

Exploring the interface between the Sun's surface and corona

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Nonequilibrium thermodynamics, explosive magnetic field rearrangements, and more contribute to the physics of an atmospheric region that brooks no simple assumptions.

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Our sun is a ball of self-gravitating gas whose core is heated by nuclear fusion. Radiation and convection move energy down a temperature gradient, from the core at 1.6×10^7 K outward to the 5800-K photosphere, the visible surface

that you see through your sunglasses (though it is unsafe to stare). The hydrostatic balance between pressure P and gravity (with acceleration constant $g_\odot$) at density ρ implies a surface thickness of only $P/\rho g_\odot = 174$ km. Dense enough to be opaque, the photosphere resembles a solid surface, shaped by gravity to a near-perfect sphere.

Throughout human history, though, the Sun has offered glimpses of its complex structure and variability. In 364 BC, Chinese astronomer Gan De observed sunspots; we now know those to be the most visible signatures of 0.1-T magnetic fields. The solar corona, which extends from the surface far into space, is visible from the ground, but only during a total solar eclipse. Also apparent during an eclipse, suspended just above the limb—the edge of the visible disk—are great prominences that glow red as hydrogen atoms transition from $n=3$ to $n=2$ excited states. The solar chromosphere is named for those colorful apparitions, humankind's first glimpse of the enigmatic interface region between the photosphere and the corona.

Photosphere, corona, and in between

The Sun's magnetic fields are generated below its surface and amplified by convection and by latitudinal variations in the Sun's rotation rate. The solar atmosphere is so highly conductive that the field and the plasma are frozen together, meaning that each parcel of plasma is married to one field line. Magnetic pressure expands the tubes of magnetic flux until the magnetic and surrounding gas pressures are in equilibrium. As a result, bubbles rise to the photosphere and pepper the surface with magnetic poles. The strongest emerged fields inhibit convection; the bubbles cool and form dark sunspots that are buffeted and eventually chopped apart by convective turbulence. Solar magnetic activity and a range of solar and space weather caused by it are modulated by an 11-year cycle. (For more on solar activity, see the article by Gordon Holman on page 56.)

Space-based telescopes routinely observe the 10^6 -K corona via emission lines in the extreme UV range of 10–100 nm;

panel a of the figure shows a view at 19.3 nm. Although the heating and dynamics of the corona are still mysterious, its overall appearance follows from a few simple assumptions—for example, that the coronal magnetic pressure (equivalently, its energy density) greatly exceeds both its gas pressure and its gravitational potential energy density. That's why the hot coronal plasma looks like it's having a bad hair day: It is shaped by the field lines to which it is frozen, and its coronal loops, streamers, and polar plumes visibly trace the complex solar magnetic field.

In the photosphere, a different set of simplifications applies. For example, gravity and pressure mold the photosphere into a relatively smooth sphere. Both photosphere and corona can be approximated by assuming that ionization and spectra are determined by local thermodynamic variables. In the interface between those regions, none of the usual helpful assumptions hold.

If you could travel upward from the photosphere, you'd find that the temperature decreases to around 4000 K and then rises toward coronal temperatures. In one-dimensional static models, the temperature rises from 7000 K to 10^5 K in an atmospheric slice whose thickness is less than 100 km. Much material in the lower end of that temperature range is observed as part of the chromosphere. Material toward the upper end of the range is also observable and makes up part of the so-called transition region. Together, the chromosphere and the transition region constitute the interface region.

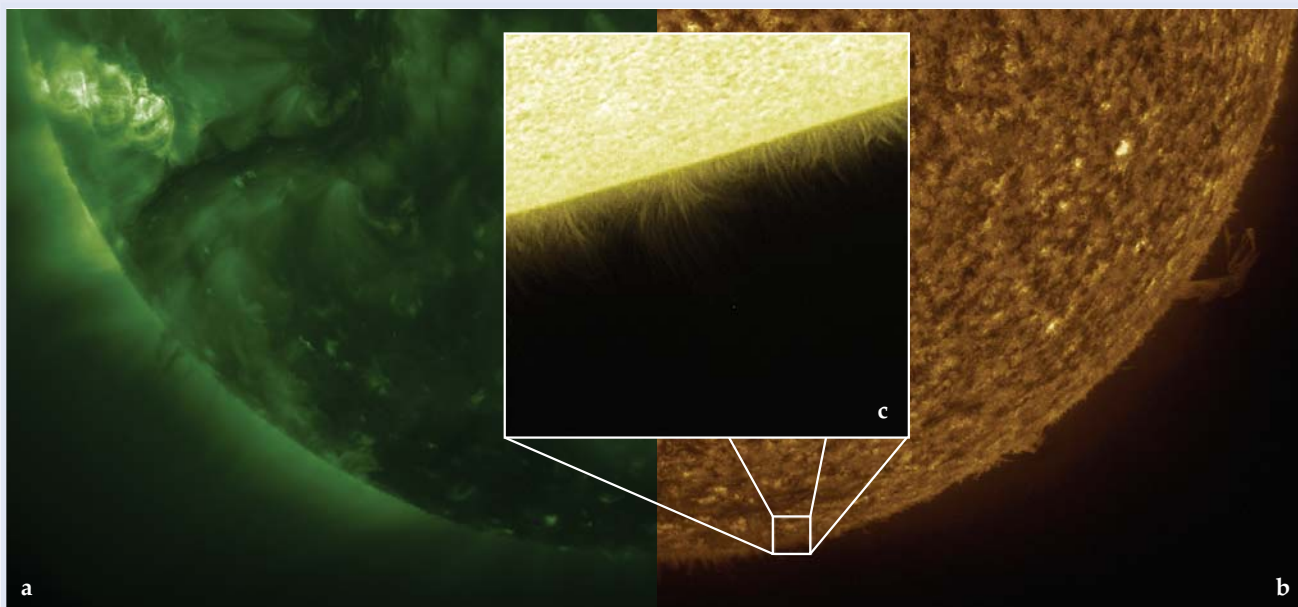
Panels b and c of the figure show the interface to be highly textured. Ubiquitous waves and flows observed in images and spectra show that it is in continual change. The extreme UV radiation it emits (and that of the corona, too) is highly variable at all time scales probed thus far, ranging from the seconds associated with direct satellite observations to the hundreds of thousands of years inferred from ice cores. The complexity of the interface is stunning, beautiful, and scientifically daunting.

Chromosphere and transition region

The smallest observed elements of the chromosphere are spicules, thin shafts of plasma that can be found all over the face of the Sun, rising and falling at tens of kilometers per second. They come in two classes. Type I spicules move on nearly parabolic trajectories. The current thinking among solar physicists is that they are launched when outward propagating acoustic waves, guided by the solar magnetic field, steepen into shocks as the atmosphere thins out.

Type II spicules are larger and faster. They may result from magnetic reconnection, a process in which field lines near a strong shear in the field rearrange their connectivity. Magnetic tension then accelerates the plasma to supersonic speeds. Type II spicules heat up and disappear as they rise, and they possibly contribute mass to the corona. Transverse waves propagate outward along both types of spicules and may play a role in atmospheric heating.

The thread-like spicules bespeak a magnetized chromosphere, but only parts of the chromosphere are magnetically



At the root of the solar corona, the transition region and chromosphere together are a laboratory for complex, nonlinear physics. **(a)** The corona, as observed by the Atmospheric Imaging Assembly (AIA) on NASA's *Solar Dynamics Observatory*. **(b)** The transition region, as viewed by the AIA. **(c)** The chromosphere, as imaged by the Solar Optical Telescope aboard the Japanese–American *Hinode* satellite. Note in particular the thin spicules near the surface, only 150–500 km across. (Images courtesy of NASA.)

dominated. The field protrudes from tiny flux concentrations that cover only a fraction of the photosphere, and the field lines spread out, eventually filling the coronal volume. Between those layers lies a large volume of presumably non-magnetic chromosphere whose nature—and even temperature—is hotly contested.

As physicists, we are strongly committed to the principle of conservation of energy, but the chromosphere would be a difficult place to confirm it. Conduction from above doesn't contribute much to chromospheric heating because the thermal conductivity is low. Estimates of the radiative gains and losses are sensitive to details of the models. But at the simplest level, far-UV emission (122–200 nm) represents energy lost by the chromosphere, and the depth of the absorption lines at longer wavelengths represents energy inputs from below. The losses are a factor of two greater than the gains; the difference, about 3000 W/m², represents a largely unexplained deficit required to heat the chromosphere. Acoustic waves apparently contribute some 10% of the deficit, but additional wave energy may yet be discovered at small scales. The chromospheric heating problem is reminiscent of, but more acute than, the coronal heating problem, a perennial challenge to solar physicists. The likely ingredients in the coronal solution are magnetic reconnection and dissipation of magnetohydrodynamic waves, but the details remain elusive.

Images show that the transition region, like the chromosphere, has a raised texture. Spicules, perhaps the extensions of their chromospheric cousins, cover the Sun like a 1970s-era shag carpet and are especially prominent at the poles. Also present in images are prominences above the limb, loop-like features, and dark material seen in absorption. The thread-like texture of all those features illustrates the complexity and ubiquity of the solar magnetic field.

The transition region and chromosphere are in close proximity, and both team with magnetohydrodynamic waves of various kinds. They should be intimately coupled via the magnetic field that threads them together, but in fact, chromospheric and transition-region features do not seem to

correspond. Observations at higher resolution may provide solar scientists with a better wiring diagram of the interface. Meanwhile, we are faced with the disturbing possibility that the transition region and chromosphere exist side by side as interpenetrating yet relatively decoupled atmospheres.

Understanding from chaos

Two- and even three-dimensional radiative magnetohydrodynamic models grow more powerful every year, as they ride the crest of Moore's law. The zoo of physical effects treated by the new models yields beautiful results, which for the first time resemble an atmosphere complete with photospheric convection, magnetic fields, an inhomogeneous chromosphere, spicules, and a rarefied transition region. How accurately do those models represent the Sun? Time will tell; for now, their rich detail leaves solar physicists craving spectrographic data with higher spatial, spectral, and temporal resolution.

The *Interface Region Imaging Spectrograph* satellite will enable quantitative tests of state-of-the-art atmospheric models. Scheduled for launch at the end of this year, it will observe the chromosphere in UV and the transition region in far-UV. The mission will yield the first spectroscopic observations capable of resolving spicular dynamics, and its detailed observations of the chromosphere and transition region together may clarify the relationship between those two fascinating and problematic components of the solar atmosphere.

Additional resources

- *Interface Region Imaging Spectrograph* mission, <http://iris.lmsal.com>.
- National Student Solar Spectrograph Competition, <http://spacegrant.montana.edu/iris>.
- JHelioviewer visualization software for solar image data, <http://www.jhelioviewer.org>.
- Movies from the *Hinode* mission, <http://solarb.msfc.nasa.gov/news/movies.html>.
- K. R. Lang, *The Cambridge Encyclopedia of the Sun*, Cambridge U. Press, New York (2001). ■