VI. CHROMOSPHERIC
and
CORONAL HEATING

THE HEATING OF THE QUIET SOLAR CHROMOSPHERE

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ABSTRACT: The quiet solar chromosphere shows three distinct regions. Ordered according to the strength of the emission from the low and middle chromosphere they are (1) the magnetic elements on the boundary of supergranulation cells, (2) the bright points in the cell interior, and (3) the truly quiet chromosphere, also in the cell interior. The magnetic elements on the cell boundary are associated with intense magnetic fields and are heated by waves with very long periods, ranging from six to twelve minutes; the bright points are associated with magnetic elements of low field strength and are heated by (long-period) waves with periods near the acoustic cutoff period of three minutes; and the quiet cell interior, which is free of magnetic field, may be heated by short-period acoustic waves, with periods below one minute. This paper reviews mainly the heating of the bright points and concludes that the large-amplitude, long-period waves heating the bright points dissipate enough energy to account for their chromospheric temperature structure.

1. Introduction

Chromospheric heating remains one of the fundamental problems in solar physics. Biermann (1946, 1948) and Schwarzschild (1948) suggested that the solar chromosphere was heated by acoustic waves that are generated by the turbulence of the hydrogen convection zone and travel outward through the photosphere, where the decreasing density of the gravitationally stratified gas causes the velocity amplitude of the waves to increase and the profile to steepen; shocks form at the base of the chromosphere and beyond, thereby heating the chromosphere. Ulmschneider (1970, 1974) proposed that the waves had to meet two conditions. They had to have the periods and initial velocity amplitudes that would enable them to produce the first shock at the observed base of the chromosphere, approximately 500 km above $\tau_{5000} = 1$ in model C of the average quiet atmosphere by Vernazza, Avrett & Loeser (1981, henceforth VAL81), and the resultant time-averaged temperature structure had to agree with the temperature structure of the empirical models, the HSRA (Gingerich *et al.* 1971) or that of VAL81. Ulmschneider and collaborators (*cf.* Ulmschneider 1986; also Ulmschneider & Kalkofen 1977) were able to construct such plane-parallel models with acoustic waves having periods near 1/2 min, but both ground-based and space-based observations failed to support the claim of shocks (*cf.* Cram 1987). From this, Cram concluded that the chromosphere was not heated by shocks and suggested that mechanisms other than wave heating were responsible for the chromospheric temperature rise.

In spite of this conclusion against acoustic heating, evidence has been accumulating that suggests wave heating of chromospheric regions that are associated with magnetic fields. Thus, Jensen & Orrall (1963) observed velocity oscillations in the K line of Ca II, and Orrall (1966) observed similar oscillations in the Hα line and noted, furthermore, that the wave

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period was positively correlated with the strength of the magnetic field. Liu (1974) found that the bright points (also called cell points, K grains, or grains), which are associated with magnetic elements in the interior of supergranulation cells, were heated by waves with periods near the acoustic cutoff period of about 3 min, where no propagating waves were expected (Schatzman & Souffrin 1967), nor predicted (Stein 1967, 1968; Leibacher & Stein 1981). And Damé (1983, 1984) studied waves with periods longer than the acoustic cutoff period in the magnetic elements on the boundary of supergranulation cells. Propagating waves in the bright points were described by Liu (1974) and by Cram (1974) in the K line, by Cram & Damé (1983) in the H line, by Damé (1983, 1984) in the H and K lines, and by Lindsey & Roellig (1987) at 350 μm and 800 μm in the H^- free-free continuum.

The mechanically heated layers that are of primary interest for the energy balance of the outer layers of the sun are the densest and, hence, lowest layers, namely, those of the low and middle chromosphere. They extend from the temperature minimum, where the temperature in the semiempirical model of VAL81 is 4200°K and the height is 500 km above $\tau_{5000} = 1$, to the end of the temperature plateau of about 7000°K at a height of 2000 km. For these layers, the VAL81 model C implies that the gas is largely neutral. Most of the radiative losses due to mechanical heating occur in the lines of ionized calcium (which in model C account for more than half the radiative cooling), in the analogous lines of ionized magnesium, in the core of the Hα line, in free-free transitions of the H^- ion, in bound-free transitions of some metals such as Si, Fe, and C, and in the far wings of the Lyman-α line and the Lyman continuum. Propagating waves heating the layers of the low and middle chromosphere have been observed in all the above line transitions in the visible part of the spectrum and in the infrared continuum, but not in transitions in the ultraviolet.

The paper is organized as follows: Section 2 discusses the association between magnetic elements, *i.e.,* photospheric areas with a typical size well below 1″ of intense vertical magnetic field, and regions of strong chromospheric emission. The paper then deals mainly with the heating of the chromosphere in the internetwork bright points: Section 3 presents evidence for outward propagation of disturbances with a typical repetition time of 3 min, discusses the expectations for vertical wave propagation from the linearized gas dynamic equations, and speculates on the nature of the "waves" that heat the bright points, and Section 4 gives estimates of the dissipated mechanical energy; the final Section presents some conclusions on chromospheric heating.

2. Association of Chromospheric Heating and Magnetic Fields

It is well known that there is a close relation between enhanced chromospheric emission and magnetic elements on the boundary of supergranulation cells (*cf.* Zirin 1988). And there is a similar association between enhanced emission from the bright points in the cell interior and internetwork magnetic elements (Sivaraman & Livingston 1982). The chromospheric emission from magnetic regions is strongly enhanced. By contrast, the emission from the field-free regions of the cell interior is much lower (Cram 1987).

The magnetic field on the cell boundary is very strong (*cf.* Stenflo 1989); its contribution to the pressure is higher than that of the gas. The field extends from the photosphere at least into the transition region between chromosphere and corona (*cf.* Athay 1976), and it may reach as high as the 2×10^{6}°K level in the corona (*cf.* Piddington 1974). The heating in these flux tubes (*cf.* Spruit 1981) occurs by means of waves with periods of 300 s, 375 s, 500 s, and 750 s (Damé 1983); the waves are regarded as internal gravity waves (*cf.* Damé; see also the discussion below) or perhaps as downward-propagating, magnetically-guided magneto-acoustic waves (Deubner 1988, Deubner & Fleck 1989). Whatever their nature, these waves carry the highest energy flux of any heating mechanism in the quiet solar chromosphere.

The bright points in the interior of the supergranulation cells also show a one-to-one correspondence with magnetic elements (Sivaraman & Livingston 1982). Thus, when a magnetic element moves, the associated bright point moves with it; a bright point is never observed without its associated magnetic element; and a magnetic element without a bright point can be understood in terms of the life time of bright points (Sivaraman & Livingston). While a magnetic field thus appears to be essential for the generation of the waves, it is probably too weak to influence their propagation. The magnetic elements appear to be located in intergranular lanes (Cram 1974, Sivaraman, Bagare & November 1990), suggesting that they arise because of the action of granular flows sweeping the magnetic field into the granular boundary regions. The heating in the bright points occurs by means of large-amplitude disturbances with a typical repeat time of 3 min, which is identical to the acoustic cutoff period of the atmosphere at the temperature minimum.

The magnetic field-free region in the cell interior, sometimes labelled the truly quiet chromosphere, is heated at a lower level. In pictures of the chromosphere in the resonance lines of Ca II, or in free-bound continua formed in the upper photosphere (*cf.* Foing & Bonnet 1984), this region appears dark. It is surmised that the atmosphere there is heated by means of short-period waves, with periods between 1/4 min and 1 min (*cf.* Ulmschneider 1990), but significant heating cannot extend higher than about 800 km since beyond that level all waves with periods shortward of the acoustic cutoff period are predominantly standing waves (Deubner 1988). However, some field-free regions may not receive a significant amount of mechanical heating at any height. This is implied by the low temperature observed in lines of the CO molecule in the infrared, which indicate temperatures well below 4000°K (Ayres 1981). However, the filling factor of these very cool, CO-emitting regions may be as small as 10% (*cf.* Athay and Ayres in the proceedings of the 1989 Cool Star Conference). It is a plausible inference from the observations of the chromospheric emission from cool stars, which imply a lower limit on the Ca II emission for very slowly rotating, old stars, that the field-free medium contributes some enhanced emission, a limit that is referred to as a basal chromosphere (*cf.* Schrijver 1987). But the heating there is likely to be significantly below the heating predicted by the acoustic heating theory (Cram 1987).

3. Waves in Bright Points

The "waves" that propagate outward into the chromosphere to heat the bright points have repetition times, or periods, that fall mainly between 2 min and 4 min, with the peak occurring near 3 min (*cf.* Liu 1974, fig. 7), *i.e.,* the cutoff period of of the gas at the temperature minimum. The waves are first observed as intensity enhancements when they are still deep in the photosphere, near $\tau_{5000} = 1$. They travel outward, gaining strength as they propagate into the chromosphere, where in most cases only the blue emission peak, K_{2v}, gets enhanced. The typical increase of the intensity of the peak is by a factor of three, and in exceptional cases a factor of five (Liu, fig. 2). Enhancement of the red peak, K_{2r}, occurs also, but much less often (*cf.* Cram & Damé 1983, fig. 2). The ratio of frequencies of occurrence of blue peak and red peak enhancements is given as 7:1 by Grossmann-Doerth, Kneer & v. Uexküll (1974) for bright points, and as 3:1 for the flux tubes of the cell boundary. At the same time, two thirds of the shifts of the K_3 absorption core are redward, implying downward velocities of the K_3-forming layer (Grossmann-Doerth *et al.*). Note that these profile statistics have never been reproduced in the modelling of bright point heating.

The importance of the 3 min waves in the heating of bright points is unexpected. Unlike the situation in a homogeneous medium, where acoustic waves may have any period and where they propagate at the sound speed, waves in a gravitationally stratified atmosphere are restricted to values of the wave period below the cutoff period, $P_{ac} = 4\pi H/a$, where H is the (projected) pressure scale height and a is the sound speed; for vertical propagation in a magnetic field-free, isothermal atmosphere, no other wave type is allowed. In particular, there is no propagation of internal gravity waves in the purely vertical direction.

When the direction of propagation is not restricted to the vertical, the wave equation admits solutions for both acoustic and internal gravity waves (*cf.* Bray & Loughhead 1974, Stein & Leibacher 1974). But for directions only moderately inclined to the vertical, the permitted gravity waves have very long period. Therefore, the inference drawn by Damé (1983) that the long-period waves he observed in the network on the boundary of supergranulation cells are gravity waves may be in error, but the conditions under which the solutions of the linearized equations are valid must be kept in mind as well. These are, above all, that the waves be plain, have small amplitude, and that the magnetic field strength be negligible. None of these conditions is satisfied.

The heating of the field-free medium inside supergranulation cells by means of short-period waves presents no difficulties to our understanding, provided such waves are present with sufficiently large energy flux. Measurements of phase delays by Deubner (*cf.* 1988) and by Lites, Chipman & White (1982) are consistent with the assumption that such waves are present, but others question heating by such waves (*cf.* Cram 1987).

The heating of the bright points by acoustic waves with a period equal to the acoustic cutoff period presents problems of a different sort. The analysis for small-amplitude waves implies that such waves cannot heat the bright points, because, if the wave period is longer than the acoustic cutoff period, the waves are evanescent, and if it is only slightly shorter, their group velocity is very small, which would allow only little energy to penetrate through the temperature minimum region into the chromosphere.

Numerical calculations of the generation of sound and internal gravity waves by the turbulence of the hydrogen convection zone are consistent with the above results on the propagation of acoustic waves. Thus, the power obtained by Stein (1967, 1968) peaks below 1 min, *i.e.,* for short-period waves, and the flux is zero at the acoustic cutoff period. This is also in agreement with the analytical estimates of Stein & Leibacher (1981), which show the power growing from zero at the cutoff period, with the rate of increase towards shorter periods depending on the assumed spectrum of the turbulence. On the other hand, we note that the cutoff period is also an eigenperiod of the atmosphere (*cf.* Lamb 1908) so that many processes should be able to excite the atmosphere to oscillations at the cutoff period.

The observational data on the waves might shed some light on the nature and the generation of the waves heating the bright points, but the data are ambiguous. Damé (1983, 1984) describes the waves as occurring typically in groups of three pulses, of which the first one is the strongest and subsequent ones are weaker (*cf.* Cram & Damé 1983, fig. 5, frame 114). This suggests perhaps that the disturbance is generated as a pulse followed by wakes oscillating at the cutoff period with diminishing amplitude, as has been investigated by Rae & Roberts (1982). This view is also supported by the narrow width evident in the disturbance (*cf.* Liu 1974, fig. 3b). However, the observational data do not exclude a periodic excitation at the cutoff period (*cf.* Cram & Damé 1983, figs. 4, 5).

Since the observational evidence so strongly suggests that acoustic waves with periods near the cutoff period of the atmosphere at the temperature minimum heat the bright points, and that the energy dissipated by these waves may be sufficient to provide all the energy support needed for the layers of the low and middle chromosphere in the bright points, we must confront the problem of the propagation of these waves. How should we imagine this? As detailed in the subsequent section, the energy dissipated by the waves is large enough to raise the degree of ionization from the low value it has in the VAL model to about 10%. This has a major effect on the value of the cutoff period, which might be doubled in the layers of the temperature plateau of 7000°K in the middle chromosphere, both because of the higher temperature there and because of the higher degree of ionization, which lowers the ratio of specific heats and thereby reduces the sound speed (*cf.* the definition of P_{ac} above). Thus, the problem of the waves, assuming that they have been generated, is only to tunnel through the layers of the temperature minimum. The damping length of waves with periods near the cutoff period is much longer than the scale height (Leibacher, Gouttebroze & Stein 1982). A significant energy flux can therefore pass through the evanescent region. In the layers of the middle chromosphere, the waves would then be again propagating.

The high degree of ionization might also solve another mystery, namely, the small size of the bright points. If the waves were confined by flux tubes, they would be expected to have spread to fill most of the available area; similarly, if the magnetic field were described by a potential field, we would expect it to have formed the canopy. In either case, the heated region should extend well beyond the observed size of 1″ to 2″. Here the high ionization and the increased temperatures caused by the waves could be imagined to create channels allowing the waves to propagate in the chromosphere. These propagation channels would be surrounded by gas that is less ionized, and hence has a higher ratio of specific heats, in which the waves would remain evanescent, *i.e.*, non-propagating. Perhaps the approximate equality of the horizontal size of the channels and the wavelength of the acoustic waves supports the picture of channels of propagation.

4. Wave Energy Flux

There are several ways in which the energy carried by the waves can be estimated: the outward propagation of the intensity enhancement observed in a spectral line yields the energy flux, the excess emission in a line and the cooling rate or the temperature function of an empirical model give the dissipation rate.

Liu (1974) estimated the wave energy flux from the rms velocity amplitude and the phase speed of the waves, *i.e.*, the speed with which the intensity enhancement in the K line propagates through the atmosphere. For this he used an empirical model with which he related the position of an intensity increase in the line profile to the position of the wave front in the atmosphere. Assuming that the waves were acoustic he then calculated the group velocity and thus the energy flux. This flux, which may be uncertain by a large margin, falls short of the flux estimated by VAL81 (*cf.* their Table 29) by only a factor of about 2. This suggests that the waves observed in the K line may carry sufficient energy for the heating of the low and middle chromosphere in the bright points.

Cram & Damé (1983) compared the average H line emission in their observations with the H line emission calculated from the empirical model of the average chromosphere, model C of VAL81. They determined the observed emitted energy from the difference between the average profile of all their observations and the average profile of the lowest decile, which was assumed to reflect only very little mechanical heating. Their estimate fell short of the emission of the empirical model by only 20%. Thus, one may conclude again that the heating of the layers in which the H line arises is consistent with heating by only these long-period waves.

Anderson & Athay (1989) determined the dissipation rate of the chromospheric heating mechanism from the empirical temperature structure of the average chromosphere, VAL model C, using a model atmosphere code. They matched the temperature curve of the empirical model in the layers of the temperature plateau below about 7000°K with a constant flux divergence per unit mass of $dF/\rho dx = 4.5 \times 10^9$ erg g^{-1} s^{-1}. In order to deduce the nature of the heating mechanism they assumed dissipation by acoustic waves, which implied a velocity amplitude of half the sound speed, a result that is consistent with heating by shock waves. As further support for their hypothesis of acoustic wave heating they pointed to the value of the microturbulent velocity in the same layers, which is approximately equal to the sound speed in these layers. Thus, the energy input into the chromosphere in the region of the temperature plateau below about 7000°K is consistent with the assumption of heating by compressional waves alone.

If we assume that VAL81 model C describes the atmosphere in the bright points, a plausible assumption for a model of the average chromosphere, and if we assume that the heating occurs by 3 min waves, the dissipation rate in the temperature plateau near 7000°K amounts to 1 eV per particle per wave pulse. Note that this occurs in a medium in which the average energy per particle is 1/2 eV per particle. These waves thus have very large amplitude (*cf.* Kalkofen 1989), and they provide enough energy to raise the degree of ionization of the gas to about 10%. The cooling of this time-dependent medium then would occur by means of radiative recombination, as suggested by Lindsey (1981).

Weak-shock theory (*cf.* Ulmschneider 1970, Bray & Loughhead 1974) permits an estimate of the wave period and the Mach number of the waves if the shocks have reached their limiting strength, where the growth of the wave amplitude due to the outward propagation in a gravitationally stratified gas is balanced by the decay of the amplitude due to dissipation. The theory is not directly applicable to the waves that heat the chromosphere in the bright points since they are not plane and the shocks are not weak. But using the theory for a rough estimate of wave properties, the dissipation rate found by Anderson & Athay implies that the shocks are fairly strong, with a Mach number of nearly 2, and that the wave period is about 1 min, not much different from the observed periods. These results are thus broadly consistent with heating of the chromosphere in the layers of the temperature plateau by compressional waves with periods near the acoustic cutoff period.

5. Conclusions

The properties of the internetwork bright points are intermediate between those of the network elements and those of the truly quiet chromosphere: The bright points are associated with relatively weak magnetic fields, whereas the network fields are very strong and the truly quiet chromosphere is probably field-free. The bright points are heated by waves with periods near the acoustic cutoff period of the atmosphere at the temperature minimum; the wave periods observed in the network elements are longer, and the quiet regions are presumed to be heated by waves of shorter period. The bright points are intermediate also in the flux of the waves heating the gas. The equality of the emission widths in the Wilson-Bappu effect of both the bright points and of the sun as star (Bappu & Sivaraman 1971) suggests that the bright points are an important element in the chromospheric emission from the sun.

The magnetic field associated with the bright points is critical for wave generation since it determines the location of the heating, but the field is probably too weak to have a major influence on wave propagation. The confinement of the waves may occur by means of propagation channels created by the waves, which heat and ionize the gas and thereby increase the cutoff period locally. In the channels, the waves would be running waves. This medium would be surrounded by gas in which the waves are evanescent.

The radiative cooling times implied by the empirical models of the chromosphere are too long to agree with the observed properties of the 3 min waves. Instead of cooling by free-free radiation of H^-, the gas may cool by radiative recombination.

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DISCUSSION:

HOLLWEG: Your results sound a lot like the spicule model by myself and Sterling . Also, I believe the NRL group found UV features resembling spicules over cell interiors. Is there a relation to the bright point waves?

KALKOFEN: It does indeed seem plausible to assume that the 3-minute oscillations, with several unequal pulses of which the first one is the strongest, are generated by an impulse followed by eigenoscillations of the atmosphere at the cutoff period, as in your spicule model and as described in work by B. Roberts. But I do not know whether there is a connection to spicules in the interior of super-granulation cells.

KNEER: I could not get the point about how the 3-min. oscillation is generated and supplied with enough energy to heat chromospheric grains.

KALKOFEN: It should not be surprising that waves of 3-min. period are found in the chromosphere, since they are an eigenperiod of the atmosphere at the base of the chromosphere. But how these wave are generated in not known. The theory by Stein (1967,1968) and by others gives zero energy flux at the acoustic cutoff. That result clearly is not in accord with the bright point observations.

UBEROI: The magnetic fields do not play any role in your work. Please comment especially about the frequency ranges you are dealing with.

KALKOFEN: The magnetic field is probably of no importance for the propagation of waves in the bright points since the value of the plasma-β is likely to be much larger than unity, perhaps as large as 100. But the observations (Sivaraman & Livingston) suggest that the magnetic field is of critical importance for the generation of the waves. The wave periods are near the eigenperiod of the atmosphere at the temperature minimum, *i.e.*, the acoustic cutoff period. The range of periods, according to Liu, is 2 min. to 4 min.

KUNDU: (i) Several years ago we tried to look for 5-min. oscillations at centimeter wavelengths using either single dish telescopes or interferometers. We did not find any 5-min. oscillations at 3, 11 or 1.3 cm wavelengths using interferometers. However, we found one period at 3-min. at 1.3 cm. This seems to be relevant to the 3-min. waves that you discussed.

(ii) Can you explain why there should be 3-min. waves and not 5-min. waves in the upper chromosphere?

KALKOFEN: (i) I am not surprised that you saw 3-min. waves at 3 cm or 1.3 cm. This is consistent with observations by Yudin (1968) at 3 cm and by Simon and Shiwabukuro (1971), who saw them at 3.3 min. and 3.5 min. The latter concluded that the 3 min. waves are unimportant for chromospheric heating based on the long cooling times (much longer than the waveperiod) given by Spiegel (1957) and by Ulmschneider for free-free transitions of H^-. The actual thermal relaxation of the medium is probably controlled instead by ionization and recombination processes, as suggested by Lindsey, with cooling times significantly shorter than the waveperiod. Hence the 3-min. waves probably are very important for chromospheric heating.

The 3-min. period is an eigenperiod of the system (Lamb 1908), and the waves are likely to be allowed to propagate in the channels created by the wave in the bright points, whereas the 5-min. oscillations may still be evanescent.

(ii) The 5-min. waves are evanescent in the upper photosphere, and so they are damped in the chromosphere. The radiation at cm wavelengths is formed in the middle chromosphere, at about 2000 km above $\tau_{5000} = 1$. At that height the wave amplitude of 5-min. waves may be too small to be detectable.

ULMSCHNEIDER: Your energy estimates depend on accurate time-dependent calculations of waves with CaII-NLTE emission. How accurate are the calculations you quoted?

KALKOFEN: The estimate by Cram & Dame (1983) of the average emission in the H line is purely observational and depends on the determination by Pasachoff of the absolute intensity in H. The VAL81 model C, used for calculating the H line emission of the average chromosphere, is a spatially and temporally averaged representation of the average chromosphere, based on UV continua. The uncertainty of using such a model for computing line emission is evident. But for the purpose of estimating the time-averaged chromospheric H-line emission, the model should be adequate.

KNEER: Besides the 3-min. oscillation the 5-min. oscillation shows up clearly in chromospheric data analysis (CaK, Hα,CaIR). In fact, it is not settled among observers that the 3-min. "chromospheric" mode is so much dominant in the chromosphere since it is not seen as a modal structure in the power spectra in the k-ω-plane. Rather what I see in the power spectra is a very broad distribution from 6-min. periods to 1-min, or shorter. The 5-min. oscillations show up as modes and the low frequency power can be identified as the signature of stochastic processes.

KALKOFEN: The k-ω diagram may be too blunt a tool for studying waves in bright points, which have small size (≈ 2") and filling factor ($\lesssim$ 10%). In addition, the 3-min. "waves" are not sinusoidal oscillations but consist of (unequal) pulses separated by 3 minutes.