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Wave Heating of the Solar Chromosphere

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Abstract. The nonmagnetic interior of supergranulation cells has been thought since the 1940s to be heated by the dissipation of acoustic waves. But all attempts to measure the acoustic flux have failed to show sufficient energy for chromospheric heating. Recent space observations with TRACE, for example, have found 10% or less of the necessary flux. To explain the missing energy it has been speculated that the nonmagnetic chromosphere is heated mainly by waves related to the magnetic field. If that were correct, the whole chromosphere, magnetic as well as nonmagnetic, would be heated mainly by waves related to the magnetic field. But contrary to expectation, the radiation emerging from the nonmagnetic chromosphere shows none of the signatures of magnetic waves, only those of acoustic waves. Nearly all the heating of the nonmagnetic chromosphere must therefore be due to acoustic waves. In the magnetic network on the boundary of supergranulation cells, on the other hand, the small filling factor of the magnetic field in the photosphere implies that only a small fraction of the wave flux that travels upward to heat the chromosphere can be channeled by the magnetic field. Hence, while some of the energy that is dissipated in the magnetic network is in the form of magnetic waves, most of it must be in the form of acoustic waves. Thus, the quiet solar chromosphere, instead of being heated mainly by magnetic waves throughout, must be heated mainly by acoustic waves throughout. The full wave flux heating the quiet chromosphere must travel through the photosphere. In the nonmagnetic medium, this flux is essentially all in the form of acoustic waves; TRACE registers at most 10% of it, perhaps because of limited spatial resolution.

Key words. Sun: chromosphere, oscillations—heating and dynamics—acoustic waves—magnetic waves.

1. Introduction

The observation that the solar chromosphere is hotter than the photosphere implies a heating mechanism that is different from radiative and convective. Biermann (1946) and Schwarzschild (1948) recognized that the heat source had to be the turbulent convection which generates acoustic waves whose dissipation provides the energy for chromospheric heating. The paper is structured as follows: In section 2, we consider measurements of the acoustic flux heating the chromosphere and describe radiative signatures of acoustic and magnetic waves and in section 3, we investigate the distribution of magnetic fields in the quiet chromosphere.

2. Observations of the acoustic flux

An understanding of the structure of the nonmagnetic chromosphere, as described by the models of Vernazza *et al.* (1981; hereafter VAL), requires a measurement of the energy flux of acoustic waves, as well as their velocity spectrum, and construction of a model. Observations of the acoustic spectrum are difficult because of limitations of both ground-based as well as space-based measurements as regards spatial and temporal resolution.

The energy flux in acoustic waves observed by Deubner and reported by Ulmschneider (1990) showed that at a height of 900 km, where the radiative cooling function per unit volume of VAL model C has its maximum, the wave flux is deficient by an order of magnitude. Wunnenberg *et al.* (2002) found that the wave sources which their observations imply lie preferentially above intergranular lanes; they are intermittent also in time. Both features are inconsistent with our understanding of continuous wave emission from the convection zone. Fossum & Carlsson (2005) observed intensity fluctuations from space with TRACE in the 1600 Å passband and found that the waves contained at most 10% of the energy flux required for chromospheric heating. They concluded that the nonmagnetic chromosphere must therefore be heated by waves related to the magnetic field (cf. Carlsson 2007). This idea can be tested by investigating signatures of the nature of waves seen in the emergent radiation from the chromosphere.

Emission from the chromosphere reveals the nature of the waves producing the radiation, in the asymmetry and evolution of the intensity, the dominant periods of fluctuations, and the magnitude of the average intensity.

In the magnetic network, the intensity in the H and K lines is more or less symmetric (Fig. 1 of Lites *et al.* 1993), with mainly simultaneous blue and red peak enhancements (frequency of occurrence in the K line of 80%, Grossmann-Doerth *et al.* 1974) and in the internetwork chromosphere, with mainly single blue-peak enhancements (frequency of 40%).

A second indicator of the nature of the waves is the time dependence of the line intensity. Figure 2 of Lites *et al.* (1993) shows the H line as a function of time and wavelength near line center; the inner panels are for the intensity of a network bright point, the outer panels, for an internetwork H_{2v} bright point. The network intensity is high most of the time and exhibits a high degree of symmetry; the intensity from oscillations in the internetwork medium is sharply peaked in time on the blue side of the line center, with the peak intensity dropping to the level of the background in a time interval of 5% of the 3 min wave period. In addition, there are long gaps in the oscillations when the emergent radiation shows only the background.

A third indicator of the nature of a wave source is the power spectrum of velocity variation, seen for the H line in Fig. 6 of Lites *et al.* (1993) and for an infrared line of Ca II in Fig. 2 of Deubner & Fleck (1990); whereas power in the network is high at low frequencies of 2–3 mHz, and low at higher frequencies of 5 mHz, power in the internetwork medium is low at low frequencies and high at higher frequencies.

A fourth indicator is seen in the filtergram (Fig. 5, from von Uexküll & Kneer 1995) exhibiting fluctuations in the K_{2v} emission peak. At the locations in the internetwork chromosphere, which was identified by a low time-average intensity, the maximal intensity exceeds the cell-interior average by a factor of at least 1.5. Von Uexküll and Kneer have identified time intervals ranging from 150 s to 188 s for fluctuations covering at least two adjacent intervals. These oscillations are clearly of the 3 min type of acoustic oscillations. No long-period oscillations are in evidence. The straightforward interpretation of these fluctuations is that they are associated with acoustic waves, and that waves related to magnetic fields are not involved.

3. Topology of the quiet chromosphere

The emission in the H and K lines separates stars with outer convection zones broadly into two groups (Noyes *et al.* 1984), one with high emission from rapidly-rotating young stars, and the other with lower emission from slowly-rotating old stars. The two groups differ by two to three orders of magnitude in the power of the chromospheric emission in the cores of the H and K lines. The high emission of fast rotators is thought to represent the effect of magnetic activity whereas the low emission of slow rotators represents the effect of basal acoustic heating (Schrijver *et al.* 1989).

The Sun is a slowly rotating main sequence star. The bulk of the nonradiative heating is due to acoustic waves. But the intensity enhancement in the K_{2v} emission of bright points in the magnetic network over that in the dark supergranulation cell interior is only 27% (Skumanich *et al.* 1975). With a filling factor of the network in the K line of 39%, the net increase of the emission from the quiet Sun over that of the dark cell interior alone is only 10%, which implies that even in the magnetic network a large part of the emission is due to acoustic waves.

The filling factor of the network of 39% at a height of 1000 km allows us to infer the gross topology of the magnetic field, assuming validity of the equations for a slender flux tube. The filling factor $f(z)$, of the magnetic field as a function of height z, then varies on a length scale of twice the density scale height, $\mathcal{H}$, i.e., $f(z) \propto \exp((z - z_0)/2\mathcal{H})$. With $\mathcal{H} \sim 100$ km, the filling factor at the top of the photosphere is $f(500\,\text{km}) \sim 3\%$, and in the middle, $f(250\,\text{km}) \sim 0.9\%$. For the idealized "thin" flux tube, the top of the nonmagnetic chromosphere, where $f \sim 100\%$, would be reached at 1200 km. The filling factor at $z \sim 250$ km in the photosphere allows us to infer broadly the properties of heating by magnetic waves in the network. The velocity amplitude of acoustic waves in Ca II bright points in the observations of Lites *et al.* (1993) has a Mach number of about 10% (Carlsson, private communication). Since the velocity amplitude of flux tube waves varies with a length scale of $4 \times \mathcal{H}$, the Mach number increases to about 20% at the base of the chromosphere ($z = 500$ km). If the initial velocity amplitude was much higher than it is at internetwork bright points, the limiting value of the Mach number of 0.3 for dissipation (Schwarzschild 1948; Hasan *et al.* 2003) would be reached in the photosphere and dissipation would set in, without significantly increasing the energy flux to the chromosphere. Thus, magnetic waves in the magnetic network can contribute at most a few per cent to chromospheric heating. We conclude that all the heating in the internetwork chromosphere is due to acoustic waves, as is most of the heating in the magnetic network.

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