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HEATING OF THE SOLAR CORONA: REVIEW

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Abstract
The heating of solar and stellar chromospheres and coronae are one of the key fundamental and yet unresolved questions of modern space and plasma physics. In spite of the multi-fold efforts spanning over half a century including the many superb technological advances and theoretical developments (both analytical and computational) the unveiling of the subtles of coronal heating still remained an exciting job for the 21st century! In the present paper I review the various popular heating mechanisms put forward in the existing extensive literature. The heating processes are, somewhat arbitrarily, classified as hydrodynamic (HD), magnetohydrodynamic (MHD) or kinetic based on the model medium. These mechanisms are further divided based on the time scales of the ultimate dissipation involved (i.e. AC and DC heating, turbulent heating). In particular, attention is paid to discuss shock dissipation, Landau damping, mode coupling, resonant absorption, phase mixing, and, reconnection. Finally, I briefly review the various observational consequences of the many proposed heating mechanisms and confront them with high-resolution ground-based and satellite data currently available.
Keywords: *Sun: atmosphere, Magnetohydrodynamics, Sun: coronal heating*

1 Introduction

The very high-temperature solar atmospheric plasma, in particular in the corona, is mainly confined in magnetic flux tubes. The actual operating heating process that generates and sustains this hot corona has so far defied a quantitative understanding despite efforts spanning over half a century. In this review paper the most popular and viable heating mechanisms of the solar atmosphere are briefly summarised. We start our journey from the lower chromosphere where mainly a hydrodynamic approach is applicable, discuss the importance of the magnetic field at transition region level, and arrive at the strongly magnetised corona where the magnetohydrodynamic (MHD) descriptions seem to be a reasonable approximation. We address, by recalling the latest results of theoretical and observational studies, the source of plasma heating in the solar (and stellar) atmosphere and how do perturbations propagate from the source and dissipate efficiently resulting in a hot coronal plasmas.

Solar coronal observations go back a very long time, at least three millennia! The Babylonian astronomers reported during a solar eclipse in 1063 BC that, "...the day was turned to night, and fire in the midst of the heaven". The next great leap in coronal research was the spectroscopical discovery of the Sun in the late 19th century. The so-called coronal "green line" at 5303 Å was a real puzzle for astrophysicists for half a century. The observed wavelength of this mysterious spectral line did not match any known elements on Earth and it was concluded that a new element, called coronium, was discovered. However, Edlén in 1939 showed that the coronium line is emitted by highly ionised iron, i.e. Fe XIV, at temperature well over 1 MK. Probably this was the moment when the coronal heating problem was borned. Recent space observations, from Skylab in the 70th through SMM, Yohkoh and in very present times SoHO, TRACE and RHESSI, have investigated the solar atmosphere with unprecedented spatial and temporal resolutions covering wavelengths from (E)UV, through soft and hard X-ray to even gamma rays. These high-resolution imaging and spectroscopic observations contributed to many discoveries in the solar atmosphere. The solar atmospheric zoo, to the best of our knowledge today, consists of features from small-scale X-ray bright points to very large coronal loops (Figure 1a). For an excellent textbook on the corona see, e.g. Golub & Pasachoff (1997). Soon after the discovery of the approximately few MK hot plasma in the solar corona theoreticians came up with various physical models trying to explain the apparently controversial behaviour of the temperature in atmosphere. The key point is the observed distribution of temperature: the solar energy is produced by thermonuclear fusion in the very hot (approximately 14 MK) internal core of the Sun. This vast amount of energy then propagates outwards, initially in the form of radiation (radiation zone) up to about $0.72\mathrm{R}_\odot$ and later by convection (convective zone) right to the solar surface (photosphere) continuously cooling the solar plasma. Surprisingly, after reaching its minimum at the top of the photosphere, the temperature starts to rise slowly throughout the entire chro-

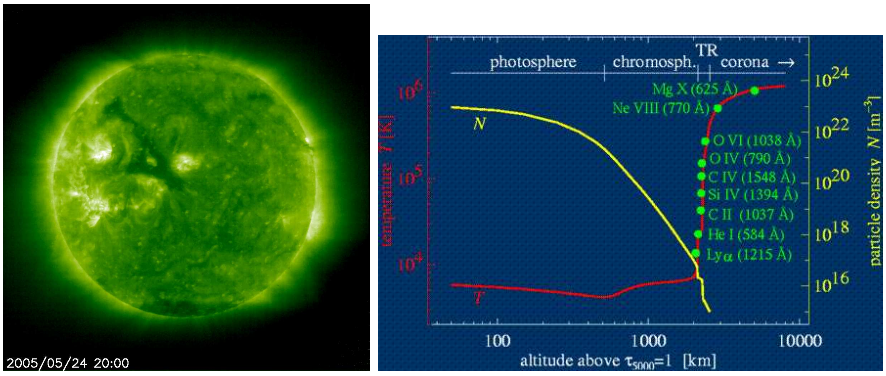

Figure 1: *Left: The very inhomogeneous and dynamic solar atmosphere. Right: Solar atmospheric temperature (red line) and density (yellow line) distributions as a function of the height measure in km. The formation of popular lines for observations is indicated by green. Note the logarithmic scales. Left figure is courtesy of H. Peter.*

mosphere (up to around 20,000 K), followed by a very steep and sharp increase in the narrow transition region (few 100,000 K) up to around 2 MK in the corona (Figure 1b). Although going continuously away from the energy producing solar core, instead of a temperature decrese, the tendency of temperature increase was found (Figure 1b). Maintaining this high temperature requires some sort of input of energy because, without it would cool down by thermodynamic relaxation on a minute-scale. Surprisingly, this non-thermal energy excess to sustain the solar corona is just a reasonably small fraction of the total solar output (see Table 1). It is relatively straightforward to estimates the entire energy budget needed for the solar corona: approximately just a tiny 10^{-4} fraction of the Sun's total energy output is needed giving, at least in theory, a fairly easy task for theoreticians to put forward various mechanisms that could divert 0.01% of the total solar output into heating the corona. The question is today not where does the coronal non-thermal energy come from, but how does it actually get to the corona and how does it dissipate efficiently there.

2 Importance of Atmospheric Magnetism

With increasing spatial and time resolution more and more structures and their dynamics were discovered at the solar surface and in the solar atmosphere.

Table 1: *Table 1: Average coronal energy losses (in erg cm^{-2} sec^{-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	$< 5 \times 10^4$	$< \times 10^5$	7×10^5
Total flux	3×10^5	10^7	8×10^5

Large-scale structures like sunspots, complex active regions, prominences, coronal loops, coronal holes are observed in great details. On the other hand, the improved resolution allowed to reveal fine structures like the magnetic pores, dark mottles, spicules, supergranular cells, filaments, X-ray and EUV bright points, etc. Since the discoveries of the solar cycle, the Hale's polarity law, the butterfly diagram for sunspots, the cyclic variations in sunspot numbers the role of solar magnetic fields became a central theme. Soon it turned out that these temporal phenomena are linked to the internal generation mechanism of the global solar magnetic field. Skylab observations made it clear for the first time that the x-ray emitting hot and bright coronal regions and the underlying surface magnetic field concentrations are strongly correlated suggesting that coronal heating and solar magnetism are intimately linked (Figure 2). Models of solar (and stellar) atmospheric heating have to comply with the observational facts (Cargill 1993, Zirker 1993). Today it is evident that the solar atmosphere is highly structured and is very likely that various heating mechanisms operate in different atmospheric magnetic structures. In closed structures, e.g. in active regions temperatures may reach up to $8 - 20 \times 10^6$ K, while in open magnetic regions like coronal holes maximum temperatures may only be around $1 - 1, 5 \times 10^6$ 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 densities in their environment. The fluctuating brightness and the associated fluctuating velocities as opposed to the quasi-static nature of the corona is a far-reaching observational constraint what is not yet modelled on a satisfactory level. There is also little known about how the heating depends on magnetic field strength, structure size (length, radius, expansion) and age and progress is accepted in the near future.

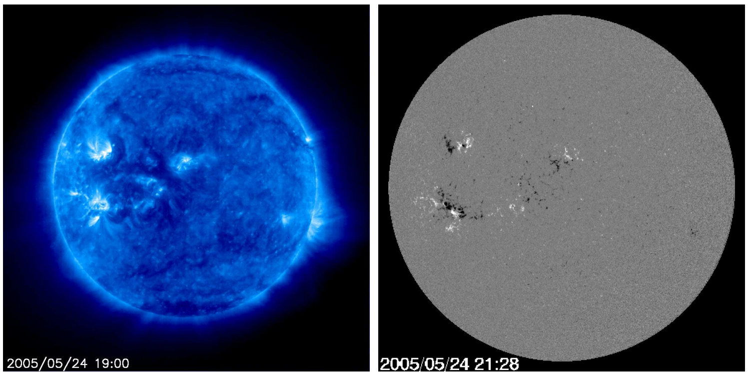

Figure 2: *Left: The solar corona in the 171 Å SoHO EIT spectral line. Right: Concurrently taken image of a SOHO MDI magnetogram at photospheric levels. Magnetic field concentrations coincide with bright patches in the SoHO EIT image indicating the role of magnetic field in the process of coronal heating.*

3 Atmospheric Heating Mechanisms

In order to explain solar (and stellar) atmospheric heating mechanism(s) models have to provide a mechanism or mechanisms that result(s) in a steady supply of energy not necessarily on a steady way. Random energy releases that produce a statistically averaged steady state are allowed for to balance the atmospheric (chromospheric and coronal) energy losses and these models became more viable (Mendoza-Briceno et al. 2004, 2005). Testing a specific heating mechanism observationally may be rather difficult because several mechanisms may operate at the same time. Ultimate dissipation occurs on very small spatial scales, sometimes of the order of a few hundred metres that even with current high spatial resolution satellite techniques cannot (and will not for a while!) be resolved. A distinguished signature of a specific heating mechanism could be obliterated during the thermalisation of the input energy. We should, instead, predict the macroscopic consequences of a specific favoured heating mechanism (Cargill 1993) and confirm these signatures by observations (Aschwanden 2003). For example one could predict the generated flows (see e.g. Ballai et al. 1998) or specific spectral line profiles or line broadenings (Erdélyi et al. 1998).

The heating process is usually split into three phases: (i) the generation of a carrier of energy; (ii) the transport of energy from the locii of generation into the solar atmospheric structures; (iii) and finally the actual dissipation of this energy

Table 2: *Table 2: Summary of the various popular heating mechanisms (see also Ulmschneider, 1998; Erdélyi 2004)*

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

in the various magnetic or non-magnetic structures of the atmosphere. Without contradicting observations it is usually not very hard to come up with a theory that generates and drives an energy carrier. The most obvious candidate is the magneto-convection right underneath the surface of the Sun. Neither seems the literature to be short of transport mechanisms. There is, however real hardship and difficulty in how the transported energy is dissipated efficiently on a time-scale such that the corona is not relaxed thermally. A brief and schematic summary of the most commonly accepted heating mechanisms is given in Table 2 (see also Narain & Ulmschneider 1996; Ulmschneider 1998; Erdélyi 2004). The operating heating mechanisms in the solar atmosphere can be classified whether they involve magnetisms or not. For magnetic-free regions (e.g. in the chromosphere of quiet Sun) one can suggest a heating mechanisms that yields within the framework of hydrodynamics. Such heating theories can be classified as hydrodynamic heating. Examples of hydrodynamic heating are, among others, e.g. acoustic waves and pulsations. However, if the plasma is embedded in magnetic fields as it is in most parts of the solar atmosphere, the framework of magnetohydrodynamics (MHD) may be the appropriate approach. These coronal heating theories are called MHD heating mechanisms (for reviews see e.g. Browning 1991; Erdélyi 2004; Gomez 1990; Hollweg 1991; Pries & Forbes 2000; Roberts & Nakariakov 2003; and Walsh & Ireland 2003). The ultimate dissipation in MHD models invoke Joule heating or in a somewhat less extent viscosity. Examples of energy carrier of magnetic heating are the slow and fast MHD waves, Alfvn waves, magnetoacoustic-gravity waves, current sheets, etc. There is an interesting concept put forward by De Pontieu et al. (2005) where the direct energy coupling and transfer from the solar photosphere into the corona is demonstrated by simulations and TRACE observations. For a recent review on MHD waves and oscillations see e.g. Roberts (2004). Finally, a popular alternative MHD heating mechanism is the selective decay of a turbulent cascade of magnetic field (Gomez et al. 2000, Hollweg 2002, van Ballegooijen 1986).

Most of the hydrodynamic or MHD heating theories consider the plasma to be collisional. If however, the plasma, whether magnetised or not, is collisionless (and the plasma in the solar corona strictly speaking is!) one has to consider kinetic approaches (for a review see e.g. Scudder 1995). 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.

Based on the times-cales involved an alternative classification of the heating mechanism can be constructed. If the characteristic time-scale of the perturbations is less than the characteristic times of the back-reaction, in a non-magnetised plasma acoustic waves are good approximations describing the energy propagation; if, however, the plasma is magnetised and perturbation time-scales are small we talk about alternating current (AC-) heating mechanisms, e.g. MHD waves (Roberts 2000, Erdélyi 2001, Roberts & Nakariakov 2003). On the other hand, if perturbations have low frequencies hydrodynamic pulses may be appropriate in a non-magnetised plasma, while if the external driving forces (e.g. photospheric motions) operate on longer times-cales compared to dissipation and transit times very narrow current sheets are built up resulting in direct current (DC-) heating mechanisms in magnetised plasmas (Priest & Forbes 2000).

3.1 Hydrodynamic Framework

After the discovery of the hot solar atmosphere in the early 1940s the model of acoustic waves generated by solar granulation were put forward as energy carrier from the top of the convective zone into the corona. The very steep density decrease causes the sound waves to develop into shocks. These acoustic shocks dissipate their energy causing plasma heating in the solar corona.

After it was discovered that coronal plasma is heavily embedded into magnetic fields the relevance of the hydrodynamic heating mechanisms for the corona part of the atmosphere was re-evaluated. It is believed today that 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 (De Pontieu et al. 2004).

For late-type stars with spectral type of 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 generator 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).

3.2 MHD Framework

At least as a first approximation the plasma is considered frozen-in in the various magnetic structures in the hot solar atmosphere. The magnetic field plays a central and key role in the dynamics and energetics of the solar corona (see Figure 2). High-resolution satellite observations show the magnetic building blocks that seem to be in the form of magnetic flux tubes (Figure 3) in the solar atmosphere. These flux tubes expand rapidly in height because of the strong drop in density. Magnetic fields fill almost entirely the solar atmosphere at about 1,500 km above the photosphere. The flux tubes are shaken and twisted by photospheric motions (i.e. by both granular motion and global acoustic oscillations, the latter being called p-modes). This 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; Alfvń waves). The dissipation of MHD waves is manifold: these waves couple with each other, interact non-linearly, resonantly interact with the closed waveguide (i.e. coronal loops) or develop non-linearly (e.g. solitons or shock

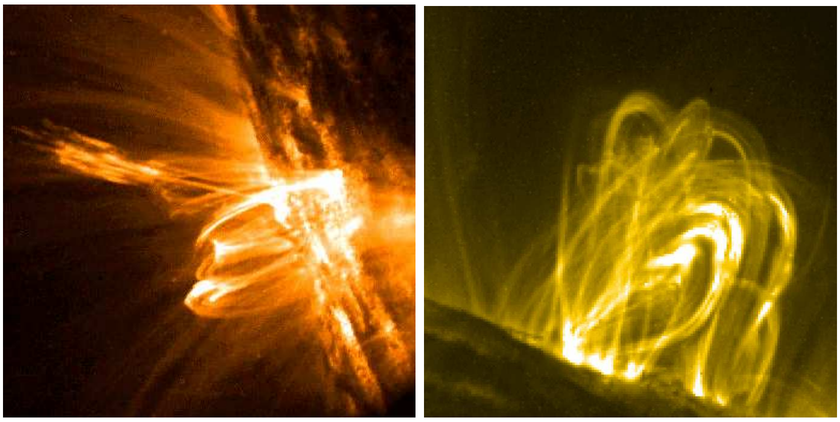

Figure 3: *TRACE images of the highly structured solar corona where the plasma is frozen in semi-circular shaped magnetic flux tubes. Left: The magnetic field in the solar atmosphere shapes the structures that we see, as the emitting gas can generally only move along the field. Sometimes, however, packets of gas are accelerated so much that they can shoot through the magnetic field almost in a straight line. Courtesy Charles Kankelborg. Right: The image shows the evolution of loop system: an increasing number of loops appears in the 1 MK range, probably as they cool from higher temperatures that they reached during the main X-ray flare phase. Courtesy TRACE (http://vestige.lmsal.com/TRACE/Public/Gallery/Images/TRACEpod.html)*

waves can form), etc. For an extensive review on the observations of MHD waves see e.g. Aschwanden (2003), while on theory see e.g. Roberts (2004).

In an inhomogeneous and magnetised plasma there are two particular dissipation mechanisms of MHD waves that received extensive attention in the past decades: resonant absorption and phase mixing. Although there are major theoretical advances on these two particular dissipation mechanisms unfortunatelly we still have only indirect evidences that they may actually operate under solar circumstances. Thanks to the fantastic imaging capabilities of TRACE, plenty of observations of MHD wave damping in coronal loops are available (Aschwanden 2003) and some of these cases may be an excellent candidate of resonant absorption. Further, it is less likely that phase mixing operates in closed magnetic structures, like solar coronal loops.

3.2.1 Mechanism of Resonant Absorption

Let us consider an ideal inhomogeneous vertical magnetic flux tube embedded in a 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 4a). Let us 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 that the driving wave is in resonance with the local Alfvén waves at the magnetic surface at r_A. In ideal MHD this would result in 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, i.e. dissipative effects (e.g. resistivity, viscosity) have to be considered at least within the vicinity of such resonant location leading to energy dissipation. Such dissipation, i.e. energy absorption of the driving wave, will result in heating of the plasma converting the energy of the driving wave into localised thermal heating. Resonant absorption, originally considered by plasma physicists as means of excess heating source for thermonuclear fusion, seems to work very well when modelling e.g. the interaction of solar global oscillations with sunspots; when applied to explain the damping of coronal loop oscillations (Ionson 1978, Erdélyi 2001), etc.

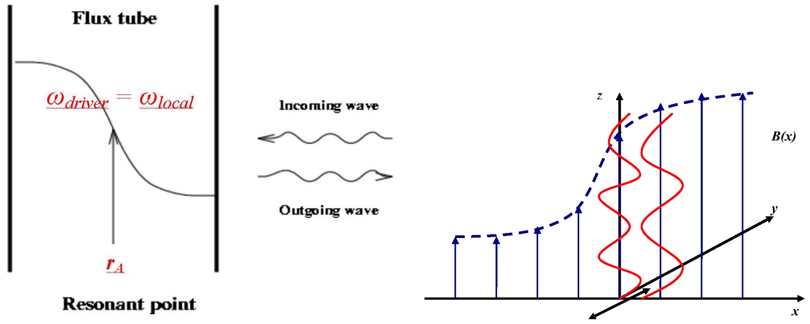

Figure 4: *Left: Schematic sketch of resonant absorption. The incoming driving wave with frequency* ω_{driver} *is in resonance with local oscillations at the resonant point* r_A *where the driver's frequency matches the frequency of the local eigenoscillations. Right: Phase-mixing of surface waves caused by gradients in the background magnetic field (or Alfvén speed) where the footpoints of the field lines are shaken in the* y*-direction.*

3.2.2 Process of Phase Mixing

Heyvaerts & Priest (1983) proposed another interesting mechanism that is in a way fairly similar to resonant absorption. There is a magnetised plasma that is inhomogeneous in the x-direction of the xz-plane where the magnetic field lines are parallel to the z-axis (Figure 4b). We perturb each field line in a coherent (e.g sinusoidal) way in the y-direction. Along each of the field lines an Alfvén wave will develop and will propagating in the z-direction with a speed characteristic to that field line. Since the plasma is inhomogenenous the Alfvén speed at two adjacent field lines is different and neighbouring oscillating field lines will be soon out of phase after some time resulting in large gradients of perturbations. At a given point when the gradients reach a critical value it is not correct anymore to assume that the plasma is ideal and dissipative effects have to be included in the analysis (just like 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 like coronal funnels, plumes, solar wind.

3.2.3 Magnetic Reconnection

Finally, if the characteristic time scales of magnetic footpoint perturbations are much larger than the local Alfvénic transit times, magnetic tension is built up gradually involving highly localised 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 attempt of 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 2, what could be measured by observing these small-scale energy releases. If the measured power-law index is greater than 2 that would indicate the solar atmosphere is heated by numerous localised events due to reconnection as a result of e.g. the continuous shuffling of the roots of coronal fields. However, if measurements would 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 could not allow drawing a final conclusion!

We have briefly listed a couple of popular heating mechanisms. We would like to emphasise that most probably 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 the much awaited Solar-B next year and Solar Dynamics Observatory (SDO) somewhat after or later on Solar Orbiter (probably around the mid of the next decade) will have the capability and capacity to answer the fundamental astrophysical question of: how solar and stellar atmosphere are heated?

4 Stellar Outlook

From the viewpoint of an astronomer the Sun is just a fairly ordinary main-sequence middle-aged low-mass star with a spectral type of G2V with 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 was 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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