COOL PLASMA AT THE BASE OF THE SOLAR CHROMOSPHERE
REVEALED BY INFRARED BANDS OF CARBON MONOXIDE

Thomas R. Ayres
Laboratory for Atmospheric and Space Physics
University of Colorado

ABSTRACT

I describe empirical evidence—cool cores in strong, middle-
infrared carbon monoxide (CO) lines—for the existence of low-
temperature plasma (T<4000K) at the levels of the solar outer atmosphere
where conventional models place the chromosphere proper (T=6000K). I
also report recent observational and interpretive studies of CO, and Ca
II K, in magnetic active regions which further support the hypothesis of
a highly inhomogeneous, thermally "bifurcated" chromosphere.

1. INTRODUCTION

Since the Spring of 1978, I and my collaborators (L. Testerman
[EG&G, Inc.] and J. Brault [NSO]) have been involved in a number of
observational studies of the infrared bands of carbon monoxide using the
1-meter Fourier Transform Spectrometer (FTS) of the McMath solar
telescope at Kitt Peak. Our initial objective was to develop the 4.6 μm
ΔV = 1 fundamental vibration-rotation bands of CO as a new diagnostic
for the temperature minimum region (T_min) at the photosphere-
chromosphere interface. Many of the individual vibration-rotation lines
are quite strong, and are predicted to achieve line-center optical depth
unity in the low chromosphere of conventional thermal-structure models
like the Vernazza, Avrett, and Loeser (1981) model "C". Furthermore,
the excitation of the low-energy molecular transitions is by collisions
with abundant neutral atoms and molecules (primarily H, He, and H_2),
which tend to enforce a Boltzmann distribution among the vibrational
and rotational substates of the ground electronic complex. Accordingly, the
line source functions should be close to the Planck function, and the
brightness temperatures in the cores of the optically-thick CO lines
should indicate, approximately, the value of the kinetic temperature
near τ_{1c} = 1.

1 Visiting Astronomer, National Solar Observatories, operated by AURA
under contract with the National Science Foundation.
The motivation for our observational work was to distinguish between previous studies that had indicated somewhat discordant pictures of the $T_{\text{min}}$ region: Ultraviolet and submillimeter continuum brightness distributions suggested $T_{\text{min}} < 4200$ K (Vernazza, Avrett, and Loeser 1976); while the inner damping wings and K, minimum features of the Ca II $\lambda 3934$(K) and Mg II $\lambda 2796$(K) resonance lines suggested a hotter value, $T_{\text{min}} \equiv 4500$ K (Ayers and Linksy 1976). Although the differences in the value of $T_{\text{min}}$ do not appear to be large, the difference in the implied energy deposition required to support the two temperature distributions is quite significant, owing to the comparative efficiency of the radiative cooling in the dense layers of the upper photosphere.

One possibility for the discordant values of $T_{\text{min}}$ is the presence of spatial or temporal fluctuations in temperature which would provide the appearance of different mean effective temperatures in the ultraviolet and submillimeter regions owing to the exponential thermal averaging of the Planck function in the ultraviolet, and the linear averaging of the Planck function in the far infrared (cf. Ayres and Linsky 1976). We hoped that measurements of the CO bands, a diagnostic that should respond to the cooler components of an inhomogeneous atmosphere, would be able to set constraints on the amplitude of the putative temperature fluctuations.

Much to our surprise, however, the CO bands revealed the presence of material that was considerably cooler ($T < 4000$ K) than we had anticipated, and a temperature structure that was still declining outward in the layers of the outer atmosphere where conventional models placed the chromosphere proper ($T \equiv 6000$ K) (see Ayres and Testerman 1981). The straightforward interpretation of the cool cores in the CO fundamental lines is that the quiet Sun is covered pervasively by very cool plasma at the levels corresponding to the $T_{\text{min}}$ in conventional models. However, in order to explain the existence of emission reversals in the Ca II and Mg II lines requires that dispersed in the cool component are small-scale, high-excitation structures---magnetic flux tubes--in which intense chromospheric temperature inversions occur. In this picture, the weak emission core of the quiet Sun K line is produced by a significant dilution of the intense flux-tube emission by the pure absorption core of the Ca II feature in the cool component.

A simple argument suggested that the carbon monoxide, itself, was capable of maintaining comparatively low temperatures in the outer atmosphere owing to the efficiency of the LTE, optically-thin radiative cooling by the CO fundamental bands (Ayres 1981). This was, in fact, a rediscovery of an important effect---CO surface cooling--that was described originally by Johnson (1973) in the context of radiative-equilibrium models of late-type stars in general. However, in the earlier work, the importance of CO cooling for solar-type, main-sequence stars was overshadowed by the strong surface cooling by LTE atomic lines. Nevertheless, the actual radiative cooling by strong atomic lines is severely reduced in the surface layers of the photosphere by NLTE effects, while the CO cooling is relatively unaffected (Ayres 1981).
I and my collaborators recognized at that time that an important test of the highly inhomogeneous, "thermal bifurcation" model would be a detailed examination of the behavior of the CO bands in active regions, specifically in photospheric faculae. We therefore undertook additional observing programs in late 1979 and early 1982 to explore the behavior of the CO 4.6 μm fundamental and 2.3 μm first overtone bands in faculae covering a wide range of Ca II K intensity. In my contribution to the Workshop, I will summarize the results of these observing programs, and schematic model atmospheres simulations that I have applied to their interpretation. Full details concerning the more recent work can be found in Ayres, Testerman, and Brault (1985).

2. OBSERVATIONS

In December 1979, I and my collaborators used a novel observing technique on the 1-meter FTS to simultaneously record interferograms covering a region about the 3934 Å resonance line of Ca II, and the 2.3 μm Δν = 2 first-overtone bands of CO. (Ideally we would have wanted to observe Ca II K and the CO fundamental bands simultaneously, but we did not have available a beam-splitter material with sufficient transparency in the near ultraviolet and 4.6 μm regions.)

Figure 1 illustrates the appearance of the Ca II K line in a quiet Sun region and several plages observed near disk center. The intensities have been normalized to a continuum point at 3999.9 Å, assuming a plage/quiet continuum intensity ratio of 1.05. Notice that although the three plage tracings have been normalized to the same continuum point, the intensity distributions in the line wings are quite different. In particular, the plage profile having the most intense Ca II core reversal ("C") also has the brightest line wings (cf. Shine and Linsky 1972). The enhancements of the K wings of the active plage relative to the weak plage ("A"), as well as the overall enhancement of the K wings of the plages relative to that of the quiet Sun ("O"), indicates that the entire photospheric temperature profile of the active regions is elevated, in some sense, with respect to that of the quiet Sun (e.g., Shine and Linsky 1974).

Figure 2 compares symmetrized profiles of the Ca II features from Fig. 1 on logarithmic relative intensity and relative wavelength scales. The individual points represent intensities measured in 0.1 Å bandpasses in line-free portions of the Ca II K wings and emission core. The right-hand ordinate depicts the brightness temperatures that correspond to the absolute specific intensities of the profiles, as calibrated according to the quiet Sun measurements of Houtgast (1970) at Δλ = +1 Å from K-line center. Notice that the brightness temperature of the "K" minimum features of the quiet Sun profile (log Δλ ≡ -0.5 Å) is about 4400 K, while the corresponding minimum features of the plage profiles occur further from line center (log Δλ ≡ -0.3 Å) and at brightness temperatures 200 K - 400 K hotter.
Fig. 1.

Fig. 2.
Figure 3 illustrates the appearance of a region from the first-overtone bands of CO near 2.3 \( \mu \)m as observed in the quiet Sun and the strong plage (C). The four CO lines clearly weaken in the plage, indicating that the temperature profile in the middle photosphere is elevated, in some sense, in the active region compared with the quiet Sun. The critical question is whether the apparent enhancements of photospheric temperature indicated by Ca II K and CO are compatible with the "homogeneous" plage models developed by Shine and Linsky (1974) or with the highly inhomogeneous, "bifurcated" model proposed by Ayres (1981).

![PLAGE/QUIET DISK CENTER](image)

Fig. 3.

Figure 4 illustrates a region from the 4.7 \( \mu \)m fundamental bands of CO recorded in a quiet region and a plage near the limb on a subsequent observing program in January 1982. Most of the moderate-strength features in the diagram are optically-thick CO lines, which exhibit a clear weakening in the plage relative to the quiet Sun spectrum. (The features marked with "@" symbols are major absorptions from the Earth's atmosphere.)

Figure 5 compares core residual intensities, and the corresponding brightness temperatures, for a number of "clean" CO fundamental lines from the plage spectrum illustrated (partially) in the previous figure, and from three quiet Sun spectra, all of which were obtained at the same heliocentric angle near the limb (\( \mu = 0.2 \)). The abscissa of the figure is an inverse line-of-sight absorptivity which is proportional to the column density at which the individual lines become optically thick: One can think of the scale as geometrical depth in the atmosphere, with
Fig. 4.

Fig. 5.
the chromosphere on the left-hand side of the figure, and the photosphere on the right-hand side. Like the Ca II K-line wings and the first-overtone CO lines, the fundamental CO features indicate that the temperature profile of the plage is elevated with respect to that of the quiet Sun. Notice, however, that: The brightness temperatures of the strongest CO line cores are quite low in the quiet Sun ($T_B < 4000$ K); there is no evidence for a chromospheric temperature inversion—a chromosphere—in either the quiet Sun or the active region; the temperature difference between the plage and quiet Sun for the strongest of the CO lines is nearly twice the maximum difference indicated by the Ca II K$_i$ features in Fig. 2; but, nevertheless, the absolute temperature indicated by the strongest CO lines in the plage is much smaller than the minimum temperature of the plage chromosphere suggested by the Ca II K line. The fact that the infrared diagnostics indicate larger temperature differences between the quiet and active regions than the near-ultraviolet diagnostics, but imply a significantly cooler photospheric temperature profile that lacks a chromospheric temperature rise, already suggests that the homogeneous plage scenario cannot be correct. In the following section, I describe numerical simulations of the Ca II K line and the CO bands which permit a more quantitative assessment of the dilemma.

3. MODEL SIMULATIONS: QUIET SUN AND PLAGE

Figure 6 illustrates schematic temperature/column-mass-density profiles for two contrasting representations of chromospheric active regions: "Homogeneous" and "Flux-Tube".
The class of homogeneous plages is represented by two models: VALC', a quiet-Sun temperature profile derived by Avrett, Kurucz, and Loeser (1984); and VALP, a moderate-strength plage temperature profile having a somewhat hotter T$_{\text{min}}$, which occurs somewhat deeper in column mass density, a significantly hotter chromosphere, and an upper chromosphere pressure an order of magnitude larger than that of the quiet Sun model. In the homogeneous picture, then, the plage is a spatially coherent entity that is uniformly hotter than the quiet Sun throughout the chromosphere and upper photosphere. Plages of lessor activity levels (i.e. lesser Ca II K emission) than VALP would have temperature profiles intermediate to that of VALP and the quiet-Sun model, while more active plages would be uniformly hotter than VALP. The differences in the appearance of the Ca II or CO lineshapes in quiet and active regions would be due to the comparatively smooth change in temperature profiles from VALC' to VALP.

The class of flux-tube plage models also is represented by two temperature profiles: COOLC, a monotonically outward declining temperature distribution lacking a chromospheric temperature inversion; and FLUXT, an intense chromospheric temperature reversal on top of a hot T$_{\text{min}}$ and hot upper photosphere. However, the atmosphere is visualized not as a smooth range of spatially homogeneous temperature profiles between the two extremes, but instead as a spatial mixture of the two distinct temperature distributions: The quiet Sun would consist mainly of the cool component with a small (<10%) admixture of the hot flux tubes; while an active plage still would consist mainly of the cool component, but with a larger filling fraction of the flux tubes (perhaps 30% - 40%). The differences in the appearance of the Ca II or CO lineshapes in quiet and active regions would be due, in this case, to the different dilutions of the FLUXT lineshapes by the COOLC lineshapes. For example, the Ca II K line would have a substantial core emission reversal in the chromospheric flux-tube component, but a pure absorption profile in the cool, photospheric component.

Figures 7a and 7b compare profiles of Ca II K and the CO $\Delta V = 1,2$ bands synthesized for the two classes of quiet/plage models illustrated in Fig. 6. The Ca II K line was represented by a two-level + continuum atom; the frequency redistribution was treated by a linear combination of R$_{\text{III}}$A and noncoherent scattering (to simulate R$_{\text{III}}$); the R$_{\text{III}}$A redistribution function was approximated according to Ayres (1984); the R$_{\text{III}}$A redistribution function was approximated according to Ayres (1984); and the numerical algorithm for the solution of the combined equations of radiative transfer and statistical equilibrium was based on the partial-linearization scheme described by Auer, Heasley, and Milkey (1972). The CO lines were calculated in LTE using the line parameters summarized by Ayres and Testerman (1981). Additional details can be found in Ayres, Testerman, and Brault (1985).

The upper panel of Fig. 7a compares disk-center ($\mu = 1$) Ca II K line emission cores synthesized using the VALC' and VALP models. The quiet-Sun profile exhibits a weak central reversal because the line emissivity is not well coupled to the mild temperature inversion of the VALC' model. The plage profile exhibits a more intense emission
Fig. 7a.
reversal owing to the higher electron densities of the VALP model at the base of the chromosphere, which promotes a stronger coupling of the line emissivity to the (steeper) temperature rise (cf. Shine and Linsky 1974). The lower panel of Fig. 7a compares disk-center (μ = 1) and limb (μ = 0.2) profiles of the 2.3 μm Δν = 2 CO first-overtone bands (left-hand side) and the 4.6 μm Δν = 1 CO fundamental bands (right-hand side), for the VALC' and VALP models. Profiles were calculated for the ΔJ = +1 (R-branch) rotational transitions originating from lower rotational level Jι = 30 of the first several lower vibrational levels: These are approximately the strongest of the vibration-rotation transitions under solar conditions. Note that the CO first-overtone lines weaken in the plage model relative to the quiet Sun model: The upper photospheric temperatures of the former are warmer than those of the latter, thereby reducing the concentration of CO molecules, and lowering the absorptivity of the overtone lines. Notice also that the overtone lines strengthen significantly at the limb compared with disk center, owing to the larger slant-path column densities of the molecules for limb lines of sight. Conversely, however, the CO fundamental lines weaken towards the limb (limb-brighten), because the features become optically thick above the T_{min}, and begin to exhibit emission cores reflecting the chromospheric temperature inversion.

The upper panel of Fig. 7b compares disk-center Ca II K line emission cores synthesized using the flux-tube models FLUXT and COOLC: The "quiet-Sun" profile is based on a 7.5%/92.5% mixture of the former and latter, respectively; while the "plage" profile is based on a 37.5%/62.5% mixture. (Also illustrated is the pure-absorption profile calculated for the COOLC model and the intense emission reversal predicted by the FLUXT model). These combinations provide quiet and plage lineshapes of Ca II K which are nearly identical to those synthesized with the VALC' and VALP homogeneous models. The bottom panel of Fig. 7b illustrates the corresponding calculations of the CO bands. The shallowest profiles in each case refer to the hot FLUXT model: Note that the CO lines weaken considerably in the hot photosphere and T_{min} region of that model, but do not disappear completely. Note, also, that the composite quiet-Sun and plage profiles of the CO first-overtone bands are quite similar to the corresponding profiles synthesized with the homogeneous models. However, the CO fundamental lines in the flux-tube scenario limb-darken in the quiet Sun, and do not exhibit emission cores in the plage profiles. Finally, the apparent difference in core brightness temperatures of the CO fundamental lines between quiet-Sun and plage is larger in the flux-tube scenario than in the homogeneous simulations.

In short, the major discriminant between the two classes of plage models appears to be the middle-infrared CO fundamental bands: The observed behavior of the fundamental lines qualitatively supports the highly inhomogeneous flux-tube model.
Fig. 7b.
4. SUMMARY AND FURTHER RESEARCH

Our initial objective was to develop the CO vibration-rotation bands as diagnostics of physical conditions in the region of the $T_{\text{min}}$ and the chromospheric temperature rise. The strong fundamental lines, in particular, promised to resolve whether the $T_{\text{min}}$ was comparatively hot, as had been indicated by studies of Ca II and Mg II, or somewhat cooler, as had been indicated by studies of ultraviolet and submillimeter continuum intensities. Instead, the CO fundamental lines revealed the existence of very cool plasma high in the solar atmosphere where the conventional wisdom would predict only hot, chromospheric material. The presence of the cool material can be understood in terms of a thermal instability driven by the strong surface radiative cooling by the CO bands themselves. The "rediscovery" of the importance of CO surface cooling has inspired a number of recent theoretical studies concerning the temporal stability and evolution of the outer photospheric layers (e.g., Muchmore and Ulmschneider 1984; F. Kneer, these proceedings).

Subsequent empirical examinations of the behavior of the CO overtone and fundamental bands in quiet and active regions has further supported the picture of a thermally "bifurcated" chromosphere: Small-scale regions having intense chromospheric temperature inversions--the flux tubes--are embedded in a pervasive, cool photosphere whose thermal profile in the outermost layers is controlled by CO cooling. The distinction between quiet and active regions is in the greater number of flux tubes in the latter as compared with the former.

Appealing as the simple picture might be, several important questions must be clarified before the model can be refined further. Firstly, the possibility of NLTE effects in the statistical equilibrium of the CO vibration-rotation levels must be examined more closely than in previous studies (cf. Thompson 1973; Heasley et al. 1978), particularly for physical conditions appropriate to models like the COOLC described above. Secondly, the geometrical relationship between the small-scale, hot flux tubes and the large-scale, CO-cooled-photosphere must be established for the higher layers of the chromosphere: If, indeed, the "flux tubes" are magnetic filaments, they should spread with increasing altitude above the photosphere; at some critical level the spreading canopies of the flux tubes should merge and fill all of the available volume, thereby completely enveloping the cool zones beneath. Finally, the study of the peculiar properties of the CO spectrum should be extended to the far-ultraviolet region, which is richly populated by electronic transitions of the A-X 4th-positive system. There, however, particular care with NLTE effects will be required.
ACKNOWLEDGEMENTS

This study was supported by the National Science Foundation under grant AST 8203450 to the University of Colorado.

5. REFERENCES


