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CHROMOSPHERIC HEATING

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Abstract. Chromospheres consist of magnetic and non-magnetic areas, which are heated by different mechanisms. For the non-magnetic areas a satisfactory acoustic wave heating picture emerges, where the wave generation calculations, the solar wave observations, the solar acoustic heating calculations and the solar chromospheric cooling observations are all roughly consistent. This picture applies for most of the solar surface and for slowly rotating late-type stars. The heating of magnetic areas is presently not well understood.

Key words: chromosphere – acoustic waves – heating

1. Introduction

Quite different from late-type stellar coronae which probably are always magnetic regions (Stepien and Ulmschneider 1989), late-type stellar chromospheres are essentially two-component regions, consisting of areas with intense vertically directed magnetic flux tubes and of essentially field-free areas. The larger the rotation rate of the star, the greater is the relative size of the magnetic areas as compared to the field-free areas. For the heating of the magnetic and non-magnetic areas different heating mechanisms apply.

UV observations show that for all stars, except for the very slowly rotating ones, the heating of the magnetic areas is dominant. This is also found when comparing network (magnetic) regions with interior (non-magnetic) regions of supergranulation cells on the sun. What heats the magnetic areas is not well known. A multitude of different (longitudinal=acoustic, transverse, torsional) magnetic tube-wave (AC = alternating current) mechanisms is likely to be involved in the heating, but also direct heating by magnetic field reconnection (DC = direct current) mechanisms seem to be at work. For recent reviews of chromospheric and coronal heating mechanisms see Narain and Ulmschneider (1990) as well as Ulmschneider, Priest and Rosner (1991).

In principle, chromospheres and coronae of stars without a mass transfering companion or without protostellar accretion, depend only on the internal structure of the underlying star: for given effective temperature T_{eff}, surface gravity g and rotation period P_{rot} the average chromospheric and coronal structures of a star must be completely determined. The logic of such a physical dependency is so far quite elusive for the magnetic areas and progress on the many magnetic heating mechanisms has been slow and not very conclusive. Because of this I primarily concentrate on the heating of field-free areas in this work. It is in the field of chromospheric heating of slowly or non-rotating stars and of the non-magnetic regions (within supergranulation cells) of the sun that now a fairly consistent acoustic heating picture has emerged in the last few years which allows for the first time to see the complicated logic which connects the physics of chromospheres with the underlying structure of the star.

For stars later than spectral type A, the acoustic heating picture works as follows: acoustic waves generated near the top of 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 and thus produces a chromosphere. From this picture it is clear that acoustic heating must always be present in stars, because the turbulent motions of a convection zone will always produce acoustic energy and the rapid density decrease in the outer atmosphere will always lead to shock dissipation of the acoustic waves. The crucial question is, however, whether this acoustic heating is sufficient to balance the observed chromospheric emission. It is the important realization in the last few years that the acoustic heating is indeed sufficient and consistent with the observations and is able to explain the heating of the non-magnetic areas of the chromospheres.

It is important to note that acoustic heating also operates in O- and B-stars, where surface convection zones no longer exist. In these stars intense radiation fields amplify microscopic acoustic disturbances until strong acoustic shock waves develop. These shocks very likely occur in individual blobs propagating on top of the rapidly expanding winds of these stars, a situation which is very different from that in chromospheres of late-type stars. For earlier reviews of acoustic heating see Narain and Ulmschneider (1990) and Ulmschneider (1990, 1991).

2. Acoustic energy generation

In 1948 Biermann realized that the solar convection zone produces acoustic waves which in turn might heat the corona. Since the pioneering work of Lighthill (1952) the methods of computing acoustic energy generation from turbulent gas flow fields have been extensively developed and tested particularly in the aircraft industry. Fig. 2.13 of Goldstein (1976) shows an excellent agreement of Lighthill's u^8 quadrupole sound generation law with experimental values from noise of jet engines, u being the flow velocity. Theoretical acoustic energy generation rates, F_M, from stellar surface convection zones of late-type stars have been computed by Bohn (1984), using Stein's (1967) theory of sound generation which includes additional multipole (monopole and dipole) terms. These calculations depend on three stellar parameters: T_{eff}, g, and the mixing length parameter α.

In Fig. 6 of Bohn (1984) the acoustic fluxes F_M are shown to rise rapidly with T_{eff} up to a maximum value near $T_{eff} \approx 10^4\ K$ of A-stars where the disappearing convection zones abruptly decrease the acoustic flux. This rise 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 finds that the total flux is $\sigma T_{eff}^4 \approx \rho u^3$, where ρ is the density. Thus with increasing T_{eff} and decreasing ρ the acoustic energy generation increases from M- to F-stars. The acoustic energy generation also increases when going from dwarfs to giant stars, because for a given T_{eff} the density in the atmospheres of giants is much smaller than in dwarfs, resulting in larger convective velocities u. Bohn finds

$$F_M \approx 7.08 \cdot 10^{-27} T_{eff}^{9.75} g^{-0.5} \alpha^{2.8} \quad . \tag{1}$$

Bohn (1981, unpublished Ph. D. thesis, Univ. of Würzburg, Germany) has also computed the acoustic frequency spectra of main-sequence stars (see Fig. 4 of Ulmschneider 1991). These spectra extend roughly over a decade in the period range of $P_A/10 < P < P_A$, where $P_A = 4\pi c_S/(\gamma g)$ is the acoustic cut-off period. γ is the ratio of specific heats, c_S the sound speed. The maximum of the acoustic spectrum is found near $P_{max} \approx P_A/6$ and shifts longerwards for late-type dwarf stars. From theoretical considerations one thus finds that for the sun with $P_A \approx 220\ s$ acoustic waves with typical periods of $P \approx 35\ s$ (Bohn (1984), Stein (1968) find $P_{max} = 29, 38\ s$ for an EE turbulence spectrum, respectively) and fluxes of about $F_M = 1.8 \cdot 10^8\ erg\ cm^{-2}\ s^{-1}$ for $\alpha = 1.0$ should be present at the top of the convection zone. For $\alpha = 1.5$, the flux F_M would be three times higher.

3. Solar observations of acoustic waves

Are such theoretically inferred waves observed on the sun? Work by Endler and Deubner (1983) and recently by Deubner (1988) and Deubner et al. (1988) indeed shows that propagating acoustic waves, similar to the theoretically inferred waves, are present in the solar atmosphere. Cross correlating simultaneous observations of velocity fluctuations in different spectral lines allows to compute the cross power spectrum $CP(\omega)$ and the phase spectrum $\Delta\phi(\omega)$ (see also Ulmschneider 1990). It can be shown that for propagating waves the phase differences $\Delta\phi$ of the velocity fluctuations in two considered spectral lines depends linearly on frequency, while for standing waves $\Delta\phi$ is constant and jumps between the values zero and 180°. By removing the influence of seeing, Endler and Deubner (1983) showed on basis of their corrected phase spectra that there are propagating acoustic waves in the solar atmosphere with periods as low as 40 s.

The authors find that this period limit is a detection limit, caused by the solar atmosphere itself. To detect an acoustic wave as frequency fluctuation of the central absorption core of a spectral line the wavelength of the wave should be considerably larger than the width of the line contribution function which has typical values of about $300 - 400\ km$. With a sound speed of $7\ km/s$ this condition is violated for waves with periods less than 40 s. In addition, detecting waves with periods $P < 40\ s$ by line broadening is difficult, because due to the limiting strength property these waves have velocity amplitudes which decrease proportional to P.

From the crosspower spectrum 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 very short period waves is not included. Taking his estimates of the heights for these lines, 300 km, 800 km and 1500 km, respectively, the acoustic fluxes have been plotted in Fig. 1a. The flux F_M at 300 km agrees roughly with Bohn's theoretical solar value at the top of the convection zone, if one allows for radiation damping by a factor of 6 (Ulmschneider et al. 1978, Fig. 5).

4. Solar chromospheric emission

The magnitude and height dependence of the empirically determined solar chromospheric radiation loss rates are powerful tests for the validity of the chromospheric

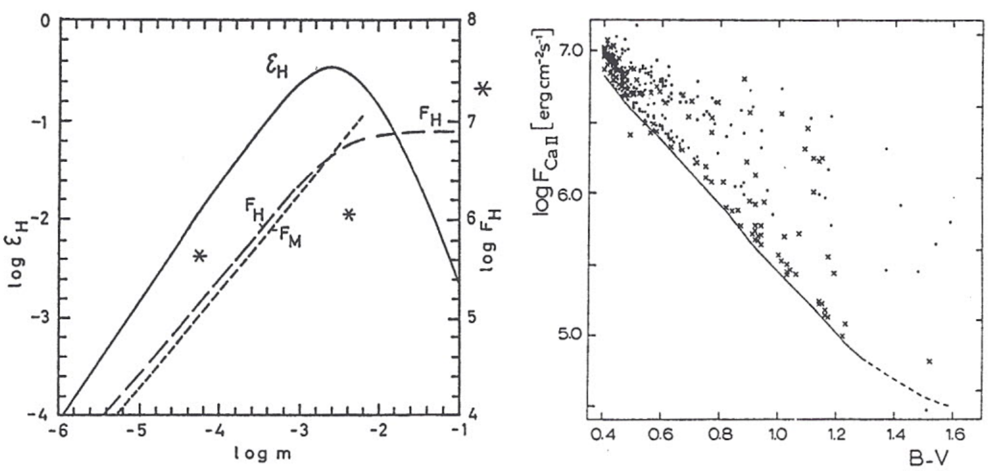

Fig. 1. a. Net heating rate ϵ_H ($erg\ cm^{-3}\ s^{-1}$) and heating flux F_H ($erg\ cm^{-2}\ s^{-1}$) versus mass column density m (g/cm^2) after Anderson and Athay (1989b), together with a theoretical limiting strength acoustic flux F_M, and directly observed acoustic wave fluxes by Deubner (1988), labeled by $*$. b. Chromospheric CaII K-line emission core fluxes F_{CaII} of giants (x) and dwarfs (•) after Rutten (1987).

heating mechanisms and permit to clarify the relative importance of the heating in magnetic and non-magnetic areas. Anderson and Athay (1989a) argue for acoustic heating as the dominant heating mechanism of the solar chromosphere: The plage and magnetic network regions ".. do not dominate the average chromosphere and thus do not require that magnetic heating be dominant for the chromosphere as a whole". Assuming a height-dependent mechanical heating rate ϵ_H, Anderson and Athay (1989b) construct semi-empirical models which conserve the total (mechanical and radiative) energy flux. Adjusting ϵ_H such that the resulting temperature distribution is consistent with that of model C of Vernazza et al. (1981), which was derived by matching observed spectral features, Anderson and Athay empirically determine the required heating rate to balance the chromospheric losses $\epsilon_R = \epsilon_H$. Integrating this heating rate over height, Anderson and Athay (1989b) find a necessary heating flux F_H which a correct chromospheric heating mechanism must provide. Both ϵ_H and F_H are shown in our Fig. 1a. It is seen that F_H and the observed acoustic fluxes by Deubner are in reasonable agreement.

5. Stellar chromospheric emission

Solar observations indicate that the areas of largest chromospheric emission seen in the core of the Ca II H+K lines, are strongly correlated with the magnetic network regions at the supergranulation boundaries and with plage regions (Schrijver et al. 1989). Fig. 1b taken from Rutten (1987) shows observations of the stellar F_{CaII} line core emission flux from dwarfs (dots) and giants (crosses). It shows three important facts. First, Fig. 1b clearly demonstrates that all late-type stars have chromospheres, because the values of F_{CaII} show a definite lower limit, the so called ***basal flux line***. Theoretical calculations of radiative equilibrium atmospheres without chromospheres show no core emission flux. The observed finite flux F_{CaII} is thus a clear indication for the existence of stellar chromospheres.

The second fact is the large variability of F_{CaII} for essentially identical stars which demonstrates the existence of at least two different heating mechanisms (for magnetic and non-magnetic areas). Dwarf stars of a given T_{eff}, which are indicated by dots in a vertical slice in Fig. 1b, all have similar gravity $log\ g \approx 4.5$ and thus, except for their rotation period P_{rot}, represent identical stars. As discussed above one gets identical values of F_M and $P = P_{max}$ from acoustic energy generation calculations for these stars. Acoustic wave calculations then lead to identical theoretical chromosphere models and consequently to unique Ca II line profiles. These emission core fluxes could be the observed basal flux values F_{CaII} which apply for the stars with largest rotation period P_{rot}.

The surface of these basal flux stars thus appears to consist mainly of non-magnetic areas which are heated acoustically. However, with decreasing P_{rot} the fraction of the magnetic areas increases and with it the emission due to the increasingly dominant magnetic heating. As shown by Vilhu (1987) this increase of the chromospheric emission flux reaches a maximum at a saturation boundary where the magnetic areas cover essentially the entire surface of the star. The emissions from T Tau-stars which lie above this saturation boundary is explained by external processes, like accretion.

Third, the range of variability of F_{CaII} caused by P_{rot} decreases markedly with increasing T_{eff} in Fig. 1b. This can be explained by the fact that the total emission at the earlier stars has a much larger acoustic contribution (due to the strong T_{eff}-dependence of the acoustic energy generation) relative to the emission contribution from the magnetic areas.

That the acoustic heating is a good explanation for the basal chromospheric emission has also been found by Mathioudakis and Doyle (1992) who recently showed that the basal Mg II fluxes of M-stars are between 1 and 2 orders of magnitude lower than Bohn's acoustic fluxes for these stars. Because Mg II is only one of the many chromospheric emitters and because acoustic waves are damped during transit from the top of the convection zone to the Mg II line emitting height, it is clear that Bohn's fluxes must be considerably larger.

An additional hint for the validity of the acoustic heating picture was given by Middelkoop (1982, Fig. 4a-c), who showed for giant stars that the chromospheric emission variability decreases very much toward late spectral types and there becomes a basal emission. As the rotation period of giants is expected to become very large due to the increasing radius in the course of their post-main-sequence evolution, the fraction of magnetic areas on these stars is supposed to decrease strongly and only the non-magnetic acoustic heating component appears to remain.

6. Acoustic wave calculations and the limiting shock strength

It has long been recognized (Ulmschneider 1970, 1991) that only by shock heating can realistic heating rates be achieved from acoustic waves and that with the typical fluxes F_M and periods P_{max} by Bohn (1981, 1984) realistic shock formation heights and shock dissipation rates are found. There are two effects which severely influence the behaviour of acoustic waves in the outer stellar atmospheres. First, the acoustic waves are strongly affected by *radiation damping*, when the wave propagates through the radiation damping zone, which in the sun extends 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 monochromatic acoustic wave calculations 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 decrease. In an isothermal atmosphere the limiting shock strength property can be derived analytically (Ulmschneider 1970, 1989). Time-dependent acoustic wave calculations show that this behaviour is also well established for non-isothermal chromosphere models (Ulmschneider 1991, Fig. 6).

The important property of acoustic waves, which have reached limiting shock strength, is that their flux F_M and dissipation rate $\epsilon_M = -dF_M/dh$ become independent of the wave flux initially injected into the atmosphere and can be given analytically by

$$F_M = \frac{1}{12} \frac{\gamma^3 g^2}{(\gamma+1)^2 c_S} P^2 p \quad , \tag{2}$$

where p is the gas pressure. For the sun both the gravity g and the wave period $P \approx P_{max}$ are given. Moreover plotting F_M versus the mass column density $m = p/g$, Eq. (2) does not permit much freedom in a comparison with the empirically determined heating fluxes F_H by Anderson and Athay (1989b). Fig. 1a shows that for $P \approx P_A/6 = 35$ s and $log\ m < 10^{-3}$ indeed a remarkable agreement exists of the magnitude and height dependence of F_M with that of F_H. The discrepancy at larger m is due to the fact that here limiting strength has not yet been reached. Please note that even if Bohn's computed theoretical fluxes F_M were wrong or if the measurements of the acoustic fluxes were inaccurate the existence of the limiting flux waves indicates that the wave has completely forgotten its origin and attains a flux which, at a given m, is only determined by the wave period. For the sun one has $F_M \approx 7.1 \cdot 10^4\ p$ for $P = 35$ s.

7. Problems of the acoustic heating picture

Despite the fact that there exists now a fairly consistent overall picture of the chromospheric heating, the details are still far from clear. The computation of acoustic sound generation depends on the mixing length theory, which has the greatest uncertainty just at the top of the convection zone, where the sound generation is at its maximum.

In addition one needs more accurate fluxes from the observation of solar acoustic waves. Here observations by Fleck and Deubner (1989) lead to a puzzle. Comparing the phase differences of velocity fluctuations in the Ca II infrared triplet (IRT) lines

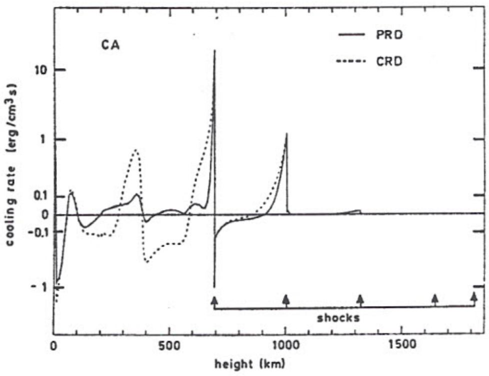

Fig. 2. Ca II K-line cooling rate ($erg\ cm^{-3}\ s^{-1}$) versus height for a solar acoustic wave calculation assuming CRD and PRD.

8542Å and 8498Å these authors find large phase speeds, using a height difference of 300 km between these lines which they infer from the Vernazza et al. (1981) model. They interpret their observation by postulating a "magic height" at 800 km below which there are running acoustic waves, but above which one has standing waves. It is difficult to picture how sawtooth shock waves should become standing waves and moreover how this standing wave hypothesis could be reconciled with the shock heating behaviour as seen in Fig. 1a. Presumably a sawtooth shock wave will have essentially lost all its energy before it reaches the reflecting layer which is essential for the standing wave picture. From our time-dependent wave calculation we suspect that, different to the Vernazza et al. model, the emission of the IRT lines is located behind the shocks and thus might be spacially correlated. An essentially cospatial formation of the IRT lines would greatly reduce the inferred phase speed.

Another uncertainty is the use of monochromatic waves in our arguments. This usage is fine in order to get a rough overall picture and it is clear that for studying the period-dependent properties of acoustic waves it is essential to use monochromatic waves. But in reality the sound generation process will be intermittent and produce wave packets. Thus it would be more appropriate to use acoustic spectra. It is not clear whether the limiting strength behaviour of Eq. (2) will be retained on the average when acoustic spectra are used. In the propagation of acoustic spectra shock overtaking will occur which occasionally leads to strong shocks. This behaviour may necessitate very long time-dependent wave calculations to generate averaged results.

Moreover the semi-empirical analysis of Vernazza et al. (1981) and of Anderson and Athay (1989b) have to be taken as highly idealized. These authors use a rather smooth chromospheric temperature dependence to match the observed spectrum. But the waves which are postulated from their inferred heating rate have a very inhomogenous, spiked temperature distribution, with the emission occuring primarily behind the shocks. Fig. 2 shows the Ca II K-line cooling rate from a typical solar wave calculation. Note the extreme concentration of the emission behind the shocks, which is further accentuated when the computation is made using partial redistribution (PRD) instead of complete redistribution (CRD).

Finally even for purely non-magnetic areas there probably is an additional heating mechanism in red giant stars. Here shocks generated by nonradial oscillations, generated from the κ-mechanism seem to be operating (Ulmschneider 1991).

8. Conclusions

Chromospheric heating is different in magnetic and in non-magnetic areas. While the heating of magnetic areas is not well known, a consistent picture of the heating of non-magnetic areas on late-type stars has emerged in the last few years. This is valid for most of the solar surface and essentially for the entire surface of very slowly rotating stars. It is found that:

- Acoustic heating occurs in all stars except possibly the A- stars, it is the main heating mechanism for non-magnetic areas.
- Magnetic areas are heated by magnetic heating mechanisms which are presently poorly understood. Whether AC or DC mechanisms are at work is unclear.
- For comparable size of magnetic and non-magnetic areas the magnetic heating is dominant.
- The acoustic wave generation calculations, the solar acoustic wave observations, the acoustic heating calculations and the chromospheric cooling observations are all roughly consistent with each other.
- There are many unanswered questions in the detail.

References

Anderson, L.S., Athay, R.G..: 1989a, *Astrophys. J.* **336**, 1089.
Anderson, L.S., Athay, R.G..: 1989b, *Astrophys. J.* **346**, 1010.
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: Dordrecht, p. 163.
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.* **224**, 245.
Goldstein, M. E.: 1976, *Aeroacoustics*, McGraw Hill: New York.
Lighthill, M.J.: 1952, *Proc. R. Soc. London* **A211**, 564.
Mathioudakis, M., Doyle, J.G.: 1992, *Astron. Astrophys.* in press.
Middelkoop, F.: 1982, *Astron. Astrophys.* **113**, 1.
Narain, U., Ulmschneider, P.: 1990, *Space Science Reviews* **54**, 377.
Rutten, R.G.M.: 1987, *Astron. Astrophys.* **177**, 131.
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, p. 135.
Schrijver, C.J., Coté, J., Zwaan, C., Saar, S.H.: 1989, *Astrophys. J.* **337**, 964.
Stein, R.F.: 1967, *Solar Phys.* **2**, 385.
Stein, R.F.: 1968, *Astrophys. J.* **154**, 297.
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.* **222**, 171.
Ulmschneider, P.: 1990, in: *Cool Stars, Stellar Systems and the Sun*, Astr. Soc. Pacific Conf. Ser. **9**, G. Wallerstein Ed., 1990, p. 3.
Ulmschneider, P.: 1991, in: *Mechanisms of Chromospheric and Coronal Heating*, P. Ulmschneider, E. Priest, R. Rosner Eds., Springer: Berlin, p. 328.
Ulmschneider, P., Schmitz, F., Kalkofen, W., Bohn, H.U.: 1978, *Astron. Astrophys.* **70**, 487.
Ulmschneider, P., Priest, E., Rosner, R.: 1991, *Mechanisms of Chromospheric and Coronal Heating*, Springer: Berlin.
Vernazza, J.E., Avrett, E.H., Loeser, R.: 1981, *Astrophys. J. Suppl.* **45**, 635.
Vilhu, O.: 1987, in: *Cool Stars, Stellar Systems and the Sun*, J.L. Linsky, R.E. Stencel, Eds., Lecture Notes in Physics **291**, Springer: Berlin, p. 110.

Discussion

A. Maggio **Question:** Let us take a star of a given mass evolving from the main sequence to the giant branch. How do you expect that the amount of acoustic heating, and the heating scale height changes during evolution?
Answer: The acoustic surface flux F_M, for given T_{eff} and gravity is given by Bohn (1981), it is decreased by radiation damping upon propagation through the photosphere. dF_M/dx is roughly given by the derivative of Eq. (2).
J. Schmitt **Question:** How does one find stars without any magnetic flux?
Answer: Looking for basal flux stars which also have very low or no Si IV, C IV and X-ray emission.
J. Linsky **Question:** I agree with you conclusions that pure acoustic heating can explain the observed basal emission of chromospheric lines. I would like to know whether the acoustic heating theory also predicts basal emission rates for transition region lines. Have you made such calculations? Are the basal heating rates at a level that can be detected by Hubble Space Telescope observations of C IV emissions from very inactive stars?
Answer: Eq. (2) shows that the heating is proportional to the gas pressure. The cooling is proportional to the square of the density. This means that due to the density decrease with height, acoustic heating will always overwhelm the cooling and result in a purely acoustically generated transition layer and even corona. However, as heating also goes into wind energy the question is what maximum temperature can you achieve. Except for late-type giants I believe there will be a basal emission in C IV. The height where the pure acoustic transition layer occurs may be large and thus the number of photons small. So far we have not calculated this.