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ON THE VALIDITY OF ACOUSTICALLY HEATED CHROMOSPHERE MODELS

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ABSTRACT

Theoretical models of solar and stellar chromospheres heated by acoustic waves have so far been constructed by using time-dependent, one-dimensional, radiation-hydrodynamic numerical codes that are based on the approximation of plane-parallel geometry. The approach seems to be justified by the fact that the chromospheres of most stars extend over very narrow height ranges compared to the stellar radius. It is demonstrated that this commonly used assumption may lead to unrealistic shock mergings, to the artificial formation of unusually strong shocks and the artificial destruction of high-frequency acoustic wave power. Comparing one-dimensional calculations with observations may lead to severe misjudgment about the nature of chromospheric heating.

Subject headings: methods: numerical — stars: chromospheres — waves

1. INTRODUCTION

It has long been known that stellar chromospheres and coronae are outer gaseous layers around stars in which mechanical energy transport and heating play a dominant role (e.g., Athay 1961; Osterbrock 1961; Kuperus et al. 1981; Narain & Ulmschneider 1996; Ulmschneider & Musielak 2003; and references therein). These outer layers are distinct from the deeper stellar photospheres, which are characterized by radiative and convective energy transport. It has been found that the most basic heating processes, namely, viscous, thermal conductive, and Joule heating, are only adequate when strong spatial gradients of physical variables like velocity, temperature, or magnetic field strength occur (e.g., Osterbrock 1961; Ulmschneider 1996). Hence, only shocks and current sheets seem to provide sufficiently steep spacial gradients to generate adequate heating. Since in density-stratified stellar atmospheres it is easy for propagating acoustic and MHD waves to produce shocks, such waves are prime candidates for the atmospheric heating.

Using the linear analytical Lighthill-Stein theory that is valid for homogeneous turbulence and that, in terrestrial applications, gives excellent agreement with experiments (Goldstein 1976), acoustic wave energy fluxes and spectra were computed by Ulmschneider et al. (1996) as well as by Musielak et al. (1994). These data were then used to construct acoustic wave–heated theoretical chromosphere models employing an increasingly sophisticated time-dependent, one-dimensional, radiation-hydrodynamic code based on a method of characteristics (Ulmschneider et al. 1977; Schmitz et al. 1985; Buchholz et al. 1998; Rammacher & Ulmschneider 2003). Similar calculations of wave fluxes and spectra of longitudinal and transverse MHD tube waves along magnetic flux tubes lead to magnetically heated theoretical chromosphere models (Fawzy et al. 2002a, 2002b). All these models used a one-dimensional plane-parallel geometry and monochromatic waves with a wave period that represents the peak of the wave spectra. With the resulting models, we simulated the Ca II K and Mg II *k* line core emission fluxes and compared them with observed emission fluxes. The comparison showed that the admittedly rather crude models based on acoustic heating reproduced quite well the observed level of the basal emission flux in late-type stars as well as the observed dependence on effective temperature and metallicity (Buchholz et al. 1998; Cuntz et al. 1999). Similar calculations for magnetically heated chromospheres showed that the simulated chromospheric emission fluxes of stars with different magnetic field coverage accounted for most of the observed range between the basal emission fluxes and the saturation limit emission of rapidly rotating stars (Fawzy et al. 2002a, 2002b).

Another approach to constructing acoustically heated chromosphere models by Carlsson & Stein (1995, 1997, 2002) used as input an observed spectrum of low-frequency velocity fluctuations in a photospheric Fe line detected by Lites et al. (1993). Using a time-dependent, one-dimensional radiation-hydrodynamic code based on the finite difference method, they constructed shock-heated solar chromosphere models and compared them with solar Ca bright point observations. Based on these calculations, the authors concluded that occasional solitary strong acoustic shocks with a repetition period of around 3 minutes, propagating in a cold radiative-equilibrium atmosphere, should be representative for the chromospheric heating everywhere on the Sun. But, as pointed out by Kalkofen et al. (1999), Wilhelm & Kalkofen (2003), and Kalkofen (2004), this extreme time-dependent chromosphere model is different from the average solar chromosphere. Recently, Fossum & Carlsson (2005) argued on the basis of similar one-dimensional acoustic wave spectrum calculations that high-frequency acoustic waves should not be present in the solar atmosphere.

For all the above-mentioned acoustic wave calculations and theoretical chromosphere models, it is important to emphasize that they have been performed using the approximation of one-dimensional plane-parallel geometry. This approach might seem to be justified by the fact that the chromospheres of most stars extend over very narrow height ranges compared to the stellar radius (2 Mm vs. 700 Mm, in the case of the Sun). However, it now appears that the use of the one-dimensional geometry can lead to very unrealistic shock mergings and to the artificial formation of unusually strong shocks and the artificial destruction of high-frequency wave power. Comparing one-dimensional calculations with observations may lead to severe misjudgment about the nature of chromospheric heating. We find that if one continues to use one-dimensional models, great care must be taken to avoid unrealistic shock mergings. The Letter is organized as follows: § 2 addresses the persistent

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problem with the current chromospheric modeling, § 3 discusses the steps that must be undertaken to resolve this problem, and § 4 gives some concluding remarks.

2. PERSISTENT PROBLEM WITH THEORETICAL CHROMOSPHERE MODELS

Wave calculations with acoustic spectra typically produce a multitude of shocks of very different strengths. Propagating at different speeds, these shocks quickly catch up with one another and merge, creating strong shocks that mop up even more shocks on their way. But shock merging can also occur in monochromatic wave calculations if the wavelengths are small.

Figure 1 shows three snapshots of a monochromatic wave with a 20 s period, and these snapshots are separated by time intervals of roughly one and three wave periods. The sequence starts at time $t = 1183.2$ s. As the wave phases are multiples of a wave period apart, the three waves have similar shape at low height. However, at a height of 1500 km, it is seen that one wave period later, at phase $t = 1204.4$ s, three shocks have merged and formed a shock of moderate strength that, by its greater speed and the imparted momentum, generated an outward flow and adiabatic cooling in its wake. After three additional wave periods, more shocks have merged, and an even stronger shock has developed, in the postshock region that shows strong adiabatic cooling. Also, in this shock-merging process, the destruction of high-frequency wave power is observed.

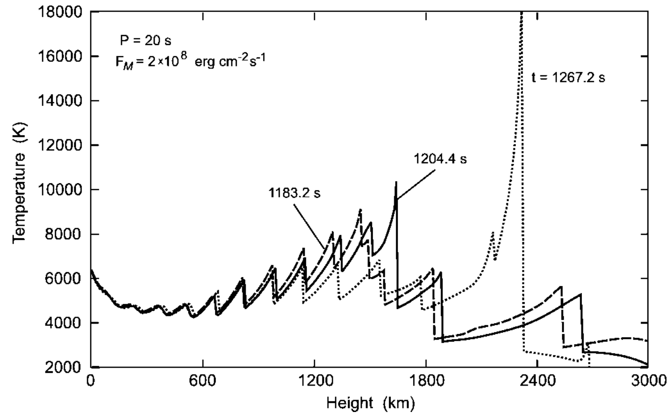

FIG. 1.—Three phases of an acoustic wave of period $P = 20$ s and acoustic energy flux $F_M = 2 \times 10^8$ ergs cm^{-2} s^{-1} at different times t in the solar chromosphere.

In a realistic situation on a solar-type star, it is quite clear that such shock mergings must be extremely rare events, except maybe for the solar Ca bright point phenomenon or for MHD tube waves propagating along isolated magnetic flux tubes. Consider two shocks propagating with different speeds in plane-parallel geometry near the solar surface. When the second shock has a higher speed than the first one, it will catch up with it and merge. In a realistic situation, such shock fronts have a horizontal extent of many hundreds or thousands of kilometers, while the width of the shock discontinuity (the shock structure) is only of the order of a molecular mean free path l. In the model C of Vernazza et al. (1981, hereafter VAL), l is 2.8×10^{-2}, 1.6, 1.7×10^2, 3.3×10^3, and 3.3×10^4 cm at heights $z = 0$, 500, 1000, 1500, and 2000 km, respectively. Here we have used $l = 1/nQ \approx 3 \times 10^{16}/n_{\rm H}$, where n is the particle density, Q represents the collision cross section, and $n_{\rm H}$ is the hydrogen number density; note that $Q = \pi(2a_0)^2$, with $a_0 = 0.5$ Å being the Bohr radius. These values indicate that l is in the meter range. Therefore, even for a tiny inclination of one shock against the other, the shocks would fail to merge and would merely intersect each other. Only in the extreme case of an almost perfect alignment (less than a meter divergence over a distance of a hundred kilometers) does shock merging occur. This shows that the perfect alignment of shocks found in one-dimensional computations is an artifact of the employed plane-parallel geometry and almost never happens in realistic situations.

Consider now acoustic waves propagating from two different sources near the stellar surface. We imagine waves created from localized sources of high turbulence in the narrow intergranular lanes as suggested by the observations of Nesis et al. (1999) and Wunnenberg et al. (2002). Since one has changes of the wave speed due to atmospheric temperature variations, these waves will expand in a complicated spherical and conical three-dimensional manner. Moreover, as the wave amplitude due to the density gradient grows in the vertical but not in the horizontal direction, it will form cap shocks in some conical region. As for waves emanating from different sources where there is little chance for perfect alignment, one cannot expect that such cap shocks will merge.

Let us now focus on the mechanical heating in a vertical column in the solar chromosphere. A three-dimensional wave emanating from a source at the bottom of that column will generate cap shocks propagating in a cone in the vertical direction. Purely hydrodynamic two-dimensional wave computations with a simplified radiation law already show this cone-like propagation and cap shock production (Bodo et al. 2000). The heating by such a wave will not be overly large because, due to geometrical spreading, the three-dimensional wave cannot be contained within the column and mechanical energy will be lost outside of it. However, for the same reason, the column will also gain mechanical heating from shocks from adjacent outside sources. Clearly, because of the missing alignments, the heating will not be provided by infrequently passing strong merged shocks but rather by frequent passages of low-amplitude shocks at a given chromospheric height. Such a situation is properly simulated only by using three-dimensional simulations with multiple sources. But it is clear that the character of the energy dissipation of the waves looks rather like the situation encountered in a one-dimensional acoustic wave calculation with many shocks, i.e., with short wave periods. Unfortunately, a three-dimensional simulation with multiple acoustic sources, as well as the necessary three-dimensional non-LTE (NLTE) radiative transfer and time-dependent ionization treatments, far surpasses current computer capabilities.

3. STEPS TOWARD MORE REALISTIC THEORETICAL CHROMOSPHERE MODELS

As a result of the above discussion, we formulate the following model imperatives: (1) For chromosphere models based on acoustic waves, the heating is by shock dissipation. (2) Acoustic waves like those on Earth propagate as three-dimensional waves from many sources near the stellar surface. Because of the geometrical spreading, the wave amplitudes are smaller than those of plane waves. Hence, at a given chromospheric location, one will have small-amplitude shocks that arrive in rapid succession from many different directions. (3) Theoretical and observational estimates provide energy spectra and fluxes carried by acoustic waves in stellar atmospheres. (4) Using a one-dimensional wave code and acoustic wave spectra as input, one invariably gets shock mergings that are an artifact of the very special plane-parallel geometry of this type of calculation. (5) Monochromatic long-period one-dimensional acoustic waves do not suffer from shock mergings because they generate shocks with similar speed that do not easily catch up with one another. (6) In monochromatic one-dimensional waves with shorter periods, shock mergings eventually occur; and the shorter the wave period, the lower the height where that happens. (7) Chromosphere models must take into account the special physical processes that operate in such stellar layers in the presence of waves, namely, the NLTE radiative transfer and the time dependence of the H, Ca, and Mg ionizations that affects the thermodynamics.

The presence of many weak shocks immediately points to a chromosphere model with relatively steady and monotonic heating as a function of height; i.e., it suggests the so-called classical chromosphere, which shows similarities to the semiempirical VAL model and others mentioned by Linsky (1980). Such models are characterized by a monotonic, outwardly rising temperature distribution that is carefully chosen to reproduce in detail the chromospheric emission by many lines and continua. Unfortunately, a fully three-dimensional theoretical model that incorporates all the cited imperatives cannot be built at the present time for lack of sufficient computer power. The reason is the enormous number of grid points necessary to represent the three-dimensional atmosphere and to resolve the shock fronts. In addition, one must have an adequate treatment of the special chromospheric physics, i.e., the three-dimensional NLTE radiative transfer and the time-dependent ionization. In one-dimensional wave calculations, only a tiny fraction of computer time is spent on the actual hydrodynamics or magnetohydrodynamics; practically all of it is used for the radiative transfer and the time-dependent ionization.

Since the VAL models show the usefulness of one-dimensional empirical models, we think that one-dimensional time-dependent theoretical models that include the special chromospheric physics should also be useful. Acceptable types of models appear to be one-dimensional monochromatic wave models when shock merging is avoided. Such models are unrealistic because one really should use acoustic wave spectra, but the distribution of mechanical heating over height by such waves is fairly realistic. This is demonstrated by the monochromatic wave calculations of stellar chromospheres mentioned above that do not suffer from shock mergings. Yet more sophisticated one-dimensional monochromatic wave calculations that avoid shock mergings may also be helpful for more detailed solar chromospheric modeling, to study the energy balance between mechanical heating and radiative cooling, because their predictions could be more thoroughly confronted with detailed observations. Figure 2, for example, shows a series of monochromatic time-dependent acoustic wave computations with periods $P = 15$, 20, 45, and 60 s and an initial energy flux of $F_M = 1.7 \times 10^8$ ergs cm^{-2} s^{-1}. The plotted temperatures were obtained by time-averaging at given heights over many wave periods. Also shown is the VAL temperature distribution and the RE temperature of the radiative equilibrium atmosphere, which is the temperature at the start of our wave calculations, i.e., in absence of mechanical heating.

The calculations were performed by simultaneously solving the hydrodynamic equations together with the fully time-dependent H, Ca, and Mg ionizations and the NLTE radiative transfer (Rammacher & Ulmschneider 2003). The radiative losses were computed by taking into account the H$^-$ continuum and the Ca II K, Mg II *k*, and H Lyα lines in pseudo–partial redistribution. The line losses of Mg II *k* were multiplied by 1.4, and those of Ca II K by 4.3. These cooling rate correction

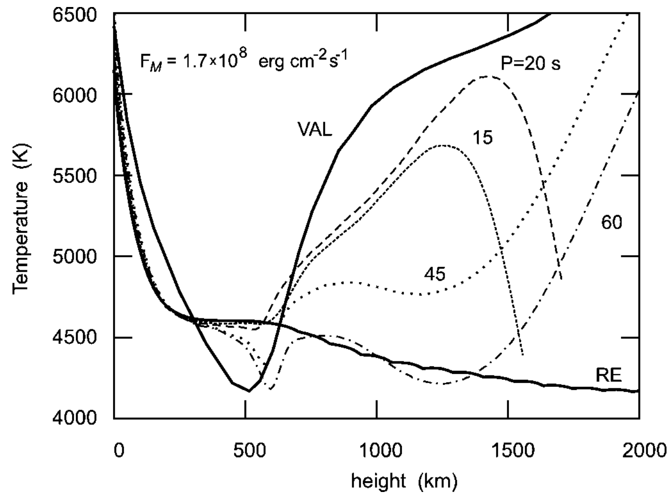

FIG. 2.—Mean temperature as function of height for monochromatic acoustic waves with periods $P = 15$, 20, 45, and 60 s and an initial energy flux $F_M = 1.7 \times 10^8$ ergs cm^{-2} s^{-1}. VAL is the temperature of model C, and RE marks the radiative equilibrium atmosphere at the start of the wave calculations.

factors increase the single line losses to represent the total losses by these ions. They were determined by a detailed comparison with the multilevel code MULTI by Carlsson (1986, 1995). This procedure is discussed in greater detail by Rammacher et al. (2005). Such correction factors also crudely take the Fe II line emission into account. Since comparisons of the emergent emission spectrum with observations have not been carried out so far, we merely display the mean temperature distributions together with the temperature distribution of the VAL model.

Figure 2 shows that the 60 s wave gives high temperatures only at great heights, while the 45 s wave produces a steeply rising temperature above a height of 1300 km. In view of the requirements discussed above, these waves do not qualify as "many shock waves arriving in rapid succession" because of their long wavelengths. Here the 15 and 20 s waves are better candidates. It is seen that they provide a mean chromospheric temperature rise up to a height of 1200 km that is in reasonable agreement with the VAL temperature distribution, while at greater heights the temperatures of the wave model drop rapidly below those of the VAL model. This drop is due to the breakdown of our monochromatic wave picture at those heights caused by shock mergings, which in a realistic three-dimensional situation would not occur. That shock mergings for 20 s waves occur at these heights is also seen in Figure 1. These unrealistically strong shocks produced by shock mergings generate mass flows that lead to adiabatic coolings, which are the cause for the drops in the mean temperature. Note that because 15 s waves have a shorter wavelength than 20 s waves, their shock mergings occur at a lower height. That the mean temperature of the 15 s wave is lower than that of the 20 s wave can be understood from analytical weak shock relations derived by Ulmschneider (1990), which show that shock heating in the one-dimensional limiting shock strength case decreases with shorter wave period. However, this may be another artifact of the one-dimensional geometry.

To be proposed as valid theoretical chromosphere models, such preliminary one-dimensional monochromatic acoustic wave models of Figure 2 must show the simulated emergent spectrum, and they have to be confronted with the observed spectrum, including the CO emission, because the success of a theoretical model depends on the ability to explain the observations. As the purpose of the present work is to warn about the dangers of using one-dimensional theoretical wave models and to suggest alternatives, this detailed evaluation will be published elsewhere.

4. CONCLUSIONS

We show that shock mergings, taking place when two or more shocks run into one another and form a stronger shock, must be uncommon phenomena in acoustically heated theoretical chromosphere models. In order to merge, two shocks with shock fronts extending over hundreds or thousands of kilometers and with thicknesses only in the meter range must be perfectly aligned. This perfect alignment of shocks is an artifact of a plane-parallel geometry and one-dimensional wave calculations and will practically never occur in reality.

Such unrealistic shock mergings will lead to the artificial formation of unusually strong shocks and to the artificial destruction of the high-frequency acoustic wave power. Comparing affected one-dimensional calculations with observations may therefore lead to severe misjudgments about the nature of chromospheric heating.

In one-dimensional wave computations to construct acoustically heated theoretical chromosphere models based on plane-parallel geometry, one must avoid shock mergings. This can be done, for instance, by employing monochromatic waves for which the shocks are initially separated by distances of a wavelength. Depending on the wave period, such shocks do not easily merge. While unrealistic in the sense that true acoustic waves appear as a spectrum and not as monochromatic waves, the heating by monochromatic waves could be a good model for the realistic distribution of the mechanical heating with height in chromospheres.

For the Sun, as an illustration, preliminary acoustically heated chromosphere models have been constructed. A monochromatic model with a 20 s wave period up to a height of 1400 km is particularly close to the VAL temperature distribution. However, whether or not such a theoretical heating model is realistic and how well it represents the chromosphere can only be answered when a detailed spectrum simulation and a comparison with the observed spectrum have been completed.

Following Kalkofen (2003a, 2003b, 2004), it has been suggested that shock amplitudes would be significantly reduced by considering spherically or conically propagating acoustic waves in the solar and stellar chromospheres and by using some area correction factors to make up for the losses out of the vertical chromospheric mass columns.

Finally, it must be emphasized that adequate calculations of theoretical chromosphere models require a full three-dimensional radiation-hydrodynamic code with multiple input sources of acoustic wave spectra. In this approach, acoustic waves would emanate from many different locations on a stellar surface, and their shocks would intersect one another but almost never merge. Since these calculations would also require a time-dependent three-dimensional NLTE radiative transfer and a fully time-dependent treatment of the H, Ca, and Mg ionizations and thermodynamics, they are not yet feasible with present computer power.

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