Radiation hydrodynamics simulations of the solar chromosphere

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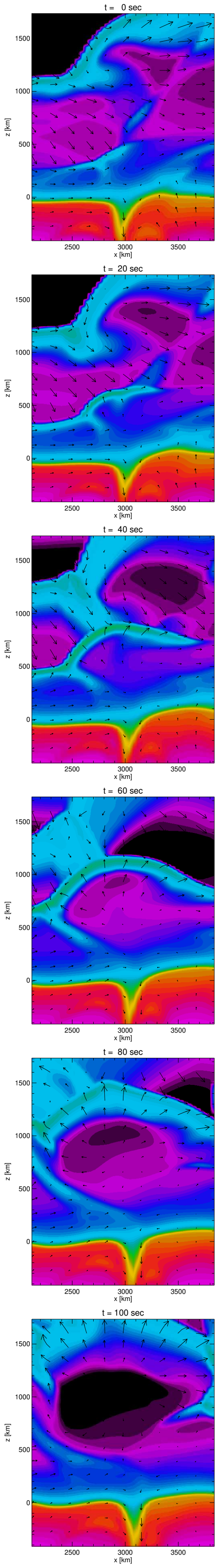

Introduction

While heating of the solar corona is commonly attributed to reconnection of magnetic field lines, the mechanism responsible for heating the chromosphere of the quiet Sun, away from active regions, is still under debate[1,2]. The basic question which we will address in this contribution is: Can generation of acoustic waves by turbulent convection in photospheric and subphotospheric layers explain the chromospheric emission of the quiet Sun?

The radiation hydrodynamics code

Recently a new version of a 2D/3D radiation hydrodynamics code was developed by B.Freytag and M.Steffen. This code can handle shocks with a minimum of numerical dissipation. Therefore generation and propagation of acoustic waves can be investigated, permitting the evaluation of wave dissipation in the chromosphere in a physically consistent manner.
For every time step first the hydrodynamics equations for a fully compressible, chemically homogeneous plasma are solved using a modified Roe scheme. After that the radiative transport equation is solved along several beams through the whole model. For each ray a Feautrier scheme is applied independently. As opacity the Rosseland mean or a frequency band scheme is used which accounts for the frequency dependency.
Magnetic fields are not included so that the code is restricted to internetwork regions.

First models

The preliminary models calculated so far are still 2D. They extend from the upper convection zone to the top of the middle chromosphere and consist of horizontally 140 and vertically 220 grid points with a spatial resolution of 40 km and 15 km and a total extension of 5560 km and 3300 km, respectively. The Rosseland mean opacity is used. Fig.3 shows such a 2D model with velocity field (*arrows*) and temperature which range from 17000 K at the bottom of the model (*pink/red*) to 2000 K in cool chromospheric areas (*black*). Above downdrafts where cool matter sinks down from the photosphere into the convection zone large acoustic waves can be seen.

Generation of acoustic waves

The simulations show that merging downdrafts (which correspond to collapsing granules in the 3D case) generate several pulses of acoustic waves (Fig.2). An example for such a wave can be seen in Fig.1.

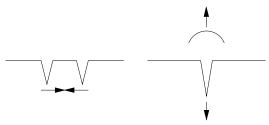

Fig.2: Merging downdrafts generate an acoustic wave.

At the beginning the wave is subsonic but gains more speed (up to 20 $\mathrm{km\,s^{-1}}$) as it propagates through the photosphere towards the middle chromosphere. As a consequence high Mach numbers are reached and the wave turns into a shock wave. The vertical temperature profiles (Fig.4) show how the shape of the wave changes on its way through the atmosphere.

Temperature stratification

Fig.5 shows the horizontally averaged temperatures which are the result of two hours simulation time. The *light yellow* and *dark yellow* areas illustrate the temperature ranges for all time steps and 5 min averages, respectively. The dynamic behaviour of the chromosphere which is indicated by the large ranges makes it difficult to define a meaningful temperature average. However, the *red line* represents the horizontal and temporal average over the whole two hours. It is too low to match the temperature stratification of the VAL III-c model[3] (*blue line*) which was derived from observations. However, these preliminary simulations already suggest that a temperature inversion may arise from acoustic. i.e. nonmagnetic waves.

Problems and future prospects

The application of the code on the chromosphere began just recently. Thus the code still has to be adjusted to the physical conditions in the upper atmospheric layers.
Among other things like the upper boundary condition the opacities must be reviewed since they have a drastic effect on the chromospheric temperature range. Fig.6 shows a time step of a simulation calculated with the frequency band scheme. Compared to the simulations with the Rosseland mean opacity (Fig.3) the temperatures in the chromosphere are even lower and the structures appear to be more subtle.
In near future we will start with 3D simulations.

Conclusions

Although small adjustments of the code may be necessary for the application on the chromosphere a small chromospheric temperature increase can already be observed in our models. Future simulations with a reviewed version of the code will show whether the resulting temperature increases even more to match observations or heating due to acoustic waves alone is not enough to explain the observed temperature in the (quiet) solar chromosphere.

References

[1] *Carlsson, M., Stein, R.F., 1995, APJ 440:L29*
[2] *Kalkofen, W., Ulmschneider, P., Avrett, E.H.,1999, APJ 521:L141*
[3] *Vernazza, J.E., Avrett, E.H., Loeser, R., 1981, APJS 45:635*

Fig.1: Time sequence of 2D temperature slices showing a propagating acoustic wave.

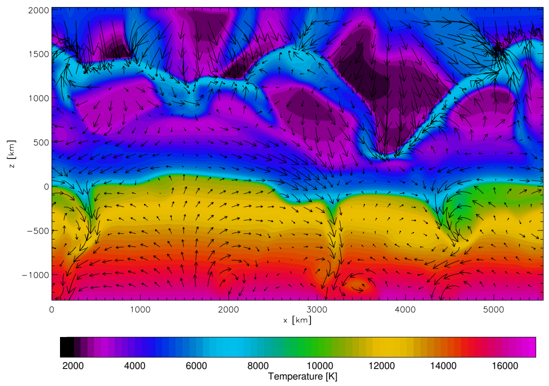

Fig. 3: Temperature and velocity field for a 2D model with Rosseland mean opacity.

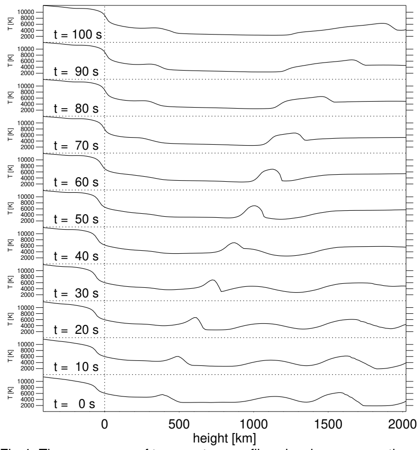

Fig.4: Time sequence of temperature profiles showing an acoustic wave.

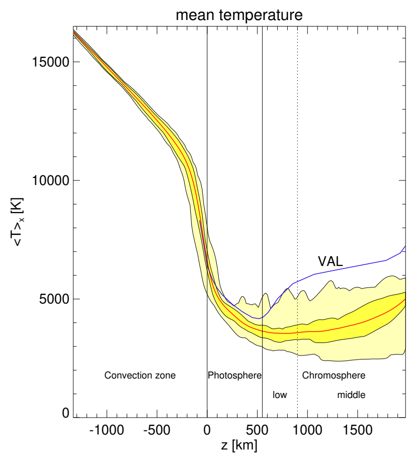

Fig.5: Range and temporal mean of horizontally averaged temperature .

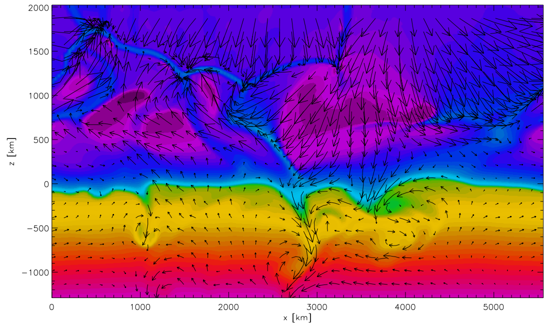

Fig. 6: Temperature and velocity field for a 2D model with opacity band scheme.