Heating of the Magnetically Closed Corona

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Explaining why the solar corona is 2-3 orders of magnitude hotter than the underlying solar surface – the famous coronal heating problem – remains one of the great challenges of space science. To understand many phenomena, include those of space weather importance, we must solve this long-standing mystery. It is important to distinguish between the magnetically closed corona, where field lines are rooted to the surface at both ends, and the magnetically open corona, where one end extends far out to space. The mechanism of heating may be fundamentally different in these two environments. Coronal holes and the solar wind are almost certainly heated by waves, likely involving turbulence, and Parker Solar Probe should reveal many of the missing details. Magnetically closed active regions and "quiet" Sun are also subjected to wave heating, but small magnetic reconnection events are thought to be even more important. These regions are responsible for the vast majority of UV and X-ray emission from the Sun and are the source of coronal mass ejections and flares. They may also provide the mass for the slow solar wind, which escapes via reconnection with adjacent open field lines (interchange reconnection).

The energy for the heating originates in the complex motions of the massive photosphere. Turbulent convection slowly displaces the footpoints of coronal field lines, causing them to become twisted and tangled. Magnetic stresses gradually build until reaching a breaking point, whereupon a sudden burst of energy is released. This basic picture of "nanoflares" has been widely accepted since advocated long ago by Parker. Many fundamental aspects have nonetheless remained out of reach. Challenges include an enormous range of physically coupled spatial scales and confusion associated with spatial and temporal averaging inherent in optically thin observations.

Reconnection heating and wave heating are not necessarily independent. Waves are generated by high-frequency motions in the photosphere, but they are also generated by reconnection in the corona and below. Both forms of heating are impulsive and involve small spatial scales. Reconnection occurs at thin current sheets, of which there are hundreds of thousands in a single active region, and wave heating occurs in resonance-absorption layers, phase-mixing layers, and small structures at the end of turbulent cascades. See the white paper by Viall et al. for more information.

Although the process of energy release has small scale, the overall level of heating varies substantially on large scales, e.g., across an active region. There are also important intermediate scales. Distinct coronal loops – the thin arching structures so noticeable in coronal images – are bundles of spatially unresolved strands that are heated by "storms" of impulsive events. What is the origin of this collective behavior?

How the plasma responds to heating, including the radiation spectrum it produces, depends strongly on another type of coupling between the corona and lower atmosphere. Downward thermal conduction along field lines causes a heating and ablation of cool plasma into the corona. This is known as chromospheric "evaporation," and there are complementary processes of cooling and draining. A crucial property of the heating is the frequency with which the impulsive events recur. Low-frequency heating is associated with wide swings in temperature and density, while high-frequency heating produces more steady conditions. The distributions of temperature and density, and therefore the relative strengths of different emission lines, are greatly affected by the heating frequency.

Because of the enormous range of spatial scales and processes involved in the coronal heating problem, we cannot treat all of them a single do-it-all numerical simulation. Instead, we are forced to study different aspects of the problem in quasi-isolation, taking account of how missing or poorly treated aspects may influence the results and conclusions. Progress toward a comprehensive understanding will be slow and steady, and success will require a close coordination among observations, theory, and numerical simulation. Improved physical understanding must be central to our planning, since only such an understanding can inform us about how the different pieces fit together. Below, we highlight some of the major steps that can be taken over the next 10-30 years.

In the 10-year timeframe, we should emphasize **observations of very hot plasma (5-10 MK)**. This is a largely unexplored regime. To understand the energy release process, we must observe the directly heated plasma, which is expected to be in this temperature range. Traditional coronal observations are at much lower temperatures (1-3 MK). By the time the plasma has cooled to these values, much of the information about the energy release has been lost. Furthermore, this cooler emission is swamped by much brighter evaporated plasma. The directly heated (very hot) plasma is expected to be quite faint, so instruments will need improved sensitivity. Also, the plasma is likely to be out of ionization equilibrium initially, so additional studies of these effects, possibly including improved laboratory measurements of atomic parameters, are needed. See the white paper by Klimchuk, Daw, & Del Zanna for more information.

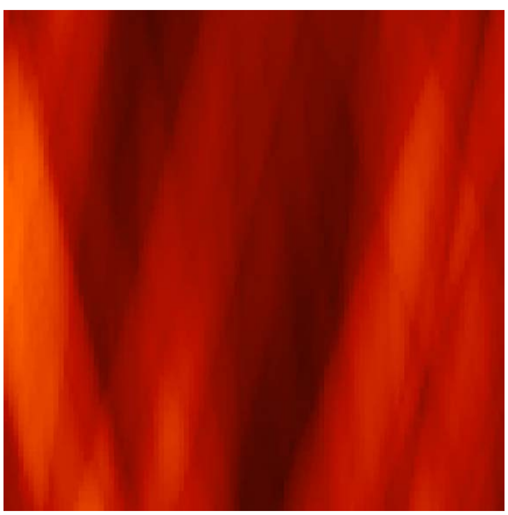

Figure 1: Synthetic image in Fe XVIII (94Å), formed at 7 MK in ionization equilibrium, based on a simulation of nanoflare-heated strands in an active region. Dimension is 1000 km (1.3 arcsec). A movie version is available.

As we have emphasized, coronal heating involves small-scale structures. The elemental magnetic strands that comprise the corona – both the observationally distinguishable loops and the even brighter "diffuse" component – have estimated sizes of order 100 km (~0.1 arcsec). Realistic nanoflare simulations suggest that they should be detectable, especially in very hot emissions, even with the tremendous line-of-sight overlap (Fig. 1). A second achievable near-term goal is to study these structures with **ultra-high-resolution observations**.

To understand the observations and their significance, we will need improved numerical simulations. In addition to the expected advances in computer hardware, we need **new and improved numerical algorithms**. One example is the treatment of viscous heating. The primary flow of energy during magnetic reconnection in the corona is from magnetic, to kinetic, to thermal, with the last step occurring mostly at shocks. There are numerical techniques for treating viscous heating in hydrodynamic shocks, but none yet exists for MHD shocks. Another potentially achievable short-term goal is the development of a method for incorporating reconnection onset conditions, so crucial for understanding the buildup and release of magnetic energy, into large-scale MHD simulations that cannot adequately resolve multiple current sheets. A prerequisite, of course, is an understanding of what those onset conditions are, which must also be accomplished.

In the 30-year timeframe, we can imagine enormous advances in two areas. On the theoretical side, we can strive for **massive simulations** that accurately treat all of the important spatial scales at once, ranging from the global corona down to the inner layers of current sheets where reconnection onset begins, and even including kinetic scales responsible for accelerating particles to high energy. (Reconnection onset occurs in the MHD regime on the Sun, but in the kinetic regime in the magnetosphere.)

On the observational side, we can strive for a **mission that flies through the magnetically closed corona**, just as Parker Solar Probe flies through the magnetically open solar wind. Challenges will include not only the extreme environment, but also the ultra-fast observing cadence needed for meaningful spatial sampling at the extreme speeds of the spacecraft. Given the ambiguities associated with line-of-sight averaging in remote sensing observations, Fig. 1 notwithstanding, *in situ* measurements may be the only way to obtain the information necessary to solve some problems.

Coronal heating powers the X-ray and UV radiation from the Sun, which is an important driver of the terrestrial upper atmosphere and has major space weather impacts, especially in the areas of communication, navigation, and spacecraft collision avoidance. There are also important implications for the development of life around the universe. Today's operational models for nowcasting and forecasting the solar spectral irradiance are highly rudimentary and largely empirical. An important goal over the next 10-30 years is to develop a **physics-based model of the solar spectral irradiance**, which will rely heavily on a comprehensive understanding of coronal heating.

In conclusion, understanding the heating of the magnetically closed corona has been and remains a top priority for NASA and the international space science community. Magnetic reconnection is a fundamental process responsible for many heliospheric and astrophysical phenomena. By studying its role in coronal heating, we can expect to develop important physical insight about all of them. Also, solving the coronal heating problem is a prerequisite to accurately predicting the solar spectral irradiance, of great space weather significance. We have outlined key areas where major progress can be made in the next 10-30 years. The future is bright!

Further detailed information on the above topics can be found in the following review articles and references cited therein:

Klimchuk, J. A. 2006, Solar Phys., 234, 41
Klimchuk, J. A. 2015, Phil. Trans. R. Soc. A, 373: 20140256
Klimchuk, J. A. and Hinode Review Team 2019, PASJ, 71 (5), R1
Viall, N. M., et al. 2020, in Space Physics and Aeronomy Vol. 1—at the Doorstep of Our Star: Solar Physics and Solar Wind, eds: N. E. Raoufi & A. Vourlidas) (Wiley-Blackwell), in press