Acoustic Energy Generated by Convection: 3-D Numerical Simulations for the Sun

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Acoustic Heating of the Chromosphere

Dissipation of acoustic waves may be an efficient heating mechanism for the lower and middle chromosphere of the quiet Sun, apart from magnetic fields. The basic idea is that the motions at the top of the solar convection zone generate acoustic waves which propagate upwards and dissipate in the lower and middle chromosphere, transporting energy into the higher layers. But still the question remains if this amount of energy is sufficient to explain the observations without invoking magnetic fields.

The Solar Chromosphere: Hot or Cold?

Recently Kalkofen (2001) opposed different models of the solar nonmagnetic chromosphere. The 1-D model by Carlsson & Stein (1994) is an example for a chromosphere with a mostly cool background and large temperature fluctuations due to upward propagating shocks. It shows no temperature minimum at the base of the chromosphere and no monotonically increasing temperature above, as it is the case for the semi-empirical models of Vernazza, Avrett & Loeser (1981, VAL81) and Fontenla, Avrett & Loeser (1993, FAL93). These models are always hot with only small fluctuations.
Observations show that next to **chromospheric emission** lines (e.g. Ca and Mg) **CO absorption** lines are also present in spectra from the quiet Sun. Thus, temperatures must be high enough to account for the chromospheric emission and - at the same time - low enough to allow CO molecules to form and remain in a sufficient amount. The required conditions cannot be simply described with one of the "extreme" models stated above, neither by a general chromospheric temperature rise, nor by an mostly cool chromosphere. An intermediate state seems more likely.
For clarification detailed simulations are needed.

Numerical Simulations with COBOLD

With a new version of **COBOLD**, a radiation hydrodynamics code developed by B. Freytag and M. Steffen, we are able to compute **self-consistent 3-D models** extending all the way from the upper convection zone to the middle chromosphere.
COBOLD allows the time-dependent solution of the hydrodynamic equations (conservation of mass, momentum, and energy) and radiative transfer for a fully compressible, chemically homogeneous plasma in 2-D and 3-D. For the models presented here, a Rosseland mean opacity is used which has been computed by H.-G. Ludwig, derived from data of **OPAL** (Iglesias et al., 1992) and **PHOENIX** (Hauschildt et al.,1997, molecules included). Alternatively, a frequency-dependent scheme is available for **ATLAS6** opacities (Kurucz, 1970). Magnetic fields are not included, restricting this version of COBOLD to internetwork regions.
Our first 3-D simulations with COBOLD reveal a **complex, inhomogeneous and highly dynamical structure of the lower and middle chromosphere** which evolves on rather short timescales. On small spatial dimensions very cool regions are present next to a "network" of hotter matter.
Fig. 1 illustrates an actual 3-D model which consists horizontally (x, y) of 140 grid points with a constant resolution of 40 km, leading to an extension of 5600 km ($\sim 7''.7$). The 200 vertical (z) grid points are non-equidistant with a resolution of 46 km at the bottom (-1300 km below $\tau_{5000} \approx 1$) which decreases with height down to 12 km for the photosphere and chromosphere. The model includes the chromosphere up to a height of $\sim$ 1800 km above $\tau_{5000} \approx 1$, thus leading to a total vertical extension of $\sim$ 3100 km.

First 3-D Models of the Chromosphere

Fig. 2 shows the temperature in a vertical slice taken from a snapshot of a 3-D simulation - a picture we already know from former 2-D simulations. The top of the photosphere and the chromosphere are dominated by upward propagating shock waves, much hotter than the surrounding gas. Different from 1-D models these shock waves can also propagate horizontally, as spherical waves in the ideal case but mostly in a more complex pattern. Shock waves are present for all time steps, mostly several at the same time. Consequently, they collide and form even more bizarre structures with small-scale brightenings. In Fig. 3 the temperature in a horizontal slice is shown, taken as a snapshot from the same 3-D simulation as Fig 2. This **"dynamic temperature bifurcation"** might explain the observations because it combines regions with temperatures high enough to produce chromospheric emission lines and regions cold enough for molecular features at the same time.
However, due to high velocities (e.g. $\langle v_{\rm hor} \rangle \sim 5\,{\rm km s^{-1}}$ at a height of $\sim$ 1000 km) there is mostly only little time until the next shock wave passes through and dissociates the CO molecules. From Fig. 3 we can estimate the radius of a typical **intermediate, cool region** to be of the order $\sim$ 500 km. An enclosing, inward travelling wave front would have completely "swallowed" such a region after only 100 sec. This time scale seems to be rather short, making further investigations necessary.

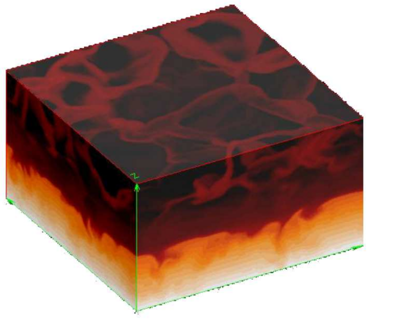

Fig. 1: Illustration of a 3-D model, extending from the top of the convection zone, to the low/middle chromosphere (internal energy).

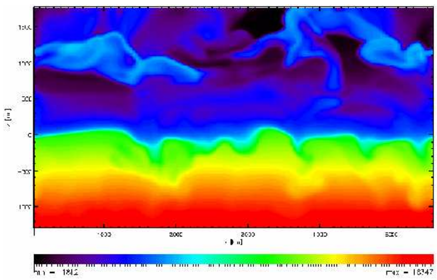

Fig. 2: Temperature in a vertical slice from a 3-D model: Downdrafts ($\rightarrow$ granulation) and shock waves.

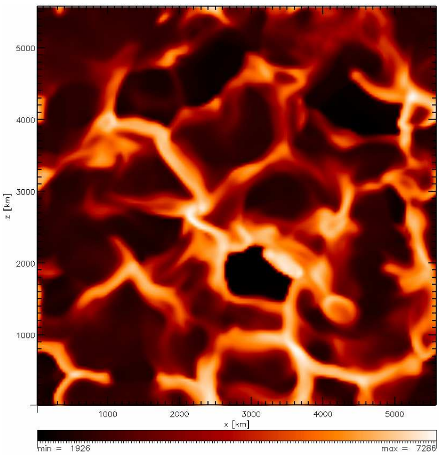

Fig. 3: Temperature in a horizontal slice from a 3-D model at a height of 1000 km (middle chromosphere).

Temperature Fluctuations

Kalkofen (2001) considers the quantity $\delta T/T$ which allows to distinguish between the two opposing cases of a hot chromosphere with small temperature fluctuations ($\delta T/T \sim 0.1$) and a cool one with large fluctuations ($\delta T/T \sim 10$).
For a first comparison we calculated the time average of the deviations from the mean temperature stratification, a quantity which should be at least qualitatively similar to $\delta T/T$. As a result, we get height-dependent average values for several 2-D and 3-D models:

z [km]	$\delta T/T$
510	0.1 (3-D), 0.2 (2-D)
810	0.2 (3-D), 0.3 (2-D)
1110	$0.3 - 0.4$ (2-D, 3-D)
1506	0.4 (2-D, 3-D)

The maximum $(\delta T/T)_{\rm max}$ is $1.0 - 1.2$ in the 3-D case and $2.1 - 2.5$ for 2-D. The difference between 2-D and 3-D is due to the fact that temperature fluctuations tend to be smaller in 3-D than in 2-D. Furthermore, $\delta T/T$ increases with height which can also be seen from horizontal slices like Fig. 3 for different heights. Near its base the chromosphere is relatively homogeneous with only small temperature fluctuations and becomes more inhomogeneous above.
The temperature profile of a shock wave depends on the spatial resolution of the simulation. Hence, a better resolution might lead to higher values for $\delta T/T$. However, our models seem to be in between the cases discussed by Kalkofen (2001).

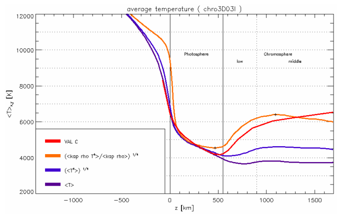

Fig. 4: Time-average of temperature stratification.

Temperature Stratification

A heating mechanism is required to explain the temperature increase in the quiet Sun's chromosphere which is clearly present in semi-empirical models like FAL93 and VAL81 (red line in Fig. 4). Can **heating by acoustic waves** reproduce the semi-empirical temperature stratificaton or are additional contributions (magnetic effects) necessary ?
To clarify this basic question we need to compare the results of our numerical simulations with e.g. the VAL C model which is static and 1-D only. For such a comparison it is crucial to average our model data in space and in time in an appropriate way. The simple arithmetic average (darkblue line in Fig. 4) does not yield a notable temperature increase. This is no surprise since the temperature in the VAL C model is derived from observed intensities and not measured directly. Consequently, the intensity is the right quantity to look at. Thus, a better averaging method is the **"emissivity mean"** which resembles an intensity (weighting with density ρ and opacity κ):

$$T_{\rm em}(t,z) = \left(\frac{\langle \kappa\, \rho\, T^4 \rangle_{x,y}}{\langle \kappa\, \rho \rangle_{x,y}} \right)^{1/4} \qquad (1)$$

The "emissivity mean" is shown in Fig. 4 as orange line which is quite similar to VAL C, including the presence of a **temperature minimum**. The stratification is surprisingly well reproduced for a so far only preliminary numerical model, although the temperature is a little higher than VAL C up to a height of $\sim$ 1300 km. But from an actual parameter study we know that improvements of some simulation details (e.g. 3-D instead of 2-D, more realistic opacities) tend to shift the temperature stratification even closer to the VAL C model.

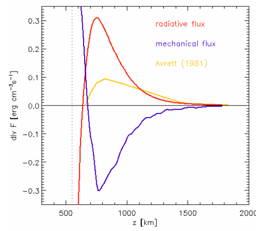

Fig. 5: Divergence of fluxes, horizontally and temporally averaged.

Radiative and Mechanical Flux

Due to the fact that **COBOLD** is **conservative** the fluxes are reliable quantities. We define the **mechanical flux** as

$$F_{\rm mech} = F_{\rm total} - F_{\rm rad} \qquad (2)$$

with the radiative flux $F_{\rm rad}$ and the total flux $F_{\rm total}$ which is constant with height (if averaged for a sufficient time). At chromospheric heights the energy transport by radiation clearly dominates, leading to a mechanical flux small compared to the radiative one, both almost constant with height. Nevertheless, there are contributions to the radiative flux in the chromosphere which can be quantified as the **divergence of the flux** ($\vec{\nabla} \bullet \vec{F} = \partial F_x/\partial x + \partial F_y/\partial y + \partial F_z/\partial z$). It can be seen from the time-averaged flux divergence (Fig. 5) that mechanical flux is converted into radiative flux with a maximum at $\sim$ 750 km. We interpret this as **dissipation of acoustic energy** and emission of radiation. As we learned from an actual parameter study more realistic simulations produce a closer match with observational data (Avrett 1981, yellow line in Fig. 5).

Conclusions

The first 3-D simulations with **COBOLD** already yield convincing results. Obviously, acoustic heating works for the chromosphere, supplying enough energy to account for the observed emission. The highly dynamic complex structure, caused by acoustic waves, might explain the differences between other models. Improved simulations might even lead to a better understanding of observational data.

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