DYNAMICS AND ENERGETICS OF THE SOLAR CHROMOSPHERE

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ABSTRACT

We present a summary of results from a number of observational programs carried out with the SUMER instrument on board SOHO. Most datasets show clear quasi-periodic dynamic behavior ("grains") in continuum intensities with frequencies 3–10 mHz. Corresponding grains are seen in intensities and velocities in neutral lines, normally with phase differences consistent with upward propagating soundwaves. We compare the observations with 1D radiation hydrodynamic simulations using MDI doppler-shifts to set the lower boundary. For continua formed in the mid-chromosphere we find that the simulations give a good match to the intensity fluctuations but that the minimum intensity is too low. We find that high frequency acoustic waves (missing from the current simulations) are unlikely to give the extra heating necessary because of the strong radiative damping (90 – 99 \%) of such waves in the photosphere. In continua formed in the low chromosphere the mean intensity is similar in the simulations and the observations but the simulated fluctuations are too large. The reported findings are consistent with a picture where a basic intensity level is set by a magnetic heating process even in the darkest internetwork areas with superimposed intensity variations caused by acoustic waves.

Key words: Sun; chromosphere; oscillations; waves.

1. INTRODUCTION

The Solar chromosphere is a region visible during a total Solar eclipse as a colored band, hence the name. Observationally, the decrease of the intensity above the limb shows a much larger scale-height in the chromosphere than in the photosphere. Furthermore, lines formed there turn out in emission instead of absorption and both facts have led to the inference of a temperature increasing with height. Unfortunately, the detailed diagnostic of the chromosphere is not straightforward. Firstly, there are not many spectral features accessible from the ground with opacity high enough to place the formation in the chromosphere. Secondly, these spectral diagnostics are neither optically thin nor formed at densities high enough to warrant the approximation of Local Thermodynamical Equilibrium (LTE). It is thus not possible to directly invert the observed intensity and Doppler shift to get temperature, density and velocity and the necessary forward modelling results in a large, non-local, non-linear system. This may be the reason why the chromosphere has not received as much attention as the transition region and corona where the line formation is more local (at least in space, non-equilibrium effects may introduce a dependency on the history of the atmosphere and complicate the interpretation).

The chromosphere covers many scale-heights in density and pressure and it is in this region of the atmosphere the plasma goes from dominating the magnetic field (high $\beta$ defined as the ratio of the gas pressure over the magnetic pressure) in the photosphere to a situation where the magnetic field dominates in the corona (low $\beta$). In this magnetic transition region we may get complicated interactions between different wave modes and much of the wave energy may also be reflected. An understanding of chromospheric dynamics and energetics may thus be important also for the understanding of the transition region and corona.

The outline of this paper is as follows: In section 2 we will review the observational picture of the Solar chromosphere. After a short discussion of what can be inferred from ground observations we will concentrate on observations from the Solar and Heliospheric Observatory (SOHO). In section 3 we employ radiation hydrodynamic simulations in order to interpret the observations. We use MDI observations to set the lower boundary condition in the simulations and we compare the simulation results with simultaneous SUMER observations. In section 4 we investigate whether high frequency waves may resolve some of the discrepancies between models and observations and finally, in section 5 we reiterate why a dynamic picture of the Solar chromosphere and a static picture are fundamentally different.


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2. OBSERVATIONS

From the ground the best chromospheric diagnostics are the resonance lines H and K from singly ionized calcium. The lines originate from the ground state of the dominant ionization stage of calcium and the optical depth scale is thus only dependent on the mass density. The source function has a strong collisional component thus giving information on the local conditions.

The Solar average calcium H line is a deep absorption line with slight emission in the line center. This emission has a central reversal such that there are two slight emission peaks with a dark core in between.

In regions absent of strong photospheric magnetic fields, the inter-network, the emission peaks of the H and K lines are absent most of the time. At times there is a brightening in the line wing (formed in the photosphere) followed by the appearance of an emission peak only on the violet side of line center (Jensen & Orrall 1963a,b). The localized brightenings are called K2V (or H2V) bright points or preferably bright grains (to indicate that they have a resolvable structure). The quasi-periodic behavior is known as the chromospheric three minute oscillation. Since 1963 the calcium bright grain literature has become extensive, see Rutten & Uitenbroek (1991) and references therein; Rammacher & Ullrich (1992); Rossi et al. (1992); Von Uexkull & Kneer (1995); Hofmann et al. (1996); Steffens et al. (1996); Kalkofen (1996).

The behavior of the calcium resonance lines in the inter-network regions can only be explained by the effects of upward propagating acoustic waves that shock 1–1.5 Mm above the height of optical depth unity at 500 nm. In fact, radiation-hydrodynamic simulations with an observed photospheric velocity field as lower boundary condition can reproduce the observed calcium H-line behavior to remarkable detail (Carlsson & Stein 1997a). The waves grow to large amplitude already at 0.5 Mm height and have a profound effect on the atmosphere. The simulations show that in such a dynamic situation it is misleading to construct a mean static model (Carlsson & Stein 1994, 1995, 2002).

With the advent of the SOHO mission a whole new window to the chromosphere was opened on a continuous basis with a package of high class instruments. For chromospheric studies the ideal instrument is the SUMER spectrograph (Wilhelm et al. (1996)) with a spatial resolution of a few arc seconds and a spectral resolution of 10 km/s per pixel enabling Doppler shifts to be determined to an accuracy of a few km/s.

The first dataset suitable for studies of chromospheric dynamics was acquired with SUMER during the commissioning phase of the SOHO mission March 8 and March 12 1996. We here summarize some of the results and the reader is referred to Carlson et al. (1997) and Judge et al. (1997) for details.

Figure 1 shows the intensity profile as a function of wavelength in Doppler units and time for two of the four datasets: O I 1355Å, O I 1358Å, C I 1364Å (upper panels) and N I 1319Å, C I 1329Å, C II 1334Å (lower panels). The line at 1319Å is normally attributed to N I but this is wrong (Carole Jordan, private communication) since the other member of the multiplet is missing and should have been stronger. This is actually the strongest unidentified line in the SUMER spectrum. The three lines of each data-set were observed simultaneously but the two data-sets were taken one after the other. Each image is shown on a linear scale, each individually scaled. Continuum brightenings are very evident as horizontal bands, especially in the panels with low peak counts (because of the scaling). We also have these brightenings in the neutral lines where they are associated with blue-shifts. The C II line also show some such “grains” (most clear one at t=3100s) and some other periods with strong Doppler shifts (close to t=600s).

Figure 1. SUMER data showing the intensity profile as a function of wavelength in Doppler units (x-axis, units of km s⁻¹) at spatial positions x = 95 – 96 along the 1 x 120 arcsecond slit, and time (y-axis, units of seconds). Data for two separate timeserises are shown, the 1355Å region in the upper panel, the 1319Å region in the lower panel. The “grains” are seen as brightenings with an intermittent ~3 minute periodicity and a characteristic spectral profile: brightenings are accompanied by a net blue shift of ~5 km s⁻¹. The x-axes have not been corrected for zero point offsets or long term drifts. From Carlson et al. (1997).
A number of other datasets have been acquired with SUMER to study chromospheric dynamics, see Carlsson (1999) for a review. The datasets are both similar and give rise to widely different conclusions. Two different datasets showing the variation of the 1319Å continuum variation are shown in figure 2. The dataset taken in March 1996 shows strong variation in continuum intensity while the dataset from July 1996 (Doyle et al. (1999)) shows much less variation. Another example is shown in figure 3 where the datasets come from (Wikstål et al., 1999) and (Judge et al., 2001). Wikstål et al. find clear evidence for upward propagating waves all the way from the continuum forming region to the transition region at temperatures of 300,000 K. This behaviour is absent in the Judge et al. data. It seems the difference in behaviour can mostly be attributed to differences in magnetic field strength, see Karlsen & Carlsson 2002 (these proceedings) and magnetic field topology (McIntosh & Judge (2001)). With these differences in mind, an attempt to summarise the observations is as follows:

- Large variations on short timescales. The continuum intensity may vary with a factor of seven and the line intensity of ionized species (like C III) may vary with more than an order of magnitude in less than 15s. The typical variation is large. Since the continuum intensity is formed in a layer where the source function has already decoupled substantially from the Planck function this implies an even larger variation in electron temperature than in brightness temperature. This difference may be from a factor of two in the low chromosphere to more than a factor of five in the upper chromosphere (Carlsson & Stein (1997b)).

- 3-10 mHz broad power peak in the inter-network for lines from neutral species. There is no sharp single peak in the Doppler shift power spectrum but many peaks that form a broad distribution in the 3-10 mHz frequency range peaked around 4-5 mHz. The power distribution is clearest in the Doppler shift but can also be seen in total line intensity. The power peak is very clear in inter-network continuum emission.

- Longer periods in the network. The maximum power is closer to 3 mHz than 5 mHz.

- The coherent patches (grains) are 3-8'' in size and the waves take the form of wave-trains of about 20 minutes duration.

- There is some grain behavior in C II and often Doppler shift variations of oscillatory nature with 3-10 mHz frequency.

- At times of maximum intensity the chromospheric line Doppler shift is 5-10 km/s in the form of blueshift.

- Time delays are difficult to measure but are mostly compatible with upward propagating acoustic waves.

- The intensity variations are asymmetric with steeper rise to high intensity than the fall to low intensity.

- Lines from doubly ionized species (Si III and C III) often show oscillations around 7 mHz coherent over 5-20°, sometimes even 40°.

- There are cases where upward propagating waves can be followed from the lower chromosphere to lines formed at lower transition region (C II) and upper transition region temperatures (O VI at 300,000 K) (Wikstål et al. (1999)).

- There may be large variations in dynamic behaviour from one area to another. One should be cautious with solid interpretations from limited sets of data.
• There is emission all the time at all locations in the neutral lines in contrast with the emission in the center of the Ca II H and K lines which is absent most of the time in the inter-network.

We will now turn to how to interpret these observations.

3. SIMULATIONS

To properly model the dynamic solar chromosphere one has to perform dynamic radiation-hydrodynamic simulations taking into account the non-local, non-linear rate equations for all important species.

Such a self-consistent radiation-hydrodynamic modelling of the solar chromosphere was performed by Carlsson & Stein (1992, 1994, 1995, 1997, 2002). We will here use the same methods to model the continuum intensity at 1119 Å and compare with observations from SUMER. See Carlsson & Stein (2002) for a detailed description of the methods.

The initial atmosphere is in radiative equilibrium above the convective zone (for the processes we consider) without line blanketing and extends 500 km into the convection zone, with a time constant divergence of the convective energy flux (on a column mass scale) calculated with the Uppsala code without line blanketing. The mean structure of the dynamic atmosphere has a low (5000 K) temperature throughout most of the chromosphere, with a temperature rise in the upper chromosphere produced by absorption of coronal radiation in the helium continua.

We obtained observations of the quiet Sun with SUMER on October 2 1996. A time series was obtained with 22 seconds cadence lasting for 4038 seconds with 4 50×120 pixel windows (corresponding to 2.2 Å×120 arcseconds) centered on λλ 1190.21 (S III), 1197.39 (Si II), 1199.55 (N I) and 1206.51 (Si III) Å. MDI was observing the same area in high resolution mode at a cadence of 60s giving Doppler shifts and magnetic fields in the photosphere (Fig. 4). A raster scan was taken with SUMER before and after the timeseries covering an area of 120×120 arcseconds2 enabling co-alignment between the SUMER and MDI observations. During the time series the slit does not cross any regions of strong magnetic field.

In the simulations, waves are driven through the atmosphere by a piston located at the bottom of the computational domain. The piston velocity is chosen to reproduce the 3750 second sequence of Doppler-shift observations in the Ni I line at 6676.8 nm (whose core is formed at 200 km above z_{9000} = 1) with MDI. We have performed 120 such 1D radiation hydrodynamic simulations corresponding to the 120 slit positions of the simultaneous SUMER time series.

Figure 5 shows the continuum intensity at λ1199Å from the numerical simulations. The predominant power is at shorter periods (2-4 minutes) than the dominant 5 minute power of the piston because these waves can propagate while the photospheric power maximum corresponds to evanescent waves. Note also the large horizontal extent of the intensity features.

Figure 6 shows the continuum intensity at λ1199Å from the SUMER observations.

A comparison between the observations and simulations reveals the following:

• The simulations have lower minimum intensities. In order to get a decent match with the observations it is necessary to add a constant intensity to the simulated intensities.

• There are regions of increased mean intensity in the observations not matched by the simulations. These regions are often labelled “network” in observational work in accordance with the correlation between high continuum intensity and strong magnetic field as evident from Figs. 4 and 6. Note, however, that along the slit we have no measured magnetic fields above 40 G.

• The simulations show brighter continuum brightenings than seen in the observations.

• There are many brightening features in the observations that are well reproduced in the simulations. This may not be so evident from comparing the Figures 5–6 but stands out in blinking the two figures against each other. A few such features are highlighted in Fig. 7.
Figure 5. Continuum intensity at \( \lambda 1199 \AA \) from the numerical simulations. A constant value has been added to the calculated intensities in order to give the same minimum intensity as in the observations.

The large horizontal extent of the continuum brightenings is well matched by the 1D simulations. This means that these structures exist already at the response height of the MDI velocity.

The amplitude of the observed continuum intensity variations is often well matched by the simulations and can thus be explained by the effect of propagating acoustic waves. There is, however, a zero-point offset; to get a good match a constant value has to be added to the intensities from the simulations. This corresponds to a heating process that is missing from the simulations. An obvious candidate is a heating mechanism connected to magnetic fields (since there are no magnetic fields in the simulations). Another candidate is high frequency acoustic waves since the piston velocities in the simulations were taken from MDI observations with 60s cadence and therefore do not contain any power at periods shorter than 120s. In the next section we will use the simulations to investigate this latter possibility.

4. HIGH FREQUENCY WAVES

Why is it necessary to perform simulations to test the hypothesis that high frequency acoustic waves can heat the chromosphere? Why not just check the existence of such waves from Doppler shift observa-

Figure 6. Observed continuum intensity at \( \lambda 1199 \AA \).

Figure 7. Enlargement of Figs. 5–6 for slit positions 75–115, time=500–2000s.

tions of photospheric spectral lines? The answer lies in the width of the response function of the Doppler shift response to the velocity field of the atmosphere. Figure 8 shows a typical response function of a photospheric line together with the amplitude of the measured Doppler shift compared to the amplitude of a sinusoidal wave as function of frequency. Waves with a frequency of 23 mHz give an observed Doppler-shift of only half the amplitude of the wave due to the width of the response function. At 50 mHz there is almost no measured Doppler-shift at all and such waves will thus not be detected in Doppler-shift measurements (but will contribute to the width of the spectral line).

For high frequency acoustic waves to heat the chromosphere they must be excited and they must be able to survive the radiative damping in the up-
Figure 8. Upper panel: Response function to line-center Doppler-shift for a typical spectral line in the solar atmosphere (solid) and three sinusoidal velocity fields with frequency 5 mHz (solid), 20 mHz (dotted) and 50 mHz (dashed). Lower panel: Amplitude of Doppler-shift compared to amplitude of the sinusoidal wave as function of frequency.

per photosphere to provide enough acoustic power to make a difference to the chromosphere. Early studies indicate that there may indeed be a peak in the spectrum of generated acoustic waves at high frequencies (Musielak et al., 1994). Results from high resolution numerical simulations of convection do not seem to support these results but instead indicate a decreasing power as function of frequency (Goldreich et al., 1994; Stein & Nordlund, 2001). If the earlier results are correct, about 90% of the total acoustic power lies above the frequencies that were included in the piston of the radiation hydrodynamic simulations described in the previous section (Theuerer et al., 1997). We will now use the numerical simulations to study how much of this acoustic power will survive the radiative damping in the photosphere.

Two additional simulations were made with a large number of depth-points to make a study of the behaviour of high frequency acoustic waves possible. The two simulations used a sinusoidal piston as the lower boundary condition with amplitudes of 0.5% of the local sound speed and periods of 20s and 10s (corresponding to frequencies of 50 and 100 mHz). Figure 9 shows the velocity scaled by the square root of the density and the sound speed (thus proportional to the square root of the acoustic power) as function of height and time. Most of the power in the waves is damped out by radiation around a height of zero. At a period of 20s about 10% of the input power reaches chromospheric heights and at a period of 10s only 1% of the input power gets through the photosphere.

Figure 9. Velocity scaled by the square root of the density and the sound speed as function of height and time in two simulations with wave periods of 20s (upper panel) and 10s (lower panel).

Even if there is substantial acoustic power generated in the convection zone at high frequencies, these simulations thus indicate that these waves are so heavily damped that they will not be able to contribute significantly to the heating of the chromosphere.
5. CONCLUSIONS

Observations of the H and K lines from singly ionized calcium show clearly that most of the time in the internetwork regions there is no temperature rise below the formation height of the line center. Furthermore, the occurrence of intermittent emission only on the violet side can only be explained by the existence of strong velocity gradients around 1 Mm above the photosphere. SOHO observations of continuum intensities formed in the lower chromosphere show large amplitudes. Given the decoupling of the source function from the Planck function, the temperature variations are factors greater than the (large) variations in the observed radiation temperature. These variations are not small perturbations on a mean atmosphere.

Simulations show that a dynamic chromosphere is fundamentally different from a static atmosphere independent of what the mean atmosphere is. Mean intensities in the ultraviolet systematically sample the high temperatures because of the non-linear nature of the Planck function at short wavelengths (Carlsson & Stein, 1997a). The long timescales of hydrogen ionization/recombination make the mean ionization state of the chromosphere typical of the high temperatures rather than the mean atmosphere (Carlsson & Stein, 2002). Semi-empirical models based on mean intensities at radio wavelengths will therefore also systematically sample the high temperature state rather than the mean state in spite of a Planck function linear in temperature at long wavelengths.

Radiation hydrodynamic simulations of acoustic waves give a rather good agreement with observations in the H and K-lines (Carlsson & Stein, 1997a) but give too low continuum intensities in the mid-chromosphere (see Section 3). This failure of the simulations indicate that there is a heating mechanism missing from the simulations. Because of the strong radiative damping of high frequency acoustic waves in the photosphere (see Section 4) it is unlikely that this heating is acoustic in origin.

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