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DOES THE SUN HAVE A FULL-TIME CHROMOSPHERE?

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ABSTRACT

The successful modeling of the dynamics of H_{2v} bright points in the nonmagnetic chromosphere by Carlsson & Stein gave as a by-product a part-time chromosphere lacking the persistent outward temperature increase of time-average empirical models, which is needed to explain observations of UV emission lines and continua. We discuss the failure of the dynamical model to account for most of the observed chromospheric emission, arguing that their model uses only about 1% of the acoustic energy supplied to the medium. Chromospheric heating requires an additional source of energy in the form of acoustic waves of short period ($P < 2$ minutes), which form shocks and produce the persistent outward temperature increase that can account for the UV emission lines and continua.

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

1. INTRODUCTION

After half a century of theoretical research, the solar chromosphere remains a puzzle. We have learned much since the early papers on the energy support of the chromosphere by Biermann (1946, 1948) and Schwarzschild (1948), but a complete understanding of the structure, dynamics, and heating still eludes us. We now recognize that the quiet solar chromosphere is bifurcated into magnetic and (largely) nonmagnetic parts. While in long exposures in the K line of Ca^{+} the magnetic medium stands out (e.g., von Uexküll & Kneer 1995, Fig. 1), the more important contribution to the overall K emission in the quiet Sun comes from the nonmagnetic medium (Skumanich, Smythe, & Frazier 1975). This Letter concerns the nonmagnetic chromosphere.

Important progress on the dynamics of the nonmagnetic chromosphere has recently been achieved by Carlsson & Stein (1994, hereafter CS94; see also Carlsson & Stein 1995), who modeled H_{2v} bright points (also called grains) of Ca^{+} resonance line emission in the quiet Sun. By taking an observed velocity spectrum as input to their simulations they bypassed the search for the underlying cause of the waves that produce the high-intensity fluctuations. The strength of their approach is shown by an excellent match between observations and their simulation. It permitted a fundamental conclusion about the nature of the waves powering the bright points: they are acoustic waves that propagate from the photosphere into the chromosphere, where they produce the strong shocks that cause the intricate velocity and intensity variations in the H and K lines from which the H_{2v} and K_{2v} bright points derive their names.

While the dynamical calculation of CS94 successfully explained the dynamics of the 3 minute oscillations in the H_{2v} bright points, it left open the question of the physical origin of the waves and whether the velocity observations captured the complete wave phenomenon present on the Sun. In addition, their model created a new problem: whereas the empirical, time-average models of the nonmagnetic chromosphere (Vernazza, Avrett, & Loeser 1981, hereafter VAL81; see also Fontenla, Avrett, & Loeser 1993, hereafter FAL93) predict that radiation originating in the chromosphere appears everywhere and all the time in emission, the CS94 dynamical model predicts that the radiation appears at any given location most of the time in absorption because it effectively denies the existence of a persistent chromosphere. Observations in the far-ultraviolet, however, show only an emission spectrum (Carlsson, Judge & Wilhelm 1997, hereafter CJW97).

In this Letter, we address the question of why the CS94 model faithfully reproduces the velocity and intensity variations in the Ca^{+} lines and, at the same time, fails to reproduce the observed persistent chromospheric emission. In § 2 we discuss evidence for standing and propagating wave models, while in § 3 we attempt to trace the reasons for the shortcomings of the CS94 model. Section 4 gives our summary.

2. CHROMOSPHERIC DYNAMICS

The objective of the study of chromospheric phenomena is to understand the structure, dynamics, and energy support of the atmosphere. This requires knowledge of the nature of the waves producing the phenomena and of their frequency spectra—assuming that waves are responsible. An early model that addresses these questions is based on the chromospheric cavity formed by the vertical temperature structure (Mein & Mein 1976; Leibacher & Stein 1981). The waves in the cavity are taken to be standing acoustic waves, and their period is set by the wave travel time between two boundaries. The lower boundary is located at the temperature minimum between photosphere and chromosphere at which the waves are reflected, and the upper boundary is located at the jump in the temperature to the corona at which the waves are refracted. The question of how this atmosphere might be heated to form the observed temperature structure is not addressed; this model concerns only chromospheric dynamics.

The cavity model explains the wave period of 3 minutes by the vertical dimension of the box, but it cannot explain two other features of chromospheric waves: first, the oscillation period in the magnetic network would be expected to be shorter than in nonmagnetic regions since the distance between the two boundaries is shorter in the network (VAL81, Fig. 10; FAL93, Fig. 3), but the period is actually more than twice as long; and second, the waves, at least those in strong bright points, are damped by shock dissipation in the upward propagation and by diffuse reflection at the upper boundary. Only a minuscule signal can therefore return to the wave excitation region, by far too little to trigger standing waves. It is clear,

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therefore, that the cavity model cannot explain the strong bright points, which are a nonlinear phenomenon. On the other hand, certain features, such as the 180° phase jump observed in the Na D_1 line (Fleck & Deubner 1989), appear to demand standing waves and thus a cavity. But this problem is outside the purview of the present Letter, which concerns the dynamics and heating of strongly dissipating acoustic waves.

The chromospheric model by CS94, based on propagating acoustic waves, addresses the dynamics but, as we shall argue, neglects most of the heating. It combines a sophisticated one-dimensional hydrodynamic code with empirical driving at the lower boundary; the velocity is taken from the Doppler motion of a photospheric Fe I line observed by Lites, Rutten, & Kalkofen (1993, hereafter LRK93). By driving the atmosphere with this observed velocity, CS94 were able to reproduce the observed time variation of the emergent H-line profile of an hour-long observing run. The faithful reproduction of the very complicated intensity and velocity variations in two of the four H_{2v} bright points studied left no doubt about the validity of the modeling. Thus, by reproducing these observations, CS94 could make a fundamental statement about the nature of the waves that cause the bright-point phenomenon, namely, that they are propagating acoustic waves—and not the standing waves demanded by the cavity model.

A further result of the model was startling. The temperature in the chromosphere cooled rapidly from very high to very low values. The cooling time was so short that even the time-average temperature decreased monotonically in the outward direction, up to a height of at least 1.8 Mm above the photospheric level of $\tau = 1$ (see Carlsson & Stein 1998, 1999). In order to reach these low average values, from a high of 25,000 K to a low of 2500 K at the top of the model atmosphere, for example, the medium had to spend at least 90% of the time at the lowest temperatures.

The success of the dynamical model, i.e., the result of the dynamical simulations, led (or misled, in our view) CS94 into believing that they had also established a new, highly variable type of chromospheric model (Carlsson & Stein 1994, 1998, 1999), in which emission occurs only during the brief high-temperature phase of the upward-propagating shock waves and practically no emission occurs during the long low-temperature phase. The temperature of the CS94 model varies between these two extremes and lacks an average mean outward temperature rise, a feature that had been a sine qua non requirement of solar and stellar chromospheres (Thomas & Athay 1961) and had served to define chromospheres.

An immediate prediction from the CS94 model is that if chromospheric lines are observed with high spatial and temporal resolution, they should show enhanced emission only during brief periods and should otherwise appear as absorption lines. Since the model was thought to apply to the whole nonmagnetic chromosphere, it should show these absorption lines everywhere in the internetwork region at least 90% of the time and for lines as well as continua formed up to a height of at least 1.8 Mm.

CJW97 tested this prediction with the space experiment SUMER on *SOHO*. Instead of the absorption lines expected in the nonmagnetic regions everywhere and most of the time, they found only emission lines, everywhere and all the time. The immediate conclusion is that the observed lines, all of neutral atoms and therefore with little temperature sensitivity of the opacity in the 4000–6000 K range, are formed in an atmosphere with a permanent temperature rise, like that of the empirical VAL81 and FAL93 models and fundamentally different from the dynamical model of CS94.

A second indication that the model proposed by CS94 does not fully describe the solar chromosphere follows from observations by Hofmann, Steffens, & Deubner (1996), who note that only 9% of the K-line emission is due to bright points. Therefore, if all chromospheric emission came from the K line, the amount of energy missing from the dynamical model would exceed the amount included by a factor of 10. But the K line contributes only about one quarter of the cooling rate in the empirical model (see VAL81, Fig. 49). In addition, the analysis of the empirical temperature structure by Anderson & Athay (1989) has shown that the cooling rate estimated by VAL81 is doubled when iron group elements, principally Fe II, are included. Thus, the CS94 dynamical model uses only about 1% of the energy supplied to the chromosphere. The missing 99% gives rise to a permanent chromospheric temperature inversion, which can account for the persistent emission spectrum.

3. CHROMOSPHERIC HEATING

To analyze the failure of the model proposed by CS94, we note that the fault may lie with (1) simplifications in the basic equations, (2) the numerical code, or (3) the input data.

1. The basic equations assume, first, that the magnetic field is unimportant, both as an agent structuring the atmosphere and as a restoring force in the wave equation, and second, that the propagation of disturbances in the upward direction may be treated in the plane-wave approximation. By restricting the discussion to the nonmagnetic chromosphere, CS94 eliminated the magnetic field as a structuring agent. The absence of long-period components in the bright-point oscillations implies that the magnetic field is unimportant also in the wave equation; the waves are therefore purely acoustic waves (Hasan & Kalkofen 1999). The geometry, however, is clearly three dimensional. Thus, the energy is spread laterally during the upward propagation of the wave, and the energy flux is thereby diluted. How this affects the behavior of the upward-propagating shocks cannot be predicted in detail since the problem is nonlinear, but in a general way one would expect wave travel times between the layers of formation of the Fe I line and H_3, the central absorption minimum of the H line, to be mostly longer in the real atmosphere than in the one-dimensional model. But the excellent agreement between the dynamical model and the chromosphere for two of four bright points argues that the one-dimensional approach of CS94 cannot be fundamentally flawed.

2. The numerical code is state-of-the-art, both in the hydrodynamics and in the radiative transfer. Again, the excellent match with the observed dynamics means that the code is unlikely to be at fault.

3. The input data concern (*a*) opacity sources controlling radiative cooling and (*b*) the velocity field controlling the dynamics. (*a*) Important opacity sources in the chromosphere have been omitted in the modeling. Their inclusion would increase radiative emission rates and therefore reduce the radiative cooling time. This would lead to longer time intervals during which the atmosphere is in the low-temperature state—except for probably minor effects due to delayed recombination for some ions. The improvement from realistic opacity sources would therefore aggravate the discrepancy of the model with the observation of emission lines, not remove it. (*b*) The observed velocity spectrum of the iron line is limited at high frequencies

both by noise in the observations and by the finite width of the radiative contribution function of the line. Lites, Rutten, & Thomas (1994) consider the LRK93 power spectrum of the Doppler oscillations at H_3 not to be trustworthy above frequencies of 10 mHz. It is therefore conceivable that wave energy enters the chromosphere in this largely invisible part of the acoustic spectrum and heats the medium. Thus, the autopsy of the dynamical model as a general chromospheric model yields one suspect, the LRK93 velocity spectrum. To inquire into the possibility that the velocity data used by CS94 are incomplete, we consider heating by waves in the high-frequency range above 10 mHz, and we begin by investigating the properties of the heating mechanism that can account for the temperature structure of the chromosphere.

Anderson & Athay (1989) determined the radiative cooling rate implied by the temperature structure of the empirical VAL models and found the rate to be proportional to mass density. Since heat conduction plays no role in the chromosphere, the empirical cooling rate must be balanced locally by the heating rate, which must therefore also be linear in mass density.

For weak, plane, monochromatic shock waves that have reached limiting strength, at which the exponential growth of the velocity amplitude in the upward propagation is balanced by dissipation, Ulmschneider (1970; see also Buchholz, Ulmschneider, & Cuntz 1998) has shown that the energy flux in an isothermal atmosphere decays exponentially with the scale length of the density. The energy flux and its derivative are therefore proportional to mass density. Although realistic shocks are not monochromatic nor is the atmosphere isothermal, a narrow spectrum of shock waves in the chromosphere has similar heating properties (Schmitz, Ulmschneider, & Kalkofen 1985). Acoustic waves can therefore furnish the energy missing from the dynamical model.

Most of the wave energy traveling to the chromosphere heats the medium, causing a permanent temperature inversion at the traditional height of $z \approx 0.5$ Mm. But at the height of formation of the photospheric Fe I line observed by LRK93, the extra energy must be hiding at acoustic frequencies exceeding 10 mHz. That the acoustic spectrum is much broader than the LRK93 observations suggest is shown by power spectra of acoustic noise generated by the turbulence of convection (Musielak et al. 1994). The frequency spectra, which vary depending on assumptions about the Kolmogorov spectrum of turbulent velocities, all show broad peaks at a frequency of about 13 mHz and extend to 60 mHz. At the height of formation of the photospheric Fe I line, $z = 250$ km, the modulation transfer function limits observable frequencies to less than 20 mHz and the hidden power exceeds the observable power by an order of magnitude (Theurer, Ulmschneider, & Kalkofen 1997). Evidently, the observational data of LRK93 that were used by CS94 do not rule out substantial chromospheric heating by these high-frequency waves.

The heating of the chromosphere with high-frequency acoustic waves solves the problem of emission in the resonance lines of neutral atoms at the base of the chromosphere by creating a persistent temperature rise in the outward direction. This model explains the CJW97 observations to the spatial resolution of the SUMER instrument of $1'' \times 2''$. The VAL81 and FAL93 models place the temperature minimum at 0.5 or 0.6 Mm above the photospheric level of $\tau = 1$. However, the empirical models do not explain observations of the strong infrared CO lines (see Uitenbroek, Noyes, & Rabin 1994) which are formed in LTE (Ayres & Wiedemann 1989) in the low chromosphere according to hydrostatic-equilibrium modeling (Avrett 1995), but do not show any evidence of a chromospheric temperature rise. These lines cannot originate from the same layers as the UV emission, given that the filling factor for CO absorption is 50%–85% (Solanki, Livingston, & Ayres 1994). This seems to imply that the CO lines are formed in the upper photosphere and the temperature minimum region (Muchmore & Ulmschneider 1985). On the other hand, the CO observations appear to require some cool material to account for the brightness temperature of 3800 K observed near the solar limb in the strong CO lines (see Noyes & Hall 1972; Ayres 1995; Avrett 1995, 1998). It is evident that the CJW97 observations of UV emission lines, which do not allow any cool material in the chromosphere, and CO observations, which demand cool gas with a very large filling factor, are incompatible if the CO absorption occurs at chromospheric heights as suggested by Ayres (1998). This conflict can be resolved only by further high-resolution observations and numerical simulations of a dynamical atmosphere that includes the formation of the CO lines in detail.

It is interesting to note that the exposure time of 15–20 s of the SUMER instrument used by CJW97 is comparable to the duration of the high-temperature phase of the wave, which amounts to 10% of the wave period of 3 minutes. The temporal resolution of SUMER is therefore adequate for probing the temporal variability of emission. The spatial resolution of SUMER is comparable to the size of a typical bright point (Liu 1974), which is a measure of the size of heated elements in the middle chromosphere. Consequently, SUMER probes essentially instantaneous, local conditions in the middle chromosphere. The persistence of emission in the H and K lines implies that the temperature is always high in the layers of formation of these lines, as is the case in the empirical models, and never as low as in the low state of the CS94 dynamical model. Whether, in the low chromosphere, the temperature could ever be as low as in the dynamical model depends on the size of the heated elements being sufficiently small that absorption lines could be hidden by emission lines. While such a scenario cannot be excluded on the basis of the observations, it can be firmly rejected on theoretical grounds: it would require the heating mechanism, which we have inferred to be based on acoustic waves generated in the convection zone, to show extreme spatial variability in order to compensate for the temporal intermittence of the dynamical model. We conclude that chromospheric emission occurs on all spatial scales and all the time and that the VAL81 and FAL93 models are therefore also valid as typical, instantaneous, thermal models of the chromosphere and not merely as time-average models. Of course, the actual chromosphere, even ignoring the strong bright points, is not time independent but dynamic: on top of the time-average atmosphere, there are low-level intensity fluctuations representing the ubiquitous bright points; their intensity variation reaches about 20% of the DC level and also shows 3 minutes as the typical timescale (see CJW97, Fig. 3).

4. SUMMARY AND CONCLUSIONS

The dynamical model of internetwork H_{2v} bright points by CS94 reproduces to high fidelity the H-line profile based on the use of the corresponding Doppler velocity spectrum of a photospheric iron line. At the same time, the model, with its intermittent chromosphere, fails to show any chromospheric signature not associated with the large-amplitude dynamics.

From observations of calcium emission and semiempirical modeling based on a wide range of observations, we point out that the energy that is radiated from the chromosphere in persistent, steady emission exceeds the energy dissipated in H_{2v} bright points by 2 orders of magnitude.

We identify dissipation by short-period ($P < 100$ s) acoustic waves as the likely mechanism by which the chromosphere is heated, resulting in a persistent outward temperature increase. Thus, the Sun has a full-time chromosphere.

The type of chromospheric model advocated in this Letter requires the strong infrared lines of CO to be formed in the upper photosphere and the temperature minimum region and is incompatible with models in which the CO lines form at chromospheric heights.

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