TITLE
*ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION***
NAMES OF EDITORS

The Solar Temperature Minimum and Chromosphere

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Abstract. Wave motions cause the brightness temperature in the centers of strong infrared CO lines to increase and decrease by about 200 K. The CO number density quickly decreases as T increases, but is slow to increase again as T decreases. This causes the strong CO lines to be formed in the temperature minimum region rather than at chromospheric heights. Thus there can be a chromospheric rise in temperature, accounting for UV emission lines and for other diagnostics of the temperature minimum and chromosphere, without producing emission in the CO line cores, which is not observed. We are able to reconcile minimum temperatures as low as 3800 K inferred from CO observations with the higher minimum brightness temperatures observed in the continuum near 150 μm, in the continuum near 160 nm, and in the wings of the Ca II resonance lines. The time-dependent modeling of Carlsson and Stein has been proposed as a possible resolution of these conflicting temperature determinations. We suggest that the CO observations can be reconciled with other temperature-minimum and chromospheric diagnostics by assuming temperature fluctuations no larger than the fluctuations of observed brightness temperature, i.e., fluctuations much smaller than those produced by shock waves in the Carlsson and Stein simulations.

1. Introduction

It has been recognized for some time that the brightness temperatures as low as 3800 K observed in the centers of the strong infrared CO lines are substantially lower than the minimum values inferred from all other diagnostics of the solar minimum temperature, namely, the observed minimum brightness temperature of about 4200 K in the continuum near 150 microns, the 4400 K minimum in the continuum around 160 nm, and the roughly 4400 K minimum seen in the wings of the Ca II resonance lines. While these do not seem to be large differences, they exceed observational uncertainties and they have prompted conflicting interpretations of the structure of the temperature minimum region and low chromosphere.

This issue has been joined by another development. Carlsson & Stein (1995, 1997, 1999) have modeled the dynamical behavior of the Ca II H line by simulating the propagation of waves traveling outward from deeper layers of the photosphere. Their calculations demonstrate remarkable agreement between the velocities inferred from a deep photospheric iron line and the observed phase shifts and brightenings that subsequently occur in the H line formed much higher in the atmosphere. They are less successful in matching the observed H line intensity values. Uitenbroek (2002) finds that the calculated brightenings and amplitude variations exceed observed values, and Ayres (2002) finds that the lowest temperatures in the Carlsson and Stein simulations are not low enough to account for the CO lines.

The lack of agreement with observed intensities does not invalidate the basic dynamical calculations of Carlsson and Stein, which, after further refinement, will undoubtedly become more realistic. The issue raised by the Carlsson and Stein modeling is whether: a) it is meaningful to consider that the atmosphere has temperatures which vary moderately about a given distribution with height (consistent with observed brightness temperature variations), or b) the temperature variations with time, as shocks develop in the atmosphere, are so large that the concept of a given temperature distribution with relatively small time variations is essentially meaningless. We approach this issue by studying the temperature minimum region (between the upper photosphere and the chromosphere) and conclude that temperature fluctuations larger than the observed brightness temperature fluctuations are not required to account for availbale observations.

2. The CO Lines

Uitenbroek, Noyes, & Rabin (1994) present observations of the detailed variation with position and time of the fundamental vibration-rotation transitions of CO at 4.67 μm near disk center. In regions of the quiet Sun away from network elements the strong 3-2 R14 line fluctuates by about $\pm$ 200 K both in position and time. These observations show that the increases and decreases of brightness temperature with time at every location are the result of wave motions.

The strongest space- and time-averaged CO lines are observed to have central brightness temperatures of 4100 K at disk center (see Avrett 1995). Noyes & Hall (1972) were the first to observe central brightness temperatures as low as 3800 K near the limb. The recent paper by Ayres (2002) confirms these low values.

Studies by Ayres & Wiedemann (1989) and Uitenbroek (2000) demonstrate that the CO lines are formed in LTE and are not affected by electron scattering, so that actual temperatures as low as 3800 K (i.e., equal to the observed brightness temperatures) must occur somewhere in the atmosphere, with temporal fluctuations of a few hundred degrees. Two questions may be asked: 1) Where do these low temperatures occur? and 2) How can these values be reconciled with the higher minimum values from other diagnostics?

With regard to where the CO lines are formed, it should be noted that $N_{\rm CO}$, the CO number density, is a sensitive function of temperature so that $N_{\rm CO}$ can decrease by an order of magnitude when the temperature increases by a few hundred degrees. While such a decrease is almost instantaneous, the reverse is not true. When the temperature decreases, the CO formation time in the chromosphere is longer than a typical wave period. Hence, temperature fluctuations will tend to reduce the opacity of CO so that the lines will be formed deeper in the atmosphere than in an atmosphere without time variations.

See Avrett, Hoeflich, Uitenbroek & Ulmschneider (1996). Reasonable estimates indicate that the CO lines are formed in the temperature minimum region, at heights of 500–600 km, and that a chromospheric temperature rise above this region would not affect the observed CO lines.

This interpretation has to satisfy the observed limb darkening in the lines and the observed off-limb behavior. The results we give below suggest that these requirements can be met.

Vernazza, Avrett, & Loeser (1981) constructed semi-empirical models for six components of the quiet Sun, ranging from component A (cell center) to component F (mainly bright network). These models used SkyLab EUV observations to determine the structure of the upper chromosphere, and other observations to determine the lower chromosphere and temperature-minimum region.

For the present purpose of simulating the CO lines, we consider a modified version of model A (called AL here) that has the minimum temperature lowered to 3800 K; from there the temperature rises quickly to chromospheric values as before. In calculating the CO lines with the PANDORA computer program (Avrett & Loeser 1992), we simulate the decrease in opacity due to temperature fluctuations by an ad hoc modification of the CO opacity calulation: in the temperature minimum region we increase the temperature values used in the LTE formula for the CO opacity by 5% above the model AL values, and by 10% in the chromosphere.

Figure 1 shows the temperature vs. height for models AL, C, and F, where C represents the average quiet Sun, and F represents bright network. When lowering the model AL temperature minimum to 3800 K, followed by a rapid increase, we found better agreement with some observations by letting the low-chromospheric temperature values of model AL exceed those of model F. Also, our latest versions of models C and F have been modified slightly from those given earlier to remain consistent with available observations.

Figure 2 shows the disk-center CO profiles near 2239 cm^{-1} from models AL, C, and F compared with satellite observations by Farmer & Norton (1989). These observations, with a resolution of about 90,000, do not resolve the narrow CO line cores fully, so that we have applied some spectral smoothing to the calculated profiles to obtain comparable results. The blend of the 2-1 R39 and 1-0 R28 lines has the lowest disk-center brightness temperature among all the CO lines (Avrett 1995). At much higher resolution this central brightness temperature should be about 100 K lower.

The Farmer and Norton observations average over cell and network. We would expect a combination of the AL and F profiles, in proportion to cell and network area contributions, to correspond to the observed profile, but we do not attempt detailed fitting here. Note that at least moderate variations with time also need to be taken into account.

Figure 3 shows how the CO profiles calculated from model AL vary from center to limb and beyond the limb. This figure shows the 4-3 R23, 3-2 R14, and 2-1 R6 lines near 2143 cm^{-1}. The top curve gives the spectrum at disk center. Each of the other curves shows the intensity along a line of sight tangent to a given atmospheric height, in spherical coordinates. The heights are -100, 0, 200, 400, 600, 800, and 900 km, where height 0 corresponds to unit radial optical depth in the continuum at 500 nm, and where -100 km is the deepest

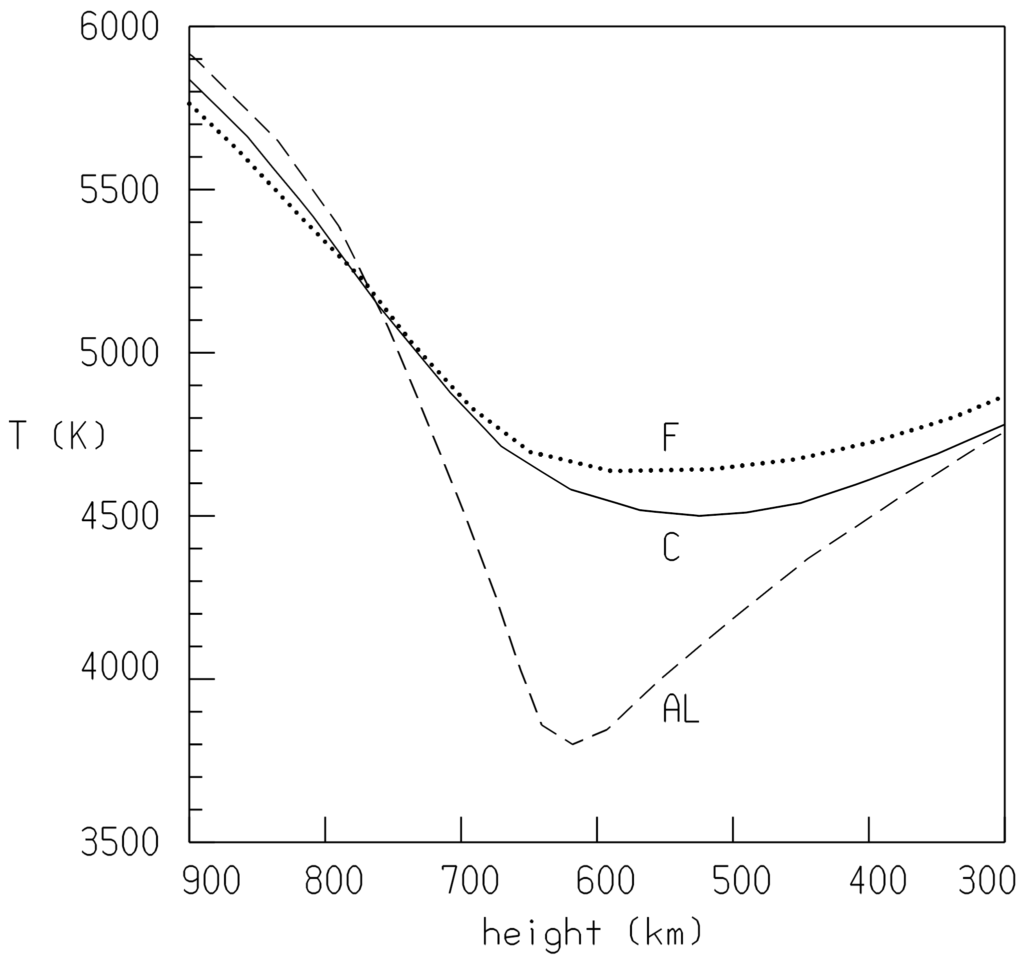

Figure 1. Temperature distributions for models AL, C, and F.

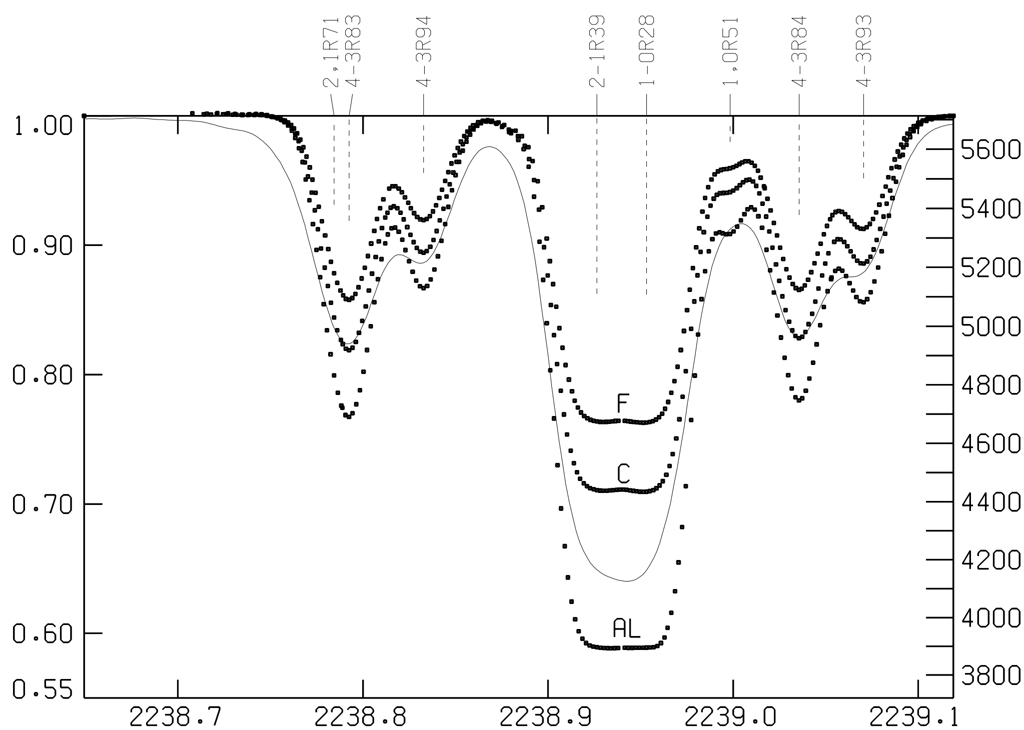

Figure 2. The solid curve shows the CO spectrum observed by Farmer & Norton (1989), averaged over a large area near disk center (see Avrett 1995). A linear combination of the AL and F calculated profiles, in proportion to cell and network areas, might be comparable to the observed distribution. The model C results are shown only for reference.

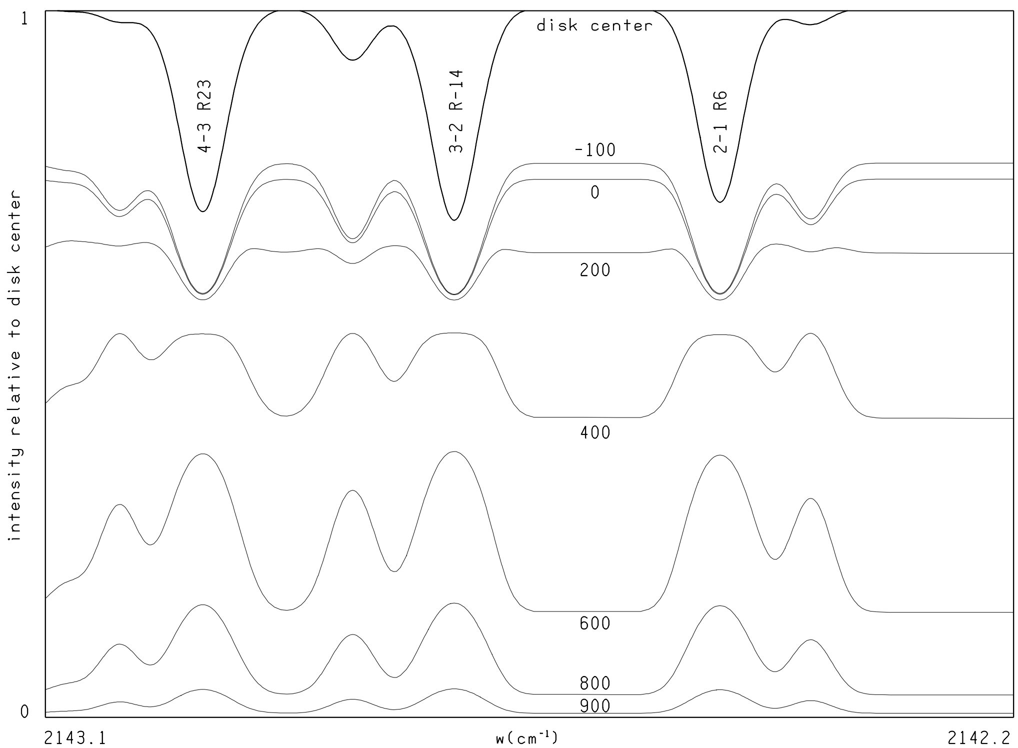

Figure 3. CO intensity profiles near 2143 cm^{-1} at disk center and for lines of sight tangent to positions on the disk close to the limb, and to positions above the limb.

layer in the model calculation. The temperature minimum of 3800 K in model AL occurs just above 600 km.

Note that the calculated continuum rapidly decreases above 100 km, while the line-center intensities diminish more slowly, so that the CO lines are in emission beyond the continuum limb. These results seem to be in rough agreement with the off-limb observations shown by Solanki, Livingston, & Ayres (1994). See also Ayres (2002) for a more detailed discussion, and particularly Figure 4 of Uitenbroek et al. The precise height determinations at the limb are critical in the interpretion of these results, and need further study. Here we have applied spectral and spatial smearing to the calculated spectrum in an attempt to mimic the instrumental resolution of the observations such as those of Solanki et al., but much more spatial smearing would be needed to match the off-limb results of Uitenbroek et al.

3. The 150 μm Region

LTE diagnostics also apply to the continuum further in the infrared and submillimeter region where the brightness temperature decreases with increasing wavelengh as the hydrogen free-free opacity decreases and unit optical depth moves higher in the photosphere. A minimum is reached near 150 μm and then

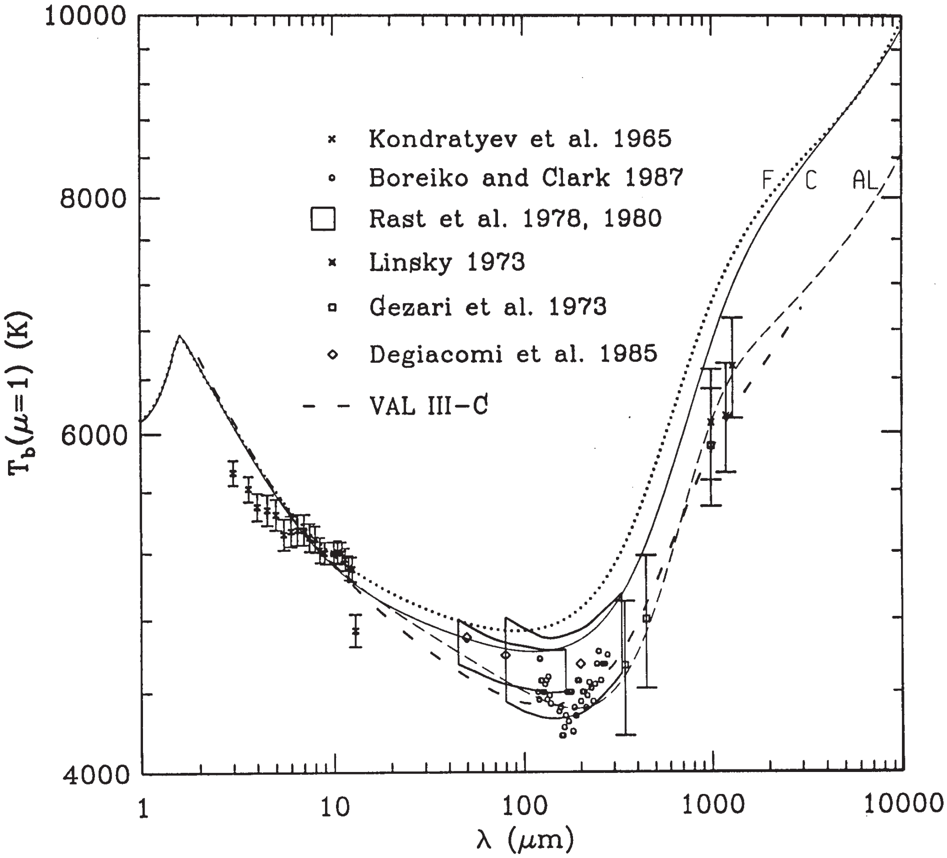

Figure 4. Continuum brightness temperatures calculated from models AL, C, and F compared with observations at millimeter and submillimeter wavelengths. See Gu et al. (1997) for the references in the figure.

the brightness temperature increases as a result of the increased temperature in the chromosphere. Cell and network structures cannot be resolved separately at such long wavelengths.

Figure 4 shows the calculated brightness temperature distributions for the three models compared with observations. Here we have plotted the calculated curves on a figure given earlier by Gu, Jefferies, Lindsey, & Avrett (1997) (the references noted in Figure 4 can be found in that paper). Note that though model AL has a minimum kinetic temperature of 3800 K, the minimum calculated brightness temperature for this model is about 4300 K, since the continuum intensity consists of contributions from a range of heights spanning 200 – 300 km. Models AL and F give cell-center and bright-network distributions that are blended together in the unresolved observations, perhaps represented by model C. These results seem consistent with the CO results given above.

4. The Ca II H Line

The inner wings of the Ca II H and K lines have opacities large enough to be formed in the temperature minimum region. Most profiles show a local intensity minimum (called H1 for the H line) between the line wings formed in the photosphere and an emission peak (H2) closer to line center which is formed in the chromosphere. The line center intensity (H3) is small, even though formed high in the chromosphere, because of line scattering in this outer region. To interpret the H1 minimum we must include theoretical treatments not only of departures from LTE but also of partial frequency redistribution, both of which not only cause the H1 brightness temperature to differ from the minimum temperature, but also contain uncertainties. Also, the emission is highly sensitive to gas motions and inhomogeneities, and in this wavelength region higher temperatures tend to have greater influence than lower temperatures because of the exponential dependence of the Planck function on temperature.

Figure 5 shows the calculated H-line profiles for models AL, C, and F compared with three profiles from Cram & Damé (1983) which have been symmetrized and put on an absolute scale (see Avrett 1985). The three Cram and Damé profiles represent averages of brightness components seen at high spatial resolution: the faintest 10%, the median 10%, and the brightest 10% in quiet solar regions. However, there are profiles which are fainter and brighter than these, and often the H2 emission occurs only in the violet wing.

These are not good fits, but there are large uncertainties in comparing static model profiles with the time-dependent asymmetric observed profiles. It should be noted that the calculated H1 minimum brightness temperature for model AL is about 4150 K even though the minimum temperature is 3800 K for this model.

5. The 160 nm Region

Finally, we consider the UV minimum region, where the continuum also has a minimum brightness temperature near 160 nm. This is the counterpart of the 150 μm region. The opacity of the solar atmosphere increases from a minimum value at 1.6 μm longward through 150 μm and shortward through 160 nm where emission from the chromosphere begins in both cases. Lines are mostly in absorption longward of about 160 nm and are mostly in emission (due to the chromosphere) shortward of this wavelength. The emission lines shortward of the 160 nm region vary in intensity but always remain in emission at all positions and at all times (see Carlsson, Judge, & Wilhelm 1997). The simplest interpretation of this behavior is that there is a persistent increase in chromospheric temperature without great fluctuations in time. In contrast, the Carlsson and Stein calculations involve strong shocks every 3 minutes or so that do not produce a persistent increase in chromospheric temperature, implying that the UV lines are in absorption except during brief intervals when they are strongly in emission. Since this behavior is not observed, Carlsson, Judge, and Wilhelm concluded that something is missing in the Carlsson and Stein calculations.

The static, semi-empirical component models roughly match the UV spectra, since they were constructed for this purpose. In the UV minimum region, model AL gives much lower intensities than are observed at high spatial reso-

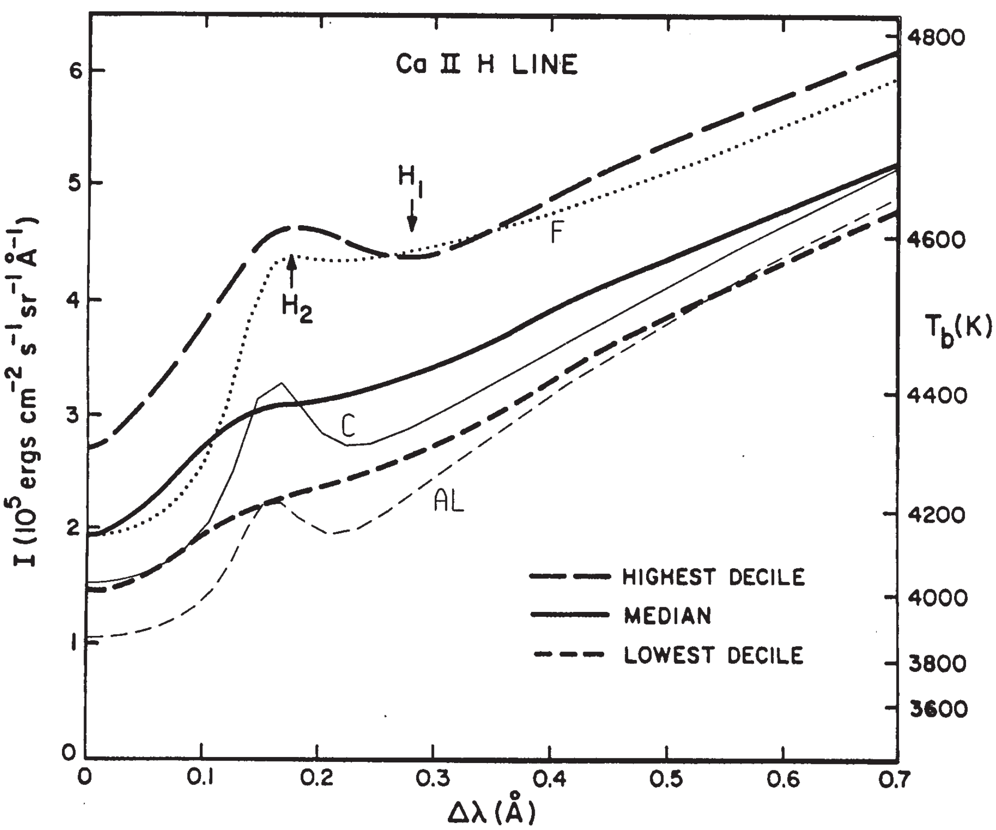

Figure 5. Comparison of the lowest-, median-, and highest-decile H-line profiles from Cram & Dame (1983) with the profiles calculated from models AL, C, and F.

lution, but temperature fluctuations at 160 nm might lead to higher intensities than would be calculated from a composite of separate time-independent models (again due to the temperature sensitivity of the Planck function, which is more pronounced at 160 nm than at 397 nm for the H line).

Figure 6 shows the calculated disk-center brightness temperatures from models AL, C, and F for wavelengths between 135 and 210 nm compared with the corresponding observations by Samain (1978, 1980). The observed values indicated by the X symbols are at wavelengths chosen between absorption or emission lines to represent the continuum as well as possible. The calculated values are based on sampled opacity values that were selected to approximate the distribution of the many lines in the spectrum. Shortward of 152 nm the level 1 continuum of Si I dominates. Longward of this wavelength the line and continuum opacities are comparable. Note that, as in the case of the H line, the lowest brightness temperatures for model AL lie well above the minimum temperature of 3800 K.

The results in these figures are intended to demonstrate the plausibility that a combination of temperature distributions such as those in the three component models can account for the observations shown here. (Note, however, that static component models cannot be expected to match observations with strong time variations.)

6. Conclusions

In this paper we have made an attempt to reconcile the observations of the CO lines with the other diagnostics of the solar temperature minimum region and chromosphere. We argue that temperature fluctuations comparable to the observed brightness fluctuations in the CO lines cause these lines to be formed in the temperature minimum region rather than at chromospheric heights, so that the chromosphere is optically thin in the CO lines. Then a chromospheric temperature rise is not in conflict with CO limb darkening and the observed behavior across the limb.

The CO observations are consistent with the variation of brightness temperatures with wavelength near 150 μm, which is also a reliable LTE diagnostic, although without high spatial discrimination. It is more difficult to reconcile these results with the higher minimum brightness temperatures observed in the continuum near 160 nm and in the H-line wing, but some possible explanations are suggested.

The dynamical, energy-balance models of Carlsson and Stein start with observed initial conditions in the deep photosphere. Otherwise they calculate a temperature distribution that evolves with time. This ab initio modeling, although tied to observed data, differs from semi-empirical modeling in which the temperature distribution is empirically determined so that the calculated and observed spectra agree as well as possible. The ab initio modeling relies on the dynamics to provide the mechanical heating and to determine the time-dependent temperature structure. The semi-empirical modeling prescribes a temperature structure (which could be time-dependent) that leads to agreement with observations (and from which the corresponding mechanical heating distribution can be calculated). Semi-empirical models use the observed spectrum to

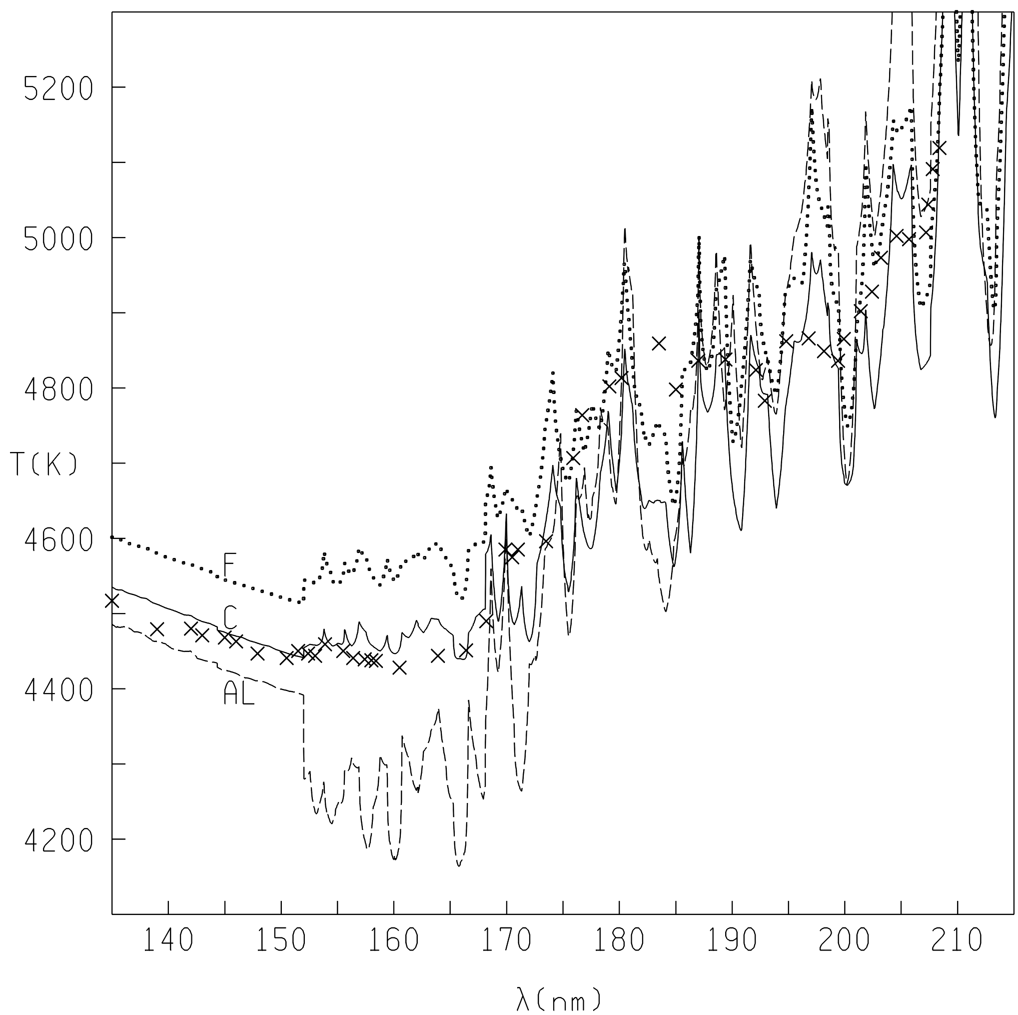

Figure 6. Observed disk-center brightness temperatures between 135 and 210 nm from Samain (1978, 1980) compared with the distributions calculated from models AL, C, and F.

determine the equivalent temperature stratification, but make the assumption that there are no substantial variations with time. Successful ab initio modeling (i.e., leading to good agreement with observations) could indicate that time variations and rapid motions are of much greater importance than is accounted for in semi-empirical modeling. The physical processes studied in ab initio modeling are thus of great interest, but results are useful only to the extent that they are consistent with observations. Kalkofen (2001) has pointed out a number of discrepancies between observations and the Carlsson and Stein calculations that have been published to date.

The contradictions between CO line observations and current semi-empirical models have been invoked as a challenge to the validity of semi-empirical modeling, and as some justification for the ab initio modeling of Carlsson and Stein (see Ayres 2002). Here we suggest that the CO observations can be reconciled with semi-empirical models (although not easily), and that the ab initio modeling is a separate issue, mainly involving the reality of extreme temperature variations with time.

I am grateful to T. Ayres, W. Kalkofen, R. Loeser, H. Uitenbroek, and A. van Ballegooijen for their comments.

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