PERSPECTIVES: SOLAR PHYSICS

How the Sun's Corona Gets Hot

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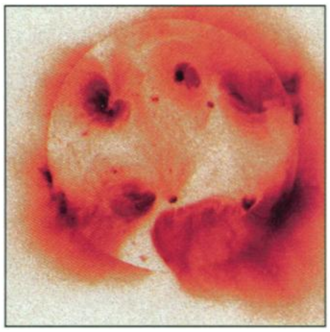
Close to the surface of the sun, the corona (the sun's outer atmosphere) suddenly attains temperatures above 1,000,000 Kelvin (K), much hotter than the 6000 K of the photosphere below. In the recent history of solar physics, no single problem has been as stubborn as that of explaining this coronal heating. The corona supplies the energy and momentum that sustains the solar wind; understanding the interdependence between the solar magnetic field and the solar wind patterns may help resolve the puzzle of the coronal heating (*1*). A flotilla of space solar observatories (including the Yohkoh, SOHO, and TRACE satellites), together with in situ solar-wind measurements from the Ulysses, WIND, ACE, and SOHO satellites, now give us an opportunity to understand these processes. The new TRACE observations reported by Nakariakov *et al.* on page 862 of this issue (*2*) illustrate the uses of these new data.



Now you see it. A false-color soft x-ray image of the solar corona made by the Yohkoh on 16 June 1998, showing the great complexity of the coronal magnetic field. Hot plasma, at x-ray temperatures, selectively illuminates parts of the coronal structure.

A routine soft x-ray image from Yohkoh illustrates the great complexity of the hot corona (see the figure) (*3*). The correlation between strong magnetic fields and bright (that is, hot) coronal features suggests a simple scaling for the volumetric heating with magnetic field—near sunspots, the hot x-ray corona is brightest. However, the coronal regions with the strongest fields are directly above the sunspots, which show hardly any x-ray emission. Thus these coronal regions are relatively cool, and something other than the magnetic intensity must be involved in the coronal heating mechanism. There is no shortage of suspects—gradients in the magnetic field, its shear or helicity, the reconnection of the field lines, miscellaneous kinds of magnetic or nonmagnetic waves, or "nanoflares" (*4*)—but pinpointing the culprit or culprits has proven difficult.

The recent discovery in TRACE images of magnetic loop oscillations ("twanging") following a flare-induced global wave disturbance (*5*) illustrates a newly developed tool for investigating coronal heating mechanisms (*6*). The characteristic frequencies and other properties of the largely invisible coronal structures can be determined by using time series of images, providing a coronal analog of terrestrial or solar seismology. Such a movie-like analysis of coronal images taken by SOHO allowed the identification of a source of the slow component of the solar wind: fragmentation in the cusp or stalk regions at the vertices of the "helmet streamers" often visible during total solar eclipses (*7–9*). Nakariakov *et al.* (*2*) also use this approach to study magnetic loop oscillations in the solar corona.

The hot solar corona consists largely of magnetic loops linked to the solar surface. Analysis of Yohkoh data clearly reveals two distinct components of loop heating, flare-like and steady (*10*), indicating that more than one heating mechanism exists. Parker's nanoflares, tiny magnetic disruptions physically different from ordinary solar flares (*11*), might sustain the steady heating by occurring in great numbers. In the quiet solar regions remote from sunspot groups, the diffuse hot corona also seems to require a steady heating mechanism; again, frequent microscopic energy releases, currently unresolved spatially or temporally, could explain the energy source. One may look for this energy source in the reconnections that must re-link the large-scale coronal magnetic features while the random motions resulting from convection attempt to entangle them (*12*). These reconnection processes remain unidentified, although the "chromospheric network" (the boundaries of the largest known convective motions) displays many forms of activity, implying vigorous magnetic energy conversion. However, such small-scale magnetic reconnection processes in the quiet sun might convert the magnetic energy predominantly into waves, rather than directly into heat or particle acceleration (*13*, *14*).

In the Yohkoh images (see the figure), one sees only the hottest part of the corona. SOHO's ultraviolet spectra of these regions have provided clear evidence for nonthermality (non-Maxwellian velocity distributions) (*15*). The Yohkoh images thus probably show the approximate locations of heat deposition in the corona. Above temperatures of a few million Kelvin, Maxwellian velocity distributions may not properly describe the coronal plasma (*16*).

Nakariakov *et al.* (2) have found a rapidly damped twanging motion following the passage of a large-scale wave associated with a solar flare. The damping could in principle result from greatly enhanced viscosity or resistivity in regions of the coronal plasma, with profound implications for much theoretical work in plasma astrophysics. The claim is that the Reynolds number or the Lundquist number (two of the dimensionless numbers used to characterize the theoretical domain of a fluid) may increase from the expected value by many orders of magnitude, enhancing coronal heating by that factor. However, these numbers reflect not only local energy dissipation, but also scale sizes and global properties. In fact, if energy dissipation is too easy this might put a short time scale on possible coronal energy storage, which could make theoretical explanations for coronal heating or flares harder, not easier! It should also be pointed out that the coronal loop oscillations must involve not only the coronal medium, but also the photosphere and chromosphere, where dissipation is much more efficient.

The lack of knowledge of the third dimension in the current solar data limits how well we can match models with observations, and thereby identify the important empirical parameters. The movie analysis used by Nakariakov *et al.* is one way to get around this constraint. A different approach underlies the recently approved STEREO deep-space mission, which will soon make the first simultaneous coronal observations from two distinct lines of sight. Other indirect methods such as vector magnetograms, from which the photospheric magnetic field can also be used to infer the coronal three-dimensional structure. This will be a key element of the future SOLAR-B space observatory. New techniques exploiting ground-based microwave observations can also measure detailed properties of the coronal field in active regions.

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References and Notes

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14. Solar flares make an alternate use of magnetic reconnection and accelerate huge numbers of particles, including "solar cosmic rays."
15. J. Kohl *et al.*, *Astrophys. J.* **501**, 127L (1998).
16. The HESSI satellite (to be launched July 2000) will study nonthermal x-ray and gamma-ray emissions.