ACOUSTIC HEATING OF STELLAR CHROMOSPHERES AND CORONAE

P. ULMSCHNEIDER
Institut für Theoretische Astrophysik,
Im Neuenheimer Feld 561,
D-6900 Heidelberg, Federal Republic of Germany

ABSTRACT Acoustic wave dissipation is a viable mechanism for the heating of chromospheres and coronae. In absence of magnetic fields in the center of supergranulation cells on the sun and on very slowly rotating stars the acoustic heating mechanism appears to dominate. In the solar chromospheric network and on moderately or rapidly rotating stars acoustic heating is a weak background effect. The theoretical limiting shock strength behaviour and the direct solar observation of acoustic waves are both consistent with the empirical chromospheric energy requirements of the sun.

INTRODUCTION

The great advances in our knowledge of chromospheric and coronal heating in the last ten years resulted from the observations using the Einstein and IUE satellites and from solar observations. These observations showed that the heating is tightly correlated with the magnetic flux which is beautifully demonstrated in the stellar rotation - activity connection and the solar magnetic flux - activity relation. It was thus not surprising that the acoustic heating theory fell into disfavour. Recently however there is mounting evidence that this is not the whole story. For areas on the sun which have weak or no magnetic fields and for slowly rotating stars as e.g. very old main-sequence stars or giants the heating by acoustic waves seems to be an important mechanism. In addition there is evidence that acoustic wave heating is always present as a background effect. It is the aim of this paper to summarize this evidence.

CHROMOSPHERIC ENERGY BALANCE AND HEATING REQUIREMENTS

Stellar chromospheres and coronae are layers with persistent mechanical heating. Let us first discuss why chromospheres and coronae constantly require mechanical heating. Consider a chromospheric gas element. From the second law of thermodynamics the energy equation describing the heat addition to this element can be written

$$\rho T \left(\frac{\partial S}{\partial t} + \mathbf{v} \cdot \nabla S \right) = \Phi_M - \Phi_R \quad , \tag{1}$$

where ρ is the density, T the temperature, S $(erg\ g^{-1}\ K^{-1})$ the entropy, $\mathbf{v}$ the solar wind speed, $\Phi_M (erg\ cm^{-3}\ s^{-1})$ the mechanical heating rate and Φ_R the radiative cooling rate.

Here thermal conductive and viscous heating have been neglected because they are many orders of magnitude too small. For grey radiation one has $\Phi_R = 4\pi\kappa(B - J)$, where κ is the absorption coefficient, B the frequency integrated Planck function and J the mean intensity. Other expressions for Φ_R are given by Ulmschneider and Muchmore (1986). Since the chromosphere does not show a large time dependence and as the solar wind speed is small we can neglect the LHS of Eq. (1). It is thus found that the chromosphere is characterized by a balance between mechanical heating and radiative cooling.

To show the importance of mechanical heating let us suppose for a moment that one has $\Phi_M = 0$. Then radiative equilibrium prevails, and one has $B = J$. With $B = \sigma T^4/\pi$ and $J = \frac{1}{2}\sigma T_{eff}^4/\pi$, where the factor 1/2 takes into account that there is only outgoing radiation, one finds $T^4 \approx \frac{1}{2}T_{eff}^4$ or $T \approx 0.8T_{eff}$. This is the well known result that radiative equilibrium atmospheres have a boundary temperature with $T < T_{eff}$. From the empirical chromospheric and coronal models which all have temperatures $T >> T_{eff}$ it is thus clear that mechanical heating is absolutely essential. The presently still largely unanswerable question is, what heats chromospheres and coronae. For a recent review of this question see Narain and Ulmschneider (1989). A powerful constraint for any possible heating mechanism is the net radiative cooling rate Φ_R. Recently Anderson and Athay (1989) have newly determined this rate using semiempirical chromosphere models. Integrating $\Phi_M = \Phi_R$ over height they obtain the empirical heating flux F_M which is shown in Fig. 9. An additional constraint is that the heating must be constantly applied, because if it were switched off, then the chromosphere would rapidly cool down to the boundary temperature at a time scale of the radiative damping time $t_{rad} = \rho c_v/(16\kappa\sigma T^3) \approx \rho c_v T/\Phi_R \approx 200\ s$. Here c_v is the specific heat at constant volume.

ACOUSTIC HEATING THEORY AND STELLAR OBSERVATIONS

The acoustic heating theory has first been suggested by Biermann (1946). For late-type stars the acoustic heating mechanism works as follows: acoustic waves generated in the surface convection zone run down the steep density gradient of the outer stellar atmosphere, and, due to energy conservation, grow to large amplitude and form shocks. Shock dissipation heats the outer layers to high temperatures. From the turbulent nature of the convection zone it is clear that acoustic energy *must* be generated. Due to the large density decrease in the outer stellar layers (for the sun e. g. 6 orders of magnitude from the top of the convection zone to the transition layer) even very small acoustic disturbances will be amplified to sizeable amplitudes higher in the atmosphere. It is thus clear that acoustic heating must always be present. The acoustic heating mechanism also works for early-type stars where surface convection zones no longer exist. Here the intense radiation field amplifies small acoustic disturbances until strong acoustic shock waves develop.

Bohn (1984) has computed the theoretical acoustic energy generation rates in the turbulent stellar surface convection zones. These calculations, which have been criticised recently because the buoyancy forces have not been properly taken into account in the treatment of turbulence, depend on only three parameters: effective temperature T_{eff}, gravity g, and the ratio α of the mixing length to the pressure scale height. As shown in Fig. 1, Bohn's results exhibit a strong increase towards higher T_{eff}. This is due to the fact that the acoustic energy generation depends on a high power of the convective velocity u. In fairly efficient convection zones one has $\sigma T_{eff}^4 \approx \rho u^3$, that is, the total stellar flux is carried mainly by the convective flux. As the convective velocity of stars is

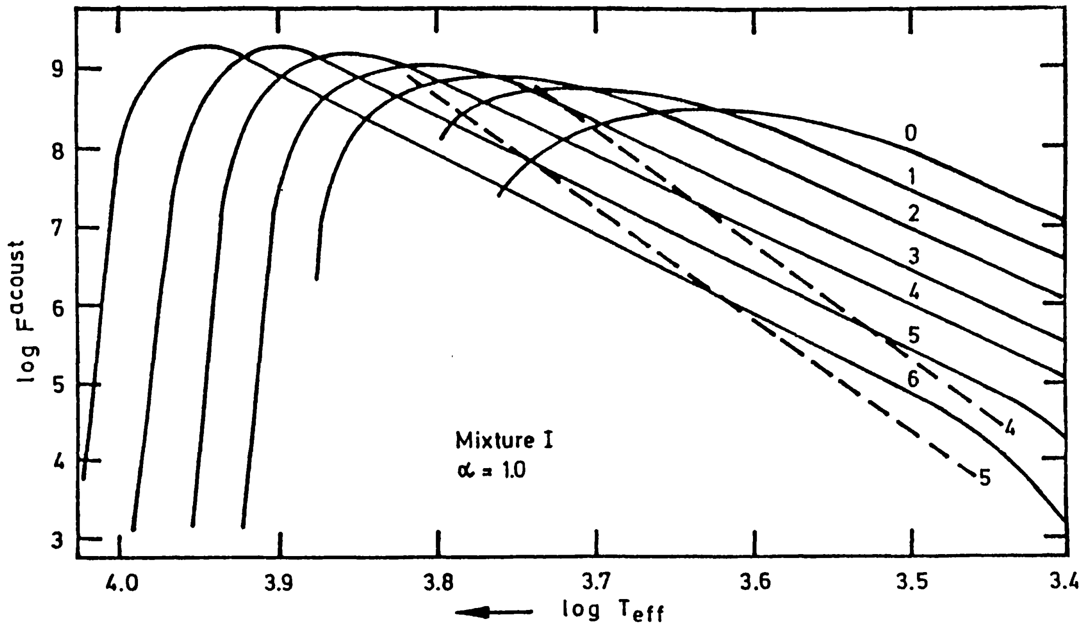

Fig. 1 Theoretical acoustic energy fluxes generated in stellar surface convection zones versus log T_{eff} *with* log g *as parameter after Bohn (1984).*

greatest near the surface where the densities are lowest, the acoustic energy generation is large only in the surface layers. Consequently acoustic energy generation does not depend on the depth of the stellar convection zone. Despite the fact that F-stars have shallow convection zones, the fact that in these stars T_{eff} is largest, before the convection zones disappear towards earlier spectral type, ensures that F-stars have the largest amount of acoustic energy production. As seen in Fig. 1 the acoustic energy generation also increases when going from dwarfs to giants, because the density in the atmospheres of giant stars is much smaller than in dwarfs, and thus requires larger convective velocities to transport the same total flux σT_{eff}^4.

Fig. 2, taken from Bohn (1981) shows the acoustic frequency spectra of main-sequence stars. The spectra extend roughly over the range $\omega_A < \omega < 10\,\omega_A$, where ω_A is the acoustic cut-off frequency. As acoustic waves with higher frequencies, due to the large density gradient, would quickly form shocks and thus would dissipate in the low photosphere, this spectral range should not be much affected by the above mentioned criticism.

Solar observations indicate that the areas which show the largest chromospheric emission e.g. in the Ca II H+K line cores, are strongly correlated with the magnetic regions at the supergranulation boundaries and with plage regions. Fig. 3 after Rutten (1987) shows the Ca II emission flux for dwarfs (dots) and giants (crosses) as function of colour. Note that all dwarfs of a given colour in a vertical slice in Fig. 3 are stars of the same kind, having the same T_{eff} and g. It is seen that these stars can have up to a factor of ten different Ca II emission fluxes which implies a corresponding difference in the magnetic flux coverage. Similar stars are thus shown to have a considerable *chromospheric emission variability*. Note, however, that towards small B-V this variability decreases markedly. Neither the stellar chromospheric variability nor the variation of the chromospheric emission across the solar surface can be explained by acoustic heating which predicts a unique value for the heating flux for a given T_{eff} and g. Here heating mechanisms associated with the magnetic field operate (see Narain and Ulmschneider 1989). Different stellar rotation

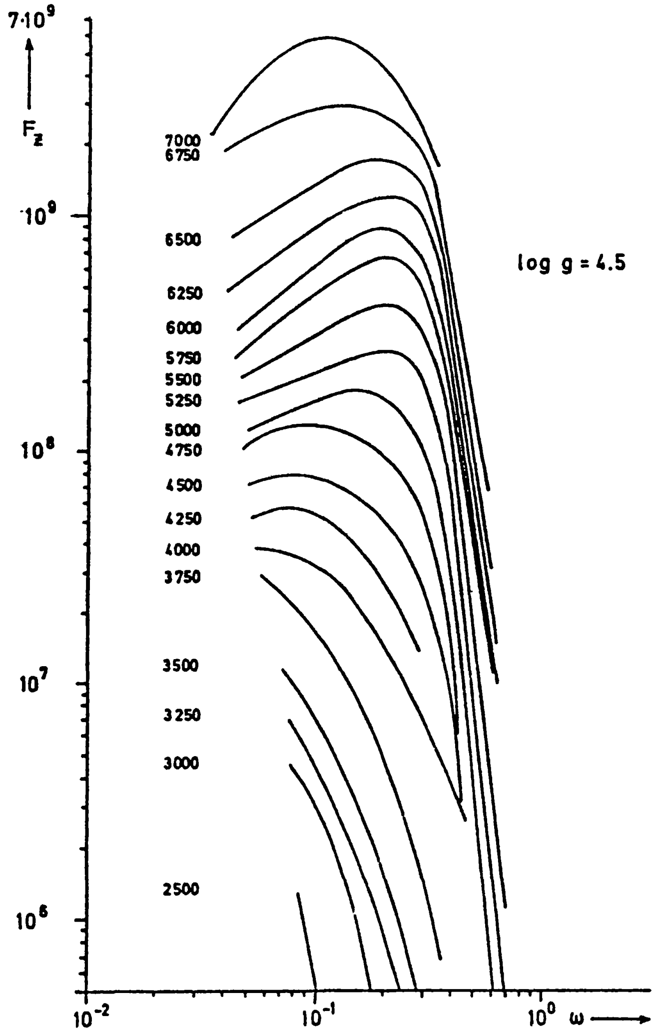

Fig. 2 Acoustic frequency spectra for stars with $\log g = 4.5$ *of various* T_{eff} *after Bohn (1981).* F_z *in erg* cm^{-2} s^{-1} Hz^{-1}, ω *in Hz*

rates lead to different magnetic field coverage and thus to different chromospheric emission.

An interesting idea by Oranje and Zwaan (1985) and particularly by Schrijver (1987) was to separate the chromospheric emission into two components: a *nonmagnetic component* which is independent of rotation and only depends on T_{eff} and possibly slightly on g, and a *magnetic field related component* which depends on rotation. For late-type stars the heating by the nonmagnetic component leads to a *basal chromospheric emission flux* which is tentatively identified as due to the heating by acoustic shock waves. This basal flux constitutes a low background emission observable in stars of very low rotation rate (the so called basal flux stars) but for faster rotating stars usually is greatly exceeded by the more energetic magnetic heating component.

The question is how to disentangle the nonmagnetic from the magnetic component, both for the sun and for stars. It can be shown that there is an excellent correlation of the magnetic heating component with the X-ray emission (see Stepien and Ulmschneider 1989, Hammer and Ulmschneider 1989, this volume). Subtracting from the measured

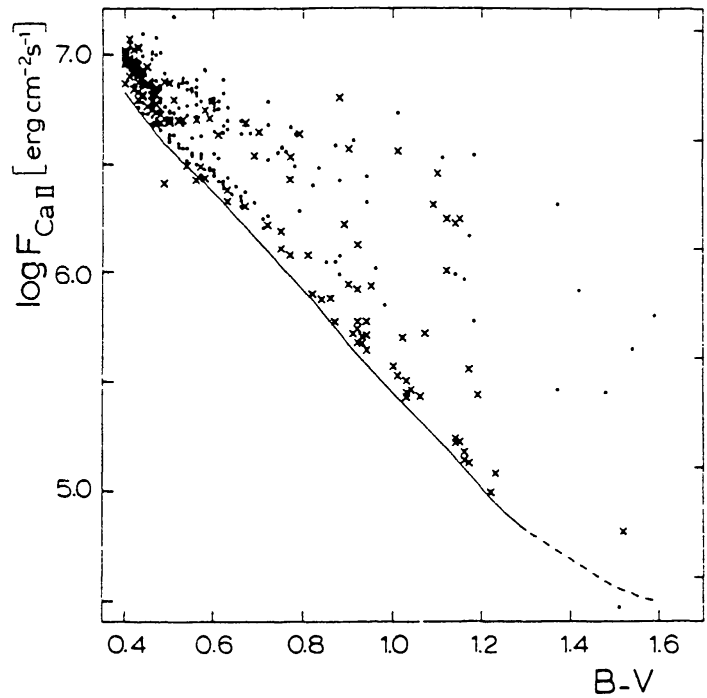

Fig. 3 Chromospheric emission fluxes F_{CaII} of stars versus colour after Rutten (1987). The drawn line is the lower limit flux.

emission flux at a given colour the lowest observed emission flux from stars at this colour, Schrijver (1983) found that the correlation between the observed X-ray flux and e.g. the Ca II emission flux is considerably improved. The lowest observed emission flux in Fig. 3 is thus interpreted as arising from pure nonmagnetic heating.

To identify this nonmagnetic heating as acoustic heating has one difficulty. From the discussion on acoustic energy generation above one would expect a higher basal flux limit for giants than for dwarfs. Actually, observations show the opposite, that the dwarfs appear to have a slightly higher basal flux limit than the giants (Schrijver et al. 1989). Ulmschneider (1988, 1989) has shown that this can be explained by greater radiation damping of the acoustic waves in the giants and by the limiting shock strength behaviour of the acoustic waves (see below), which leads to a lower limiting acoustic flux due to the lower gas pressure in giant star atmospheres.

The idea, that in the heating of chromospheres two components, a basal nonmagnetic, probably acoustic component and a magnetic, rotation dependent component are at work, can explain several other observations. The low chromospheric variability of the F-stars (see Fig. 3) may be explained as the addition of an increasingly stronger acoustic heating component to a given variable magnetic heating component, when going to stars of earlier spectral type. Red giant stars, due to their low rotation rate resulting from angular momentum conservation during the large evolutionary increase in radius and from angular momentum loss by massive stellar winds, are another class of stars, where the two component chromospheric heating theory can be tested. Middelkoop (1982, Fig. 4a-c) showed that the chromospheric emission variability decreases very much toward late spectral type and there becomes a low basal emission. The same was found by Judge (1989) who studied late- type giants with peculiar chemical abundances. These are highly evolved stars in their red giant and AGB evolutionary state. Judge finds that these late M- and C-stars (the latter after correction for the Mg II circumstellar shell absorption) all fall on the same emission versus T_{eff} relation and do not show a chromospheric emission variability, consistent with the fact that in these stars only the nonmagnetic acoustic heating component seems to be present.

LIMITING SHOCK STRENGTH BEHAVIOUR

A typical acoustic wave calculation in the solar atmosphere is shown in Fig. 4. There are two effects which severely influence the behaviour of acoustic waves in stellar atmospheres. First, the acoustic wave energy flux is strongly affected by *radiation damping*, when the wave propagates through the radiation damping zone, which in the sun extends

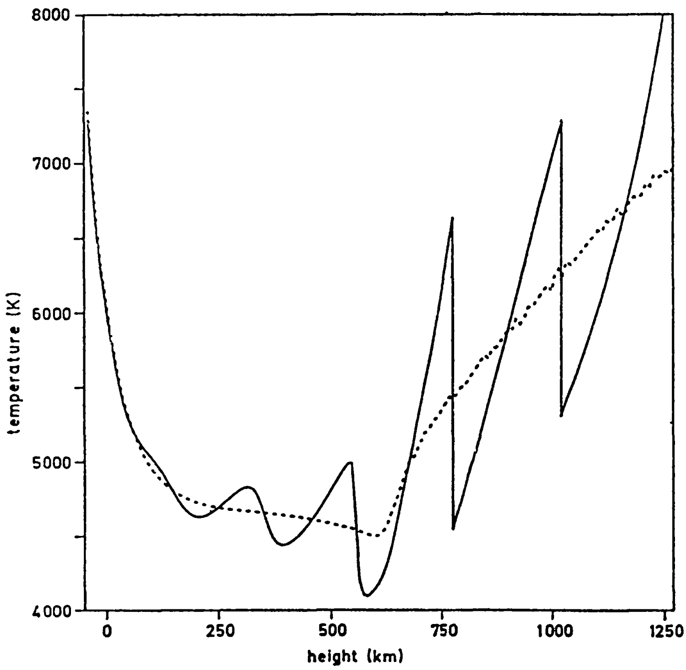

Fig. 4 Time-dependent acoustic wave calculation in the solar atmosphere. The wave period is $P = 30$ s.

to heights of about 200 km, but for other stars can be much more extended (Ulmschneider 1988). Second, it is a persistent result of time-dependent acoustic wave calculations (c.f. Fig. 4) that acoustic shock waves, once formed, tend to quickly reach *limiting shock strength.* This behaviour, where the wave amplitude becomes essentially constant with height, and independent of the initial amplitude, results from the balance of shock dissipation which decreases the wave amplitude and amplitude growth which is caused by the steep density gradient. In an isothermal atmosphere the limiting shock strength is given by (Ulmschneider 1970, 1989)

$$M_S^{Lim} = 1 + \frac{\gamma g}{4 c_S} P \quad , \tag{2}$$

where $\gamma = 5/3$ is the ratio of specific heats, $c_S(T_{eff})$ the sound speed and P the wave period. After Fig. 2 the acoustic wave spectrum generated by the turbulent motions in the stellar convection zone extends from the acoustic cut-off period P_A roughly one decade to shorter wave periods with a maximum near $P_A/10$. This maximum shifts towards $P_A/5$ and longerwards for late-type dwarf stars. Thus acoustic waves typically have wave periods of $P = P_A/5$ to $P_A/10$. For the latter period one has

$$P = \frac{1}{10}\,P_A = \frac{1}{10}\,\frac{4\pi c_S}{\gamma g} \quad . \tag{3}$$

From Eqs. (2) and (3) one has $M_S^{Lim} = 1.3, 1.6$ for $P = P_A/10, P_A/5$, respectively. Note that this result is roughly valid for all late-type stars, independent of gravity and T_{eff}. Consequently the velocity-, temperature- and pressure amplitudes of limiting acoustic shock waves are also roughly the same for all late-type stars. With $v \approx 2c_S(M_S^{Lim} - 1)/(\gamma + 1) \approx 0.23 c_S$ one finds

$$F_M^{Lim} = \frac{1}{3}\rho v^2 c_S \approx 2.4 \cdot 10^4\, p \quad , \tag{4}$$

for $P = P_A/10$, and $F_M^{Lim} \approx 9.2 \cdot 10^4\, p$ for $P = P_A/5$ ($P \approx 22$, $44\ s$ for the sun). These limiting acoustic wave fluxes, which are roughly valid for all late-type stars, have been plotted in Fig. 9. It is interesting that empirically determined heating flux and the limiting strength acoustic shock wave fluxes have the same pressure dependence.

The limiting strength behaviour of acoustic shock waves can be used to look into the question of the existence of purely acoustically heated coronae. As shown by Hammer and Ulmschneider (1989, this volume) valid coronal models exist when the limiting acoustic flux is able to satisfy the minimum coronal heating flux requirements. These authors conclude that it is not very likely that pure acoustic coronae occur.

SOLAR OBSERVATIONS OF ACOUSTIC WAVES

Thanks to the recent extensive work particularly by the Deubner group (Endler and Deubner 1983, Deubner 1988, Deubner et al. 1988, Deubner and Fleck 1989) it is now certain that propagating acoustic waves with periods as low as 40 s and significant energy fluxes are present in the solar atmosphere. The success of this group is due mainly to the extensive use of Fourier analysis methods in the data handling, to the data acquisition using long time series by which spectral resolution is greatly improved, and due to the powerful method to remove from the data seeing effects caused by the earth's atmosphere.

In a typical observation by Deubner et al. a spectrograph with a slit of 256" × 0.5" is used to observe the center of the solar disk in equatorial direction. From the spectrum narrow bands (e.g. NaI 5896Å, FeI 5930Å or CaII 8498Å, CaII 8542Å, FeI 8496Å) are observed simultaneously, usually using a CCD detector, taking one frame every 10 s for a total observation time of 3-5 hrs. Cross correlating two successive frames allows to apply shifts Δx in slit direction x to compensate for solar rotation and for the image motion caused by the earth's atmosphere. Fitting high order parabolas to the absorption line profiles, line core positions, and thus Doppler velocities $v_j(x,t)$ as well as intensities are obtained for the various lines j. For a given position x on the sun one takes temporal Fourier transforms

$$\tilde{v}_j(\omega) = |\tilde{v}_j(\omega)| \exp^{i\phi_j(\omega)} = \int_{-\infty}^{+\infty} v_j(x,t) \exp^{-i\omega t} dt \quad , \tag{5}$$

and for two lines $j = 1, 2$ evaluates the cross correlation

$$\tilde{CC}(\omega) = |\tilde{v}_1(\omega)\tilde{v}_2^*(\omega)| \exp^{i\Delta\phi_{12}(\omega)} = CP(\omega) \exp^{i(\phi_1(\omega)-\phi_2(\omega))} \quad . \tag{6}$$

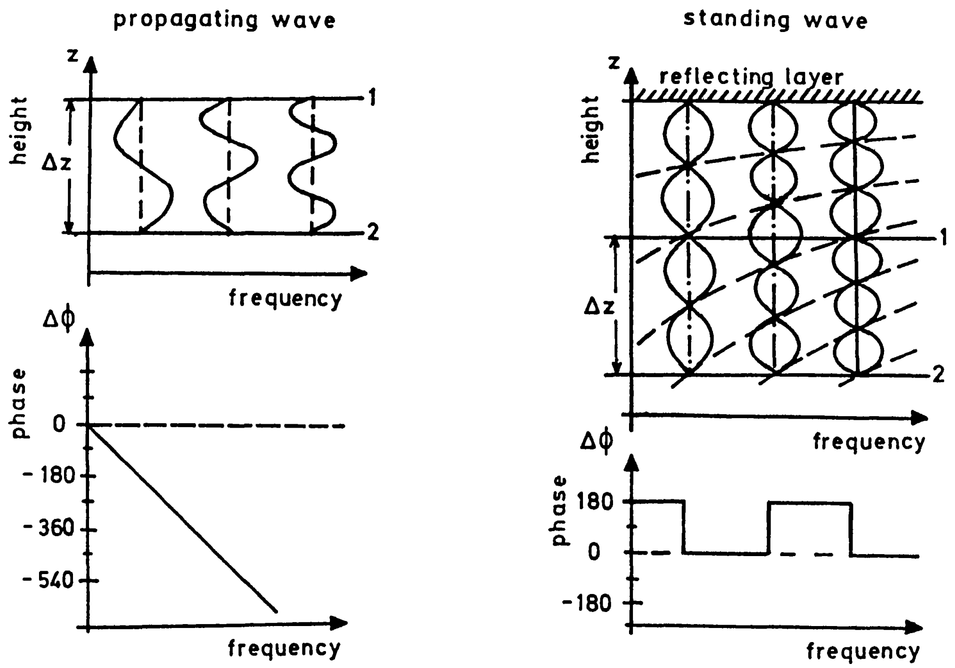

Fig. 5 Phase behaviour of propagating and standing acoustic waves.

Here $CP(\omega)$ is the cross power spectrum and $\Delta\phi_{12}(\omega)$ the phase spectrum. For a propagating acoustic wave, as shown in the left panel of Fig. 5, the phase difference $\Delta\phi_{12} = \phi_1 - \phi_2$ between the velocity oscillations in the two lines 1,2, which are formed a height distance Δz apart, is given by $\Delta\phi_{12}/360^o = -\Delta z/\lambda = -\nu\Delta z/c_S$ and thus is a linear function of the wave frequency ν. Here λ is the wavelength and c_S the sound speed. Standing waves, assumed to be generated by one-sided reflection at the steep transition layer temperature rise, as seen in the right panel of Fig. 5, show a dependence of the phase $\Delta\phi_{12}$ on frequency which jumps between two constant values 180^o and zero. These jumps occur whenever a node surface (dashed in Fig. 5) intersects a line forming layer.

Endler and Deubner (1983), by plotting $\Delta\phi_{12}(\omega)$ for all points x, found that indeed the signatures of propagating acoustic waves are present. Yet the phase returned to zero

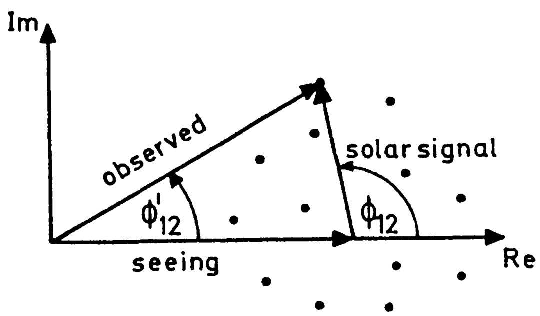

Fig. 6 Correction of the observed cross correlation for seeing. The seeing signal is along the real axis.

for waves with periods of less than 100 *s*. This they attribute to seeing, in particular to image motion across the slit. When due to the action of the earth's atmosphere, the solar granulation pattern is suddenly moved across the slit, then the velocity signals in

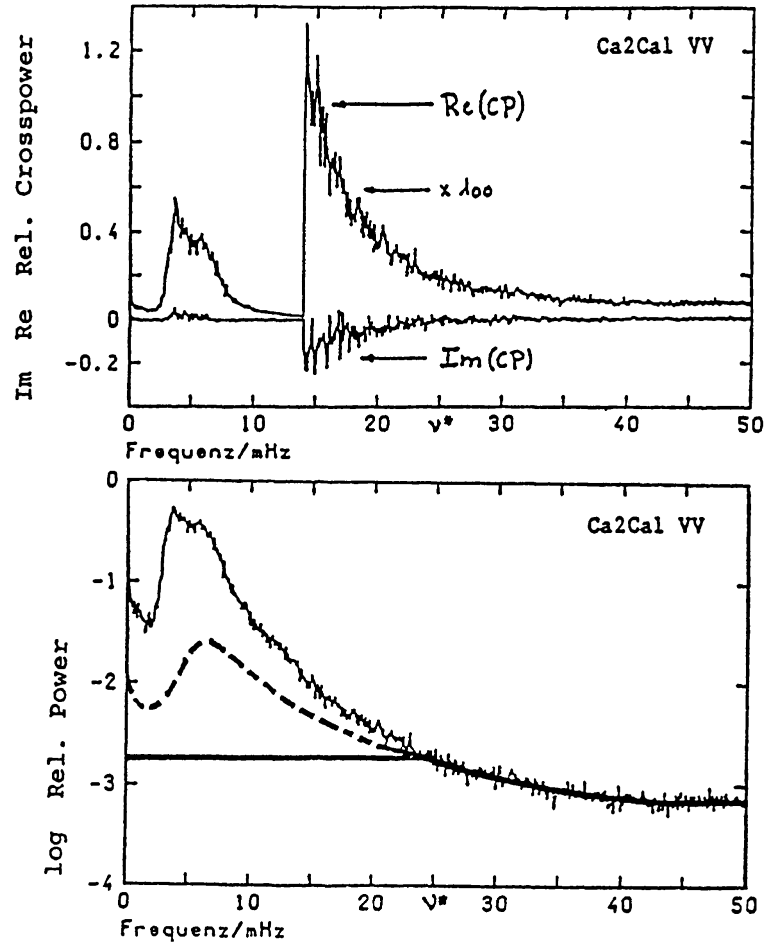

Fig. 7 Correction for seeing of the cross correlation of the lines CaII 8542Å and CaII 8498Å after Deubner et al. (1988).

both lines 1,2 are changed simultaneously, resulting in a signal of zero phase shift between the lines. As the seeing creates a spurious signal with $\Delta\phi_{12} = 0$, that is, in direction of the real axis in the plot of $\tilde{CC}(\omega)$ in the complex plane, the solar signal can be corrected for seeing as shown in Fig. 6. Applying such a correction Endler and Deubner (1983) detected the presence of propagating acoustic waves with wave periods as low as 40 s.

To derive numerical values of the acoustic flux the expression

$$F_M \approx \overline{\rho v^2 c_S} \approx \bar{\rho} \int CP_{SCM}(\omega) c_G d\omega \quad , \tag{7}$$

has been used by Deubner et al. (1988). Here $\bar{\rho} = (\rho_1 \rho_2)^{1/2}$ is a mean density between the two lineforming layers, c_G is the group speed which is essentially the sound speed, and $CP_{SCM}(\omega)$ is the cross power, corrected for the three important effects of seeing, coherence and modulation transfer function. The uncertainty of $\bar{\rho}$ could in principle be avoided by using the autocorrelation for line j instead of the cross correlation, in which case $\bar{\rho} = \rho_j$. However, for the autocorrelation the seeing correction can not be made and leads to an uncertain power spectrum.

The corrections applied by Deubner et al. (1988) to the observed $CP(\omega)$ are visualized

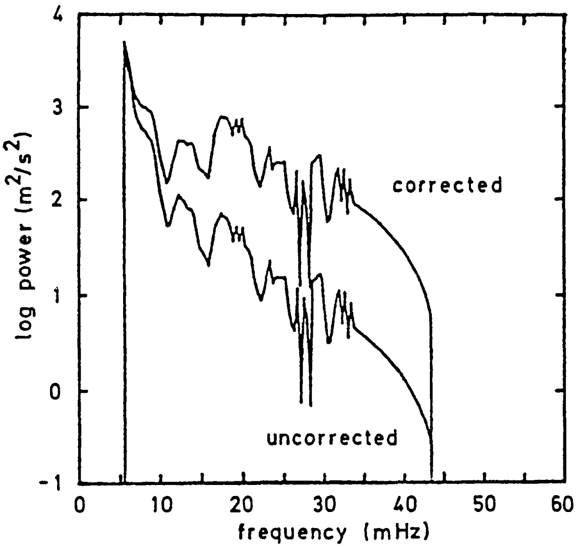

Fig. 8 Correction for the modulation transfer function of the cross correlation of the lines FeI 5383Å and TiI 5381Å after Deubner et al. (1988).

in Fig. 7. In a plot of the real and imaginary parts of $\tilde{CC}(\nu)$ in the top panel of this Fig. (here $\omega = 2\pi\nu$), it is seen that for frequencies greater than ν^* (roughly at $P = 40$ s) the imaginary cross power vanishes. Assuming that for frequencies $\nu > \nu^*$ the cross power is entirely due to seeing, the authors correct the real part of $\tilde{CC}(\nu)$ by subtracting the value at ν^*, see the lower panel of Fig. 7. This leads to the seeing corrected cross power $CP_S(\omega)$. The second correction has to do with the fact that the observed cross power has coherent (standing wave) contributions. To remove these nonpropagating contributions Deubner et al. construct a $\omega - k_x$ diagram where the regions of acoustic waves, gravity waves and evanescent waves can be identified. The ratio of acoustic power to the total power in each frequency strip in this diagram allows to correct the cross power for coherence, $CP_{SC} = CP_S\ AC/(AC + EV)$. This essentially removes wave periods larger than 200 s from the cross power spectrum. A typical result is shown in Fig. 8, marked uncorrected. The third correction is for the modulation transfer function. The theoretical simulation of line profiles in the solar atmosphere, permeated by acoustic waves of a given amplitude v, allows to calculate the velocity shifts of the line core and thus the Doppler velocity v_{Dop}. As the line contribution functions are fairly wide (in the order of $300 - 500$ km) it is clear that only for long period acoustic waves can we expect that $v \approx v_{Dop}$. However, for waves of period $P = 40$ s with wavelength $\lambda \approx 280$ km considerable reduction of v_{Dop} relative to v occurs due to cancellation effects of the contributions from the wide lineforming region. The modulation transfer function $f_M = v_{Dop}/v$ thus decreases from a value 1 at long wave periods P to essentially zero at very short wave periods. From modulation transfer functions evaluated theoretically for the different lines, the cross power can be corrected $CP_{SCM}(\omega) = CP_{SC}(\omega)/(f_{M1} f_{M2})$. This correction operation is shown in Fig. 8.

Using Eq. (7), Deubner (1988) finds for the low and middle photosphere acoustic fluxes of $F_M = 2.0 \cdot 10^7 erg\ cm^{-2}\ s^{-1}$, for the height of NaI 5896Å, $F_M = 1.2 \cdot 10^6 erg\ cm^{-2}\ s^{-1}$ and for the height of CaII 8542Å roughly $F_M = 4.5 \cdot 10^5 erg\ cm^{-2}\ s^{-1}$. He notes that these values tend to be lower bounds because the acoustic flux of short period waves, where seeing overcomes the solar signal, is not included. Taking his estimates of the heights of these lines, 300 km, 800 km and 1500 km, respectively, the acoustic fluxes have been plotted in Fig. 9. It is seen that there is a relatively good agreement with the empirical heating fluxes of Anderson and Athay (1989) and with the limiting shock strength results.

In a recent paper by Fleck and Deubner (1989) some difficulties with the above picture of propagating short period waves have been reported. Phase spectra between velocities in the CaII IRT lines 8542Å and 8498Å show a very low phase difference of 7^o instead of the 230^o expected on basis of the estimated height difference $\Delta z \approx 300\ km$. Fleck and Deubner interpret this result as due to a large phase speed caused by standing waves. This picture, however, has its own difficulties as the 180^o phase jumps, which are expected for standing waves due to the crossing of node surfaces, have not been observed. Such phase jumps have indeed been found in velocity- intensity phase spectra of the NaI 5896Å line, which shows that a large fraction of the waves in the period range near $P \approx 125\ s$ must be standing waves. In addition it is difficult to picture propagating short period ($P \approx 40\ s$) acoustic shock waves which are reflected in the transition layer to form a standing wave pattern. Such waves would be dissipated long before they reach this layer. We suggest an alternative interpretation of the 'missing' phase shift in the CaII IRT lines. In a time-dependent chromospheric acoustic shock wave calculation we have simulated the CaII IRT as well as the H and K lines. We found that the behaviour of the three IRT lines showed a large correlation consistent with an emission concentrated in the post shock regions. This would mean that the emission in a dynamic, time-dependent situation occurs from height intervals Δz which are much smaller than the large height distances determined from the line contribution functions in static, monotonic solar models. Emission from a similar spatial region naturally leads to a correlated behaviour and thus small phase shift.

CONCLUSIONS

Form the above discussions one may draw six conclusions:

1. Acoustic heating *must exist* because any turbulent layer will produce acoustic energy and because the amplification due to the photospheric density decrease over many orders of magnitude assures a considerable amplitude for acoustic waves.
2. Acoustic heating is an important if not *dominant contribution* in the *absence* of magnetic fields e.g. in the interior of the supergranulation cells on the sun, on basal flux stars as well as late-type giant stars where the rotation rate is very small, and possibly F-stars, where the acoustic heating efficiency is greatest.
3. Purely acoustically heated coronae are in principle possible, but would have very low base pressure.
4. Acoustic heating is a *background effect* in the presence of magnetic heating, i.e. in the solar chromospheric network and in all moderately and rapidly rotating stars.
5. Limiting strength acoustic shock waves of short ($P \approx P_A/5$) period *satisfy* the empirical chromospheric energy requirements.
6. Acoustic waves with the necessary periods and amplitudes to satisfy the chromospheric energy requirements *are observed* on the sun.

REFERENCES

Anderson, L.S., Athay, R.G..: 1989, Astrophys. J., in press
Biermann, L.: 1946, Naturwiss. **33**, 118
Bohn, H.U.: 1981, Ph. D. thesis, Univ. of Würzburg, Germany
Bohn, H.U.: 1984, Astron. Astrophys. **136**, 338

Deubner, F.-L.: 1988, in Pulsation and Mass Loss in Stars, R. Stalio, L.A. Willson Eds., Kluwer Academic Publ., p. 163
Deubner, F.-L., Fleck, B.: 1989, Astron. Astrophys., in press
Deubner, F.-L., Reichling, M., Langhanki, R.: 1988, in Advances in Helio- and Asteroseismology, IAU Symp. **123**, J. Christensen-Dalsgaard, S. Frandsen Eds., p. 439
Endler, F., Deubner, F.-L.: 1983, Astron. Astrophys. **121**, 291
Fleck, B., Deubner, F.-L.: 1989, Astron. Astrophys., in press
Hammer, R., Ulmschneider, P.: 1989, this volume
Judge, P.G.: 1989, in The Evolution of Peculiar Red Giant Stars, IAU Coll. **106**, H. R. Johnson, B. Zuckerman Eds. Cambridge Univ. Press, Cambridge, England, p. 303
Middelkoop, F.: 1982, Astron. Astrophys. **113**, 1
Narain, U., Ulmschneider, P.: 1989, Space Science Reviews, in press
Oranje, B.J., Zwaan, C.: 1985, Astron. Astrophys. **147**, 265
Rutten, R.G.M.: 1987, Astron. Astrophys. **177**, 131
Schrijver, C.J.: 1983, Astron. Astrophys. **127**, 289
Schrijver, C.J.: 1987, in Cool Stars, Stellar Systems and the Sun, J.L. Linsky, R.E. Stencel Eds., Lecture Notes in Physics **291**, Springer, Berlin, Germany, p. 135
Schrijver, C.J., Coté, J., Zwaan, C., Saar, S.H.: 1989, Astron. Astrophys. **337**, 964
Stepien, K., Ulmschneider, P.: 1989, Astron. Astrophys. **216**, 139
Ulmschneider, P.: 1970, Solar Phys. **12**, 403
Ulmschneider, P.: 1988, Astron. Astrophys. **197**, 223
Ulmschneider, P.: 1989, Astron. Astrophys. in press
Ulmschneider, P., Muchmore, D.: 1986, in Small Scale Magnetic Flux Concentrations in the Solar Photosphere, W. Deinzer, M. Knölker, H.H. Voigt Eds., Vandenhoeck and Ruprecht, Göttingen, Germany, p. 191

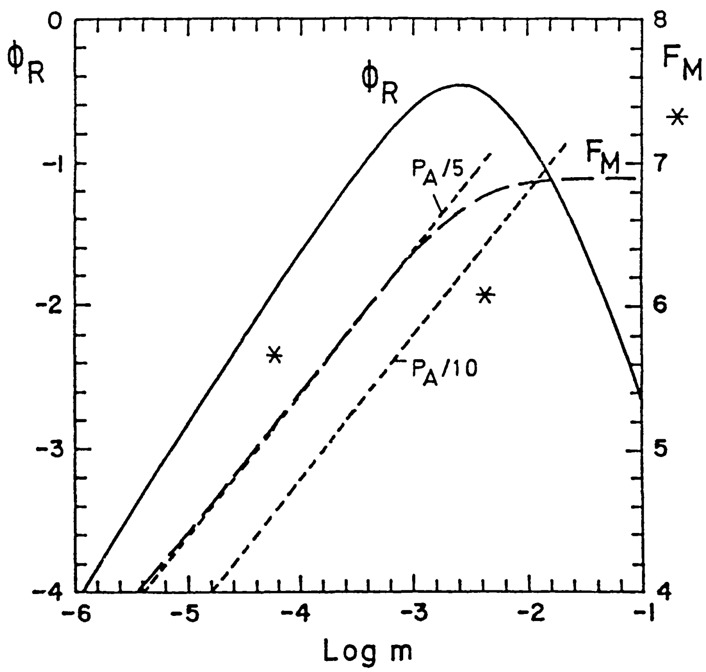

Fig. 9 Net radiative cooling rate Φ_R (erg cm^{-3} s^{-1}) and mechanical Flux F_M (erg cm^{-2} s^{-1}) after Anderson and Athay (1989), together with theoretical limiting strength acoustic fluxes F_M^{LIM}, labeled $P_A/5$, $P_A/10$, and directly observed acoustic wave fluxes by Deubner (1988), labeled by $*$.