The Validity of Dynamical Models of the Solar Atmosphere

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Abstract Important results on the structure and dynamics of the nonmagnetic solar chromosphere are based on hydrodynamic models that oversimplify either the geometry of the atmosphere or the interaction of radiation and matter. Although the observed granulation pattern is well reproduced by the three-dimensional (3D) models, oversimplification of radiative relaxation leads to the prediction of temperature fluctuations that are too high (by a factor of 10 to 100) and result in a monotonic decrease with height in the chromosphere of the horizontally and temporally averaged temperature, and hence in the prediction of absorption lines at wavelengths where only emission lines are observed on the Sun. New values of solar abundances of oxygen and other metals are based on 3D hydrodynamic models with temporal and spatial fluctuations that are far greater than those observed. These new abundances destroy the previous agreement of observed modes with acoustic eigenmodes that had been predicted for the old abundances from a solar model for which the sound speed throughout most of the Sun was determined to an accuracy of a few parts in 10^4 . One expects that, when radiative relaxation is properly accounted for, 3D models will reproduce the essential characteristics of the solar atmosphere, among them a positive temperature gradient in the outward direction and hence exclusively emission lines in the extreme ultraviolet at all times and positions in the nonmagnetic chromosphere. A minimum characteristic length of 0.1 arcsec is identified for the solar atmosphere, below which there is no significant structure in the actual Sun, only in wave models of the Sun. This criticism does not detract from the notable success of hydrodynamic modeling to explain the mechanism by which chromospheric H_{2V} and K_{2V} bright points are formed.

Keywords Abundances · Acoustic waves · Line profiles · Radiative transfer · Sun: photosphere, chromosphere, granulation

1. Introduction

How well do we understand the quiet solar chromosphere? A full understanding of its structure would imply, on one hand, that we know what that structure is and, on the other, that

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we know how to explain it in terms of the appropriate radiative, hydrodynamic, and magnetohydrodynamic equations. Restricting the question to the temperature structure of that part of the quiet solar atmosphere where magnetic fields are weak and presumably unimportant, *i.e.*, the internetwork region, the question is whether there is agreement at least on the basic facts to be explained.

In detail: Does the temperature generally increase outward throughout the chromosphere, or does it generally decrease, *i.e.*, is the temperature generally high in the layer of formation of the emission peaks of the strongest lines in the visible solar spectrum, the H and K lines of ionized calcium, with most fluctuations of the order of hundreds of degrees or less, or is the temperature generally low in those layers, with upward excursions of thousands of degrees? In short, as Carlsson and Stein (1995) ask in the title of their *Astrophys. J. Lett.* paper: Does a nonmagnetic solar chromosphere exist?

As these questions suggest, there is no agreement even on the most basic features of the quiet solar chromosphere. How is that possible, after half a century of observational and theoretical research? Are observations not sufficiently detailed, or are the computers not sufficiently powerful, or do we lack insight for making physically plausible choices in simplifying the difficult computational problem in order to make it tractable?

The construction of acoustic wave models of the solar chromosphere is very demanding of computer resources, even in internetwork regions, where magnetic fields are considered dynamically unimportant. It is therefore necessary to make simplifying assumptions concerning four aspects.

1. *Geometry of the atmosphere:* Can the waves be considered plane acoustic waves in a one-dimensional (1D) medium, or are they more general waves in 2D or 3D media that spread out laterally as they advance?
2. *Chromospheric heating:* What is the flux of acoustic waves and their spectra that enter the atmosphere from the convection zone and dissipate their energy in the chromosphere, thereby heating the medium?
3. *Computational accuracy:* Is the density of points on the spatial grid sufficient to provide a reasonable numerical solution of the hydrodynamic equations?
4. *Radiative transfer:* Is greater accuracy needed to properly account for the radiative energy exchange among neighboring gas elements and for the energy radiated from the atmosphere? It is necessary to balance net dynamical heating by net radiative cooling. The radiative cooling is given by an integral over the entire spectrum involving not only the continuum but also large numbers of weak and strong absorption and emission lines, including departures from local thermodynamic equilibrium (LTE) and wave motion. This should be done at every time step and at every 3D grid point, but at least the results should be generally consistent with 1D calculations of radiative cooling.

The greatest savings in computer effort are obtained by simplifying the geometry of the problem – at the expense of having to represent inherently 3D processes in fewer dimensions – and by simplifying the radiative transfer calculations, which consume most of the computer time.

The only really satisfactory approach to chromospheric modeling is the 3D approach, in which the geometry is fully represented and, when convection is part of the model, the acoustic wave input is automatically included, provided that the convection-zone model correctly describes the pressure fluctuations that generate the acoustic waves, a requirement that does not appear to be satisfied. Assuming that points 1 and 2 have been addressed successfully, the only remaining uncertainties for the numerical solution are the density of points of the numerical spatial grid, and the treatment of radiative transfer. Regarding point 3, we

hope that the numerical grid could be pushed to a limit where a further increase in spatial resolution has negligible effect on the quality of agreement between intensities observed on the Sun and intensities predicted from simulations. Regarding point 4, we hope that, by increasing the resolution of the frequency and angle dependence of the absorption and emission in detail, including non-LTE effects, the gains would approach a limit. The difficulty with point 4 is that radiative transfer is highly complex and computationally very demanding, and has not been treated in sufficient detail in the dynamical modeling. This is the major problem in 3D dynamical simulations. None of the 3D simulations include non-LTE effects such as departures from LTE in H^- , the principal continuum source in the photosphere.

This paper examines differences between empirical and theoretical models of the quiet, nonmagnetic chromosphere and asks whether the call for observations with higher spatial resolution (Leenaarts *et al.*, 2009) is justified, or whether there are more promising ways to expend effort with the aim of narrowing the disagreements between theoretical dynamical models and the empirical non-dynamical models that have been constructed to match observations, or the observations themselves. Section 2 discusses features of chromospheric models in which the theoretical models differ fundamentally from empirical models and therefore, presumably, from observations. Section 3 discusses the atmospheric temperature structure and temperature fluctuations in empirical and theoretical models. Section 4 estimates characteristic time scales due to the dynamics and time scales due to radiative energy exchange. Section 5 investigates the treatment of radiation and radiative relaxation, and Section 6 asks whether the magnetic canopy plays a role in showing the equivalence of 3D hydrodynamic models and 1D empirical models. Section 7 considers recent changes in the solar oxygen abundance. Section 8 compares the geometries of acoustic wave models, and Section 9 draws conclusions.

2. Features of Chromospheric Models

To compare the chromospheric models we take as a reference standard the coolest of the empirical models of Fontenla, Avrett, and Loeser (1993; hereafter FAL), which we compare with the following time-dependent theoretical acoustic wave models: *i*) the 1D dynamical model by Carlsson and Stein (1994, 1995, 1997a; hereafter CS); *ii*) the 2D nonequilibrium hydrogen ionization model by Leenaarts *et al.* (2007); and *iii*) the 3D model of Wedemeyer *et al.* (2004; hereafter W04).

Figure 1 displays two 1D models of the chromosphere: the time-dependent acoustic wave model of Carlsson and Stein (1994, 1995) and the time-independent empirical model A of FAL. The figure shows the range of variation of the kinetic temperature of the time-dependent CS model (two thin lines), the corresponding time-averaged temperature (thick lines), a corresponding time-averaged wavelength-dependent brightness temperature referred to as semi-empirical by CS (dashed), as well as the starting model (dotted), which is a solar model in radiative equilibrium; and the coolest of the empirical FAL models, FALA (dash-dotted).

Note that the time-averaged temperature in this figure can be viewed as the wavelength-dependent brightness temperature in the Rayleigh–Jeans limit of the Planck function, and the semi-empirical CS model can be viewed as the time-averaged wavelength-dependent brightness temperature in the Wien limit of the Planck function at the wavelength of the K line.

A characteristic feature in the figure is the distinct temperature minimum of the empirical FALA model at a height of 0.5 Mm above unit monochromatic optical depth in the

Figure 1 Temperatures and extreme temperature excursions in the 1D wave model as functions of height above $\tau_{5000} = 1$ (Carlsson and Stein (1995), Figure 3).

continuum at 5000 Å, which separates the chromosphere from the photosphere. The semi-empirical CS model has a temperature minimum at a height of 0.75 Mm, where it is cooler than the coolest FAL model (FALA) by 550 K and the intensity at the wavelength of the K line is lower than that of the VAL-A model by a factor of three. The time-averaged temperature of the theoretical model extends only to the height of 1.8 Mm, whereas the empirical model extends to 2.2 Mm (*cf.* Table 10 of Vernazza, Avrett, and Loeser (1981): hereafter VAL). At their tops, both models have approximately the same monochromatic optical depth at 5000 Å; the theoretical model is compressed in its height range mainly because of its lower average temperature and therefore smaller scale height.

An unexpected and unexplained feature of the dynamical model is that the temperature of the model with both mechanical heating by acoustic waves and radiative heating is lower than the temperature of the model with radiative heating only.

The time-averaged temperature of the dynamical model decreases monotonically in the outward direction. Since the extreme upward excursions of the temperature are larger than those downward, the instantaneous value of the time-dependent temperature must be mostly below the time-averaged temperature to compensate for the high upward excursions. On average, the temperature gradient of the model is negative. As a consequence, many of the lines formed in the chromosphere are predicted by the time-dependent theoretical model to be absorption lines, contrary to observations. However, the time-independent empirical FALA model predicts only emission lines, in agreement with observations.

Note that the semi-empirical temperature requires an averaging time interval that is long compared to the wave period of three minutes, *e.g.*, an observing time interval of one hour. However, the FALA model, *i.e.*, the coolest brightness component of the FAL models, represents a time interval of the order of the exposure time, which is a few seconds.

Observations of the EUV spectrum contradict the prediction of intermittent absorption lines in the wave model. As Carlsson, Judge, and Wilhelm (1997: hereafter CJW) note in discussing the space observations of lines of C I, N I, and O I with SUMER (Wilhelm *et al.*, 1995) on SOHO (*SOLar and Heliospheric Observatory*; Fleck, Domingo, and Poland, 1995), “all chromospheric lines show emission above the continuum everywhere, all the time.” How do these authors address the evidence in favor of emission lines only, and hence a positive temperature gradient in the chromosphere? In their 1997 paper, CJW recognize that “something important is missing from the calculation”... perhaps “a magnetic canopy.”

But they provide no description of the mechanism by which the magnetic canopy transforms the predicted absorption lines into the observed emission lines.

In revisiting this problem of the absent absorption lines in the space observations, the authors (Stein *et al.*, 2003), while claiming realistic simulations, allow that “there is possible disagreement with SUMER observations, that the cores of C I, N I, and O I lines show emission everywhere.” We point out that the disagreement concerns not only the line cores since the line wings are also in emission, and that the disagreement is not only “possible,” it is evident.

We conclude that this 1D acoustic wave model does not describe essential features of the nonmagnetic solar chromosphere, namely, the omnipresence of emission lines and the complete absence of absorption lines.

However, despite its limitations, the theoretical 1D CS model provides, for the first time, a correct, detailed explanation of the formation of H₂V bright points, with a period of three minutes. This success is all the more notable when viewed against the attempts of an earlier era to explain bright-point formation with empirically determined source functions and velocity profiles (*cf.* Grossmann-Doerth, Kneer, and von Uexküll, 1974). Among the shortcomings of the dynamical model is that while the simulated H₂V peak intensity is much too high (Carlsson and Stein (1994), Figure 7; Uitenbroek (2002), Figure 6), the time-averaged intensity is much too low (*cf.* Figure 1).

Other 1D hydrodynamic models are similarly implausible. For example, in Ulmschneider and Kalkofen (2003), the temperature at a height of $z = 1.4$ Mm fluctuates between 4000 K and 8000 K; and in Cuntz, Rammacher, and Musielak (2007), the temperature at the top of the chromosphere in one model drops to 2500 K. In general, the 1D models, as a class, do not meet observational constraints.

Figure 2 shows the instantaneous temperature structure of a 2D theoretical atmosphere, by Leenaarts *et al.* (2007), which extends from the convection zone to the corona. Noteworthy features of this model are the temperature decrease from 6000 K at a height of 2.2 Mm to 3500 K at 2.7 Mm (where empirical models locate the chromosphere-corona transition region); the temperature of 2400 K in the upper chromosphere in the height range of 1.5 Mm to 1.8 Mm; and the positive temperature gradient at photospheric heights between 100 km and 400 km.

At transition region heights, the temperature of the gas implied by solar observations is between 10^4 K and 10^6 K (*cf.* VAL), and the lines emitted there are observed to be in emission. There is no observational evidence in favor of absorption lines or of temperatures below 4000 K at those heights as shown by the 2D model. The minimum temperature of 2400 K in Figure 2 is not calculated, but set as a lower limit by the computer program in

Figure 2 Snapshot of the kinetic temperature as a function of height above the photosphere in the 2D dynamical model of Leenaarts *et al.* (2007).

Figure 3 Temperature in simultaneous horizontal cuts of the 3D dynamical model of Wedemeyer *et al.* (2004).

order to prevent the temperature from dropping still lower. Again, there is no evidence in favor of such low temperature values anywhere in the quiet solar atmosphere.

The positive temperature gradient in the photosphere of this model causes lines formed there to be in emission. The quiet solar photosphere does not produce emission lines (except in some special cases involving non-LTE effects).

We conclude that this 2D model does not describe the quiet solar chromosphere. Other 2D models are not acceptable either. Stein and Nordlund (2000) conclude that 2D models generally are not consistent with observed line profiles.

Figure 3 shows the 3D model of W04 with four simultaneous horizontal cuts at chromospheric heights between 500 km and 1250 km, separated by 250 km. Characteristic features of the model are the high temperature fluctuations, between 2000 K and 7000 K, and the extremely low temperature of 2000 K or less, in the middle chromosphere, which is not supported by any observations; as well as the apparent evidence for horizontal shocks. Such shocks have not been observed in the solar chromosphere (although there are indications of a horizontal shock in the photosphere associated with a magnetic field; *cf.* Rybák *et al.* (2004) and H. Wöhl (2010, private communication)).

We conclude that this 3D model does not describe the quiet solar chromosphere.

All three dynamical models of the quiet solar chromosphere evidently have serious defects, whatever their geometry. To find out what may be responsible for these failures, we analyze basic length and time scales that characterize these atmospheres.

3. Atmospheric Temperature Structure and Temperature Fluctuations

There are three measures of the atmospheric temperature structure that highlight the differences between *i*) observations and the empirical models derived from them and *ii*) theoretical, acoustic wave models. They are:

1. the average or typical temperature;
2. the magnitude of temperature fluctuations; and
3. the average or typical temperature gradient.

The first measure determines the wavelength distribution of the emitted radiation; the second distinguishes between temperature fluctuations of low amplitude, at the percent level, and variations of the temperature by at least a factor of two; and the third tells us by the sign of the gradient whether the emergent spectrum will be characterized by emission lines or by absorption lines.

Consider Table 1: At zero height, which corresponds to the monochromatic optical depth of $\tau = 1$ at 5000 Å, the average empirical models (called C) of VAL and FAL (the subscripts 81 and 93, *e.g.*, in the table indicate the years of publication of the papers) have the same temperature as the respective coolest models (called A); but models C of VAL and FAL differ from each other by 100 K. For the most recent observations of Fontenla *et al.* (2009: hereafter FCHHT), models B and D differ by 20 K. On the other hand, the 3D dynamical models of W04 and Stein and Nordlund (1998: SN98 in the table) have fluctuations of 5700 K and 5000 K, respectively. While the differences in the empirical models refer to the average brightness temperature of different observed regions, it is still remarkable that the instantaneous brightness temperature fluctuations in the 3D simulations are orders of magnitude larger.

At a height of 250 km, in the middle photosphere, the same empirical models show a variation of 60 K, but differ from each other by 100 K. In models C and F of Fontenla *et al.* (2006: hereafter FATH), the difference is 30 K, and the difference from the FAL model is also 30 K. The high-resolution balloon observations reported by W. Schmidt (2010, private communication) show fluctuations of about 100 K.

In the CS model, the temperature spreads over 100 K (*cf.* Figure 1). This model is placed in the column of the empirical models even though it is a hydrodynamic model, because the temperature fluctuations reflect the Doppler motion of the Fe I line observed by Lites, Rutten, and Kalkofen (1993), which was used by CS94 as the driver of the acoustic waves. Thus the model does not depend directly on the gas motions in the convection zone as do the other 3D theoretical models.

At the height of the temperature minimum in almost all empirical models ($z = 500$ km), the temperature variation in the empirical models is less than 300 K, whereas it is 4000 K in the W04 model.

The temperature difference of 1600 K at $z = 875$ km between the coolest VAL model and the empirical model of Fontenla, Balasubramaniam, and Harder (2007: FBH) is large even though both are empirical models. However, note that the FBH model is constructed so as to represent the off-limb CO observations of Ayres and Rabin (1996), but the cool layer is otherwise chosen so as to be essentially transparent to radiation from the solar disk. The FBH model introduces a nongravitational function in place of the turbulent pressure used by FAL to account for the extension of the atmosphere. In the photosphere the FBH model is essentially the same as the FAL model.

In the upper layers of the chromosphere ($z \approx 1.5 - 2$ Mm), SUMER observations of three-minute oscillations indicate a very low amplitude of oscillations of the intensity, and hence of the brightness temperature. For example, converting the count rate in Figure 3 of CJW into fluctuations of the brightness temperature, we find an amplitude of 150 K in the EUV lines of C I, N I, and O I; and in the Lyman continuum, in the SUMER observations reported by Wilhelm and Kalkofen (2003), the fluctuations spread over 100 K. The theoretical CS94 model, on the other hand, has fluctuations of the kinetic temperature of 8000 K.

Table 1 Temperature variations in empirical and hydrodynamical models.

Height [km]	Observed/Empirical	δT_{obs} [K]	HD model	δT_{hydro} [K]
0	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	0	SN98	5000
	$T_{\text{FAL93,C}} - T_{\text{FAL93,A}}$	0	W04	5700
	$T_{\text{FAL93,C}} - T_{\text{VAL81,C}}$	100		
	$T_{\text{FCHHT09,D}} - T_{\text{FCHHT09,B}}$	20		
250	$T_{\text{Schmidt09}}$	100	W04	2300
	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	60		
	$T_{\text{FAL93,C}} - T_{\text{FAL93,A}}$	60		
	$T_{\text{FAL93,C}} - T_{\text{VAL81,C}}$	100		
	$T_{\text{FATH06,F}} - T_{\text{FATH06,C}}$	30		
	CS94	100		
500	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	270	W04	4000
	$T_{\text{FAL93,C}} - T_{\text{FAL93,A}}$	150		
	$T_{\text{FAL93,C}} - T_{\text{VAL81,C}}$	240		
750	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	280	W04	5300
875	$T_{\text{VAL81,A}} - T_{\text{FBH07}}$	1600	CS94	2400
1000	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	275	W04	5600
			CS94	4000
1250	$T_{\text{VAL81,C}} - T_{\text{VAL81,A}}$	275	W04	5500
1500–2000	T_{CJW97}	150	CS94	8000
	T_{WK03}	100		

Table 1 indicates that, except for the FBH model near its temperature minimum (875 km) and the CS94 model in the layer of formation of the Fe I line (250 km) whose Doppler motion drives the oscillations in the theoretical model, the fluctuations in the hydrodynamical models are one to two orders of magnitude larger than those implied by observations.

4. Dynamical and Radiative Cooling Times and a Basic Length Scale

We want to understand why the simulated temperature fluctuations in the three dynamical models we have discussed and others like them are so different from those observed that they do not resemble the medium they are intended to describe, and whether they all suffer from the same defect. We return to Figure 3 since, among the three papers discussed here, W04 present the most detailed, pertinent, and helpful analysis of the features of their 3D model, which may hold the key to understanding the cause of the failure of this model, and perhaps all 3D hydrodynamic models so far.

Figure 3 shows a snapshot of the horizontal temperature variation of the 3D model at four different heights. Striking features are the high contrast between hot and cool regions – 6800 K and 2800 K, respectively, at the base of the chromosphere; and 7400 K and 1800 K, respectively, in the middle chromosphere – the cool regions often separated by thin, hot sheets 100 km to 200 km thick and with a vertical extent of several scale heights, lasting

a minute or more (Figure 3; and Figure 3 of W04), and the persistence of extended cool regions of up to 2 Mm diameter.

We associate a time scale with the size of a typical cool region by assuming that acoustic waves are the agent of change. Taking the sound speed of 7 km s^{-1} from empirical models, the sound crossing time for a cool region of 1 Mm diameter is 150 s; at the low temperature of the 3D model the sound speed is lower by a factor of two and the sound travel time is correspondingly longer. An increase by another factor of two in time is required for a cool region of 2 Mm diameter, resulting in a dynamical relaxation time of ten minutes.

W04 estimate various relaxation time scales. From the autocorrelation of the temperature variation in horizontal layers they obtain 20–25 s in the chromosphere, and at least 120 s at the bottom of the photosphere; and 200 s from the time variation of the emergent continuum intensity.

We note that Beck *et al.* (2008) determine a decorrelation time from observations of the H line, finding a value of *ca.* 40 s.

W04 also estimate a radiative cooling time. They find a value of about 200 s for a temperature of 7000 K, the time rapidly increasing with decreasing temperature. Given 200 s as a lower limit of the radiative cooling time, they conclude that the thermal structure of the atmosphere is controlled mainly by adiabatic expansion, thereby effectively considering radiation to be a minor contributor to chromospheric structure and, *a fortiori*, to photospheric structure.

A cooling time of the atmosphere can also be estimated from observed line radiation. Consider the decay of the intensity of the emission peak on the blue side of line center in the K line of Ca II. When the intensity enhancement at some position in the supergranulation cell interior exceeds a certain threshold value, the phenomenon is referred to as a K_{2V} bright point (von Uexküll and Kneer, 1995). Figure 4 shows observations by Liu (1974), made at Kitt Peak, of the K line intensity of such a bright point at three instants of time during the three-minute evolution of the line profile.

Figure 5, from Liu (1974, Figure 3), shows the increasing intensity at the K_{2V} wavelength with 8 s spacing of the exposures. The instantaneous intensity minus the intensity at $t = 0$ is plotted against height, which is based on the Harvard-Smithsonian Reference

Figure 4 Line profile at three consecutive times in the evolution of the K line during a three-minute oscillation (Liu, 1974).

Figure 5 Observed time variation of the intensity of the blue side of the K line profile, with the intensity of the reference intensity at $t = 0$ subtracted, and plotted vs. estimated height (Liu (1974), Figure 3). The cadence of the observations is 8 s.

Atmosphere (HSRA: Gingerich *et al.*, 1971). Individual exposures are shifted upward successively by 5%. These height values were introduced only as a rough measure of successive heights where emission occurs and to separate the intensity profiles.

Consider the time variation of the intensity: The K_{2V} peak, on the blue side of line center, grows from its minimum of 3.5%, relative to the intensity of the nearby continuum at 4000 Å, to its maximum of 17%, in 120 s. The last half of the intensity increase occurs in 9 s. The decay back down to half the maximal intensity enhancement occurs in 8 s. Given the exposure time of 3.8 s, the rise and decay times are the same.

The line profile of an H_{2V} bright point tells the same story. Observations of the H line on Sacramento Peak by Beckers, Mauter, and Mann (1972) and discussed by Kariyappa (1992) show decay to half the peak intensity enhancement of an H_{2V} bright point in 6 s, and thus essentially the same cooling time as the K_{2V} bright point observed by Liu. The H line observations discussed by Cram and Damé (1983) are in qualitative agreement with the above cooling times of the H and K lines. Since the hydrodynamic cooling time is much longer than the cooling time observed in the H and K lines, much of the cooling must be mediated by the radiation field. For convenience we refer to this cooling as “radiative cooling,” with the understanding that hydrodynamic effects must also play a role.

The 2D observations of K_{2V} bright points by von Uexküll and Kneer (1995) agree qualitatively with the above bright-point observations that were taken along a slit. We note that it would take a bright point traveling at a right angle to the slit at the speed of sound one minute to cross a slit that is 380 km wide, and therefore much longer than the estimated intensity decay time of 8 s (I am indebted to R. Hammer for pointing out this possibility).

Figure 6 Time-varying simulated images in the CH G-band showing the emergent intensity at three instants of time, separated by one minute (from Stein and Nordlund (1998), Figure 19).

We conclude that the cooling time in the middle layers of the solar chromosphere is less than 10 s, and thus shorter by an order of magnitude than either the dynamical cooling time, or the radiative cooling time estimated by W04 for their dynamical model. Note that although most of the cooling is likely to be due to radiation, some portion will be due to the dynamics, *i.e.*, to adiabatic cooling.

The time interval during which the intensity decays corresponds to a spatial interval of 60 km, or an angular distance of 0.1 arcsec on the Sun, again using the speed of sound (7 km s^{-1}) to convert a time interval (8 s) into a spatial interval. We may conclude that significant structure of a size smaller than about 60 km cannot be maintained in the middle chromosphere for longer than about 10 s, and therefore does not really occur.

In the photosphere and low chromosphere there are no such dramatic events as the shocks that produce the Ca II bright points in the middle chromosphere. For the photosphere we can obtain a limit on the relaxation time from the simulated granulation pattern seen in radiation in the CH G-band. Figure 6, from Stein and Nordlund (1998), shows the time-varying simulated intensity at three instants of time, separated by one minute. The granulation pattern can easily be followed for the two minutes displayed, indicating that the relaxation time in the simulation is at least two minutes long (for a discussion of the relaxation time in the photosphere, see Section 6 below).

For the photosphere we can also estimate a photon mean free path, λ , and therefore a characteristic decay distance. Using the tabulated model C of VAL (or of FAL) for the relation between monochromatic optical depth at $5000 \text{ \AA}$ and geometrical height, we find, at $\tau_{5000} = 1$, $\lambda \approx 90 \text{ km}$ and a characteristic length of 90 km or, again, about 0.1 arcsec on the Sun.

Given the characteristic length, we do not expect significant horizontal temperature variations in the photosphere on a scale below 0.1 arcsec. And, indeed, we find a difference of only 15 K at a height of 150 km between the average empirical model, model C of VAL, and the coolest model, model A (*cf.* VAL, Tables 10 and 12); in the corresponding FAL models the temperatures at that height are the same. Similarly small fluctuations are found in observations made in 2009 by the *Sunrise* balloon experiment (Hirzberger *et al.*, 2010; W. Schmidt, 2010, private communication) which have very little scattered light. Their rms intensity contrast at $3000 \text{ \AA}$ is 28%, corresponding to a brightness temperature fluctuation of 80 K for an assumed local temperature of 4000 K, and 130 K for a local temperature of 5000 K. By contrast, the fluctuations of the kinetic temperature in the 3D wave model of W04 are $\delta T_{\text{kin}} \approx 5700 \text{ K}$ (at $z = 0$), similar to the fluctuations of 5000 K of Stein and Nordlund (1998).

Figure 7 Spatially resolved line profile of Fe I 6083 Å (blue lines) and spatially averaged profile (red line) predicted by a 3D hydrodynamic model (Asplund (2005), Figure 3).

Compare this with the range of brightness temperature variations, δT_{br} , of the simulated Fe II line at 5414 Å (Stein and Nordlund, 2000) or of the simulated Fe I line at 6083 Å (Asplund *et al.*, 2000a; Asplund, 2005), shown here in Figure 7, both of which cover $\delta T_{\text{br}} = 700$ K, and thus are larger by an order of magnitude than the observed temperature variation. Note that fluctuations of the kinetic temperature in an atmosphere may exceed the fluctuations of the corresponding brightness temperature. The 700 K value therefore represents a lower limit on the kinetic temperature variation in the photosphere of the dynamical model. In contrast to this result, Scott *et al.* (2009) computed a line profile of Ni I in a dynamical model and found “impressive agreement with observations.” A similar sentiment is expressed by Nordlund and Stein (2009) who found observations of photospheric spectral lines to agree with their “realistic” models “to within fractions of one percent” (see also Pereira, Kiselman, and Asplund, 2009).

Note that a comparison of observed intensities, and the brightness temperatures derived from them, with rms values determined from simulations would be expected to show a smaller separation of observed and simulated values. However, the effect of much larger fluctuations of the simulations would be expected to persist. For a discussion of rms values in the continuum intensity distribution, see Wedemeyer-Böhm and Rouppe van der Voort (2009) – I am indebted to the referee for this observation.

A caveat concerning the estimate of very low temperature fluctuations in empirical models of the photosphere, *i.e.*, the small temperature difference between models of cell center and network elements, is due to the fact that the relaxation length estimated for photons at 5000 Å is comparable to the spatial resolution of the observations on which the empirical models are based. But even if the temperature difference between the average VAL and FAL models and the corresponding coolest models should be larger than we have estimated, the fluctuations should still be only in the linear regime, and thus smaller by more than an order of magnitude than those modeled in the acoustic wave simulations.

Similar large differences between model predictions and observations are found in the upper chromosphere. The intensity variation due to three-minute chromospheric oscillations observed with SUMER at 770 Å in the Lyman continuum is 20% to 40% (Wilhelm and Kalkofen, 2003; hereafter WK), corresponding to a variation of the brightness temperature of 50 K to 100 K. Contrast this with the simulations by Carlsson and Stein (1994, Figure 4) of three-minute waves, which are based on observations by Lites, Rutten, and Kalkofen (1993) of the Doppler motion in a photospheric Fe I line at 3996.8 Å. In the CS model, the kinetic temperature varies between 2000 K and 10 000 K (*cf.* Table 1), with a corresponding variation of the brightness temperature at 770 Å by many orders of magnitude (*cf.* Kalkofen, 2003b).

Another indication that the actual temperature variation in the solar chromosphere is small comes from SUMER observations of the bright network relative to the darker supergranulation-cell interior. At 770 Å, the intensity is higher in the network than in the cell interior by a factor of two (*cf.* Curdt *et al.*, 2001), indicating that the brightness temperature is higher by 2.5%. Note that with an exposure time of 10 s and a spatial resolution across the slit of 1'', these space observations give a picture of instantaneous, local conditions in the upper solar chromosphere.

Thus, from the photosphere through the middle chromosphere to the high chromosphere, the observed intensity fluctuations are small, typically in the percent range, whereas the intensity fluctuations predicted by the dynamical simulations are much larger, exceeding those observed by more than an order of magnitude.

5. The Treatment of Radiation and Radiative Relaxation

It is noteworthy that the spatial scales of the 3D hydrodynamic solution of W04 agree more or less with the scales of the observed granulation pattern in the solar photosphere, except for occasional, much larger horizontal sizes in the model. Hence, the spatial grid of the hydrodynamic solution must be largely adequate for the description of the granulation pattern in a dynamical model, and thus also for a genuine solar model, *i.e.*, a theoretical model that satisfies observational constraints on intensity fluctuations in lines and continua. Shortcomings of current theoretical models must therefore be due to the treatment of relaxation we have called radiative – even though dynamical as well as radiative effects are involved – rather than to the treatment of the dynamics alone, at least in the 2D and 3D models.

Which features of the radiative transfer in the multidimensional models have been simplified too much to represent solar as well as stellar conditions? In the W04 model, for example, the radiative transfer is treated in the gray approximation of the opacity, making use of the Rosseland mean. This is clearly an unrealistic simplification, allowing easy escape of the energy from the medium and therefore very strong radiative cooling. Similarly, in the multi-group method used by Leenaarts *et al.* (2007), the wavelength dependence of the opacity is represented by four groups, or bins. The results for the model show that this is still simplified too much. In addition, neglecting velocity shifts in the line opacity underestimates or overestimates radiative losses from the atmosphere for emission or absorption lines, respectively.

The multi-group method with four bins was first used by Nordlund (1982) in a dynamical model of solar granulation. This pioneering work was recognized as such in a conference in Munich (Nordlund, 1985a). It is instructive to recall a comment made by Richard N. Thomas at the conference in the discussion following the paper by Nordlund (1985b) on “The Dynamics of Granulation and Its Interaction with the Radiation Field.” Thomas, in typical clairvoyance, said: “I don’t believe you, but it is fascinating. Real frequency distribution and line blanketing could help the models.”

When Nordlund’s method was extended to the middle chromosphere (Asplund *et al.*, 2000b), it did not produce a model with a temperature minimum followed by a temperature rise; instead, it produced a monotonic decrease of the time-averaged temperature, reaching 4000 K at the top of that model at $z = 1$ Mm – for a recent model, see Figure 2 of Carlsson, Hansteen, and Gudiksen (2010) or Figure 7 of Hayek *et al.* (2010) – rather than a temperature of 6000 K, as in the empirical, observation-based models.

The structure of the atmosphere might depend critically on the details of the opacity of the gas, not only on its bulk properties. Fault for the failure of the models may lie in the

description of the opacity, including lines with velocity shifts, and non-LTE effects. What is clear from the analysis of the W04 paper is that the large amplitudes of temperature and velocity fluctuations in the model are due to the (near) absence of radiative relaxation, and thus to the treatment of radiative transfer. Better theoretical models therefore require a more targeted treatment of radiative transfer, with opacities that cover the critical photon mean free paths, in lines as well as continua, that should be able to smooth the huge fluctuations of purely hydrodynamic models. Observations with higher spatial resolution advocated by Leenaarts *et al.* (2009) would not help, in this view, but may be useful for checking the estimates of the fundamental length of 0.1 arcsec derived from the decay of the intensity enhancement of Ca II bright points.

Perhaps one should replace the formal way of choosing the frequencies for the four bins described by Skartlien (2000) and Trampedach and Asplund (2003) by a more intuitive approach in which opacities corresponding to the critical photon mean free paths of 100 km to 1000 km are emphasized, in lieu of current choices where, *e.g.*, the single photon mean free path in higher layers of the W04 model is comparable to the solar diameter. In any case, departures from LTE in lines and continua need to be included, and not merely monochromatic scattering.

6. The Magnetic Canopy and Wave Dissipation

As Table 1 shows, there are very large differences between observations and empirical 1D models on one hand (Table 1, columns 2 and 3), and theoretical 3D acoustic wave models on the other (columns 4 and 5). It is generally agreed that the quiet interior of supergranulation cells is described by hydrodynamic equations. The solution of these equations must therefore be compatible with models based on observations. The question of how to transform a theoretical 3D model into an equivalent empirical 1D model is usually answered by referring to what is called the magnetic canopy (*cf.* CJW; Carlsson and Stein, 1997a, 1997b). In tracing this presumed transformation it is instructive to investigate what tasks the canopy must accomplish in order to show the equivalence of the two kinds of models.

Table 2 compares observed temperatures and temperature variations in the empirical model of FAL93 with simulated temperatures and their fluctuations in the theoretical model of W04, as functions of the heights at which the theoretical model shows horizontal cuts. The data on which the empirical FAL model (columns 2 and 4) is based refer to observations made at different times; the temperatures and their fluctuations that are taken from the theoretical W04 model (columns 3 and 5) all refer to the same instant of time.

The most striking differences between the two models are: *i*) the rise of the empirical temperature (column 2) from the base of the chromosphere ($z = 500$ km) to the top of the

Table 2 Empirical and simulated temperatures and their fluctuations.

Height [km]	T_{FAL93} [K]	$T_{\text{W04}}^{\text{min}}$ [K]	δT_{obs} [K]	δT_{W04} [K]
0	6500	4900	0	5700
250	4900	3500	60	2300
500	4400	2800	150	4000
750	5300	1900	570	5300
1000	5900	1800	410	5500
1250	6400	1700	400	5500

layers displayed in W04 ($z = 1250$ km), *i.e.*, from $T = 4400$ K to $T = 6400$ K; *ii*) the drop of the lowest theoretical temperature in a layer (column 3) from $T = 2800$ K to $T = 1700$ K; *iii*) the magnitude of the temperature fluctuations (columns 4 and 5), which is higher in the theoretical model by more than an order of magnitude; and *iv*) the top of the chromosphere and base of the transition region, which is higher in the empirical models by 0.4 Mm (*cf.* Figure 1 and FAL, Table 1).

In order to transform the theoretical 3D model into an equivalent empirical 1D model the canopy must solve three energy problems in the theoretical model: *i*) it must raise the lowest temperatures sufficiently to achieve a positive gradient throughout the chromosphere so only emission lines arise in the chromosphere, *ii*) it must increase the thickness of the theoretical chromosphere by about 0.4 Mm, and *iii*) it must lower the temperature fluctuations by more than an order of magnitude.

No mechanism has been proposed that would raise the temperature throughout the theoretical chromosphere ($z > 500$ km), changing the negative temperature gradient into a positive gradient everywhere, raise the top of the theoretical chromosphere, and lower the amplitude of temperature fluctuations throughout the theoretical atmosphere ($z > 0$) by at least an order of magnitude. The magnetic canopy does not appear to provide a viable explanation for the peculiar features of theoretical acoustic wave models. In the interior of supergranulation cells, acoustic waves must be the wave type that is responsible for the structure and dynamics of the chromosphere. The fault for the unexplained features of the theoretical model must therefore lie in assumptions made in the radiative transfer.

As was shown in the discussion of relaxation times, the W04 model takes dynamical relaxation into account, which has a characteristic time scale of 200 s. However, it does not take into account the kind of relaxation that is seen in the decay of the emission peaks of the Ca II lines to half the enhanced intensity increase, *i.e.*, what we have called radiative relaxation, which has a time scale of 10 s and is therefore shorter than the purely dynamical relaxation time by more than an order of magnitude.

A consequence of dynamical relaxation alone is that temperature fluctuations grow over the longer time span of the dynamics, leading to fluctuations of 5000 K or more instead of 300 K or less. Conversely, temperature fluctuations in the dynamical model of 5000 K point to the neglect of radiative relaxation. Since the simulated temperature amplitude is about 5000 K throughout the solar atmosphere ($0 < z < 2$ Mm), radiative relaxation must have been largely neglected everywhere in constructing the theoretical model. Furthermore, the large amplitude of temperature fluctuations down to the deep photosphere ($\tau = 1$) suggests that radiative relaxation is also largely neglected in the convection zone. The strong correlation between fluctuations of temperature, velocity, and density (*cf.* Stein and Nordlund (1998), Figure 10) implies that pressure fluctuations in the convection zone are also large, especially in its upper layers, which are the primary site for generating acoustic waves, leading to the emission of a high acoustic flux. In view of the low acoustic flux observed with TRACE from the Sun by Fossum and Carlsson (2005), that is an unexpected prediction.

An important consequence of the large amplitude of temperature fluctuations in the dynamical 3D model is a high level of radiative emission. Consider the radiative transfer equation: The net radiative cooling rate, Φ , is given by

$$\Phi = \int_{\nu} d\nu \int_{(4\pi)} d\Omega \kappa_{\nu\mu} (S_{\nu\mu} - I_{\nu\mu}),$$

where $\kappa_{\nu\mu}$ is the frequency- and angle-dependent opacity, $S_{\nu\mu}$ is the source function, and $I_{\nu\mu}$ is the specific monochromatic intensity. The integration of frequency ν extends over the whole spectrum, and the integration over Ω extends over all directions specified by the angle

cosine μ . Now consider the panel in the lower right corner of Figure 3 (*i.e.*, panel f) and the thin hot wall that is located at 3000 km from the bottom boundary and 1700 km from the right boundary. It has a width of 200 km and a temperature of 7000 K and separates two cool regions of 2000 K. For a frequency for which the photon mean free path is comparable to the thickness of the wall, the mean intensity in the hot wall is largely determined by the more extensive cool regions on either side of the wall. For local thermodynamic equilibrium (LTE), the source function would be given by the Planck function. In the hot wall, its value is much higher than that of the mean intensity; thus the contribution to the net cooling rate by emission and absorption in the hot wall is positive. Compared to the analogous situation in the actual solar atmosphere, the theoretical atmosphere will have much stronger cooling because of the much higher amplitude of temperature fluctuations. We therefore expect the theoretical atmosphere to be cooler than the solar atmosphere, with the possible exception of the deepest layers, where the higher radiative emission may not yet have reduced the temperature. In the limiting case of very strong cooling, the temperature structure of the theoretical atmosphere should approach that of a radiative equilibrium atmosphere. This limiting case would arise when the remaining acoustic flux is negligible compared to the radiative flux and would be effective mainly in the upper chromosphere. But it may be difficult to recognize the limiting case because of the ambiguity caused by the huge temperature fluctuations of 5000 K.

Thus, the peculiar features of the theoretical 3D model of W04, namely, a negative temperature gradient and excessively high fluctuations of the temperature and other state variables of the atmosphere, can be understood as caused by inadequate treatment of radiative relaxation, which allows temperature perturbations in the wave model to grow to large amplitude. Other theoretical models share the essential features of the W04 model.

7. The Solar Oxygen Abundance

The binning method of Nordlund (1982) was used by Asplund *et al.* (2004) in an investigation of the solar oxygen abundance with an acoustic wave model in which the amplitudes of both the intensity and the velocity fluctuations (*cf.* Figure 7) are significantly larger than observed: the amplitude of the temperature fluctuations in the model is at least ten times as large as the observed fluctuations in brightness temperature, and the velocity amplitude is at least twice that of the Fe I line observed by Lites *et al.* (1993; *cf.* Carlsson and Stein (1997a), Figure 3). The large velocity fluctuations of the 3D simulations compared to those observed by Lites, Rutten, and Kalkofen (1993) broaden the emergent line profile and thereby mimic larger metal abundances. Consequently, lines formed in the new 3D model with the old, standard abundances have line strengths, for all lines, that are too large. To compensate for the high level of fluctuations in the wave models, the values of the abundances for all photospheric lines were adjusted downward (*cf.* Asplund *et al.*, 2009) from their old, higher, values, which were based on the empirical Holweger–Müller model of the solar photosphere (Holweger and Müller, 1974). The new, lowered abundances thus owe their values to the high levels of temperature and velocity fluctuations and thus, ultimately, to the lack of radiative damping in the hydrodynamic model.

We point out that the freedom to change the internal temperature structure of the Sun, which depends on the abundances of the metals, is highly constrained by *i)* the agreement of 10^5 predicted internal oscillation frequencies with observed modes (*cf.* Chitre and Dwivedi, 2008), and *ii)* the accuracy of a few parts in 10^4 with which the sound speed throughout most of the solar interior is known (Boothroyd and Sackmann, 2003).

The lowered metal abundances as well as the large temperature and velocity fluctuations are artifacts due to the simplified treatment of radiative relaxation in the 3D model atmospheres. Also artificial is the increasingly small-scale structure of the theoretical models, which increases with increasing numerical resolution. This increase in amplitude is a feature of the models, not of the Sun, since below a length of 0.1 arcsec, no significant structure should be found if the estimate given in Section 4 is realistic.

For a detailed discussion of the recent history of solar abundance determinations, see Nordlund, Stein, and Asplund (2009).

8. The Effect of Geometry in Acoustic Wave Models

All hydrodynamic models show temperature fluctuations that are far larger than those observed in the quiet Sun, but the causes are different for different geometries. In 1D models, acoustic waves are restricted to the vertical direction. Thus there is no dilution due to horizontal spreading of the wave energy, and also no compensating influx into a given vertical column from the sides, and hence no smoothing of the vertical distribution of wave energy. In the low-amplitude limit, the growth rate of the wave amplitudes in 1D is strictly exponential, for which a pressure perturbation (in the isothermal limit) grows as $p \sim \exp(z/\mathcal{H})$, where z is height, p is the pressure perturbation due to an upward-propagating wave, and $\mathcal{H}$ is the scale height in the atmosphere. Such plane waves would be expected for a plane source due to a collapsing granule, for example, as shown by Skartlien, Stein, and Nordlund (2000). The plane source represents an extreme case of a broad source region (Kalkofen *et al.*, 2010) for which the wave amplitude becomes very large and the dissipation rate as a function of height becomes distorted, with higher rates at low height and reduced dissipation at greater height (*cf.* Kalkofen, 2004). The other extreme is a point source (Bodo *et al.*, 2000) which in the low-amplitude limit corresponds to wave propagation in a cone with a vertical axis. The point source model corresponds more to the observations of bright points (Kalkofen, 2003a), which suggest that the upward-propagating disturbance due to an acoustic wave expands in the lateral direction and behaves more like $p \sim z^{-2} \exp(z/\mathcal{H})$ (*cf.* Bodo *et al.*, 2000; Kalkofen, 2003a).

The 2D models confine wave propagation to a vertical slab and therefore also have faster amplitude growth with height than does the actual atmosphere.

The 3D models assume the correct geometry but suffer, as stated earlier, from the neglect of radiative smoothing of temperature fluctuations, which are much too high in the numerical simulations. These temperature fluctuations are accompanied by high velocity fluctuations, as seen in Figure 7.

All modelers of the temperature structure of the solar chromosphere accept as a *sine qua non* condition the requirement that the predictions from a model must agree in character with observations. Of the modern theoretical models produced during the last quarter of a century, none meets the requirements discussed here. How is that possible?

When the acknowledged leaders in hydrodynamic modeling (*e.g.*, Stein and Nordlund, 2000) tell the reader that they are demonstrating realistic simulations of solar surface convection and obtain excellent agreement of the predicted emergent intensities with observations of the profiles of weak photospheric lines – even though the statement applies only to spatially and temporally averaged profiles of such lines, and not to temporally resolved lines – no one is likely to question these judgments unless prepared to unravel the arcana of radiation hydrodynamics. But Stein and Nordlund themselves apparently did not appreciate the connection between excessively high wave amplitudes and small-scale structure

in the atmosphere, having become used to increasing levels of structure as the numerical resolution of the models is increased. They claim that at a horizontal numerical resolution of 25 km their simulations “show more detail than is visible even in the best observations of solar granulation,” whereas bright-point observations suggest (*cf.* Cram and Damé (1983), Figure 2a) that the size of structure in the Sun is comparable to the spatial resolution of high-quality observations, *ca.* $0.''1$ (70 km).

9. Conclusions

The quiet solar chromosphere in the interior of supergranulation cells is generally well described by sets of static, one-dimensional, empirical models for different cell and network features with small differences in temperature structure. All such models have smoothly varying temperatures, fluctuations in the linear regime, and a positive gradient in the upward direction, and hence show only emission lines, in agreement with observations. On the other hand, all theoretical acoustic wave models of the chromosphere have temperature fluctuations in the nonlinear regime. In models with 1D and 2D geometries, the wave energy is channeled into too few dimensions, resulting in growth rates for upward-traveling disturbances that are too high to agree with observations. Models in 3D can be expected in the future to provide the foundation of an accurate theoretical description of the atmosphere, but all current 3D models, beginning with Nordlund (1982), suffer from oversimplification in the description of radiative damping of temperature fluctuations. Consequently, temperature fluctuations in the wave models are too high, typically by an order of magnitude or more; velocity fluctuations also appear to be too high. Absorption lines formed in the photospheric regions of wave models are therefore too strong. In compensation, abundances for all elements have been reduced, leading to the prediction of reduced metal abundances in the Sun. A prime example is oxygen, for which, according to this view, errors in the treatment of radiative cooling have resulted in the prediction of a lower abundance, and hence a change in the internal structure of the Sun, thereby destroying the agreement between 10^5 modes observed on the Sun and eigenmodes predicted on the basis of a solar model. The new, lower abundances of metals are a consequence of the oversimplified treatment of radiative interactions in the wave models, and seem incorrect.

The older abundance values for the metals were based on empirical models. Even if the observations for which these models were constructed had been taken with lower resolution than the 0.1 arcsec that we have estimated for the basic length in the atmosphere, the low level of fluctuations in a medium with radiative damping should guarantee low levels of temperature and velocity fluctuations. The old value for the oxygen abundance, from the Holweger–Müller model such as given by Grevesse and Sauval (1998), should therefore not be discarded.

Another consequence of the high amplitude of temperature and velocity fluctuations is the expectation of high energy flux of acoustic waves emitted from the convection zone. This prediction is surprising in view of the low acoustic wave flux observed with TRACE by Fossum and Carlsson (2005).

The comparison with the Sun of temporally and spatially resolved hydrodynamic models shows wide discrepancies and makes it clear that current 3D models do not describe the solar atmosphere, for example, by showing absorption lines where only emission lines are observed and amplitudes of temperature fluctuations far in excess of those observed. The excellent agreement commonly cited by modelers for spatially and temporally averaged, state-of-the-art models is misleading, and the claim of realistic simulations is untenable in

view of the large, and unobserved, fluctuations in the models as well as the sign of the temperature gradient in the chromosphere.

Observations of H₂V and K₂V bright points show that the cooling time in the middle chromosphere is about 10 s, whereas the wave model of Wedemeyer *et al.* (2004) has a cooling time of 200 s or longer. The signature of the oversimplified treatment of radiative energy exchange is seen in temperature fluctuations that occur on a longer time scale than those observed in the quiet solar atmosphere by a large factor, typically an order of magnitude. All 3D acoustic wave models show these slow fluctuations of the temperature and, typically, time-averaged temperatures that decrease with height in the chromosphere. All acoustic wave models constructed in the last quarter century (including those of the present author) are invalidated either by the forcing of the waves to progress without (in 1D), or with insufficient (in 2D), spreading in upward propagation, or (in 3D) by the failure to properly account for relaxation of temperature fluctuations in the atmosphere in which radiative effects appear to play a major role.

The short radiative cooling time of temperature perturbations inferred from observations in the middle chromosphere implies that there is a basic length in the atmosphere below which there are no significant structures in the quiet solar atmosphere. Observations with a spatial resolution much below 0.1 arcsec should reveal whether the estimate of 70 km for the basic length is realistic, but we estimate that no further significant structures would be found.

The conclusion of this paper is that the spatial numerical grid used in the current simulations is sufficiently fine-grained to represent the atmosphere, and that the only serious flaw of current 3D hydrodynamical simulations is in the treatment of radiative cooling. The starting point for improved modeling should therefore be an investigation of improved treatments of radiative interactions in 3D models.

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