PROPAGATION OF RADIATION DAMPED ACOUSTIC WAVES IN STELLAR ATMOSPHERES

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ABSTRACT

The propagation of radiatively damped acoustic waves along magnetic flux tubes and its implication for the unknown chromospheric and coronal heating mechanism is discussed. It is shown that the behaviour of the radiative cooling strongly determines the structure of the chromosphere and the transition-layer.

1. INTRODUCTION

Fourtyfive years since Edlên's discovery that the solar corona is a very hot gas it is still unknown which mechanism produces these enormous temperatures. This situation in recent years has become even more painful because using the IUE and Einstein satellites it has been observed that possibly all stars (except the A stars) have hot envelopes (Ulmschneider 1979, Linsky 1980, Vaiana et al. 1981). The observations indicate that the unknown heating mechanism is strongly tied to the magnetic field. This is seen in the chromospheric network of the sun but also in young stars and tidally interacting stars which show strongly enhanced chromospheric (MgII and CaII line) and coronal (X-ray) emission.

The question is whether the magnetic field is directly involved in the heating as in flare-like mechanisms or whether the magnetic field is only indirectly involved by guiding and modifying the flow of magnetohydrodynamic waves. Let us discuss the latter possibility. It is now well known that the granulation cells and the convective instability concentrate the solar magnetic fields into intense flux tubes at the cell boundary with field strengths of about B=1500G and diameters of about 100 km at the bottom of the photosphere. There are three types of waves which propagate along magnetic flux tubes (Spruit 1982): torsional, transverse and longitudinal waves. The torsional (Hollweg et al. 1982) and transverse waves do not change the tube cross section and thus do not show pressure and temperature fluctuations to first order. Their main restoring force is magnetic tension. In longitudinal waves the tube cross section changes and the main restoring force is gas pressure. From this it is clear that this wave mode closely resembles a pure acoustic wave.

It has been shown (Ulmschneider and Stein 1982) that the presence of magnetic fields in the convection zone leads to greatly enhanced monopol type mhd wave generation compared to the much less efficient quadrupole-type acoustic wave generation when magnetic fields are absent. Thus longitudinal and transverse tube waves are efficiently produced. The cyclonic motions of cool downflowing stellar gas outside the flux tubes at the boundaries of the granulation cells (Schüssler 1984) make it likely that the torsional waves are efficiently produced as well. Due to the large amplitudes of these waves strong mode coupling is expected between the three wave modes.

Longitudinal and acoustic tube waves (which propagate in rigid tubes of the same geometry) are very similar because they obey the same three hydrodynamic equations and because the energy density in the gas pressure perturbation is much less than that in the magnetic pressure perturbation. As found by Herbold et al. (1985) the longitudinal waves in typical solar flux tubes are essentially acoustic waves propagating along the magnetic tube. In the mhd wave picture the chromospheric heating thus appears to be a consequence of acoustic shock dissipation. This does not favour the longitudinal tube wave mode. Due to the strong coupling longitudinal waves can be generated and acoustic shocks can be driven by the other tube modes as Hollweg et al. (1982) have shown.

2. NON-LTE TEMPERATURE ENHANCEMENT

Produced either in the convection zone or by mode coupling are the longitudinal tube waves capable of explaining the empirical chromospheric radiation loss and the observed temperature stratification? This question can only be answered by detailed time-dependent calculations where the hydrodynamic, radiative transfer and statistical rate equations are consistently solved for the important chromospheric emitters. Vernazza et al. (1981) have shown that in the sun the main chromospheric emitters are the H- continuum (in the low chromosphere), the principal lines of CaII and MgII (in the middle chromosphere), and the Lyman α line (in the upper chromosphere). From our model calculations (Schmitz et al. 1985) we find that in the low and middle chromosphere realistic temperature rises can only be obtained if significant departures from LTE in the H- emitter occur. One finds that the departure coefficient is given by

$$b_{H-} = \frac{R'+r}{R+r} , \quad (1)$$

where the radiative capture rate R' is only a function of temperature, the radiative absorption rate R is a constant and the collisional rate r is only a function of the hydrogen density. As in flux tubes the internal gas pressure is much less than the outside pressure the hydrogen density will be a small quantity decreasing with height. The temperature in the chromosphere on the other hand increases with height. Thus r is small compared to R', raising the departure coeff. b considerably above one and making it a strongly varying function of temperature. The net radiative cooling rate (erg $cm^{-3}s^{-1}$) is

$$\phi_R \approx 4\pi\, n^*_{H-} \int \alpha_\nu^{bf} \; (B_\nu^{bf} - b_{H-} J_\nu) \; d\nu \; , \quad (2)$$

where n^* is the H- number density in LTE, α the bound-free absorption cross section, B the Planck function, ν the frequency and $J(T_{RE})$ the mean intensity which in the outer layers of the sun is independent of height. Equ.(2) shows that large values of b strongly increases the effective radiative equilibrium temperature T_{RE} thus leading to considerably (between 500K and 1000K) higher chromospheric temperatures.

To raise the chromospheric temperature could one not simply put more energy into the atmosphere? As shown by Schmitz et al. (1985) even a factor of ten more acoustic flux does not raise appreciably the chromospheric temperature because this flux leads to shock formation at much lower height. Thus the excess wave energy is waisted heating the photosphere without much influence on the chromosphere. The strong Non-LTE heating is therefore essential for obtaining realistic chromospheric temperatures.

3. SCATTERING IN CHROMOSPHERIC RESONANCE LINES

In the middle and upper chromosphere the resonance lines of CaII and MgII are the most important emitters. The dominant process for the radiative transfer in these lines is scattering. Yet scattering does not contribute in the energy equation. In a two level atom the amount of scattering is described by the photon destruction probability

$$\varepsilon = n_E \cdot \Omega_{21} / (n_E \cdot \Omega_{21} + A_{21}) \quad (3)$$

where the first term in the bracket is the collisional deexcitation probability and A_{21} is the spontaneous emission probability. In typical chromospheric conditions ε lies between 10^{-2} and 10^{-9} thus scattering is much more likely than collisional deexcitation. As A_{21} and Ω_{21} are constants ε is a function only of the electron density n_E. Kalkofen and Ulmschneider (1984) have described a core saturation method for calculating the radiative cooling by resonance lines which is appropriate for time dependent calculations. This method assumes complete redistribution and allows for departures from LTE. The net radiative cooling rate from the two level atom can be approximately written as

$$\phi_{12} = h\nu_{12}\, n_1\, B_{12}\, \varepsilon\, (B_\nu - S_{12}) \quad (4)$$

where $h\nu$ is the photon energy, $n_1 B_{12}$ is the absorption rate, B_ν is the Planck function and S_{12} is the line source function. Only when the source function departs from the Planck function is line cooling possible. It is seen that scattering i.e. small ε greatly decreases the cooling rate. Moreover the difference between Planck and source function is not independent of ε. The larger ε the stronger is the coupling between radiation field and the thermal pool and the closer the source function approaches the Planck function. In Fig. 1 in a typical chromospheric wave calculation the relation between ε, B_ν and S_{12} is shown.

Multiplying the result of a two level calculation for the MgII k line by a factor 7 to account for the other important lines of MgII and CaII one can solve the energy equation with fairly realistic cooling rates up to the middle chromosphere before Lyman α becomes important. Fig. 1 shows a typical chromospheric acoustic wave calculation. The time-averaged temperature distribution is indicated by $\bar{T}$. The additional cooling by line radiation lowers the chromospheric temperatures from those obtained in the calculation where H- was the only emitter.

4. THE TRANSITION-LAYER RISE

Presently it is not known why after a relatively slow rise the temperature at the top of the chromosphere suddenly begins a rapid increase

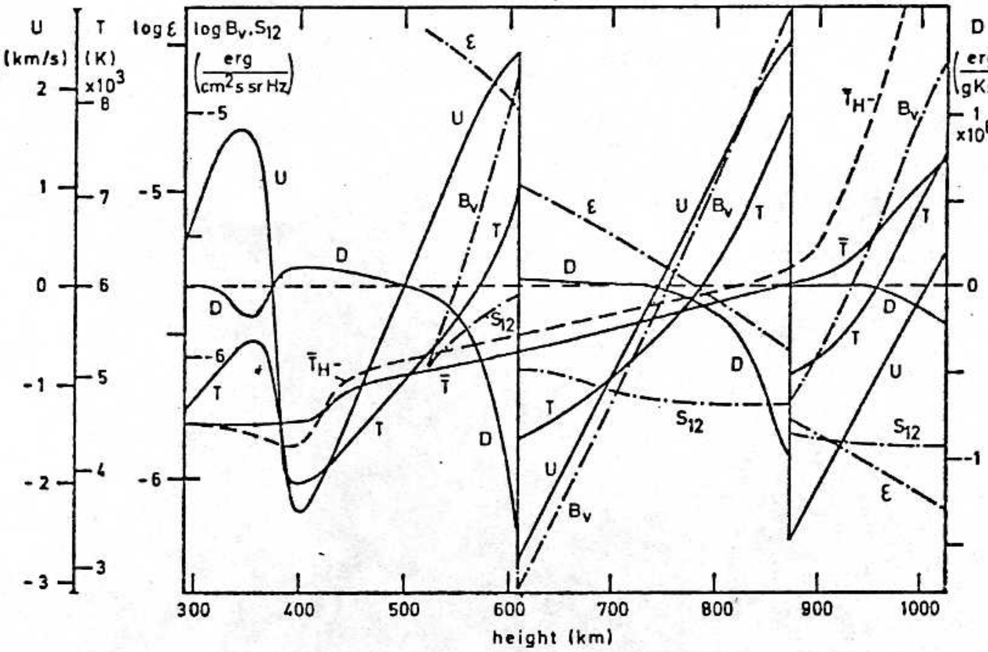

Fig.1 Acoustic wave in the solar atmosphere. The gas pressure is reduced by a factor of ten to simulate conditions in a magnetic flux tube. Temperature T, velocity u and radiation damping function D are shown as function of height x at time t=1258 s for a wave with period 30 s and initial flux 2.5 10^7 erg $cm^{-2}s^{-1}$. Time averaged temperatures are indicated by $\bar{T}$ (T_{H-} with only H-). For the line MgII k the Planck function B_ν, the source function S_{12} and the destruction probability ε are given.

to coronal values. Likewise it is unknown why the solar chromosphere-corona transition-layer occurs at a height of about 2000 km and not at a much greater height. Again acoustic wave calculations may point to a possible explanation. Fig. 1 shows that the mean chromospheric temperature rises slowly with height due to the rapidly decreasing density which in turn continuously steepens the shocks. Superimposed over the mean atmosphere the wave moves with relatively large temperature amplitudes. Let us consider a gas element in the high chromosphere and assume for a moment that H- is the only cooling mechanism. If the temperature in the shock becomes high enough H- will be destroyed. Only after the temperature behind the shock decreases below 8000K can H- form and resume radiative cooling. Thus in a time-dependent situation the gas element after having been passed by a shock does not have enough time to radiate away all of the mechanical energy deposited by that shock until the next shock arrives. Consequently the next shock will find the gas element slightly hotter, which in turn leads to a longer timespan during which cooling is switched off, etc. This shows that at a given height depending on the wave the destruction of an important emitter leads to an instability which produces a rapid temperature rise. This effect in principle is independent of H- and applies to the Mg, Ca and Lyman lines, too. Schmitz et al. (1985) found that for a given wave energy the height of the transition-layer depends primarily on the wave period. Long-period waves have lower transition layer heights because they form stronger shocks and thus trigger the instability earlier.

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