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STRUCTURE AND DYNAMICS OF THE SOLAR CHROMOSPHERE

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Structure and Dynamics of the Quiet Solar Chromosphere

The problem of chromospheric dynamics and heating consists of two problems: one, concerning the magnetic network on the boundary of supergranulation cells (CB), where the oscillation period is seven minutes, and the other, concerning the cell interior (CI), where the oscillation period is three minutes. The observational data on the oscillations and the emission of radiation can be used to determine the structure and dynamics of the atmosphere provided answers are known to three critical questions, concerning
the nature of the waves powering the bright points,
the origin of the observed oscillation periods and
the mechanism of chromospheric heating.

The recent modeling of the dynamics of the CI by Carlsson & Stein (1994; hereafter CS94), which combines a sophisticated treatment of gas dynamics and radiative transfer in a one-dimensional model with empirical velocity input from the observations by Lites, Rutten & Kalkofen (1993; hereafter LRK93), answered the first of these questions: the waves powering K_{2v} bright points are propagating acoustic waves. This firm conclusion declares invalid the model of Leibacher & Stein (1982, cf. also Deubner 1995), which explains the observed period with standing acoustic waves in a chromospheric cavity. The CS94 model achieves excellent agreement with the H line profile observed by LRK93, but it cannot account for the heating of the medium.

On the question of the origin of the wave period, the CS94 model gives no information since the driving of the waves is empirical.

On the third question, the heating of the chromosphere in the CI, their model predicts that the temperature in the chromosphere is declining in the outward direction up to a height of at least 1 Mm most of the time, so even the time-average temperature is dropping monotonically in the outward direction, implying that lines formed in the chromosphere up to a height of at least 1 Mm appear in absorption most of the time and everywhere in the CI. The observations by Carlsson, Judge & Wilhelm (1997) with SUMER, however, show only emission lines, all the time and everywhere in the chromosphere. These observations therefore require a permanent, monotonic temperature rise in the outward direction, similar to that of the empirical model of Vernazza, Avrett & Loeser (1981).

The problem of the CI can be resolved with a two-component model (Kalkofen 1998), which combines a model for K_{2v} bright points with a model for the background. The bright point model (Kalkofen 1996) has the same aims as the CS94 model, except that the empirical driving from the LRK93 observations is replaced by impulsive excitation, as suggested by the properties of the Klein-Gordon equation (Lamb 1909, Rae & Roberts 1982, Kalkofen et al. 1994). The model for the background is virtually identical to Ulmschneider's models (Ulmschneider 1971, cf. also Theurer, Ulmschneider & Kalkofen 1997) except that it is called upon only to provide the background heating that causes the permanent temperature inversion, and not also to produce the distinct bright points.

In the background model, short-period acoustic waves generated by the turbulence of the convection zone (Stein 1968) form shocks in the chromosphere, beginning at the temperature minimum, and they heat the atmosphere. The argument in favor of this form of heating is that the density dependence of the radiative emission rate from the chromosphere (Anderson & Athay 1989) matches the shock dissipation rate of weak shocks (Ulmschneider 1970); both are proportional to mass density. Note also that short-period acoustic waves have their peak power at frequencies above 10 mHz, where the observations of LRK93 see only noise. These waves are therefore not present in the CS94 model and cannot be available for empirical driving. A discussion of this two-component model for publication is in preparation.

The magnetic network on the CB poses the problem of waves with a period of seven minutes and the question of the heating of the chromosphere. It was noted that acoustic waves with a period of seven minutes are evanescent and transport no energy in the linear wave regime, but internal gravity waves are allowed since this wave period is longward of the Brunt-Väisala period, where such waves are propagating. It was therefore supposed that the seven-minute waves were internal gravity waves (e.g. Damé 1983, Lites 1984); Lou (1995) showed that the chromospheric temperature structure allowed the wave periods observed by LRK93 as resonances. Deubner & Fleck (1990) proposed a heuristic model to explain the heating of the chromosphere by such waves. But Kalkofen (1997; hereafter K97) showed that their mechanism did not lead to the expected wave amplification and therefore was not viable.

The data that have to be explained by a model for the dynamics and structure of the CB chromosphere are the power spectrum of the Ca II lines in the chromosphere and the velocity coherence spectrum between the base and the middle of the chromosphere (LRK93 Figs. 6 and 7). Following the investigation of Choudhuri, Auffret & Priest (1993), K97 achieves agreement with the LRK93 observations with a model based on impulsive excitation of transverse waves in magnetic flux tubes, propagation upward into the chromosphere and conversion to longitudinal magneto-acoustic waves, and dissipation by shock formation.

The model (K97) assumes that only the lowest wave period in the spectrum of waves in the magnetic network needs to be explained, with a period of seven minutes. This assumption is borne out be recent observations with SUMER (Curdt & Heinzel 1998), which show only oscillations in the range of 6.9 to 7.6 minutes. This period is explained in the model as the cutoff period of transverse waves. An assumption made in the paper (K97) is that the wave excitation in the photosphere gives predominantly transverse waves; longitudinal waves are excited with much lower efficiency. This supposition is confirmed by a theoretical investigation (Hasan & Kalkofen 1998).

The picture that emerges from work performed with the support of the NASA grant is that the heating of the chromosphere is due to waves, and that the observed 3-minute and seven-minute periods are the cutoff periods of those waves.

In the CI, the three-minute waves are acoustic waves, both for the K_{2v} bright points and for the background. In the bright points, the three-minute period is due to impulsive excitation, and in the background, to stochastic excitation. In the CB, the seven-minute period is the cutoff of impulsively excited transverse flux tube waves, which couple to longitudinal waves after becoming nonlinear in the upward propagation in the stratified atmosphere.

While the view expressed in my work cited in this report may not yet have found universal acceptance, there is little doubt that the nature of the waves is correctly described. But the mechanism by which the oscillations are excited requires further theoretic study, simulations, and observations to confirm the conclusions.

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CHROMOSPHERIC OSCILLATIONS IN K_{2v} BRIGHT POINTS

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ABSTRACT

The 3 minute waves observed in K_{2v} emission from bright points in the quiet solar chromosphere are shown to be oscillations of the atmosphere at the cutoff period of acoustic waves, implying impulsive excitation. Other interpretations of the period are shown not to be viable since they fail the dual requirement of spatial intermittence, in which most of the supergranulation cell interior is inert over the course of an hour, and temporal intermittence, in which the active locations in the cell interior are active at most half the time. It is speculated that the episodic excitation of the K_{2v} oscillations is due to collisions of granules with magnetic elements of mixed polarity with a field strength of at least 0.5 kG.

Subject headings: Sun: chromosphere — Sun: magnetic fields — Sun: oscillations — waves

1. INTRODUCTION

Chromospheric waves that are visible in emission features of the H and K lines of Ca II arise in two different regions of the quiet Sun and show different radiative signatures as well as different temporal behavior; they are, therefore, presumably different in nature, although perhaps not in the manner of excitation. The emission regions are referred to as K_{2v} bright points and network bright points. The K_{2v} bright points are located in the interior of supergranulation cells (CI), and the network bright points in the magnetic network on the cell boundaries (CB). The periods observed in the K_{2v} bright points are mainly near 3 minutes but range from 2 to 5 minutes, those in the network range from 6 to 15 minutes.

Early observations that have identified the 3 minute oscillation period in K_{2v} bright points are by Jensen & Orrall (1963) and Orrall (1966) for the K_3 absorption feature of the K line, by Liu (1974) for the K_{2v} emission feature, by Bhatnagar & Tanaka (1972) for the Hα line, and by Simon & Shimabukuro (1971) for the 3 mm and Yudin (1968) for the 3 cm free-free continua (for a more extensive discussion of early observations, cf. Kalkofen 1992). The problem of the oscillations in K_{2v} bright points is thus one of long standing, and it is believed also to be connected to the heating of the solar chromosphere (cf. Ulmschneider et al. 1977).

The 3 minute wave period has been explained by different physics (for references earlier than those given, cf. the papers listed below): Deubner (1995) sees them as standing acoustic waves in a chromospheric cavity (cf. Leibacher & Stein 1981); von Uexküll & Kneer (1995, henceforth UK) regard them as chance superpositions and beats of modes forming the extension of the global solar 5 minute p-modes to shorter periods where the chromospheric cavity presumably selects the period; Rutten (1995) interprets them as accidental events analogous to white caps on the surface of a body of water; Rammacher & Ulmschneider (1992) simulate them as propagating acoustic waves that are emitted in the convection zone as a spectrum of waves with periods generally below 40 s by means of the Lighthill mechanism and are transformed into 3 minute waves by means of shock merging; Kalkofen et al. (1994) view them as propagating acoustic waves formed as the consequence of impulses to unspecified structures in the CI, which result in oscillations of the atmosphere at the acoustic cutoff period; and Carlsson & Stein (1995) model them as propagating acoustic waves with the piston motion taken from observations.

The various descriptions of the period represent incompatible physical realities. It is likely that K_{2v} bright points constitute a single phenomenon. The correct explanation can be sorted out only by observations. I discuss the implications of some recent observations for the nature of the bright point waves in § 2, argue the case for a connection with magnetic fields in § 3, and draw conclusions in § 4.

2. CELL INTERIOR BRIGHT POINTS

A statistical analysis by UK of K-line observations shows that K_{2v} bright points occur in the span of 1 hr in only 20% of the CI area—bright points are defined here as emission with an intensity of the K_{2v} emission peak that exceeds the average K_{2v} intensity in the CI by at least 30% (threshold $I_{max}/\bar{I} = 1.3$); thus 80% of the CI is inert at this amplitude level. The average location in the CI, which includes both active and inert areas, shows K_{2v} emission 5%–10% of the time (for the higher threshold of 1.5). Referring the emission to the active 20% of the area alone, K_{2v} emission occurs 25%–50% of the time or perhaps somewhat more often at the lower threshold of 1.3. The confinement of the emission to particular locations is also evident in the Fourier transform of a filtergram series spanning 1 hour by Damé (1984), which shows that oscillatory power in certain frequency bands is not distributed uniformly but is found only at well-defined positions. The restriction of the emission to a fraction of the CI is also implicit in the small number of bright points in a supergranulation cell (cf. Brandt et al. 1992). These data provide selection criteria for theories of bright point waves.

Consider the chromospheric cavity. It is formed by the temperature structure of the outer solar atmosphere. Since the temperature rises everywhere steeply into the photosphere on one side and the high chromosphere on the other, the cavity and its oscillations ought to be present everywhere and all the time. It is already difficult to argue that the cavity should be modified above the magnetic network (cf. Deubner & Fleck 1990) in order to explain the absence of the 3 minute waves and to accommodate the much longer wave periods seen in the network; at least in the CI, the cavity should make itself felt throughout. But the observations of UK show that only a small fraction of the CI is active and even the active locations are quiet at least half the time. The cavity model does not explain these aspects—nor does it explain why the temperature in the chromosphere rises in the outward direction.

Other theories of the bright point phenomenon that fail to account for the localization of the bright points are those based on beats and superpositions and on the analog of white caps on the ocean, as well as the wave generation that relies on the Lighthill mechanism. UK note that their observations show a rich and varied behavior of the intensity and point out that this is incompatible with the predictions by the impulse model of monotonic decay of the velocity amplitude following an excitation (more about the impulse model below).

The only model left is that of Carlsson & Stein (1995). It is successful in predicting the behavior of the H_3 absorption minimum in the core of the H line observed by Lites, Rutten, & Kalkofen (1993) from the corresponding motion of a photospheric Fe I line. Since the calculation is based on propagating acoustic waves, it provides a further, and conclusive, argument against the standing wave picture in the chromospheric cavity and related explanations. But the model does not test a theory of wave generation since the excitation of the oscillations is based on the observed motion of a photospheric layer immediately below the bright point, and it does not address the question of area coverage since the simulation is based on plane waves.

A critical test for a successful theory of oscillations in K_{2v} bright points is to explain Liu's (1974, his Fig. 7) histogram of wave periods observed by the times of maximal brightening of the K_{2v} emission peak. The histogram shows a broad distribution of repetition times, conventionally called periods, which has its maximum at approximately 3 minutes but extends from 2 minutes to more than 5 minutes. I begin with a discussion of wave propagation in a stratified medium to arrive at a statement about expected wave periods, consider their modification by actual conditions in the solar atmosphere, and then discuss the observations by UK of the K_{2v} intensity variations against the background of the theory.

The propagation of small disturbances in a one-dimensional, isothermal, gravitationally stratified atmosphere without (and with) a magnetic field is described by the Klein-Gordon equation (cf. Rae & Roberts 1982); solutions for the velocity of upward traveling waves increase exponentially, with an e-folding distance of twice the density scale height. The waves are propagating if the periods are shorter than the acoustic cutoff period, and evanescent if they are longer.

Lamb (1908, 1932) obtained a solution of the wave equation for a velocity impulse imparted to the atmosphere at some height. The impulse provides broad-band excitation, with a spectrum given by $\omega/(\omega^2 - 1)^{1/2}$, for $\omega \geq 1$, where $\omega = 1$ is the cutoff frequency of the atmosphere (cf. Kalkofen et al. 1994; e.g., their Fig. 4). Behind the initial disturbance, the atmosphere oscillates at the acoustic cutoff period. Asymptotically (with time) the oscillation is described by a sine function that decays with time and whose period is the acoustic cutoff period. A histogram of wave periods constructed for this solution is essentially a δ-function at the acoustic cutoff.

Since acoustic waves increase exponentially in amplitude as they travel upward, the disturbances form shocks in which the behavior of individual waves is modified by the previous history of the atmosphere. In numerical simulations for an atmosphere initially at rest, the wave amplitude after the first peak still decays in a monotonic manner. A histogram of wave periods for this case shows a distribution that is broader than that of the analytic solution, but still much narrower than Liu's.

An extension of the histogram to shorter periods arises from oscillations in which an impulse kicks the atmosphere before it has come to rest following the preceding excitation, and the extension to longer periods probably occurs only from relatively short intervals of rest between excitations. The extended intervals, which for the threshold value of $I_{max}/\bar{I} = 1.5$ for the excess intensity can amount to 20 minutes or more, are easy to recognize as gaps and have not contributed to the histogram.

The data of UK (their Fig. 2) show that for well-developed oscillations at the locations of K_{2v} bright points, the period is close to the acoustic cutoff period. Selecting from the periods listed by UK all those covering two or more consecutive oscillation intervals, there are 26 such intervals in eight sequences of 2 to 5 intervals per wave train. The periods range from 150 s to 188 s, and their average is 166 s $\pm$ 10 s. The various oscillation sequences are close to this average: the two sequences of two adjacent intervals give an average of 176 s, the four sequences of three intervals give 166 s, and the two sequences of 5 intervals give 162 s. The average period is shorter than the acoustic cutoff period. This is plausible, however, since the average is affected by excitations that occurred while the atmosphere was still moving, but probably not by gaps between excitations.

Thus, the explanation of K_{2v} bright points in terms of impulse-generated oscillations at the acoustic cutoff period provides an understanding of the value of the period at the maximum of the histogram and of its general shape. The questions not addressed by the above analysis concern the agent of the impulse and the target.

3. CONNECTION BETWEEN BRIGHT POINTS AND MAGNETIC FIELDS

A small number of bright points, one to two dozen per supergranulation cell (Brandt et al. 1992), is distributed among hundreds of granules, which have a mean life time of 5–10 minutes for average granules (Wittmann 1979) and 2–3 minutes for small ones (Muller & Roudier 1992). Thus, in the span of an hour the appearance of the CI changes completely. Yet K_{2v} bright points remain confined to particular locations covering only a small fraction of the area. This remarkable location stability in a dynamic and highly variable medium suggests that bright points are anchored. A plausible explanation is that bright points are associated with magnetic elements.

The question of a relation between CI bright points and magnetic fields has been addressed by Sivaraman & Livingston (1982). Their conclusion of a one-to-one association of bright points and magnetic elements has never been confirmed, but it is made plausible by the often observed location of bright points over intergranular lanes (Sivaraman, Bagare, & November 1990; cf. also Suemoto, Hiei, & Nakagomi 1990) and by the concentration, seen in numerical convection simulations (Steiner 1995), of magnetic field lines in positions that may correspond to intergranular lanes. It is also consistent with recent Big Bear estimates of the density of CI magnetic fields (Wang et al. 1995). These estimates appear to imply, however, that only about half the magnetic elements produce a bright point.

The fact that the numbers of CI magnetic elements and of bright points agree within a factor of 2 supports the hypothesis that they are related. A difference of the two numbers is expected if magnetic elements can become visible as bright points only when the magnetic field strength exceeds a threshold value, or when the census of bright points is taken over a time interval that is shorter than the gaps between large-amplitude oscillatory behavior; for the intensity threshold of 1.5, the gaps implied by the UK data on the temporal filling factor of oscillations in the active part of the CI vary considerably but appear to be on average about 20 minutes long.

An important question concerns the magnetic field that can serve as the source point for the 3 minute waves in K_{2r} bright points. It is clear that its properties cannot be the same as those of the magnetic network, where the field is concentrated in more or less vertical tubes of intense magnetic flux with a field strength of approximately 1.5 kG (Rüedi et al. 1992; Stenflo 1994). Otherwise we should observe the same long-period waves as those of the network, and no 3 minute waves. On the other hand, the field must be much stronger than that measured by Stenflo (1982) by means of the Hanle effect, which is diffuse and has a strength of only a few gauss; such a field is dynamically unimportant.

We estimate the minimum field strength by demanding that the contributions to the momentum equation by a magnetic element as the presumed target and a granule as the presumed projectile be comparable. Starting with the equation in the form of horizontal pressure equilibrium of a completely evacuated flux tube with field strength $B_{\rm eq}$ embedded in an external medium with gas pressure $p_{\rm ext}$, the balance equation is $B_{\rm eq}^2/8\pi = p_{\rm ext}$. For the momentum equation in the CI we equate the magnetic pressure exerted by the element with field strength B and the dynamical pressure exerted by the granule with velocity v. Using the definition of the sound speed, a, in order to eliminate the density we obtain the equation $B/B_{\rm eq} \approx v/a$ from which we can estimate the minimum field strength of the magnetic element.

The speed of supergranular flow is of the order of 0.5 km s^{-1} (e.g., Muller et al. 1994). We may suppose that the typical speed of granules is approximately the same. Collisions among granules of that speed may well be responsible for the low-amplitude oscillations that are seen practically everywhere in the CI; these oscillations indicate with their typical period of 3 minutes (cf. UK, their Fig. 3) that they, too, are generated impulsively. But collisions among granules are far too numerous to satisfy the observational constraints of spatial and temporal intermittence. It is much more likely that the collisions that give rise to bright points are caused by granules moving with speeds of 1–2 km s^{-1} or even 3 km s^{-1} (Muller et al. 1994), i.e., the speed of network bright points on the CB whose excitation is presumably due to collisions of such granules with magnetic flux tubes (Muller & Roudier 1992). Since these large velocities are of the order of one-third of the sound speed, the magnetic field strength required for K_{2r} bright points should be of the order of one-third of the field strength of completely evacuated flux tubes, i.e., approximately 0.5 kG in the photosphere. Magnetic fields of this strength in the CI have been measured by Keller et al. (1994), Lin (1995), and Grossmann-Doerth, Keller, & Schüssler (1996). Unlike the network fields, which appear in the form of more or less vertical magnetic flux tubes, the CI fields appear as clusters of mixed polarity (Wang et al. 1995). Fields with a strength of at least 0.5 kG are dynamically important in the turbulent environment of moving granules and could serve as the foot points of chromospheric waves.

The waves that are excited at the sites of the CI magnetic field elements are presumably longitudinal magneto-acoustic waves in magnetic flux tubes, although, depending on the field topology, the possibility that they are pure acoustic waves cannot be excluded. Note that both modes have nearly the same cutoff period (Spruit 1981). If the waves are longitudinal tube waves, the topologies of the magnetic fields in the CI and of the tightly bunched magnetic flux tubes on the CB must differ significantly in order to explain the absence in the CI of the long-period oscillations observed in the network bright points (cf. Lites et al. 1993, their Fig. 6). Thus, only longitudinal magneto-acoustic waves must be excited in the CI, and not also transverse magneto-acoustic waves as on the CB (cf. Kalkofen 1996). A plausible magnetic field structure with the required properties has the field lines diverging rapidly in the upper photosphere, a feature that is favored by the predominantly mixed polarity observed in the magnetic elements and the paucity of CI fields. However, such a field structure could not guide and confine the waves, as expected on the CB; instead, the channeling would depend on the properties of upward propagating waves in a stratified atmosphere (cf. Kalkofen 1991). Observationally, the two longitudinal wave modes may be indistinguishable.

There is thus circumstantial evidence linking K_{2r} bright points and magnetic elements. In addition to the features mentioned above, there is other consistent behavior: both bright points and magnetic elements are carried by the supergranular flow, both have the same typical lifetimes of a few hours, and both are independent of the 11 yr solar activity cycle. The ultimate test, of course, will be direct observational confirmation of the connection between bright points and magnetic field elements.

4. CONCLUSIONS

The 3 minute waves observed in the K_{2r} bright points located in the interior of supergranular cells are oscillations of the atmosphere at the cutoff period of acoustic waves. The data indicate episodic, impulsive excitation.

Other theories of K_{2r} bright points, such as those based on a chromospheric cavity or on the Lighthill mechanism of sound generation, are untenable since they cannot account for two kinds of intermittence exhibited by bright points: spatial intermittence, in which a large part of the cell interior is inert; and temporal intermittence, in which the active locations in the cell interior experience long periods of inactivity.

It is speculated on the basis of the location stability of K_{2r} bright points, the approximate equality of the numbers of bright points and magnetic elements, and the agreement between estimated and measured magnetic field strengths that the foot points of the bright points coincide with magnetic fields, perhaps of mixed polarity, with a strength of at least several hundred gauss. It may therefore by expected that the 3 minute waves that are excited at the sites of the magnetic elements are longitudinal magneto-acoustic flux tube waves, although this would depend on the topology of the magnetic field.

If the postulated connection between K_{2r} bright points and magnetic fields exists, the bright points can serve as convenient tracers of these cell-interior magnetic fields.

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OSCILLATIONS IN CHROMOSPHERIC NETWORK BRIGHT POINTS

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ABSTRACT

Intensity oscillations observed in the H and K lines of Ca II in network bright points in the quiet Sun are interpreted in terms of transverse and longitudinal magnetoacoustic waves propagating upward inside magnetic flux tubes. It is supposed that the waves are generated impulsively in the photosphere as transverse waves. As they propagate upward, their velocity amplitude increases exponentially until they become nonlinear in the chromosphere, where they transfer power to longitudinal waves. The impulsive generation produces waves at the cutoff frequency of transverse waves. On the assumption that this frequency signature is transferred to the longitudinal waves, the magnetic field strength implied by the period observed in the chromosphere is consistent with the Zeeman effect observed in the photosphere.

Subject headings: Sun: chromosphere — Sun: magnetic fields — Sun: oscillations — waves

1. INTRODUCTION

The chromosphere in the quiet Sun as shown by the H and K lines of Ca II is structured by magnetic fields, revealing supergranulation cells (see Damé 1984, Fig. 4) and differentiating between cell boundary (CB) and cell interior (CI). The two regions differ in dynamical behavior and spectroscopic signature: in the magnetic network on the CB, the periods of oscillation of the atmosphere are much longer, the maxima of the emergent intensity in the H and K lines are more extended, and the line profiles are less asymmetric, with lower prominence of the blue emission peaks K_{2V} and H_{2V}, than in the CI. This suggests that the physics of the phenomena on the boundary differs from that in the interior of the supergranulation cells.

In the network bright points (NBPs) on the CB, the periods of oscillation, typically near 7 minutes, are longward of the acoustic cutoff period and of the Brunt-Väisälä period; both are near 3 minutes in the upper photosphere. At the observed periods, acoustic waves are therefore evanescent and transport no energy. Internal gravity waves, on the other hand, are allowed to propagate and are able to transport energy. Some observers therefore consider the waves in the magnetic network to be internal gravity waves (Damé 1983, 1984; Damé, Gouttebroze, & Malherbe 1984; Lites 1984; Deubner & Fleck 1990; Kneer & von Uexküll 1993). In order to provide a theoretical underpinning for this hypothesis, Lou (1995a, 1995b) investigated the periods observed in NBPs and found them to be plausible for magnetogravity waves in an atmosphere with the temperature structure of the empirical model of Vernazza, Avrett, & Loeser (1981).

A detailed heuristic picture of NBPs was drawn by Deubner & Fleck (1990), who found the phase velocity of waves in the intensity of chromospheric lines to be directed upward (see, however, Kneer & von Uexküll 1993). On the assumption that the waves are internal gravity waves, their dispersion relation implies that the group velocity is directed downward. Thus, in this scenario, energy is transported from the chromosphere toward the photosphere, i.e., in the direction opposite the one demanded by physical intuition.

An awkward feature of heating by downward-propagating waves is that the energy must first be transported upward into the chromosphere above the layer of formation of the H and K lines and probably also above the layer of formation of the h and k lines of Mg II—and that without significant dissipation. To carry the energy from its source in the photosphere or convection zone to the chromosphere, Deubner & Fleck imagine collection and upward transport of mechanical energy from long-period motions in the interior of supergranulation cells. At chromospheric heights, but still in the CI, the energy is to be transferred to magnetogravity waves, which then travel into the magnetic flux tubes on the CB, where the narrowing magnetic funnels are presumed to increase the wave amplitude, leading to dissipation.

This picture lacks specificity as far as energy generation, propagation, transformation, and dissipation are concerned. But its principal defect is the postulated growth of the velocity amplitude in the downward propagation because of the geometrical decrease of the cross section of the flux tubes, which must be balanced against the countervailing tendency of decay of the velocity because of the density stratification of the atmosphere. Consider the slender-tube approximation for an isolated, vertical flux tube in a gravitational field: the energy flux density is independent of height, and both the tube diameter and the velocity amplitude decrease downward with an *e*-folding distance of four scale heights in order to compensate for the exponential increase in the mass density with an *e*-folding distance of one scale height. Thus, instead of an increase downward, the velocity amplitude suffers a decrease downward, making dissipation of the putative magnetogravity waves impossible. Although the topology of the magnetic field in the chromosphere differs considerably from that of a thin magnetic flux tube, it is unlikely that this helps the argument of the gravity wave scenario.

This Letter discusses a different model of oscillations in NBPs. It assumes impulsive generation of transverse magnetoacoustic waves in the photosphere, propagation upward with exponential growth of the amplitude, transfer of power to longitudinal magnetoacoustic waves in the nonlinear regime, and dissipation in the chromosphere. Critical properties of the model are consistent with observations, and extant numerical modeling lends support, but important features require further investigation.

Previous papers on chromospheric oscillations addressed the problem of the K_{2V} bright points in the CI (Kalkofen 1996a) and of the quiet background in the CI (Theurer, Ulmschneider, & Kalkofen 1997). The present Letter concerns the bright points in the magnetic network on the CB. Section 2 examines the properties of magnetoacoustic waves and tests predictions against chromospheric observations, § 3 discusses the estimate of the magnetic field strength from observed oscillation periods, and § 4 suggests observational tests of the model.

2. WAVES IN MAGNETIC FLUX TUBES

A basic observed feature of waves in the magnetic network on the CB is seen in the velocity power spectrum of H_3 (Fig. 6 in Lites, Rutten, & Kalkofen 1993, hereafter LRK93), which shows peaks at 400 s, 550 s, and 1100 s. The longest period, at nearly 20 minutes, and possibly the peak at 9 minutes, may be artifacts due to the observational window since the observation time of 1 hr is only a small multiple of these periods. I therefore assume that the period to be matched by a theory is the one at 400 s only. Similar remarks apply to the periods observed by Damé (1984) in the K line at 300 s, 375 s, 500 s, and 750 s. The 300 s period can probably be identified with the solar 5 minute oscillations. Thus, the periods to be explained by a theory are 400 s and 375 s.

A magnetic flux tube supports three kinds of body waves, namely, torsional waves and transverse and longitudinal magnetoacoustic waves. The torsional waves are not dispersive and hence are propagating for any period. The two magnetoacoustic waves are dispersive; they are propagating when their periods are shorter than their respective cutoff periods and are evanescent when the periods are longer. The cutoff periods are $P_\lambda = P_{ac}[(60 + 50\beta)/(63 + 48\beta)]^{1/2}$ for the longitudinal wave (also called sausage mode), and $P_\kappa = P_{ac}[2\gamma(1 + 2\beta)]^{1/2}$ for the transverse wave (kink mode), where $P_{ac} = 4\pi H/a$ is the acoustic cutoff period, H is the pressure scale height, a is the sound speed, γ is the ratio of specific heats (5/3 in P_λ), and β is the dimensionless pressure ratio $\beta = 8\pi p/B^2$, where p the gas pressure inside the magnetic flux tube and B is the strength of the magnetic field (Spruit & Roberts 1983).

The propagation of magnetoacoustic waves in a thin flux tube embedded in a one-dimensional, isothermal, stratified atmosphere and that of plane acoustic waves in the field-free medium are described by the Klein-Gordon equation (Rae & Roberts 1982). The solution for impulsive excitation of acoustic waves was given by Lamb (1909, 1932). Solutions for the impulsive excitation of either of the magnetoacoustic waves are formally the same; the additional requirement on the medium is that the value of the plasma β be height independent, which is satisfied for the weaker condition of a horizontally uniform temperature. After an excitation, the head of the wave travels at the tube speed; it is followed by a wake oscillating at the cutoff period (Spruit & Roberts 1983). In general, only waves with periods that are short compared with the cutoff period travel at the tube speed. For the longitudinal mode, the tube speed is $c_\lambda = a[2/(2 + \gamma\beta)]^{1/2}$, and for the transverse mode, $c_\kappa = a[2/\gamma(1 + 2\beta)]^{1/2}$. Both waves satisfy the dispersion relation $\omega^2 = k^2 - 1$, where ω is the wave frequency, k is the wave number, and unity represents the cutoff frequency in dimensionless units.

A criterion for a wave as a plausible cause of NBPs is that it provide an explanation for observed spectral features. Now, torsional waves have no distinctive frequency signature, nor do they show Doppler motion at disk center. Such waves can therefore probably be excluded as candidates. For longitudinal waves, the distinctive feature is the cutoff period, P_λ. Although P_λ depends on the strength of the magnetic field, it never deviates by more than 2% from the acoustic cutoff period, P_{ac}, which is equal to 3 minutes in the solar atmosphere. At a period of 7 minutes, longitudinal waves are therefore evanescent, and at 3 minutes, the observed signal is barely distinguishable from noise (LRK93, Fig. 6). These waves can therefore also be excluded as candidates. Finally, transverse waves do not produce a Doppler signal at disk center and thus remain invisible in the power spectrum, unless the wave amplitude is large. But in that case, the flux tube oscillations show a small Doppler displacement every time the tube reaches maximal excursion, i.e., twice each wave period. Hence, the wave period is twice the observed period, i.e., 14 minutes, and the corresponding value of the plasma β is equal to 2.5. For such a large value of β, i.e., such a weak magnetic field, a flux tube is convectively unstable (Spruit and Zweibel 1979); furthermore, a typical value of β in the network is 0.3 (Stenflo 1994). Thus, all magnetic wave types are eliminated as candidates for *directly* producing the power spectrum observed in the chromosphere.

A second criterion to be satisfied by candidate waves is seen in the velocity coherence spectrum (LRK93, Fig. 7), which measures the transmission of wave energy from the layer of formation of the Ca I line at 4227 Å at the base of the chromosphere to the H_3 layer in the middle chromosphere. At 7 minutes, the phase coherence in the CB is hardly distinguishable from noise. Thus, the longitudinal waves seen in the Doppler displacement in the middle chromosphere do not originate from longitudinal waves entering at the base.

A possible scenario satisfying the observational constraints is suggested by the work of Muller & Roudier (1992) and Muller et al. (1994), who observed NBP formation by collisions of fast granules with magnetic flux tubes. The collisions repeat on a timescale of 7 minutes, and the resulting NBPs have a lifetime of 18 minutes. A typical bright point shows a sudden enhancement of the emitted white light intensity and fades gradually following the initial or repeated excitations. Such collisions could generate transverse waves that would couple to longitudinal waves upon growing to high amplitude in the chromosphere (Kalkofen 1996b). The longitudinal waves would form shocks and thereby heat the chromosphere.

Choudhuri, Auffret, & Priest (1993) modeled the scenario suggested by Muller & Roudier as the collision of a fast granule with a vertical magnetic flux tube in a study of coronal heating. Copious amounts of wave energy were generated only by fast granules with speeds of 2 or 3 km s^{-1}. A collision excited transverse magnetoacoustic waves, but only for short duration of the interaction; for long-duration collisions the flux tube was merely displaced laterally. The time separating the two regimes was half the cutoff period of the waves. The numerical study showed that a fast collision causes the flux tube to sway at the cutoff period of transverse magnetoacoustic waves and that much of the wave energy is in short-period components.

The physics of the collision is described by the Klein-Gordon equation. Its solution for impulsive wave excitation (Lamb 1909) shows a velocity spectrum at the generation site with a high peak at the cutoff and much energy at shorter periods (Kalkofen et al. 1994, Fig. 8), in agreement with the simulations of Choudhuri et al. (1993).

After an excitation, the waves travel upward in the atmosphere, and their velocity amplitude, v, increases as $\exp(z/4H)$ in the thin-tube approximation. When v becomes comparable to the tube speed c_κ, they couple to longitudinal magnetoacoustic waves (see, e.g., Ulmschneider, Zähringer, & Musielak 1991) and transfer power to them. The interaction of the two modes is facilitated when the two tube speeds are comparable; they are equal, $c_\lambda = c_\kappa$, when $\beta = 0.2$ (see § 3 for β from observed P_κ). One might expect the nonlinear wave interaction to favor equipartition of the energy so that large amounts of energy can be transferred. Since the longitudinal mode can form shocks, which dissipate the energy, the coupling ensures an ample source of energy for heating the medium as long as the primary wave has not exhausted its supply.

In the photosphere, the waves travel as transverse waves and are therefore invisible in the Doppler effect at disk center. After coupling to longitudinal waves in the chromosphere, they become observable in the Doppler effect. Although the inhomogeneity of the medium would allow wave coupling, this must be minimal even at the base of the chromosphere in order to be consistent with the low phase coherence of about 0.2 between the Ca I line and the H_3 absorption minimum (LRK93, Fig. 7).

This scenario satisfies the observations if (1) the collisions of granules with flux tubes in the photosphere generate transverse waves but practically no longitudinal waves, (2) the transfer of energy occurs when the transverse waves reach the middle chromosphere, and not earlier, and (3) the signature of transverse waves, their cutoff period P_κ, is preserved in the mode coupling. (1) The apparent absence of longitudinal waves at the base of the chromosphere is consistent with numerical simulations of the excitation of magnetoacoustic waves that gave energy fluxes in transverse waves (Huang, Musielak, & Ulmschneider 1995) that were larger than those in longitudinal waves (Ulmschneider & Musielak 1997) by an order of magnitude. Although these authors considered wave generation only for a turbulent velocity spectrum, it seems plausible that the transverse modes would be favored also by impulsive wave generation. (2) The energy flux of transverse waves at the generation site in the photosphere must meet the dual condition of giving a velocity amplitude that is sufficiently low at the base of the chromosphere to be in the linear regime and sufficiently high in the middle chromosphere to lead to nonlinear wave coupling and dissipation. The rough energy estimate provided by Choudhuri et al. (1993) satisfies the former though not quite the latter, at least in the slender-tube approximation. But at some height in the atmosphere, the packing of flux tubes must limit their spreading, and then the assumption of constant tube cross section is a better approximation. For that case, the e-folding distance of the velocity amplitude is $2H$ instead of $4H$, with an increase of v in the layer of formation of H_3 by as much as a factor of 4 if we assume the tube cross section to be constant in the layers above the base of the chromosphere. The resulting velocity amplitude is then sufficiently high to be in the nonlinear regime. (3) For the wave coupling in the nonlinear regime, Ulmschneider et al. (1991) found that monochromatic transverse waves of period P_k transferred energy mainly to longitudinal waves of half the period, $P_l = P_k/2$, but also some energy, though much less, to waves with the period $P_l = P_k$. Thus, the signature of transverse waves, their cutoff period P_κ, would be preserved in the transfer. We may therefore identify a peak in the power spectrum of the longitudinal waves in the chromosphere with the cutoff period of the primary, transverse waves.

A puzzling difference between K_{2V} bright points and network bright points is that the temporal evolution of the emergent H-line intensity from NBPs does not show sharp peaks but extended maxima (see LRK93, Fig. 2). This behavior may have several causes. (1) The nonlinear wave coupling is inherently noisy, generating extraneous signals, as seen, for example, in the choice of transfer of energy to waves at the same period or half the period. (2) Since the presumed cutoff period P_κ is longer than twice P_λ, a longitudinal wave at the period $P_l = P_\kappa/2$ will still be in the evanescent range of longitudinal waves. For such an excitation, additional wave periods appear in the spectrum (Kalkofen et al. 1994, Fig. 12). (3) Upward traveling waves in the flux tube form oblique shocks (Zhugzhda, Bromm, & Ulmschneider 1995). The arrival time of a wave at a particular height is therefore spread across the flux tube, resulting in a spreading of the original signal.

Another feature of NBPs is the absence in the middle chromosphere of waves with periods much below the cutoff period in spite of their presumed presence in the photosphere. The reason may be the same as for K_{2V} bright points, where short-period waves are observed in the photosphere (Carlsson & Stein 1994, 1997) but are not found in the chromospheric spectrum (Liu 1974; LRK93, Fig. 6), namely, preferential dissipation of short-period components in shocks and escape toward the top of the atmosphere.

3. THE MAGNETIC FIELD STRENGTH

Since the cutoff period of transverse magnetoacoustic waves depends on the plasma β in the excitation layers, the chromospheric power spectrum reveals the strength of the photospheric magnetic field. However, the equations cited above apply only to idealized conditions, which do not obtain in the solar atmosphere, where both the temperature and β depend on height.

Although the temperature dependence of P_κ is weak since it enters as $\sqrt{T}$ via the acoustic cutoff period, P_{ac}, the temperature variation in the photosphere is large. The value of P_{ac} will therefore correspond to an average value of T (Sutmann & Ulmschneider 1995). For the estimate of β it seems reasonable to take P_{ac} from observations of acoustic waves in K_{2V} bright points in the CI, where P_{ac} is equal to 3 minutes (Liu 1974), recognizing that the temperature in the CB may be different from that in the CI.

A constant value for the pressure ratio β does not require the temperature in the atmosphere to be constant throughout; it is sufficient that it be constant in horizontal layers, i.e., inside the flux tube and in the surrounding atmosphere. This property is found for idealized flux tubes that are very thin, i.e., whose diameter is much smaller than the pressure scale height and the photon mean free path in the tube (Kalkofen et al. 1986). Both conditions are approximately satisfied for the strong flux tubes in the network, where the estimated diameter is 100 km (Lin 1995), although empirical modeling shows a modest temperature difference between flux tubes and the ambient medium, but mainly in the upper photosphere (Keller et al. 1990), where it matters less for P_κ.

Ignoring the uncertainties in T and β, the values obtained from the relation between P_κ and β are $\beta = 0.24$ and 0.15 for the peaks at 400 s and 375 s, respectively. The magnetic field strength implied by these estimates is high but broadly consistent with observations of the Zeeman effect (Rüedi et al. 1992; Stenflo 1994), which show a maximum at $\beta = 0.3$ in a histogram of β-values versus magnetic field strength, and with the empirical flux tube modeling by Kneer, Hasan, & Kalkofen (1996), which gave values of β between 0.3 and 0.5. Note that if the power spectrum of LRK93 is due to a broader distribution with 400 s as the lower period limit, the deduced value is the corresponding lower limit on a distribution of β, and the implied magnetic field strength is an upper limit.

4. OBSERVATIONAL TESTS

The scenario of NBPs presented in this Letter can be verified by observations of proper motion or velocities, focusing either on transverse or on longitudinal waves.

At the center of the solar disk, only longitudinal waves show a Doppler effect (assuming a vertical flux tube), and at the limb, only transverse waves do. In a general, noncentral collision, i.e., with finite impact parameter, between a granule and a flux tube, both transverse and torsional waves are excited; the latter will also be visible in the Doppler effect only at the limb of the Sun. Torsional waves have not been discussed, since they cannot explain the power and coherence spectra of LRK93 and are unaffected by gravity (Spruit & Roberts 1983). Nevertheless, they can transport energy and dissipate in shocks (Hollweg 1992) and are therefore likely to play a role in chromospheric and coronal heating.

At disk center, the transverse waves are visible only in the horizontal motion of emitting regions. To estimate the proper motion, we note that for a sound speed of 7 km s^{-1} and β = 0.2, the tube speed is c_κ = 6.5 km s^{-1}; for stronger fields, c_κ is higher but will not exceed 7.7 km s^{-1} (for $\beta = 0, a = 7$ km s^{-1}). At the height of formation of the H_3 absorption minimum in the middle chromosphere, where the kink waves are nonlinear, the wave amplitude matches the tube speed, $v \approx c_\kappa$. For the 400 s period, an NBP should therefore show a displacement of 800 km, a distance that is comparable to its diameter.

Near the solar limb, the transverse waves are also visible through the swaying of the flux tube seen projected into the line of sight. While at the H_3 level both wave modes contribute to the Doppler effect, almost all the wave energy at the base of the chromosphere should be in the transverse waves. Four scale heights below the layer of formation of H_3, the velocity amplitude of transverse oscillations should be approximately 2 km s^{-1} in the thin-tube approximation. The (periodic) Doppler signal would be further reduced by projection, so for observations close to disk center the signal would be small. However, it should be relatively free of contamination by longitudinal waves and the noise from the nonlinear mode coupling. If torsional waves are also excited in the collisions, they will contribute to the Doppler motion, but without the periodicity of the transverse waves.

Instead of being excited by collisions of flux tubes with granules, the transverse waves can also be excited by the turbulence of the convection (Huang et al. 1995). Since the maximal velocities of the convective elements in the turbulent cascade of the Kolmogoroff spectrum are comparable to the velocities of fast granules, the energy fluxes emitted in these two different excitation models are comparable. They differ in the initial spectrum of the wave motion, with the impulse model displaying a dominant peak at the cutoff period P_κ, analogous to the excitation of oscillations in K_{2V} bright points (cf. Kalkofen 1996a), and the turbulence model having its maximum at shorter periods, analogous to the turbulent excitation of 3 minute oscillations (cf. Theurer et al. 1997). The differences between the two excitation models will be reduced in the upward travel of the waves because of the preferential dissipation of the shorter period components.

The characteristic periods of the waves can be determined from the power spectrum, as in LRK93, from the histogram of wave periods measuring the arrival time of waves at the height of formation of the H_3 absorption feature, or from some other feature in the H and K lines, as in the histogram of wave periods of K_{2V} bright points (Liu 1974).

The relation between cutoff period and magnetic field strength can be verified for individual bright points by measuring simultaneously the Zeeman effect in the photosphere and the oscillation period in the chromosphere. Because of the uncertainty introduced by the height variation of the temperature and of β, the test of the model should determine the trend of P_κ with β demanded by the equation defining the cutoff period, which associates stronger magnetic fields and thus lower values of β with shorter periods.

If the chromospheric oscillations contain a signal at the cutoff period P_κ, as suggested in this Letter, the power spectrum of the H and K lines in chromospheric bright points can serve as proxy for the magnetic field strength in photospheric flux tubes.

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Acoustic wave propagation in the solar atmosphere

V. Observations versus simulations

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Abstract

We study the evolution of spectra of acoustic waves that are generated in the convection zone an(propagate upward into the photosphere, where we compare the simulated acoustic spectra with th spectrum observed in an Fe I line. Although there is no pronounced 3 min component in the spec generated in the convection zone, there are dominant 3 min features in the theoretical spectra, in agreement with the observed spectrum. We interpret the occurrence of the 3 min features as the response of the solar atmosphere to the acoustic waves which shifts high frequency wave energy low frequencies. We also find qualitative agreement for the acoustic power between the wave simulations and the observations.

Key words: hydrodynamics – shock waves – waves – Sun: chromosphere – Sun: oscillations

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