HEATING OF CHROMOSPHERES AND CORONAE

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Abstract. Almost all nondegenerate stars have chromospheres and coronae. These hot outer layers are produced by mechanical heating. The heating mechanisms of chromospheres and coronae, classified as hydrodynamic and magnetic mechanisms, are reviewed here. Both types of mechanisms can be further subdivided on basis of the fluctuation frequency into acoustic and pulsational waves for hydrodynamic and into AC– and DC–mechanisms for magnetic heating. Intense heating is usually associated with the formation of very small spatial scales, which are difficult to observe. Yet, global stellar observations, because of the dependence of the mechanical energy generation on the basic stellar parameters (T_{eff}, gravity, rotation, metallicity) can be extremely important to identify the dominant heating mechanisms.

1. Introduction

Chromospheres and coronae are hot outer layers of stars where the temperatures are much higher than the stellar effective temperature T_{eff}. In chromospheres the temperatures rise in outward direction to values of around 10000 K, while in coronae the temperatures are in the million degree range. These layers are observed in the Radio, IR, UV and X-ray spectral ranges. EINSTEIN observations showed that *O- and B-stars*, which do not have surface convection zones, have strong X-ray emission which is attributed not to contiguous layers around those stars, but to shocks generated by rapidly moving individual gas blobs driven by radiative instability in the outer stellar envelope.

F-, G-, K- and M-stars have chromospheres and often coronae much like our Sun. These are attributed to the wave- and magnetic energy generation in the surface convection zones of these stars. Late giants and supergiants have chromospheres but not coronae. Finally, *A-stars* appear to have neither chromospheres nor coronae and there is a conspicuous X-ray gap for A-stars, although there is theoretical evidence for very weak chromospheres and coronae. Thus very likely all nondegenerate stars have hot outer layers.

As typical non-accreating stars do not receive energy from infinity, the chromospheres and coronae must be completely determined from the properties of the underlying star, that is, from the convection zone. Because convection zone models depend on four parameters T_{eff}, gravity g, metallicity Z as well as the mixing–length parameter α and as the rotation determines the magnetic flux generation by the dynamo mechanism, chromospheres and coronae should be physically completely determined by specifying only a small number of physical variables (e.g. T_{eff}, g, Z, α, P_{rot}). This review summarizes the various heating processes, but also discusses the mechanical energy generation to give an overview of the present state of our knowledge to understand chromospheres and coronae in terms of the basic stellar parameters. One finds that heating often has to do with the generation of very small spatial scales, which unfortunately are difficult to observe even on the Sun. Surprisingly here, global stellar observations can often be used to discriminate between the various heating mechanisms, because they bring the dependence of the mechanical energy generation by the various processes on the basic stellar parameters into play. For more extensive reviews of heating mechanisms see Narain & Ulmschneider (1996) as well as Ulmschneider (1997).

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energy carrier	*dissipation mechanism*
hydrodynamic heating mechanisms	
acoustic waves, $P<P_A$	shock dissipation
pulsational waves, $P>P_A$	shock dissipation
magnetic heating mechanisms	
1. alternating current (AC) or wave mechanisms	
slow mode mhd waves, longitudinal mhd tube waves	shock dissipation
fast mode mhd waves	Landau damping
Alfvén waves (transverse, torsional)	mode-coupling resonance heating compressional viscous heating turbulent heating Landau damping
magnetoacoustic surface waves	mode-coupling phase-mixing resonant absorption
2. direct current (DC) mechanisms	
current sheets	reconnection (turbulent heating, wave heating)

TABLE 1. Mechanical heating mechanisms for stellar chromospheres and coronae, P is the wave period and P_A the acoustic cut-off period.

2. Overview of Heating Mechanisms

Table 1 gives a summary of the proposed mechanical heating mechanisms responsible for steady heating. Steady here means, that we do not discuss occasional localized events like large flares, but concentrate on the persistent mechanisms which provide the energy to balance the chromospheric and coronal losses. A heating mechanism consists of three processes, the *generation* of the mechanical energy carrier, the *energy transport* and the *energy dissipation*. Table 1 shows the various proposed energy carriers which can be classified as *hydrodynamic* and *magnetic* mechanisms, with the latter subdivided into AC-mechanisms and DC-mechanisms.

Ultimately all mechanical energy carriers derive their energy from the nuclear processes in the stellar core. In late-type stars, this energy is transported in the form of radiation and convection to the stellar surface, where in the surface convection zone the generation of mechanical energy takes place. The mechanical energy generation results from the gas motions of the convection zone, which are largest in the regions of smallest density near the top boundary of that zone. Because of this the mechanical energy carriers, particularly the waves, are generated in a narrow surface layer.

As the gas motions in the convection zone can be described by a common temporal and spatial turbulence spectrum, consisting of a characteristic distribution from large to small gas bubbles and from long to short time scales, it is clear that different parts of that spectrum are correlated with one another. We thus expect to see correlations between the various heating mechanisms because of this common energy source.

3. Elementary Dissipation Processes

In the dissipation process, mechanical energy is converted into heat. That is, organized motion or potential energy is converted into random thermal motion. Consider a typical fluctuation in the solar chromosphere with a characteristic diameter $L = 200\ km$, temperature- $\Delta T = 1000\ K$, velocity- $\Delta v = 3\ km/s$ and magnetic field perturbation $\Delta B = 10\ G$. Using values for the thermal conductivity $\kappa_{th} = 10^5\ erg/cm\ s\ K$, viscosity $\eta_{vis} = 5 \cdot 10^{-4}\ erg\ s/cm^3$ and electrical conductivity $\lambda_{el} = 2 \cdot 10^{10}\ s^{-1}$ we find for
the thermal conductive heating rate:

$$\Phi_C = \frac{d}{dz}\kappa_{th}\frac{dT}{dz} \approx \frac{\kappa_{th}\Delta T}{L^2} \approx 3 \cdot 10^{-7} \quad \left[\frac{erg}{cm^3 s}\right] \tag{1}$$

the viscous heating rate:

$$\Phi_V = \eta_{vis}\left(\frac{dv}{dz}\right)^2 \approx \frac{\eta_{vis}\Delta v^2}{L^2} \approx 1 \cdot 10^{-7} \quad \left[\frac{erg}{cm^3 s}\right] \tag{2}$$

the Joule heating rate:

$$\Phi_J = \frac{j^2}{\lambda_{el}} = \frac{c_L^2}{16\pi^2\lambda_{el}}(\nabla \times B)^2 \approx \frac{c_L^2 \Delta B^2}{16\pi^2\lambda_{el}L^2} \approx 7 \cdot 10^{-5} \quad \left[\frac{erg}{cm^3 s}\right]. \tag{3}$$

Here j is the current density and c_L the light velocity. The three heating rates show that normally these processes are inadequate to balance the empirical chromospheric cooling rate of $10^{-1} erg/cm^3\ s$. Only when the length scale L is considerably decreased, can the heating rates be raised to acceptable levels. For acoustic waves as well as slow mode mhd- and longitudinal mhd tube waves, this is accomplished by shock formation. For magnetic cases, by the formation of current sheets. That is, for an efficient dissipation process one must have large variations of the physical variables over very small scales. Thus in recent years considerable effort has gone into the study of how, in magnetic field regions, areas with small scales develop naturally. We now discuss the various heating mechanisms in greater detail.

4. The Hydrodynamic Heating Mechanisms

As mentioned above there are two hydrodynamic mechanisms, both wave–mechanisms, which can be subdivided on basis of the acoustic cut-off frequency. *Acoustic waves* of period $P < P_A = 4\pi c_S/(\gamma g)$ (c_S is sound speed, g gravity, γ the ratio of specific heats) propagate freely into the outer stellar atmospheres and because of the large density gradient steepen into shocks when propagating in outward direction as consequence of wave energy flux conservation. Shock heating is a very efficient way of mechanical energy dissipation.

Pulsational waves, where $P > P_A$, prominent e.g. in Mira-type stellar pulsations but also in other late-type giants, constitutes a second hydrodynamic mechanism. These waves are generated by the kappa–mechanism. The kappa–mechanism functions similarly as the internal combustion engine in motorcars. In the internal combustion engine a reactive gas mixture is compressed in a pulsational motion and is ignited at the moment of strongest compression resulting in a violent decompression. This ensures that the pulsational motion is amplified. In the kappa–mechanism the opacity of stellar envelope material increases (due to the adiabatic temperature and pressure increase) when the star contracts in a pulsational motion. This opacity increase leads to a large heat input by radiative absorption into the compressed envelope layers. The overheating subsequently produces a rapid expansion, driving the pulsation. The pulsational waves propagate to the outer stellar atmosphere where they form shocks.

This same process in principle, and possibly with different drivers, works also for nonradial oscillations. Any process which kicks on the basic pulsational and vibrational modes of the outer stellar envelope belongs to the category pulsational wave mechanism. For the Sun the 3 min oscillation is such an example of a basic resonance which is generated by transient events produced by the convection zone. A systematic study of this heating mechanism for late-type stars is missing at the present time.

5. Magnetic Heating Mechanisms

According to the fluctuation frequency the magnetic heating mechanisms are subdivided into *wave- or AC(alternating current)-mechanisms* associated with high frequency field motions and *current-dissipation- or DC(direct current)-mechanisms* associated with slow field motions. Let us first discuss the AC–mechanisms.

As seen in Tab. 1 the slow–mode mhd waves and longitudinal tube waves, which are essentially acoustic waves, heat by shock dissipation. For the heating by transverse and torsional Alfvén waves there is a variety of dissipation processes:

5.1. MODE-COUPLING

Mode–coupling is not a heating process by itself, but converts wave modes, which are difficult to dissipate, by non-linear coupling into other modes, where the dissipation is more readily achieved. Typical cases are the conversion of transverse or torsional Alfvén waves into acoustic-like longitudinal tube waves.

5.2. RESONANCE HEATING

Resonance heating occurs when, upon reflection of Alfvén waves at the two foot points of the coronal loops, one has constructive interference. For a given loop length $l_{||}$ and Alfvén speed c_A, resonance occurs, when the wave period is $mP = 2l_{||}/c_A$, m being a positive integer. Waves which fulfill the resonance condition are trapped and after many reflections are dissipated by Joule-, thermal conductive or viscous heating.

5.3. COMPRESSIONAL VISCOUS HEATING

Compressional viscous heating, proposed by Strauss (1991), is a very promising mechanism for coronal regions, where the gyro frequency is much larger than the collision frequency. Swaying an axial magnetic flux tube sideways with velocity $\mathbf{v}_\perp$ results in a transverse Alfvén wave which is incompressible ($\nabla \cdot \mathbf{v}_\perp = 0$) to first order. This is different for tubes with helicity, where one has $\nabla \cdot \mathbf{v}_\perp \approx \dot{\rho}/\rho$. With a wave induced increase of the density, the magnetic field is compressed and the gyro frequency increased. Gyrating around the field lines more quickly, the ions after colliding with each other, generate larger velocities in non-perpendicular directions as well, which constitutes the heating process.

5.4. TURBULENT HEATING

In a turbulent flow field with high Reynolds number there are bubbles of all sizes. The energy usually is put into the largest bubbles. Because of the large inertial forces the big bubbles are ripped apart into smaller bubbles, and these in turn into still smaller ones etc. This process is called turbulent cascade. A turbulent flow field can be described by three characteristic quantities, density ρ_o, bubble scale $l_k = 2\pi/k$, and the mean velocity u_k of such bubbles. k is the wavenumber. It is easily seen, that from these three quantities only one combination for a heating rate can be formed:

$$\Phi_k = \rho_o \frac{u_k^3}{l_k} \quad \left[\frac{erg}{cm^3 s}\right]. \tag{4}$$

If there are no other losses, like by radiation, all the energy which is put in at the largest bubbles must reappear in the smaller bubbles etc. Thus if $k1$, $k2, \cdots$ represents a series of smaller and smaller bubbles one must have $\Phi_{k1} = \Phi_{k2} = \cdots =$ const. This implies

$$u_k \sim l_k^{1/3}, \tag{5}$$

which is the *Kolmogorov law*. The range $l_{k1} \cdots l_{kn}$ of validity of this law is called the *inertial range*. Consider what happens if l_k becomes very small. From Eqs. (2) and (5) one finds for the viscous heating rate $\Phi_V = \eta_{vis}(du/dl)^2 \approx \eta_{vis} u_k^2/l_k^2 \approx \eta_{vis} l_k^{-4/3}$, which goes to infinity for $l_k \to 0$. Thus at some small enough scale, viscous heating sets in and the inertial range ends. It is seen that turbulent heating lives from the formation of small scales. One can visualize the process as follows. Because of the continuous splitting of bubbles into smaller sizes, with the velocities decreasing much less rapidly, one eventually has close encounters of very small bubbles with large velocity differences where viscous heating dominates.

One can use the known width of the inertial range to estimate the frequency range of the generated acoustic and mhd–wave energy spectrum. One finds (Ulmschneider 1997) that this range can extend up to 100 Hz in the Sun if radiative exchange between the gas bubbles is considered negligible.

5.5. LANDAU DAMPING

Landau damping occurs at coronal heights, where the collision rate becomes small. As Chen (1974) has well explained, this process is analogous to surfing on ocean waves. When surfing, a surfboard rider launches himself in propagation direction into the steepening part of an incoming wave and gets further accelerated by this wave. In Landau damping, the propagating wave accelerates gas particles which, due to their particle distribution function, happen to have similar direction and speed as the wave. Because a distribution function normally has many more slower particles than faster ones, the wave looses energy to accelerate the slower particles. This gained energy is eventually shared with other particles in the process to reestablish the distribution function which constitutes the heating mechanism.

5.6. RESONANT ABSORPTION

In the process of resonant absorption one considers magnetoacoustic surface waves in a magnetic field B which points in z-direction, and varies from B_1 to B_2 in x-direction. The surface wave, with its field perturbation $\delta B = B_x'$ in x-direction, has a phase speed $v_{ph} = ((B_1^2 + B_2^2)/(4\pi(\rho_1 + \rho_2))^{1/2}$, such that at an intermediate position x_o, the phase speed becomes equal to the local Alfvén speed $c_{Ao} = B(x_o)/\sqrt{4\pi\rho(x_o)}$. Now consider the wave fronts of the peak and the trough of a surface wave generated by shaking the entire interface in x-direction. Because to the right of x_o, the Alfvén speed is larger and to the left smaller, the wave fronts at a later time get tilted relative to the phase, propagating with speed c_{Ao}. This tilt increases with time until the wave fronts approach each other closely at the position x_o. This leads to small scales and intense heating at this field line.

5.7. PHASE-MIXING

For phase-mixing one considers the same magnetic field geometry as for resonance absorption, however, the shaking $\delta B = B_y'$ of the wave is now in y-direction, perpendicular to the x- and z-directions. As the Alfvén speeds of two closely adjacent regions x_1 and x_2 are different, the fields $B_y'(x_1)$ and $B_y'(x_2)$, after propagating for some time will be very different, leading to a current sheet and strong dissipation. Both resonance absorption and phase-mixing need an extended loop-length for the field disparity to become large enough.

5.8. RECONNECTION

As examples of the DC heating mechanisms we consider two different situations where current sheets are thought to exist. The first is an arcade system (Priest 1991), which by slow motion is laterally compressed and develops a current sheet, where oppositely directed fields reconnect. The other example, after Parker (1992), is a tangled and braided web of coronal loops created by slow foot point motions. Initially the field is axial and in the minimum energy configuration. Subsequent slow stochastic foot point motion at both legs of the loops tangle and braid the loops in a very complicated manner, by which there is a buildup of magnetic energy. The system thus tries to return to its minimum energy configuration. At many locations in the web oppositely directed fields occur, giving rise to local current sheets, which by reconnection (in the form of microflares) release the magnetic field energy. The energy is dissipated both directly and via the generation of waves and turbulence. Note that reconnection likewise happens in small scale regions.

The question, whether microflares is a significant coronal heating mechanism and what its importance is as compared to wave heating (DC– versus AC–heating), has recently been studied by Wood, Linsky & Ayres (1996) by observing CIV and Si IV transition layer lines in late-type stars.

They found that the total line profiles can be explained as a combination of a very broad profile, attributed to microflares, and a narrow profile, attributed the wave heating. Studies of this type, particularly with respect to the four stellar parameters T_{eff}, gravity, Z and rotation, are expected to make great progress in the identification of the individual heating processes and generally in our understanding of coronal heating as a function of the basic parameters of the underlying stars.

6. Hydrodynamic Energy Generation

In terrestrial situations, monopole, dipole and quadrupole sound generation is a sequence of progressively less important ways to produce acoustic waves. While monopole generation depends on mass injections and dipole generation on rigid vibrating surfaces, quadrupole generation is the most efficient way of sound production from turbulent flows even on Earth. The theory of quadrupole sound generation from turbulence was originally developed by Lighthill and Proudman in the 1950's and resulted in the famous Lighthill–Proudman formula

$$F_A = \int_{\Delta z} 38\rho \frac{u^8 dz}{c_S^5 H} , \tag{6}$$

This theory was greatly extended and applied to the solar convection zone by Stein (1967). The Lighthill–Stein theory has recently been rediscussed by Musielak et al. (1994) and was employed by Ulmschneider, Theurer & Musielak (1996) to compute acoustic wave energy fluxes for a large number of late–type stars.

On basis of the acoustic fluxes for main sequence stars and giants, theoretical chromospheric models have been computed and Ca II and Mg II emission line fluxes were simulated by Buchholz, Ulmschneider & Cuntz (1997). These simulated fluxes are in good agreement with observed minimum Ca II and Mg II line emission fluxes (basal flux line) which conclusively demonstrates that acoustic waves are one of the principal chromospheric heating mechanisms. Moreover it could be shown that for stars with little or no magnetic fields, acoustic heating is the dominant mechanism. It should be noted that this conclusion could not have been made with much confidence on basis of solar observations alone, as it is very difficult to discriminate between magnetic and non–magnetic heating on the Sun.

7. Magnetic Energy Generation

Consider a cylindrical magnetic flux tube of length $l_{\|}$ and diameter $l_{\perp}$ where the magnetic field B is along the axis of the tube. The convective gas motions outside the tube lead to magnetic field perturbations δB either in tangential or in radial direction. One then has $\delta B \approx B l_{\perp}/l_{\|} \approx B u\tau/l_{\|}$, where u is the velocity and τ the characteristic time of the convective flow. From this the energy density of the perturbation is (where c_A is the Alfvén speed)

$$E = \frac{\delta B^2}{4\pi} \approx \frac{B^2}{4\pi}\left(\frac{u}{l_{\|}}\right)^2 \tau^2 = \rho_o c_A^2 \left(\frac{u}{l_{\|}}\right)^2 \tau^2 . \tag{7}$$

1. For slow tube motion ($\tau > l_{\|}/c_A$) one has a generated energy flux for the DC–mechanism

$$F_{DC} = E\frac{l_{\|}}{\tau} = \rho_o c_A^2 \frac{u^2}{l_{\|}}\tau, \tag{8}$$

2. for fast tube motion ($\tau < l_{\|}/c_A$), with an effective $l_{\|} = c_A\tau$, one has a generated energy flux for the AC–mechanism

$$F_{AC} = \rho_o u^2 c_A . \tag{9}$$

In principle, applying a time-dependent 3D mhd convection zone code to a sufficienly large stellar surface element would allow to compute both the generated AC– and DC–mechanical energy fluxes. With these fluxes one could then construct definitive models of the chromospheres and coronae. Unfortunately the present computer power is not quite adequate for this ultimate aim.

What has been done so far is to evaluate AC-fluxes, that is, to compute transverse and longitudinal mhd tube wave energy fluxes for solar and stellar magnetic flux tubes (Huang, Musielak &

Ulmschneider 1995 and Ulmschneider & Musielak 1997). These authors perturbed a magnetic flux tube sticking in a stellar convection zone by outside turbulence. Here as in the Lighthill–Stein case a Kolmogorov–type energy spectrum was used. The transverse wave was excited by shaking the flux tube and the longitudinal wave by applying turbulent pressure fluctuations, both as function of time. It was found that the transverse waves were by a factor of 15 more efficiently generated than the longitudinal waves. It is presently attempted (Cuntz, Ulmschneider & Musielak 1997) to explain the empirical rotation-activity correlation, which would identify longitudinal tube waves as the main heating mechanism for magnetic chromospheres.

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