TWO-COMPONENT MODELING OF THE SOLAR IR CO LINES

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ABSTRACT

One-dimensional hydrostatic models of quiet and active solar regions can be constructed that generally account for the observed intensities of lines and continua throughout the spectrum, except for the infrared CO lines. There is an apparent conflict between a) observations of the strongest infrared CO lines formed in LTE at low-chromospheric heights but at temperatures much cooler than the average chromospheric values, and b) observations of Ca II, UV, and microwave intensities that originate from the same chromospheric heights but at the much higher temperatures characteristic of the average chromosphere. A model M_{CO} has been constructed which gives a good fit to the full range of mean CO line profiles (averaged over the central area of the solar disk and over time) but this model conflicts with other observations of average quiet regions. A model L_{CO} which is approximately 100 K cooler than M_{CO} combined with a very bright network model F in the proportions $0.6L_{CO}+0.4F$ is found to be generally consistent with the CO, Ca II, UV, and microwave observations. Ayres, Testerman, and Brault found that models COOLC and FLUXT in the proportions 0.925 and 0.075 account for the CO and Ca II lines, but these combined models give an average UV intensity at 140 nm about 20 times larger than observed. The $0.6L_{CO}+0.4F$ result may give a better description of the cool and hot components that produce the space- and time-averaged spectra. Recent observations carried out by Uitenbroek, Noyes, and Rabin with high spatial and temporal resolution indicate that the faintest intensities in the strong CO lines measured at given locations usually become much brighter within 1 to 3 minutes. The cool regions thus seem to be mostly the low-temperature portions of oscillatory waves rather than cool structures that are stationary.

1. Introduction

Because the solar surface can be studied at high spatial resolution, more is known about the atmosphere of the Sun than about any other stellar atmosphere. Even so, the basic structure of the solar atmosphere has not been determined well enough to explain all the available observations.

To a first approximation, a one-dimensional model in hydrostatic equilibrium can be constructed to account for the spectrum emitted from each type of feature seen at high spatial resolution on the solar surface, since the horizontal extent of most features is large compared with the vertical thickness of the emitting region. Thus, different cell and network components of quiet regions, various active regions, sunspot umbrae and penumbrae, and flaring regions can be modeled separately. Suppose the intensity spectrum computed from a one-dimensional model agrees with the observed intensity values from a given component region in lines and continua over a wide range of wavelengths, thus probing a wide range of atmospheric depths. Then we could conclude that the stratification of temperature and density in the model represents the actual conditions in the observed component region. Such models derived from observed spectra would give useful physical information about the atmosphere, such as the flow of energy in various forms and the heating mechanisms that are most important. However, only rough agreement has been achieved between such models and available observations even when the CO vibration-rotation lines are excluded.

The problem with the CO lines is that 1) they are formed in LTE (Ayres & Wiedemann[1]) so that the observed brightness temperature at each wavelength in a line should be close to the kinetic temperature at unit optical depth for that wavelength, 2) the strongest lines have central brightness temperatures around 4100 K at disk center, and values as small as 3700 K at the solar limb (Noyes & Hall[2]; Ayres & Testerman[3]), whereas 3) all other diagnostics of the solar temperature minimum (e.g., the Ca II and Mg II resonance line wings and the UV and microwave minimum brightness temperature ranges) indicate an average quiet-Sun minimum temperature of at least 4400 K. The CO lines show that part of the atmosphere is much cooler than indicated by these other diagnostics.

In this paper we exhibit a model that fits the average CO spectrum at disk center, and examine how various cool and hot models might be combined to agree with all diagnostics. In Section 4 we call attention to the recent observations of Uitenbroek, Noyes, and Rabin that show the temperature of the cool regions to vary with time.

The results reported here were obtained in collaboration with E. S. Chang, R. L. Kurucz, and R. Loeser. A more complete account is being prepared for publication in The Astrophysical Journal.

2. CO Observations and Modeling

In their Spacelab-3 ATMOS experiment on the Space Shuttle, Farmer & Norton[4] obtained disk-center solar spectra with high spectral resolution throughout the infrared wavelength range λ = 2.1-16.5 μm. They give the intensity averaged over a circular region extending from disk center out to 0.28 solar radii for $\lambda < 4.97$ μm, and out to 0.58 solar radii for $\lambda > 4.97$ μm (2010.5 cm^{-1}). We have selected a set of 215 fundamental and first overtone lines of $^{12}C^{16}O$ and $^{13}C^{16}O$ between 2.3 and 6.9 μm (4350 to 1450 cm^{-1}) for the present study. The set includes very weak lines as well as the strongest ones.

Figure 1 shows the overall results of our CO line calculations based on an atmospheric model M_{CO} adjusted to fit these lines as well as possible. Brightness temperature is plotted as a function of wavenumber. Each of the 215 CO lines in the set is represented by a vertical line extending from the continuum value down to the calculated line-center brightness temperature. There are no CO lines in the gap between the fundamental lines on the left and the first overtone lines on the right. The first overtone lines are formed deep in the photosphere in the temperature range 5700-6300 K, while the fundamental lines have their continuua in the 5300-5700 K range and calculated line centers at brightness temperatures as low as 4200 K.

The solid curve in Figure 2 is the observed CO spectrum near 2239 cm^{-1} (4.466

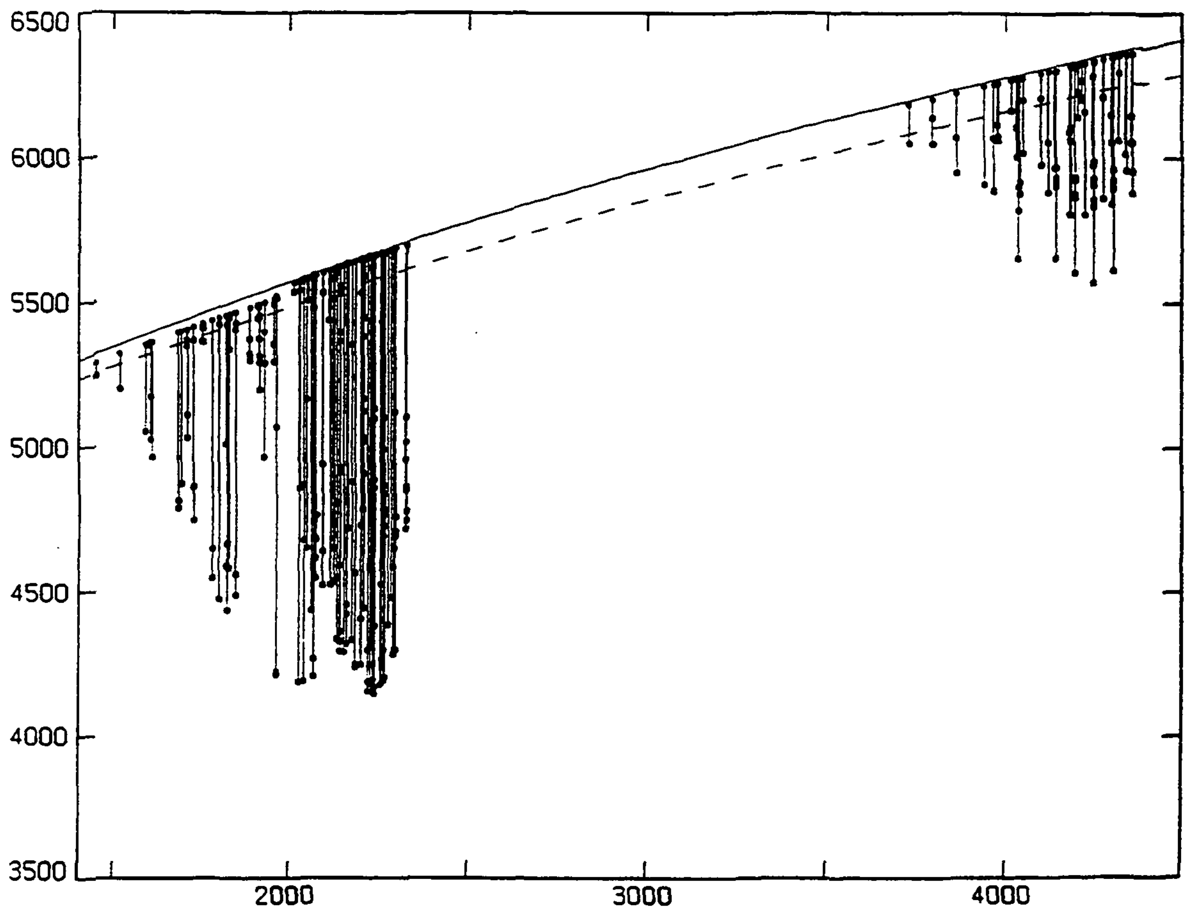

Fig. 1. Calculated brightness temperatures for the 215 CO lines in this study. The solid and dashed lines represent the calculated continuum at disk center and at 0.58 solar radii, respectively.

μm) while the dots represent the spectrum calculated from model M_{CO}. The scale on the left is residual intensity. The corresponding brightness temperature, derived from the calculated continuum, appears on the right. The computed values represent the intensity integrated over the same area of the solar disk as observed. We included the effect of solar rotational broading and attempted to apply the same instrumental broading to the calculated spectrum as in the ATMOS experiment. We used what we considered to be the best available atomic and molecular data and solar abundance values (as will be discussed by Chang, Avrett, Kurucz, and Loeser, in preparation). The temperature distribution was the only function that was adjusted by trial and error in order to get a best fit to the set of CO lines. The corresponding density distribution is determined by assuming hydrostatic equilibrium. The CO lines are assumed to be formed in LTE but the calculated model takes account of non-LTE effects for H^- and the atoms that contribute to the opacity and to the electron density.

Figure 3 shows the temperature as a function of the continuum optical depth at 500 nm for model M_{CO} based on the CO line observations. Each vertical line segment in this figure extends from the central brightness temperature value calculated for a CO line to the observed value for that line, and is thus an approximate measure of the temperature change needed to match the observations. While some further adjustments could be made, the temperature values seem within about 100 K of the best distribution based on these observations. The disk-center CO lines do not give information about temperatures below 4100 K. We have extrapolated model M_{CO} to 3800 K to account for the lower values at the limb, and then introduced a rapid temperature rise to the much higher values in the upper chromosphere.

The temperature distribution in Figure 3 differs substantially from the one that roughly fits other diagnostics of the temperature minimum region and low chromosphere. Figure 4 shows the average quiet-Sun temperature distribution from Maltby et al.[5], and tabulated as model C by Fontenla, Avrett, & Loeser[6]. As before, the vertical line segments indicate the differences between the calculated and observed brightness temperatures in the core of each CO line.

Figure 5 compares the same observed spectrum as in Figure 2 with the one calculted with model C. Since the minimum temperature in the model is 4400 K the calculated values in the cores of the strongest lines cannot be any smaller. Note that there are also some systematic differences between the two models in the deeper layers.

3. Comparisons With UV Data

Now consider the observed and calculated intensities in the UV wavelength range 135-174 nm. The dots and crosses in Figure 6 are observations of the disk-center continuum intensity (between various emission and absorption lines) by Brekke[7] and Samain[8], respectively. The dashed lines indicate the brightness temperatures that correspond to the intensity at a given wavelength. Brekke & Kjeldseth-Moe[9] report that recent UV observations with a better absolute calibration than before imply that the minimum observed brightness temperature at disk center should be increased

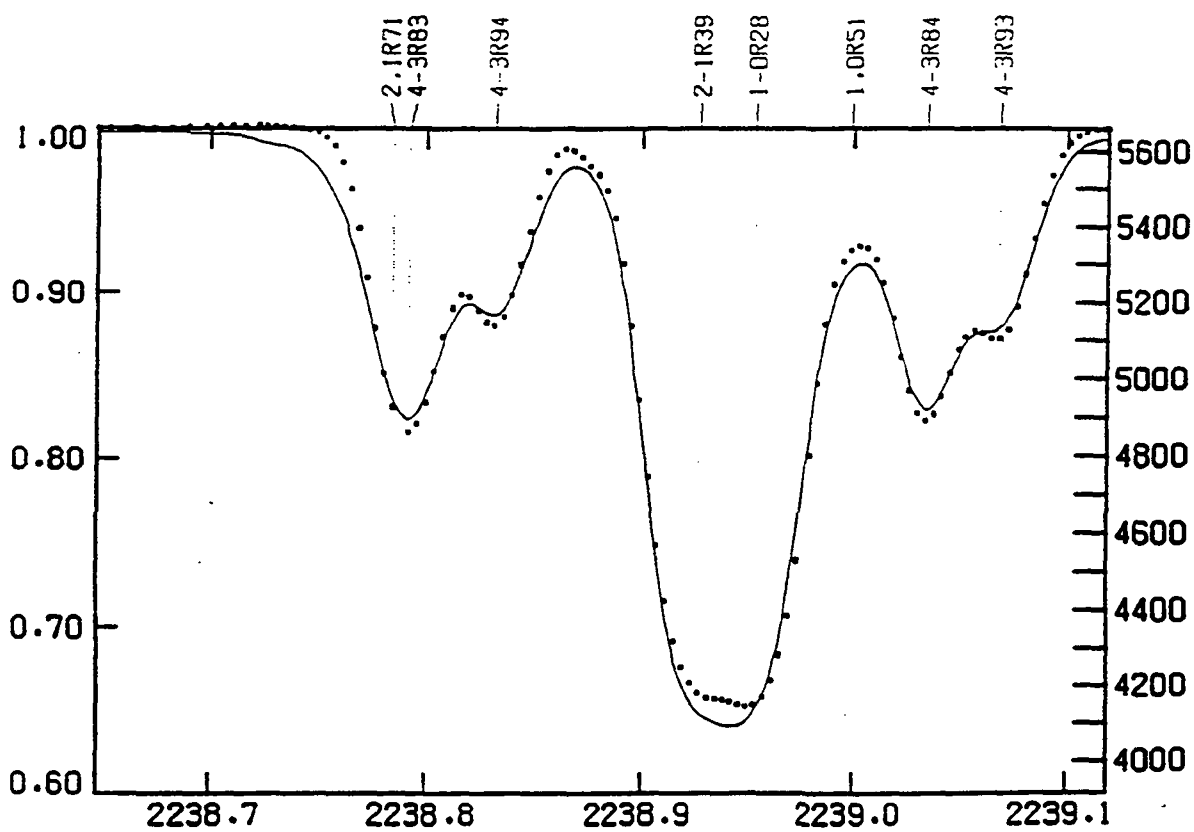

Fig. 2. CO spectrum near 2239 cm^{-1} (4.466 μm) from model M_{CO} (dots) compared with the ATMOS observations of Farmer and Norton (solid line). The scale on the left is residual intensity. The corresponding brightness temperatures appear on the right. Hyphens are used in the CO line designations at the top for $^{12}C^{16}O$, and commas for $^{13}C^{16}O$.

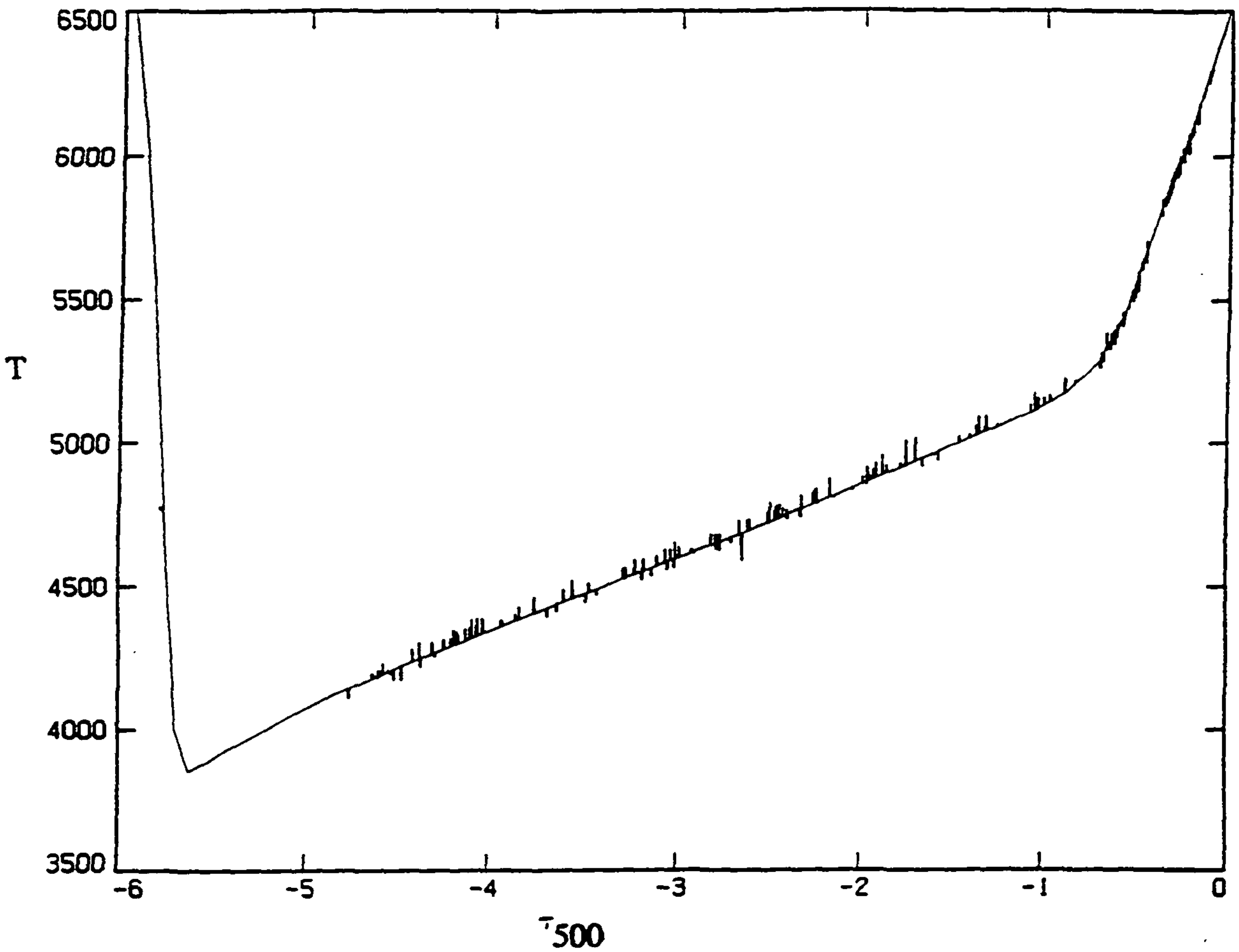

Fig. 3. T vs. τ_{500} for model M_{CO}. The vertical line segments indicate the differences between the calculated and observed brightness temperatures in the core of each CO line.

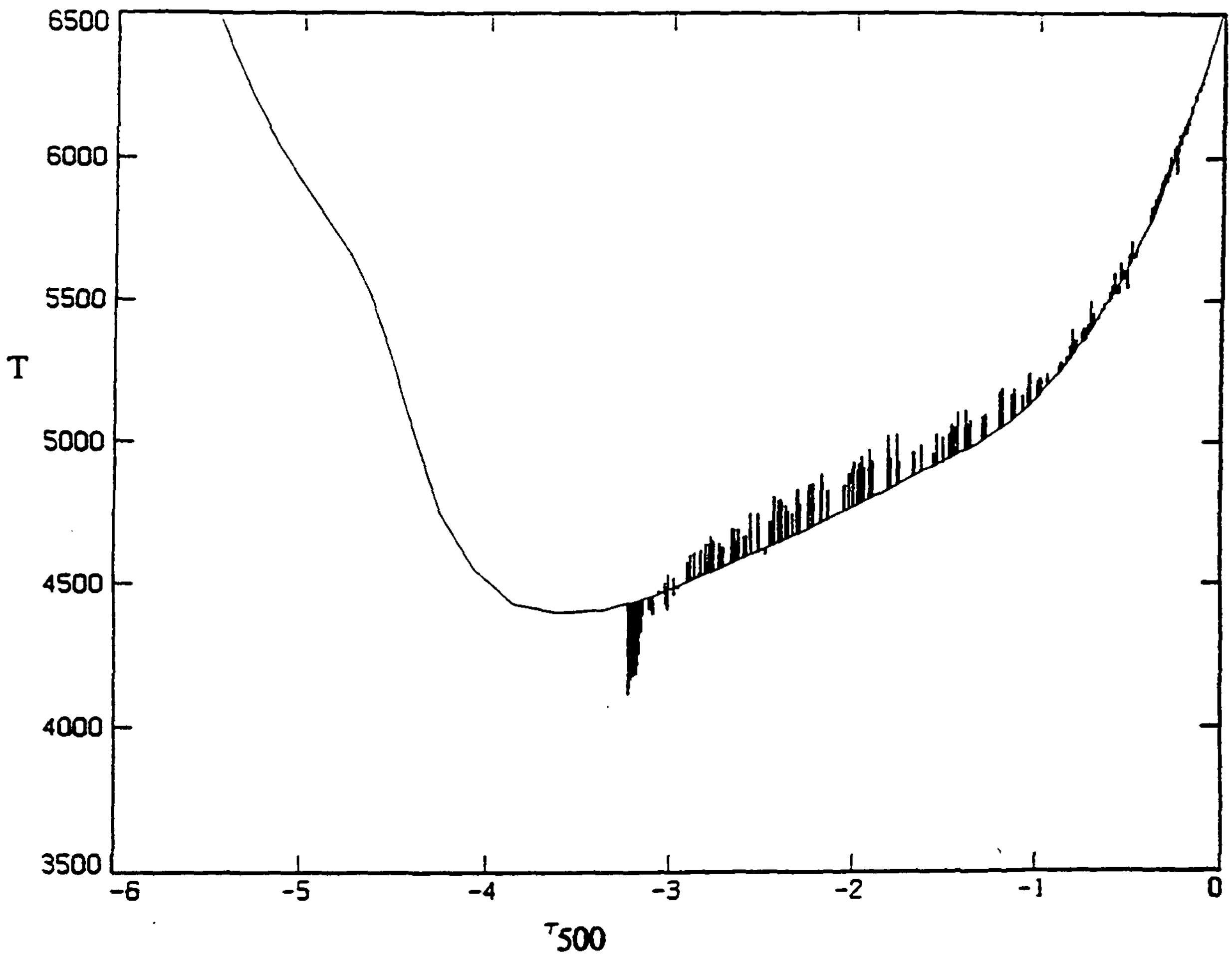

Fig. 4. T vs. τ_{500} for model C. The vertical line segments have the same meaning as in Figure 3.

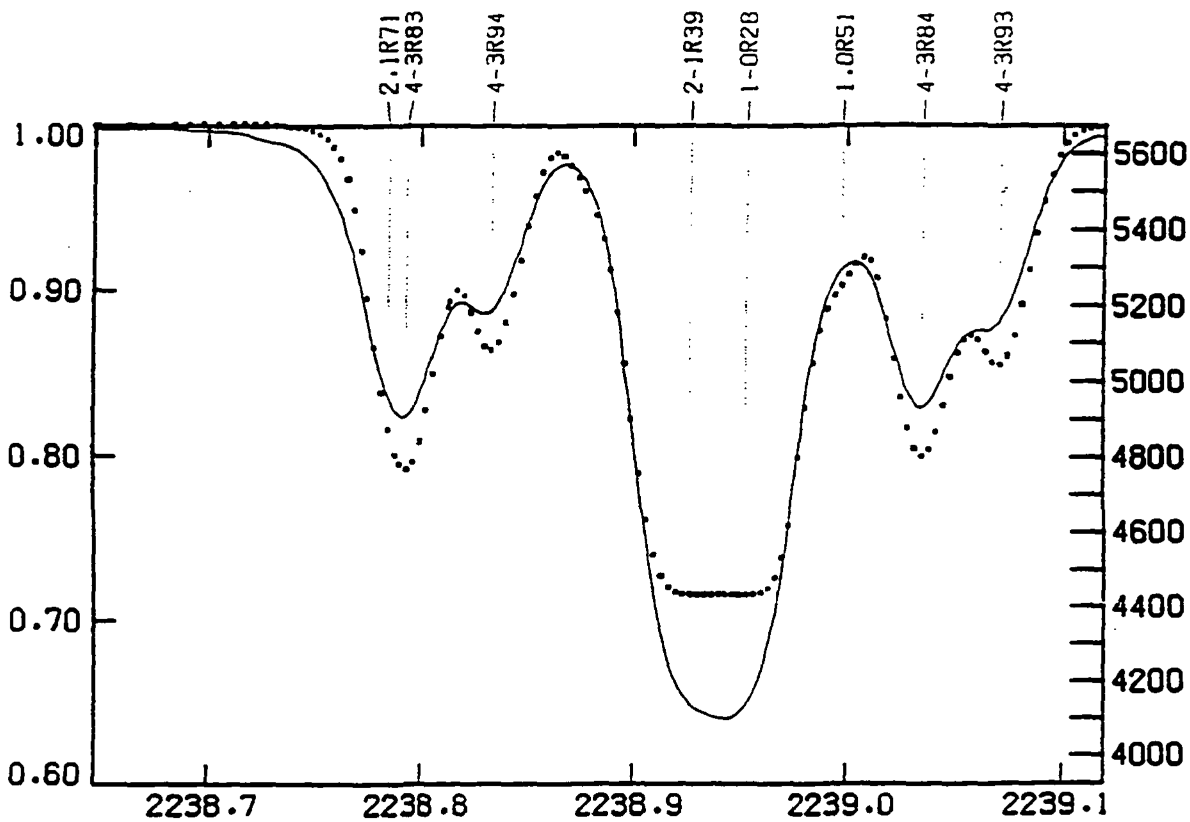

Fig. 5. Same as Figure 2 except that the calculated values are from model C.

from 4450±50 K to 4520±25 K. (This upward adjustment has not been applied to the observations in Figure 6.)

The curves labeled C and M_{CO} are the intensity distributions that are calculated from these two models. These are non-LTE calculations that include the overall effects of absorption and emission lines in the spectrum. Note that the model C intensities are in reasonable agreement with the observations while the model M_{CO} intensities are too low by a factor of 2 or more. We also plot the intensity distributions calculated from the COOLC and FLUXT models of Ayres, Testerman, & Brault[10]. They found that these separate cool and hot models when combined together with relative covering factors 0.925 and 0.075, respectively, approximately account for both the infrared CO line observations and the emission observed in the Ca II K line. However, the intensity at 140 nm from this combination of COOLC and FLUXT models is about 20 times larger than observed.

What other combination of cool and hot models might explain not only the CO and Ca II lines but also these UV observations? We have found that a model L_{CO}, roughly 100 K cooler than M_{CO}, combined with the very bright network model F given by Fontenla, Avrett, & Loeser[6], with relative covering factors 0.6 and 0.4 is consistent with the CO, Ca II, and UV observations. The UV results are shown in Figure 7. This combination is also consistent with observations in the far-infrared and sub-millimeter range where the emission also originates in the temperature minimum region and low chromosphere.

4. Discussion

Observations of the infrared CO lines indicate the presence of a cool component in the atmosphere at low-chromospheric heights. The CO lines are highly sensitive to this cool component because of the rapid increase of the CO line opacity with decreasing temperature in the 3500-4500 K range. Other diagnostics are not as sensitive to these low temperatures, and do not require the two-component modeling discussed above. However, our $0.6L_{CO}+ 0.4F$ combined model seems to explain both the CO observations and the other diagnostics.

The contrast in Figure 7 that might be resolved at very high spatial resolution is greater than that observed by Foing & Bonnet[11]. Their spatial resolution was sufficient to detect any features of 1-2 arc sec size. They found the maximum brightness temperature between the bright network and the darkest internetwork features to be roughly 150 K at 160 nm. This may indicate that model F is too bright to serve as the hot component in this simple modeling procedure, or that we must consider the radiative interaction between the component regions in calculating the spectrum.

Another interpretation is that the two components are not spatially distinct and constant with time, but that local time variations are important. This view is strongly supported by recent observations by Uitenbroek, Noyes, & Rabin[12] and Uitenbroek & Noyes[13] who obtained spatially and temporally resolved CO spectra near 4.67 μm with a new infrared array detector at the McMath-Pierce solar telescope at Kitt Peak. Fig. 2 of Uitenbroek & Noyes shows a space-time map of the 3-2 R14 line-

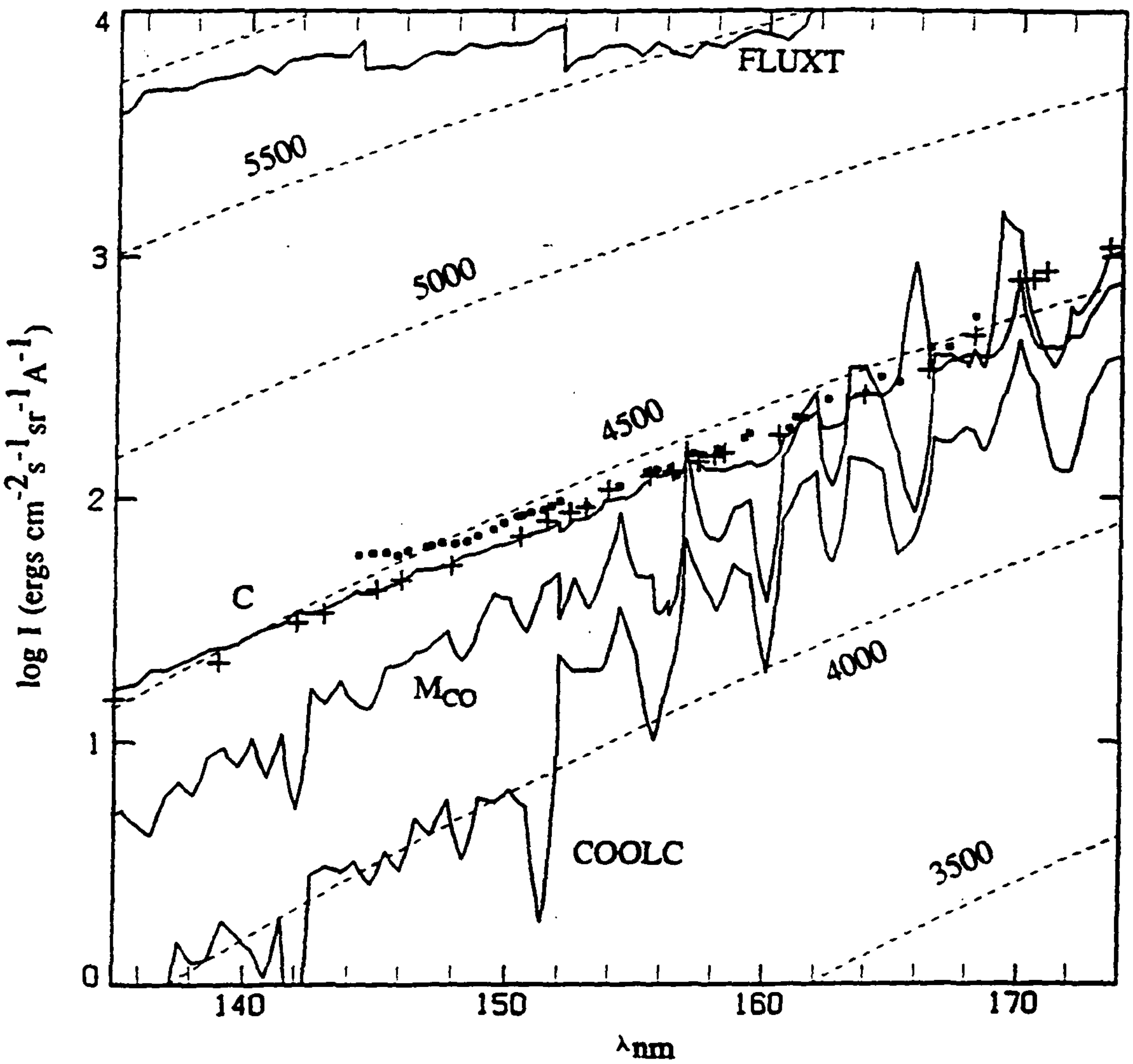

Fig. 6. Observed and calculated disk-center intensities in the UV wavelength range 135-174 nm. Brightness temperatures are indicated by dashed lines. The dots and crosses are continuum observations by Brekke and Samain, respectively. The calculated distributions include sampled opacities due to various lines. Calculated results are shown for models COOLC, M_{CO}, C, and FLUXT.

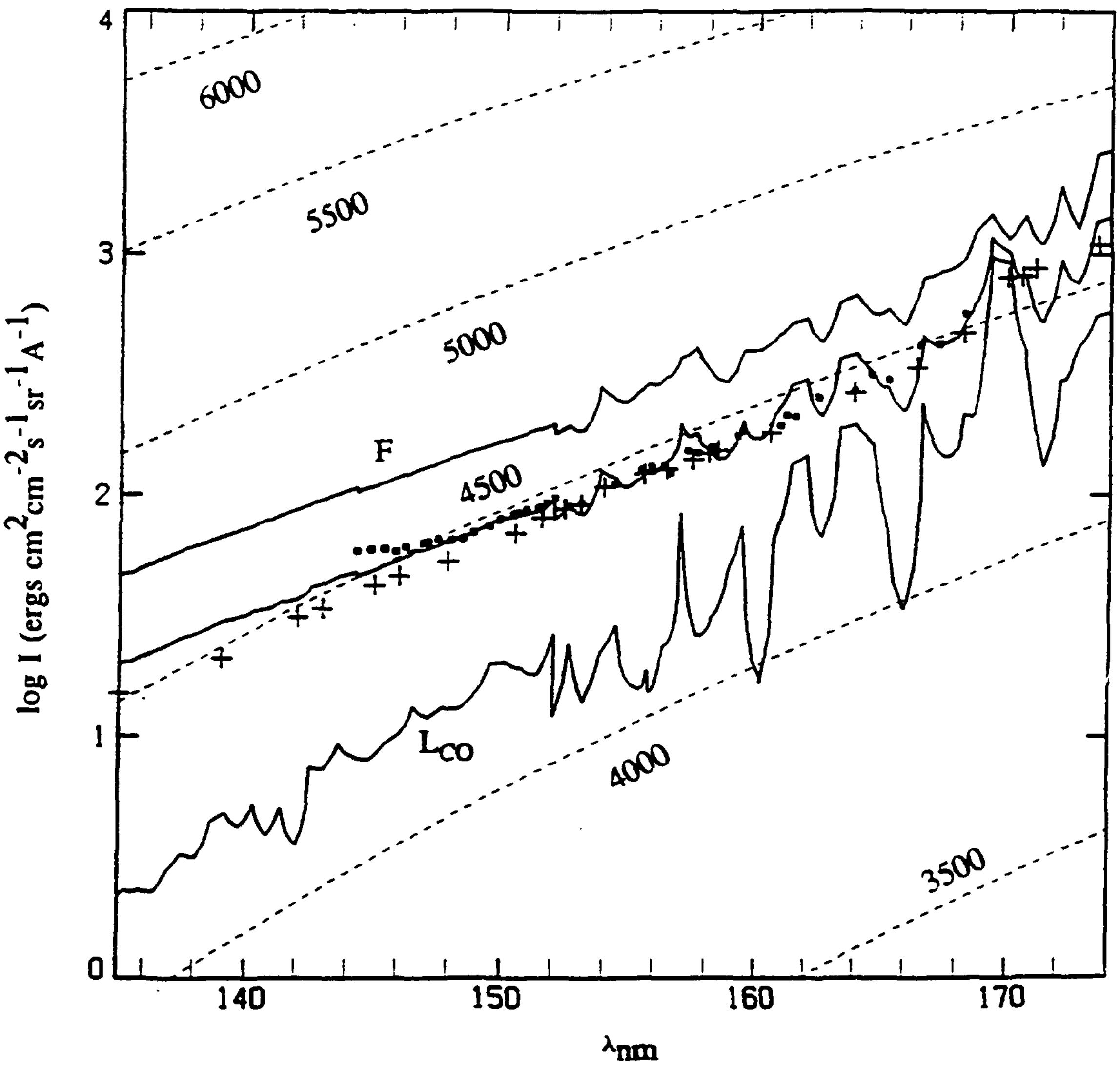

Fig. 7. Same as Figure 6 except that the lower and upper calculated intensities are from models L_{CO} and F, and the middle distribution represents $0.6L_{CO}+0.4F$.

core brightness temperature along a 94 arcsec slit placed over a quiet region near disk center during a period of 23 minutes. They find peak-to-peak temperature fluctuations of approximately 400 K and substantial time variations at each position. These observations clearly show that dynamical effects play an important role in determining the low temperatures seen in the cores of the strong CO lines.

5. Acknowledgements

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6. References

1. T. R. Ayres and G. R. Wiedemann, *ApJ,* **338** (1989) 1033.
2. R. W. Noyes and D. N. B. Hall, *ApJ,* **176** (1972) L89.
3. T. R. Ayres and L. Testerman, *ApJ,* **245** (1981) 1124.
4. C. B. Farmer and R. H. Norton, *A High-Resolution Atlas of the Infrared Spectrum of the Sun and the Earth Atmosphere from Space*, NASA Pub. 1224, 1989, vol. 1.
5. P. Maltby, E. H. Avrett, M. Carlsson, O. Kjeldseth-Moe, R. L. Kurucz, and R. Loeser, *ApJ,* **306** (1986) 284.
6. J. M. Fontenla, E. H. Avrett, and R. Loeser, *ApJ,* **406** (1993) 319.
7. P. O. L. Brekke, *Observed Structure and Dynamics of the Solar Chromosphere and Transition Region Based on High Resolution Ultraviolet Spectrograms*, Ph.D. Thesis, University of Oslo, 1992.
8. D. Samain, *A&A,* **74** (1979) 225.
9. P. O. L. Brekke and O. Kjeldseth-Moe, *ApJ,* **431** (1994) L55.
10. T. R. Ayres, L. Testerman, and J. W. Brault, *ApJ,* **304** (1986) 542.
11. B. Foing and R. M. Bonnet, *A&A* **136** (1984) 133.
12. H. Uitenbroek, R. W. Noyes, and D. Rabin, *ApJ,* **432** (1994) L67.
13. H. Uitenbroek and R. W. Noyes, *Chromospheric Dynamics*, ed. M. Carlsson (Institute of Theoretical Astrophysics, University of Oslo, Norway, 1994), p. 129.