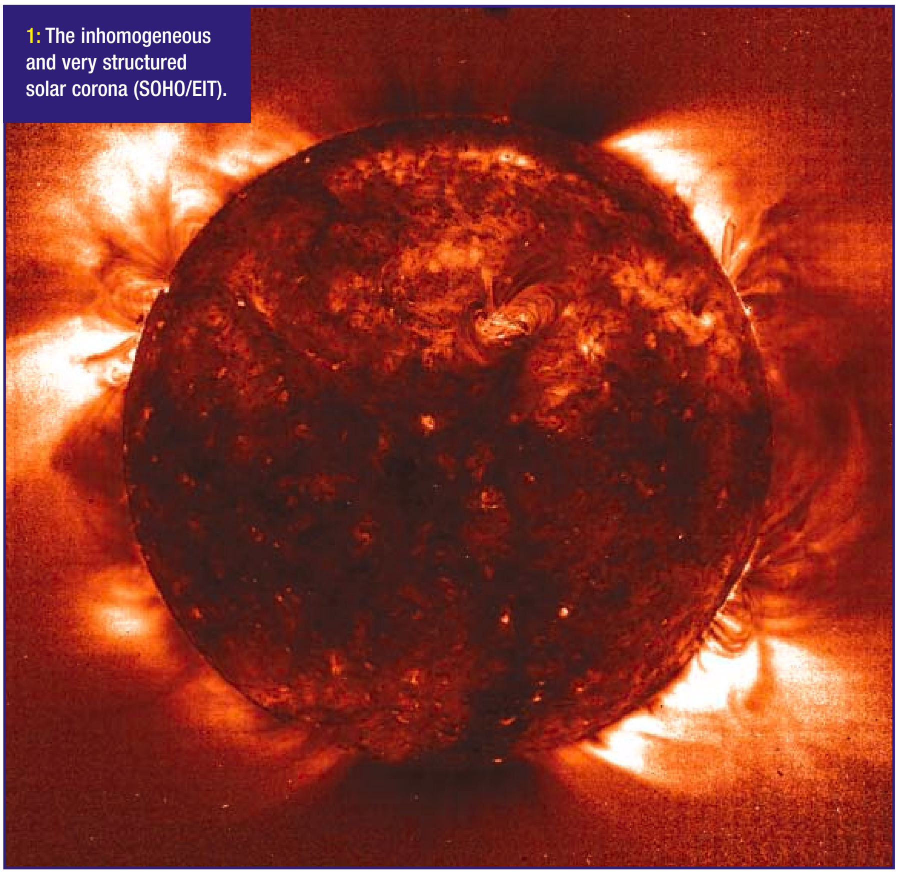
Heating in the solar atmosphere

Robert Erdélyi reviews ways and means of heating the solar corona.



1: The inhomogeneous and very structured solar corona (SOHO/EIT).

Abstract

The solar coronal plasma, mainly confined in magnetic flux tubes, is maintained at temperatures of several millions of K. The heating process that generates and sustains the hot corona has so far defied a quantitative understanding despite efforts spanning over half a century. In this paper I review the most popular and viable mechanisms of heating the solar atmosphere, from low chromospheric levels through the transition region up to the corona. I address two principal questions: What is the source of plasma heating in the solar (and stellar) atmosphere? How do perturbations dissipate efficiently, resulting in hot plasmas? The latest results of theoretical and observational studies provide some answers, but there remains much to be learned.

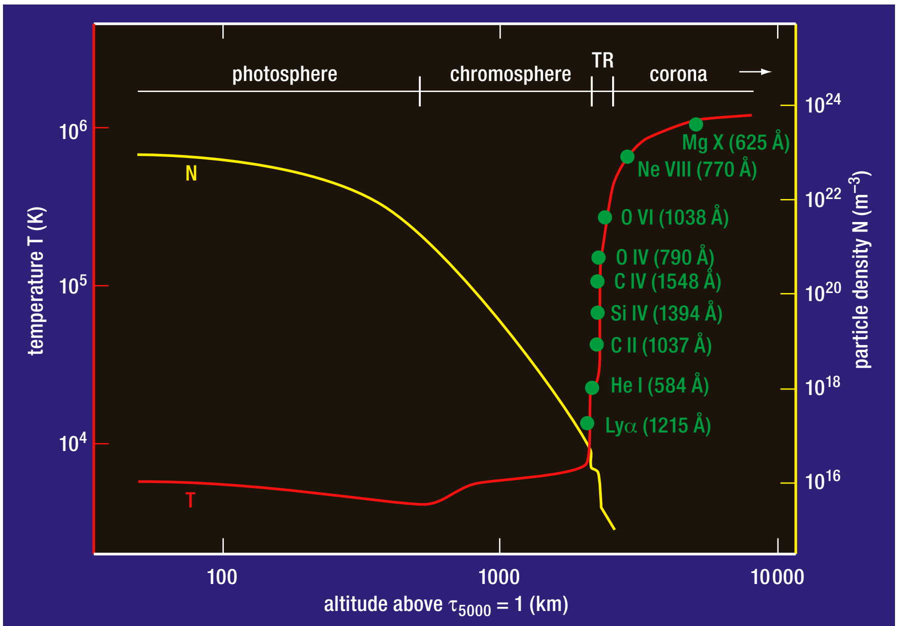
Observations of the solar corona go back at least three millennia. One of the earliest records of the corona was made by Babylonian astronomers who reported during a solar eclipse in 1063 BC that "the day was turned to night, and fire in the midst of the heaven". The discovery of spectroscopy in the late 19th century revealed the existence of a coronal "green line" at 5303 Å – a major puzzle for astrophysicists for 50 years. The wavelength of this spectral line did not match any known elements and it was thought that a new element (coronium) had been discovered. The solution of this solar mystery came in 1939 when Edlén showed that the coronium line is emitted by highly ionized iron, Fe XIV, at temperatures well over 1 million K. Modern satellite observations from Skylab in the 70s, through SMM, Yohkoh and in present times SOHO, TRACE and RHESSI have revealed the solar atmosphere with unprecedented spatial and temporal resolutions covering wavelengths from (E)UV, through soft and hard X-ray to even γ-rays. Both spectroscopic and imaging instruments have contributed to the discovery of many and various fine-scale structures in the solar atmospheric zoo from small-scale X-ray bright points to large solar coronal loops (figure 1). For an excellent textbook on the corona see Dolub and Pasachoff (1997).

Once it was established in 1939 that the solar corona is much hotter than the photosphere, it did not take long for the theoreticians to come up with reasonable mathematical models that tried to explain this apparently controversial feature. The major problem is the observed behaviour of temperature in the solar atmosphere: energy is produced in the very hot (approximately 14 million K) internal core part of the Sun by thermonuclear fusion, then it propagates outwards, initially in the form of radiation (in the radiation zone) up to about 0.72 $R_\odot$ and later by convection (in the convective zone) right to the solar surface (photosphere), continuously cooling the solar plasma. But after reaching its minimum at the top of the photosphere, the temperature starts to rise slowly throughout the chromosphere (up to around 20 000 K), followed by a very steep increase in the narrow transition region (a few 100 000 K) up to around 2 million K in the corona (figure 2). If one goes continuously away from the source of the energy, the solar core, one would expect a monotonic temperature decrease; this tendency is reversed above the temperature minimum and the temperature actually increases in the solar atmosphere (figure 2).

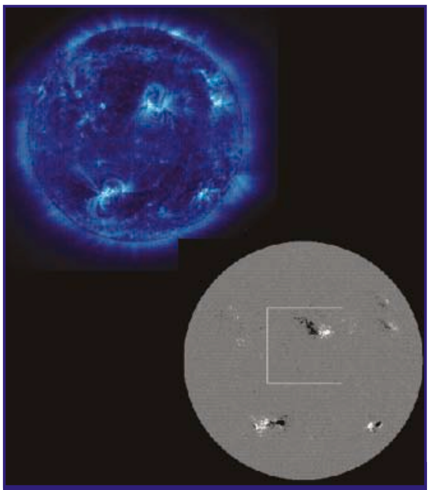
The existence of the corona requires an input of energy above that which would occur by thermodynamic relaxation from the photospheric output. The excess of this non-thermal (sometimes also called mechanical) energy to sustain the solar corona is surprisingly just a small fraction of the total solar output (see table 1). Estimates show that the total energy budget is just approximately 10^{-4} of the Sun's total energy output making it, in theory, relatively easy to suggest mechanisms to divert 0.01% of the total solar output into heating the corona.

Solar magnetism

As the spatial resolution of observations improved, more and more structures were discovered at the solar surface and in the solar atmosphere. Examples of well-known large-scale structures are sunspots, complex active regions, prominences, coronal loops and coronal holes; while examples of fine structures are the magnetic pores, dark mottles, spicules, supergranular cells, filaments, X-ray and EUV bright points. One of the earliest discoveries in solar physics was the solar cycle, i.e. Hale's polarity law, the butterfly diagram for sunspots, the cyclic variations in sunspot numbers (discussed in more detail in this issue by Tobias and Weiss on pages 4.28–4.33, and Bushby and



2: Temperature (red line) and density (yellow line) distributions as a function of the height measure in km in the solar atmosphere. The formation of popular lines for observations is indicated by green. Note the logarithmic scales. (Courtesy H Peter.)



3: The solar corona in the 171 Å SOHO EIT spectral line (upper left) and the corresponding SOHO MDI magnetogram (lower right) at photospheric levels. Magnetic field concentrations coincide with bright patches in the SOHO EIT image, indicating the role of magnetic field in the process of coronal heating.

Table 1: Average coronal energy losses (in erg $cm^{-2} s^{-1}$)

Loss mechanism	quiet Sun	active region	coronal hole
Conductive flux	2×10^5	10^5–10^7	6×10^4
Radiative flux	10^5	5×10^6	10^4
Solar wind flux	$<5\times10^4$	$<10^5$	7×10^5
Total flux	3×10^5	10^7	8×10^5

Mason on pages 4.7–4.13). It soon turned out that these temporal phenomena are linked to the internal generation mechanism of the global solar magnetic field. Skylab observations made it clear that there is a strong correlation between X-ray emitting hot and bright coronal regions and the underlying surface magnetic field concentrations suggesting that coronal heating and solar magnetism are intimately related (figure 3).

Similar correlations were found between the ubiquity of small-scale structures and the magnetic solar cycle. Very recent studies of the photospheric magnetic carpet also seem to suggest that such correlations exist even at smallest scales (discussed by Proctor on pages 4.14–4.20 of this issue).

Observational constraints

An acceptable model of solar (and stellar) atmospheric heating has to comply with a few observational facts (Cargill 1993, Zirker 1993). It is now evident the solar atmosphere is highly structured and it is likely that various heating mechanisms operate in different atmospheric structures. In closed structures, for example active regions, temperatures may reach up to 8–20×10^6 K, while in open magnetic regions such as coronal holes, maximum temperatures may only be around 1–1.5×10^6 K. Next, observations also show that temperature, density and magnetic field are highly inhomogeneous. Fine structures (e.g. filaments in loops) may have 3–5 times higher densities than is usual in their environment. An interesting constraint is the contrast between fluctuating brightness and the associated fluctuating velocities and the quasi-static nature of the corona. There is little known about how the heating depends on magnetic field strength, structure size (length, radius, expansion) and age.

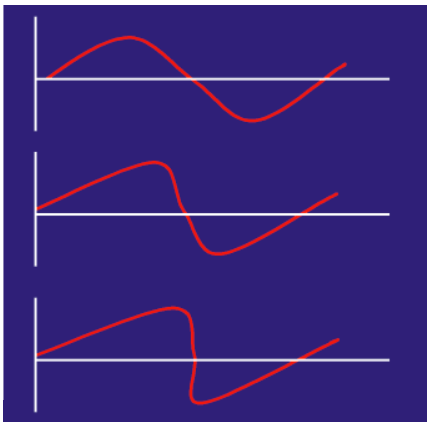
We are mainly interested in solar (and stellar) atmospheric heating mechanisms that can provide a steady supply of energy to balance the atmospheric (chromospheric and coronal) energy losses, although this energy does not need to be produced in a steady way, i.e. random energy releases that produce a statistically averaged steady state are allowed for. Observational tests of a specific heating mechanism may be difficult because several mechanisms might operate at the same time. Theoretical estimates often predict very small spatial scales where the ultimate dissipation occurs, sometimes of the order of a few hundred metres, that even with current high spatial resolution satellite techniques cannot be resolved – and will not be for a while. Also, the unique signature of a specific heating mechanism could be obliterated during the thermalization of the input energy. Ideally one should predict some macroscopic consequences of a specific favoured heating mechanism (Cargill 1993) and confirm these signatures by observations (e.g. generated flows, specific spectral line profiles or line broadenings, etc).

The heating process comprises three phases: the generation of a carrier of energy; the transport of energy into the solar atmosphere; and, finally, the dissipation of this energy in the various structures of the atmosphere. Usually it is not difficult to establish a theory that drives an energy carrier without contradicting observations. Neither does the literature seem to be short of transport mechanisms. There is, however, real hardship in understanding how the transported energy is dissipated efficiently. A summary of the heating mechanisms is given in table 2 (Ulmschneider 1998).

The heating mechanisms that operate in the solar atmosphere can be classified depending on whether they involve magnetism or not (Narain and Ulmschneider 1996). If the heating mechanism operates in magnetism-free regions (e.g. in the chromosphere of the quiet Sun) one can work within the framework of hydrodynamics and such heating theories can be classified as hydrodynamic heating. Examples of such heating mechanisms could be acoustic waves and pulsations. On the other hand if the plasma is embedded in magnetic fields the framework of magnetohydrodynamics (MHD) may be the appropriate approach and these theories are called MHD heating mechanisms (Browning 1991, Gomez 1990, Hollweg 1991, Pries and Forbes 2000). The ultimate dissipation in MHD models invoke Joule heating or, to a lesser extent, viscosity. Examples of the energy carriers of magnetic heating are the slow and fast MHD waves, Alfvén waves, magnetoacoustic-gravity waves and current sheets. A popular alternative MHD heating mechanism is the selective decay of a turbulent cascade of magnetic field.

In most of the hydrodynamic and MHD heating theories the plasma is considered to be collisional. If however, the plasma, whether magnetized or not, is collisionless (and the plasma in the solar corona is, strictly speaking!) one has to consider kinetic approaches. A proper description of the heating mechanisms is cumbersome and would require heavy computations and kinetic codes. Compromising ways to proceed may be the Chew-Goldberger-Low (CGL) closure or the semi-phenomenologic Abraham-Schrauner description of the plasma, where the latter formalism is based on a closure hypothesis of the kinetic equation that is not yet experimentally proven.

Alternative classification of the heating mechanism is based on the timescales involved. If the characteristic timescale of the perturbations is less than the characteristic times of the back-reaction, in non-magnetized plasma acoustic waves are good approximations for describing the energy propagation; on the other hand, if perturbations have low frequencies, hydrodynamic pulses may be appropriate. If the plasma is magnetized and perturbation timescales are small, we speak about alternating current (AC) heating mechanisms, e.g. MHD waves (Roberts 2000, Erdélyi 2001, Roberts and Nakariakov 2003).When the external driving forces (e.g. photospheric motions) operate on longer timescales compared to dissipation and transit times, very narrow current sheets are built up resulting in direct current (DC) heating mechanisms (Priest and Forbes 2000).



4: Wave steepening into shock.

5: TRACE image of the highly structured solar corona where the plasma is frozen in semi-circular magnetic flux tubes.

Table 2: Summary of heating mechanisms (Ulmschneider 1998)

Energy carrier	Dissipation mechanism
Hydrodynamic heating mechanisms	
Acoustic waves ($P < P_{\text{acoustic cut-off}}$)	Shock dissipation
Pulsational waves ($P > P_{\text{acoustic cut-off}}$)	Shock dissipation
Magnetic heating mechanisms	
1. Alternating current (AC) or waves mechanisms	
Slow MHD waves	Shock damping, resonant absorption
Longitudinal MHD tube waves	
Fast MHD waves	Landau damping
Alfvén waves (transverse, torsional)	Mode-coupling, resonance heating, phase mixing, compressional viscous heating, turbulent heating, Landau damping, RA
2. Direct current (DC) mechanisms	
Current sheets	Reconnection (turbulent heating, wave heating)

Hydrodynamic heating mechanisms

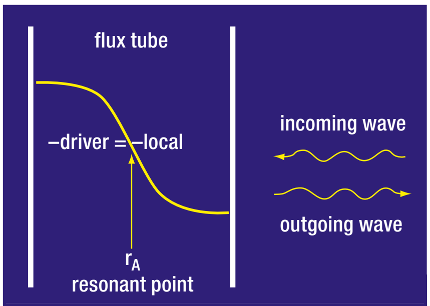
In the early 1940s, after the discovery of the hot solar atmosphere, the model of acoustic waves generated by solar granulation was put forward as energy carrier from the top of the convective zone into the corona. Because of the steep density decrease the sound waves could develop into shocks (figure 4) and will dissipate their energy, heating the corona. Once it turned out that the solar coronal plasma is heavily embedded into magnetic fields, the relevance of the hydrodynamic heating mechanisms for the corona was re-evaluated. Hydrodynamic heating mechanisms could still contribute to atmospheric heating of the Sun, but only at lower layers, i.e. possibly in the chromosphere and up to the magnetic canopy. For late-type stars with spectral type *F* to *M*, acoustic shocks are important heating mechanisms. In early-type stars (*O* to *A*) with no convection zone, the strong radiation plays the role of acoustic wave generation that steepens into shock waves. Finally, pulsational waves are mainly prominent in Mira-stars and in other late-type giants where the wave generation is triggered by the κ-mechanism (that is related to the opacity increase of the stellar envelope).

MHD heating mechanisms

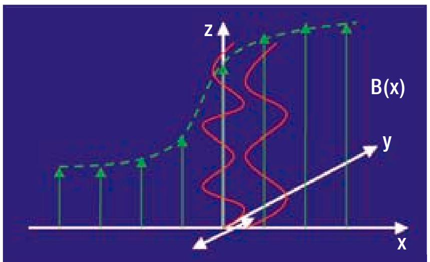
In the hot solar atmosphere, at least in a first approximation, plasma is frozen-in to the various magnetic structures. This also means that the magnetic field plays a central role in the dynamics and energetics of the solar corona (see figure 3). Observations show that the magnetic building blocks in the solar atmosphere seem to be in the form of magnetic flux tubes (figure 5). Because of the strong drop in density with height, these flux tubes expand rapidly and fill the solar atmosphere almost entirely at about 1500 km above the photosphere. The flux tubes are shaken and twisted by photospheric motions, both granular motion and global acoustic oscillations, the latter called *p*-modes. Thompson discusses acoustic oscillations in the Sun in greater detail in this issue pages 4.21–4.21). These magnetic flux tubes are excellent waveguides. If the characteristic time of these photospheric footpoint motions is much less than the local Alfvénic transient time, the photospheric perturbations propagate in the form of various MHD tube waves (e.g. slow and fast MHD waves, Alfvén waves). The dissipation of MHD waves is manifold: these waves can couple with each other, nonlinearly interact, resonantly interact with the closed waveguide (i.e. coronal loops) or nonlinearly develop (e.g. solitons or shock waves can form), etc. A whole textbook could be written just on the very rich variety of forms of MHD wave dissipation.

If the magnetized plasma is inhomogeneous there are two particular MHD wave dissipation mechanisms that have received extensive attention in the past decades: resonant absorption and phase mixing. In spite of the theoretical advances on these two particular dissipation mechanisms of MHD waves, at the moment there is no direct evidence that either of the two mechanisms actually operates under solar circumstances. There are, however, thanks to the fantastic imaging capabilities of TRACE, plenty of observations of MHD wave damping in coronal loops where there may be a tendency for resonant absorption to be a strong candidate for damping of MHD waves and oscillations. Furthermore, recent theoretical work has shown that it is unlikely that phase mixing can operate in closed magnetic structures.

Let us start with resonant absorption. Suppose



6: Schematic sketch of resonant absorption. The incoming driving wave with frequency ω_{driver} is in resonance with local oscillations at the resonant point r_A where the driver's frequency matches the frequency of the local eigenoscillations.



7: Phase-mixing of surface waves caused by gradients in the background magnetic field (or Alfvén speed) where the footpoints of the field lines are shaken in the *y*-direction.

there is an ideal inhomogeneous vertical magnetic flux tube embedded in magnetic free plasma such that the Alfvén speed has a maximum at the axis of the tube and the Alfvén speed is monotonically decreasing to zero as a function of the radial coordinate (figure 6). Let us also suppose that there is a sound wave continuously impinging horizontally at the boundary of this flux tube. If the phase speed of this impinging (or driving) sound wave matches the local Alfvén speed at a given location of the radius, say at r_A, we say the driving wave is in resonance with the local Alfvén wave at the magnetic surface at r_A. In ideal MHD this would bring infinite amplitudes of the perturbations, resulting in large gradients. However, once the gradients of perturbations become large, one cannot assume any longer the plasma is ideal; dissipative effects (e.g. resistivity, viscosity) have to be considered at least within the vicinity of such a resonant location, leading to energy dissipation. Such dissipation – absorption of the energy of the driving wave – will result in heating of the plasma, converting the energy of the driving wave into localized thermal heating. Resonant absorption, originally considered by plasma physicists as a means of excess heating for thermonuclear fusion, seems to work very well when modelling, for example, the interaction of solar global oscillations with sunspots and when applied to explain the damping of coronal loop oscillations (Ionson 1978, Erdélyi 2001), etc.

The second mechanism, phase mixing, which was originally proposed by Heyvaerts and Priest (1983), is in a sense very similar to resonant absorption. Let us assume there is a magnetized plasma that is inhomogeneous in the x-direction of the xz-plane where the magnetic field lines are parallel to the z-axis (figure 7). Then perturb each field line with a coherent (e.g sinusoidal) perturbation in the y-direction. Along each of the field lines an Alfvén wave will propagate in the z-direction with a speed characteristic to the actual field line. Since the Alfvén speed at two adjacent field lines is different, neighbouring oscillations will be out of phase after some time, resulting in large gradients of perturbations. Once the gradients reach a critical value it is not correct anymore to assume the plasma being ideal and dissipative effects have to be included in the analysis (just as in the case of resonant absorption), resulting in local heating. This dissipation of the initial perturbations is called phase mixing. Phase mixing is an excellent candidate for MHD wave energy dissipation in open magnetic regions such as coronal funnels, plumes and the solar wind.

Finally, if the characteristic timescales of magnetic footpoint perturbations are much larger than the local Alfvénic transit times, magnetic tension is built up gradually, involving highly localized current sheets that may release their energy through field line reconnection. This mechanism is called magnetic reconnection. There is plenty of evidence that reconnection works under solar atmospheric conditions at large scales, releasing magnetic stresses at highly mixed polarity fields. However, whether this mechanism is viable to heat the solar atmosphere on micro- and nano-scales requires further detailed theoretical investigations and observations. An interesting approach to solving this debate is to consider the power-law distribution of the various energy releases. It turned out that there is a critical value of the modulus of power-law distribution, approximately equal to two, that could be measured by observing these small-scale energy releases. If the measured power-law index is greater than two that would indicate the solar atmosphere is heated by numerous localized events due to reconnection as a result of, for example, the continuous shuffling of the roots of coronal fields. However, if measurements show a power index of less than two it is expected that a more global heating mechanism may be responsible for the observed temperature behaviour in the solar atmosphere. Unfortunately observations with the current accuracy do not allow us to draw a final conclusion.

I have briefly listed a couple of popular heating mechanisms. It is likely that different heating mechanisms operate in different solar and stellar structures. It is also likely that these mechanisms work simultaneously and their signatures are present in the high-resolution spectral and imaging data at the same time. Maybe the next-generation space missions like Solar-B, SDO or Solar Orbiter will have the capability and capacity to answer the fundamental astrophysical question: how are solar and stellar atmospheres heated?

Stellar outlook

The Sun is a fairly ordinary main-sequence middle-aged low-mass star with a spectral type of *G2V* and an X-raying corona. Non-degenerate stars of nearly all spectral types show UV and X-ray emission and display evidence of chromospheric and coronal activities as measured by the OSO-series, the IEU and Einstein satellites. *F*-, *G*, *K* and *M*-stars have chromospheres and often coronae similar to the Sun where radiation is generally attributed to surface convection of these stars. Late giants and supergiants do not really seem to have coronae, while *A*-stars do not have either chromospheres or coronae. Since chromospheres and coronae of average stars do not receive energy from beyond the stellar atmosphere (except from the T-Tau stars where chromospheric emission originates from mass-infall from accretion disks) it means that stellar atmospheric emission depends solely on the structure of the underlying stellar interior structure. With increasing computer power one may expect that by carefully computing the energetics of surface convection one can predict the chromosphere and corona of a star. ●

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