Praxis Publishing, 2004, and C. Schrijver, "The Coronae of the Sun and Solar-type Stars" 11^{th} Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ASP Conference Proceedings, **223**, 2001).

Observational solar physics must contend with the limitations of remote sensing. For every photon observe, we try to determine from where in a 3D volume it originated, how much energy it contains, and what process generated it. To make headway in constraining the dynamic processes, several advances are necessary:

First, coupled chromosphere-coronal dynamics require multi-wavelength observations. We need to observe highly disparate thermal regimes — multiple atomic species are required to provided robust thermal discrimination.
Second, high-resolution observations are necessary to resolve the evolution of individual magnetic loops. Our current observations have shown that the detection rate of spicules is strongly biased with spatial resolution — we observe ten times more spicules at $0.1''$ resolution than at $0.5''$ resolution.
Third, we must be able to resolve the timescales at which energy is being deposited. This means observing cadence needs to be shorter than the frequency of propagating Alfven waves ($<$60 s), though recent analysis has shown that the transition regions exhibit statistically

significant emission variability at up to 50 mHz.
Fourth, significant spectral resolving power is necessary. In optically thin lines, we need to be able to resolve the difference between non-Maxwellian velocity distributions and velocity gradients along the line of sight (R>50000).
Fifth and most importantly, the observing scheme must allow for simultaneous or nearly simultaneous observations of coherent thermal-magnetic structures. In the chromosphere, a fibril array might be $15'' \times 15''$. In the corona, a loop arcade might be $100'' \times 20''$. Thermal conduction acts to rapidly reduce temperature gradients along magnetic loops after energy deposition. This generates apparent velocities greater than 200 km/s. Resolving these events links our requirement for imaging cadence linearly to spatial resolution.

These observational constraints will require a sea change in technical approach. Compared to current instrumentation, we will need to increase collecting power by an order of magnitude. High-cadence, spectrally resolved, multi-wavelength observations require orders of magnitude higher telemetry and storage increases. To observe both the chromosphere and corona simultaneously will require both EUV and UV/visible instrumentation. There is evidence that ions are thermalized differentially in the chromosphere so spectral windows will have to be chosen, not for convenience, but in order to elucidate the physics.

By 2050, we hope that solar atmospheric models will more accurately describe heat transport from the photosphere and heat generation from atmospheric dynamics such that synthetic data are a good match for observations tuned to any arbitrary temperature. Our present understanding represented by models is limited, at least in part, by the data provided by current instrumentation. As models advance in the coming years, observations need to advance in step to provide constraints and verification on modeled parameters.

The design of remote sensing instruments is an exercise in compromise, as the basic dimensionality of the data exceeds the dimensions of our detecting apparatus. Yet, correctly balancing these holds the key to a full understanding of the mechanisms driving the energy balance in the solar atmosphere. This will require the continued development of capable instrumentation, mission scenarios, models and data pipelines in the coming years.