CHROMOSPHERE: HEATING MECHANISMS

Mechanical heating

Chromospheres (and coronae) exist because of mechanical heating. Mechanical heating comprises all processes which convert nonradiative hydrodynamic or magnetic energy into thermal energy, that is, into microscopic random thermal motion. The physics of chromospheres (and coronae) is different from the physics of stellar atmospheres and interior layers, where the energy input is exclusively due to radiation, convection and thermal conduction. As observations show that the chromospheric emission depends strongly on the magnetic field, one subdivides the chromospheric heating processes into pure hydrodynamic mechanisms and magnetic mechanisms. Both types of mechanisms can be subdivided further into fast and slow processes. For the magnetic mechanisms the fast or wave mechanisms are called AC (alternate current) mechanisms and the slow mechanisms DC (direct current) mechanisms.

A mechanical heating mechanism consists of three processes, the *generation* of the energy carrier, the *transport* of this mechanical energy and its *dissipation*. Ultimately the mechanical energy comes from the nuclear processes in the stellar core. The energy generated there is transported in the form of radiation and convection to the stellar surface, where in the surface convection zone the mechanical energy is generated. The mechanical energy generation is due to the gas motions of the convection zone, which are largest in the regions of smallest density near the top boundary of that zone. Consequently the mechanical energy is generated in a narrow surface layer.

As current observations cannot tell with certainty whether a solar surface region is devoid of small scale magnetic fields or not and because heating in current channels with diameters of meters cannot be resolved at the present time, it is difficult to identify a specific heating mechanism from the list of proposed processes. For an extensive list of proposed heating mechanisms see Narain & Ulmschneider (1996) and also the chapter on coronal heating in this volume. Usually several mechanisms act at the same time. Surprisingly only by stellar observations (where the chromospheres are reduced to point sources!), was one able to definitively identify acoustic waves as the important basic mechanism for stellar chromospheres. The reason for this is that for stars the effective temperature T_{eff} can be changed by one order of magnitude, the gravity g by four, the metallicity by three and the rotation rate by two orders of magnitude. This greatly enlarges the range of theoretical predictions and thus permits crucial observations.

In the following subsections the necessity of mechanical heating, the zoo of mechanisms, the mechanical energy generation calculations, the observed mechanical heating rates and the possible total chromospheric heating picture are discussed in greater detail.

Necessity of mechanical heating

Consider a gas element in the chromosphere where flows introduced by the solar wind can be neglected. The total heating rate, that is, the amount of net heat per sec, Φ_T ($erg\ cm^{-3}s^{-1}$), flowing into the element across its boundaries, is given by

$$\Phi_T = \Phi_R + \Phi_J + \Phi_C + \Phi_V + \Phi_M = 0 \quad ,$$

as in dynamical equilibrium the chromosphere does not show time-dependence. The terms on the right hand side stand for radiative, Joule, thermal conductive, viscous and mechanical heating. A typical empirical chromospheric cooling rate from the standard solar model is $-\Phi_R = 10^{-1} erg\, cm^{-3} s^{-1}$. Consider a typical acoustic or magnetohydrodynamic disturbance in the solar chromosphere with characteristic values, size $L = 200\ km$, temperature $\Delta T = 1000\ K$, velocity $\Delta v = 3\ km\ s^{-1}$ and magnetic field perturbation $\Delta B = 10\ G$. Using appropriate values for the thermal conductivity κ_{th}, viscosity η_{vis} and electrical conductivity λ_{el} one finds (in $erg\, cm^{-3} s^{-1}$)

$$\Phi_C = \frac{d}{dz}\kappa_{th}\frac{dT}{dz} \approx \frac{\kappa_{th}\Delta T}{L^2} \approx 3\cdot 10^{-7} \quad ,$$

$$\Phi_V = \eta_{vis}\left(\frac{dv}{dz}\right)^2 \approx \frac{\eta_{vis}\Delta v^2}{L^2} \approx 1\cdot 10^{-7} \quad ,$$

$$\Phi_J = \frac{c_L^2}{16\pi^2\lambda_{el}}\left(\nabla\times B\right)^2 \approx \frac{c_L^2\Delta B^2}{16\pi^2\lambda_{el}L^2} \approx 7\cdot 10^{-5} \ ,$$

where c_L is the light velocity. It is seen that in the chromosphere Φ_C, Φ_V and Φ_J can be neglected relative to Φ_R and that the main energy balance is between radiative cooling and mechanical heating. If mechanical heating were switched off then one would obtain radiative equilibrium, $\Phi_R = 4\pi\kappa(J - S) = 0$. That is, in a radiative relaxation time scale of about a fraction of an hour radiative equilibrium would be reached. Here κ is the opacity, J the mean intensity and S the source function.

However, the heating rates Φ_C, Φ_V and Φ_J can become much bigger if the length scale L becomes very small. 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. Heating terms of the small L type are collected in the mechanical heating term Φ_M. Mechanical heating thus occurs when small scales form naturally.

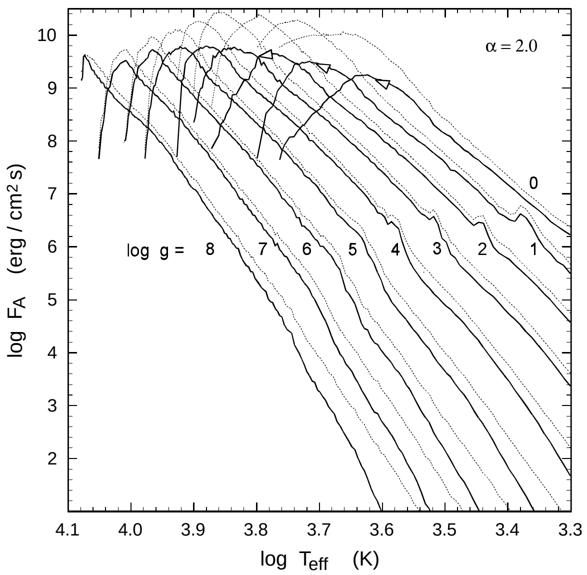

Figure 1: Acoustic fluxes for $\alpha = 2$.

The zoo of heating mechanisms

The *hydrodynamic mechanisms* consist of pulsational waves with periods larger than the acoustic cut-off period, $P > P_A = 4\pi c_S/(\gamma g)$ (where c_S is the sound speed and $\gamma = 5/3$ the ratio of specific heats), and acoustic waves where $P < P_A$. These hydrodynamic mechanisms dissipate via shocks. The *magnetic mechanisms* are the acoustic-like slow mode magnetohydrodynamic (mhd) waves and longitudinal tube waves as well as the transverse and torsional Alfvén waves. The latter two wave types are difficult to dissipate in the chromosphere and numerous dissipation mechanisms, mode-coupling, resonance heating, turbulent heating, have been studied. In addition magnetoacoustic surface waves are present which dissipate via mode-coupling, resonant absorption and phase-mixing. The DC-mechanisms associated with magnetic field reconnection very likely operate at heights above the chromosphere. The so-called turbulent and explosive events seen in the C IV transition layer line are thought to be caused by such reconnection processes. For more details see Narain & Ulmschneider (1996).

Mechanical energy generation

Mechanical energy is generated by the turbulent gas motions in the convection zone. Numerical convection studies and observations indicate that the turbulent flows can be described by a Kolmogorov-type energy spectrum. Using such a spectrum where the rms turbulent velocity is provided from convection zone models (which depend on T_{eff}, g and the mixing-length parameter α, where $\alpha = 2$ agrees well with observations), acoustic wave energy fluxes for the Sun and a large number of stars have been computed using the Lighthill-Stein theory (Ulmschneider et al. 1996). Lighthill's theory of quadrupole sound generation is in excellent agreement with observations in terrestrial applications. Acoustic fluxes thus obtained are shown in Fig. 1. The Lighthill-Stein theory also provides acoustic frequency spectra which extend from the cut-off period P_A to about a factor 100 smaller with a maximum roughly at period $P_M = P_A/5$. For the Sun one finds typical values of the total acoustic wave energy flux of 1.7×10^8 $erg\ cm^{-2}s^{-1}$ and period $P_M = 60\ s$, using a mixing-length parameter $\alpha = 2.0$.

The fluxes of longitudinal and transverse waves in magnetic tubes have been computed for the Sun by squeezing and shaking a tube model by external time-dependent turbulent flows at a given excitation height. Fig. 2 shows the instantaneous and averaged generated longitudinal (top) and transverse (bottom) tube wave fluxes as function of time. The Fig. shows the very stochastic nature of the generation process. The wave energy generation occurs in spurts which is in good agreement with observations. The spurts are caused by sudden enhancements in the flow velocity. In Fig. 2 the same time-dependent turbulent velocity fluctuations were applied. For the Sun a typical average longitudinal wave flux of 1.5×10^8 $erg\ cm^{-2}s^{-1}$ and for the transverse flux a value about 20 times higher were found with a flat maximum extending from $P_M = 90\ s$ to larger periods. In view of the same acoustic wave flux inside and outside the tube one should realize that the gas density inside the tube is roughly by a factor of 6 smaller than the external density. Relative to this low density, the wave flux inside the tube is large, leading to rapid shock formation, but also to severe NLTE effects which strongly modify the radiative losses.

Empirical mechanical heating rates

Standard empirical solar chromosphere models indicate that active regions (where magnetic fields dominate) need mechanical fluxes of $F_M = 1.3 \times 10^8$, while quiet regions 1.4×10^7 $erg\ cm^{-2}s^{-1}$. These values have been multiplied by a factor of 2.3 to account for the line losses by Fe II.

Direct measurements of velocity fluctuations have been used to estimate the acoustic flux in the solar chromosphere. Because velocity fluctuations are observed as Doppler shift fluctuations of the cores of spectral lines, one must be careful to correct for seeing and for the effects of the line contribution function. Deubner (1988) finds $F_M = 2 \times 10^7, 1.2 \times 10^6, 4.5 \times 10^5$ $erg\ cm^{-2}s^{-1}$ at the heights 300, 800, 1500 km, respectively.

The emission cores of the Ca II H and K and of the Mg II h and k lines are reliable indicators of chro-

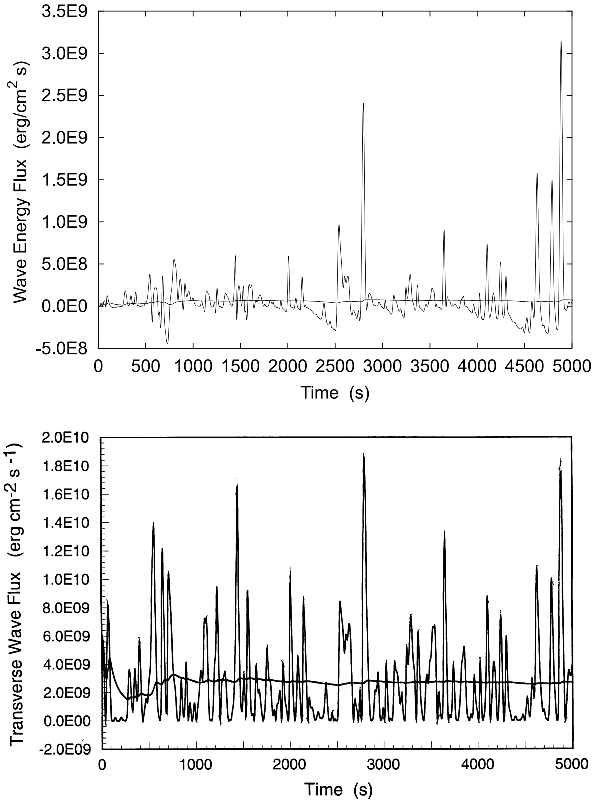

Figure 2: Instantaneous and average longitudinal (top) and transverse (bottom) mhd wave energy flux.

mospheres. Plotting for many stars the empirical core emission fluxes in these lines versus T_{eff} one finds that the fluxes show a well defined lower limit which extends e.g. for Ca II from $F_{Ca} = 1 \times 10^7$ for early F-stars to 2×10^4 $erg\ cm^{-2}s^{-1}$ for late M-stars. This limit is called *basal flux line.* It has been shown recently that this basal emission can be reproduced by acoustic heating (Buchholz et al. 1998). However, one finds that stars with the same T_{eff} and gravity g show different chromospheric emission and that this emission is larger when the stars rotate more rapidly. As rapidly rotating stars with a surface convection zone generate more magnetic fields via the dynamo mechanism it is clear that the excess heating is caused by magnetic heating mechanisms. A rapidly rotating star has more than an order of magnitude more chromospheric emission than the basal emission.

The total chromospheric heating picture

The successful reproduction of the basal flux line by acoustic wave heating models clarified that the fundamental heating process in chromospheres are acoustic waves. This mechanism operates independent of rotation. The faster a star rotates the more it is covered by magnetic fields which at photospheric and subphotospheric heights appear in the form of magnetic flux tubes. The fluctuating gas flows in the turbulent convection zone outside the tubes excite longitudinal, transverse and torsional magnetohydrodynamic tube waves. By shock formation the longitudinal waves in the lower and middle chromosphere heat the flux tubes which explains the excess emission in the magnetic regions. With more tubes on the star, more tube wave energy is generated. The much more efficiently produced transverse waves have two problems, they suffer severely from leakage of the wave energy away from the tube and they are difficult to dissipate. Very likely they are responsible for the heating of the high chromosphere and the transition layer. Here stellar observations of the C IV line (Wood et al. 1996) indicate that in addition to wave heating, DC-heating by microflares generated by reconnection events augments the Alfvén wave heating. These reconnection events are the result of slow horizontal convective motions (called foot-point motions) which lead to twisting and braiding of the magnetic flux tubes. Thus the convection zone is not only the source of AC-heating but also of DC-heating. The probably less efficiently generated torsional waves very likely traverse the chromosphere without dissipation and become important in the corona and in the stellar wind. An efficient three-dimensional simulation of the magnetohydrodynamics in stellar convection zones should in the future be able to completely explain the phenomenon chromosphere which, in absence of any input from interstellar space must, after all, be completely dependent on the interior of the star.

Bibliography

Buchholz B, Ulmschneider P, Cuntz M 1998, Basal heating in main-sequence stars and giants: Results from monochromatic acoustic wave models *Astrophys. J.* **494** 700–714

Deubner, F-L 1988 Observations of solar oscillations, in: *Pulsation and Mass Loss in Stars*, R Stalio, L A Willson Eds. Kluwer Dordrecht pp. 163–179

Narain U & Ulmschneider P 1996 Chromospheric and coronal heating mechanisms II *Space Sci. Rev.* **75** 453–509

Ulmschneider P, Theurer J, Musielak Z E 1996 Acoustic wave energy fluxes for late-type stars *Astron. & Astrophys.* **315**, 212–221

Wood B E, Linsky J L, Ayres T R 1996 Evaluating possible heating mechanisms using the transition region line profiles of late-type stars *Astrophys. J.* **478** 745–765