Resolution of the COmosphere Controversy

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Abstract. I describe the influence of spatial and spectral resolution on measurements of the off-limb emissions of the 4.7 \( \mu \)m CO \( \Delta v = 1 \) rovibrational bands, the key diagnostic for the presence of cool \( T \sim 3600 \) K gas at low-chromosphere altitudes. Looking forward to the ATST era, I conclude that a telescope aperture of at least twice the present McMath-Pierce 1.5 m is needed to unambiguously distinguish between alternative inhomogeneous atmospheric scenarios. Surprisingly, though, spectral resolution plays a critical, compensatory role, and should be pushed to its limits as well.

1. Introduction

My original presentation was entitled “TRACEing Chromospheric Waves.” It concerned a project carried out in May 1999 to correlate and track wave disturbances through the upper photosphere and low chromosphere by means of coordinated groundbased and space observations. However, there seemed to be some interest—perhaps a bit of controversy—at this Workshop with regard to the nature the so-called “COmosphere” (a term coined by G. Wiedemann: Wiedemann et al. 1994), a region of the solar outer atmosphere inhabited by surprisingly cool material (down to nearly 3500 K), diagnosed by the anomalous extreme-limb behavior of the CO \( \Delta v = 1 \) “fundamental” bands near 4.7 \( \mu \)m (see Ayres 2002, and references to previous work therein).

I therefore decided to change the topic of my presentation, to instead focus on the question of the impact of spatial and spectral resolution on measurements of the CO 4.7 \( \mu \)m bands, the key diagnostics of cool material in the altitude range extending from the height of the classical temperature minimum (at about 500 km above \( r_{0.5 \mu m} = 1 \)), apparently several hundred kilometers into the low chromosphere itself. The issue of resolution is particularly timely given that the Advanced Technology Solar Telescope (ATST) presently is in its critical design phase when fundamental instrumental characteristics like telescope aperture and spectrograph performance must be defined and—very importantly—justified.

The CO bands in the thermal infrared provide potentially a significant design driver because the diffraction limit at 5 \( \mu \)m obviously is an order of magnitude worse than in the visible for a given telescope aperture; the IR intensities are comparatively faint, demanding a large collecting area to boost sensitivity; and the CO lines themselves are very narrow, requiring high spectral resolution \( (\omega/\Delta \omega \sim 150,000) \) to fully resolve the line cores and thereby accurately record
the central brightness temperatures (which for these LTE transitions provide a proxy of the local kinetic temperatures where the line cores become optically thick: this is a valuable, unique feature of the $\Delta v = 1$ rovibrational bands of CO which is not reproduced in any of the scattering dominated “NLTE” lines of visible or ultraviolet spectra).

Furthermore, the principal signature of an extended cool region above the classical $T_{\text{min}}$ are the surprising off-limb emissions of the CO bands, first discovered by Bill Livingston of National Solar Observatory (NSO) as reported in Solanki, Livingston, & Ayres (1994). The CO “emissions” (which actually display very low brightness temperatures $\sim 3600$ K, but are seen at high contrast against the dark IR sky, once the background continuum has fallen away) occur over a fairly narrow spatial interval, roughly 0.7" between the continuum limb and the higher lying edge defined by strong $\Delta v = 1$ CO lines. This is comparable to the diffraction limit of the 1.5 m McMath-Pierce solar telescope, but the CO displacement can be measured accurately as a differential effect (see below). Nevertheless, rarely is there a good substitute for fully resolving a cosmic phenomenon (ask a stellar astronomer who’s seen a TRACE movie).

Therefore, in the present paper I will try to answer the question of how much resolution, spatial and spectral, is needed to minimally address the issues in the current controversy swirling around the COmosphere: How much cool gas occupies the altitude range 500–1000 km? How did it get there? What role does it play, if any, in the energy balance of the “magnetic transition zone” (which separates the high-$\beta$, kinetically dominated photosphere from the low-$\beta$, field-dominated corona)? Observations can most effectively address the first question, specifically through the off-limb emissions of CO and the center-limb behavior of the $\Delta v = 1$ bands (see Ayres 2002). The second two issues are largely the purview of theory. (Papers in these Workshop proceedings by Gene Avrett and Wolfgang Kalkofen offer alternative views concerning the presence of ultra-cool gas in the low chromosphere.)

2. New Observations

I first will describe a series of recent (April 2002) very high spectral resolution ($\omega/\Delta \omega \sim 2 \times 10^5$) measurements of the center-limb behavior of CO 4.7 $\mu$m rovibrational bands using the 1 m Fourier transform spectrometer (FTS) on the McMath-Pierce telescope (Ayres, Plymate, & Keller 2002). These new, very high quality spectra set a context for the off-limb discussion by providing an improved estimate of the minimum temperature of the quiet solar atmosphere.

A fast tip/tilt image stabilization system, developed by Christoph Keller and Claude Plymate of NSO, was used to carry out observations very close to the edge of the disk. The upper panel of Figure 1 illustrates the disk center ($\mu \equiv \cos \theta = 1$) spectrum with telluric absorptions removed (top: actually a superposition of many independent scans). The left hand ordinate indicates residual intensities relative to the disk center continuum level, and the right hand ordinate provides the equivalent brightness temperature (approximately the local kinetic temperature where $\tau_{lc} \sim 1$ for these LTE CO transitions). The lower traces are observations very near the limb, from $\mu = 0.30$ (44" inside the infrared edge) to
Figure 1. Recent FTS spectra at disk center and near extreme limb.

$\mu = 0.076$ (2.8 inside the limb). The middle panel compares traces from the Shuttle-borne ATOMS FTS (Farmer, Norton, & Geller 1989: shaded) with the superposition of several independent FTS scans at disk center. The ATOMS spectral resolution ($\sim 9 \times 10^4$) is significantly lower than the McMath-Pierce FTS, and the under-resolution of the CO absorption cores leads to an overestimate of the central brightness temperatures by $\sim 200$ K. The bottom panel is a blowup of a cluster of CO absorptions at the limb. The minimum brightness temperature is below 3600 K, implying that somewhere in the solar outer atmosphere temperatures are that low or lower. The key issue is whether there is a fairly pervasive cool layer; or isolated pockets of much colder material bathed in a warmer background atmosphere more like the standard reference models (Vernazza, Avrett, & Loeser 1973, 1976, 1981 [VAL]).

3. Line Spread Functions

In order to characterize the effects of resolution, one must define appropriate instrumental responses to be applied to simulated observations. Figure 2 depicts the spatial and spectral line spread functions used in the present analysis, on linear and logarithmic scales.
Figure 2. Spatial and spectral line spread functions for IRIS.

The thick curves in each panel are empirical blurring functions derived from a translimb sequence in May 1996, taken under good observing conditions at the McMath-Pierce, and in the double-pass mode of the NSO Infrared Imaging Spectrograph (IRIS: see Ayres 2002). The other curves are idealized Gaussian instrumental profiles. In the spatial panel, resolutions corresponding to four telescope apertures are illustrated: 1.5 m (dot-dashed—current McMath-Pierce, largest in the solar world); 3 m (dashed); 4 m (dotted—ATST design goal); and 10 m (solid—Do you think that the Keck people would let me use one of their telescopes for solar IR observing? After all, they have two, and they sit unproductively idle all day long.). Note that the idealized 1.5 m blurring function has a narrower response function than the actual McMath-Pierce telescope–IRIS combination, owing to extended scattering wings of the empirical profile.

In the spectral panel, three resolving powers are depicted: 50,000 (about the best we do with IRIS considering the effects of grating scatter: the empirical double-pass profile has a narrow core, but the extensive Voigt wings redistribute continuum light into the dark line center, simulating a significant decrease in spectral resolution); 75,000 (what the NOAO PHOENIX cryogenic echelle achieves in nighttime stellar work); and 150,000 (what is needed to fully resolve the CO cores, easily attained with the NSO FTS).

4. Thermal Models

Thermal models adopted to simulate the artificial long-slit spectra are shown in Figure 3. The VAL C’ is the standard solar reference model of Maltby et al. (1986; with the heritage of the VAL series). COOL0 and COOL1 are two “COMospheric” extensions that are used in combination with VAL C’ to simulate an inhomogeneous atmosphere, in the context of static models. The COOL
stratifications were designed to reproduce the center-limb behavior of the CO 4.7 μm rovibrational lines under the conditions where the hypothetical cool component is the majority atmospheric constituent at those altitudes [COOL0; 80% coverage], or the minority constituent [COOL1; 20%]: the latter thermal profile is more extreme because it has to make up for the 4× smaller surface coverage.

The jumble of lighter shaded thermal profiles refer to temporal snapshots of a particularly strong Ca II K-line “cell flash” from the Carlsson-Stein (1995, 1997 [C–S]) radiation-hydro simulations: note that the cool phases of the acoustic disturbances roughly trace out the lower temperature bound of the COOL0 model. The solid dots labeled “AL” depict a cool-component model recently proposed by Gene Avrett (these proceedings), in conjunction with an artificial truncation of CO opacities above 600 km to mimic the possible effects of non-equilibrium chemistry in the highest CO-forming layers. In Gene’s model, the cool component would be a minority contributor to the spatially average atmosphere, so AL should be compared with COOL1. Clearly there still is a major disagreement concerning the physical description of these crucial layers of the solar outer atmosphere.

Figure 4 is a rendering of over-the-limb numerical simulations of CO 4.7 μm spectra like those which will be used later to test the influence of various spatial and spectral resolutions. This particular simulation—consisting of alternating 1 Mm zones of COOL1 and 4 Mm of VAL C′—was chosen because it shows high contrast “dark points” at disk center, and the convergence of the dark regions at the extreme limb owing to “shadowing” effects. (Note that while illustrative, this is not the preferred model to explain the CO off-limb emissions: see below.) The simulation depicts the appearance of a long-slit spectrogram with the dispersion running from left to right, and the spatial direction (crossing the limb in the upper segments) running from bottom to top. The darker stripes indicate deeper “absorption” relative to the lighter continuum-dominated areas.
The spectral range extends from about 2142.3 cm\(^{-1}\) at the left to 2143.5 cm\(^{-1}\) on the right (cf., Fig. 1). The extreme limb segments are displayed on an expanded spatial scale to illustrate the fine structure close to the edge of the disk. The topmost segment, labeled "normalized," represents the upper portion of the limb spectrum divided by the average spectrum over the range 10''–13'' inside the limb: the procedure equalizes the intensities across the spectrum, and—most importantly—in the real observations helps suppress telluric absorptions. Note: the subsequent simulations, demonstrating the influence of resolution, will depict just the normalized spectrograms in the translimb regime. Full details concerning the geometry of the over-the-limb simulations, and the LTE "1.5-D" radiation transport modeling can be found in Ayres (2002).

The following figures (Figs. 5–8) each contains a matrix of twelve images that illustrate the results of taking a translimb CO simulation for one of the specific atmospheric model scenarios and degrading it spatially and spectrally to mimic the range of ideal instrumental configurations depicted in Fig. 2.

With present technology, we sit about at the lower left hand corner of the matrix. With ATST and a high-performance thermal IR spectrograph, achieving good control of scattered light, we would be near the upper far right. The line drawings in the bottom row are the predictions of the various filtered models: thin solid curves are for the fully-resolved case—the 10 m telescope; the other cases are dotted, dashed, dot-dashed, etc. The best available current measurements of the half-power point displacements of the CO lines (Ayres 2002) are shown shaded in the leftmost panel. The observations are not repeated in the other panels because the simulated spectral resolutions are higher than appropriate for the real data; and spectral resolution makes a surprisingly large difference.

For the particular model depicted here—VAL C'—the poor fit to the observed translimb CO extensions is relatively independent of spatial and spectral
resolution, and the homogeneous thermal profile can be eliminated as a viable candidate on the basis of existing observations. (Note that Gene Avrett's cool component "AL" model would be in a similar predicament—under-predicting the CO off-limb extensions—particularly given the artificially reduced chromospheric molecular opacities imposed on that model to force the CO formation back into the upper photosphere.)

Figure 6 shows the results for an inhomogeneous model that has only a minor 20% mixing ratio of the cool component (COOL1). (This is the example illustrated more extensively in Fig. 4, above.) At the nominal current resolutions, spatial and spectral, this particular inhomogeneous model under-predicts (lowest curves, left hand panel) the observed CO off-limb extensions; although one also sees in the right hand panel that with high spectral resolution there is very little difference between the predictions as a function of telescope aperture (assuming that the instrumental response is ideal). Nevertheless, the simple appearance of the spectrogram at 4 m/150,000 resolution is significantly different from that of the standard homogeneous reference model (Fig. 5). The conical off-limb CO lineshapes are produced by the relatively low opacity of the CO transitions in the intermittent hot/cold environment along the line of sight for the VAL C' + COOL1 inhomogeneous model.

A "hidden" aspect of the comparison is that the minority cold component model predicts the existence of very dark ~ 1" "cold spots" (ΔT ~ 1000 K) in disk-center thermal maps taken in the cores of strong CO lines (e.g., Fig. 4), yet no such features have been identified in current CO images taken under good observing conditions. As discussed by Ayres & Rabin (1996), it would be possible
Figure 6. Inhomogeneous model: 80% warm + 20% cool.

to “hide” the small-scale dark points required by the minority cool component scenario if the spatial scales of the structures were well below the resolution of the McMath-Pierce. However, the required size scales would be only a few hundred kilometers [≈ 0″/4], and it is difficult to imagine how such structures could be formed and sustained in a pervasive enough fashion to produce the necessary impact on the center-limb behavior of the CO bands, and their off-limb emissions. Han Uitenbroek (2000, and these proceedings) has shown that darkenings in the weaker Δν = 1 lines like 7–6 R68 seem to be associated with convective overshooting; but the stronger transitions like 2–1 R6 and 3–2 R14 form much higher in the atmosphere, in stable layers that ballistic, adiabatically cooling convective plumes are unlikely to reach.

Figure 7 shows a simulation for an inhomogeneous model with a repeating structure of 1 Mm of the VAL C′ warm component and 4 Mm of the cool component COOL0. Here, the most degraded resolution spectrograms are a good match to the predictions (by design), but the highest resolution spectrograms (upper right) are distinctly different from the previous examples (Figs. 5 and 6), providing a potential opportunity to distinguish among them.

Figure 8 displays a final simulation based on the Carlsson-Stein radiation-hydro model of Ca II K “bright grains.” The C–S model is appropriate for the internetwork cells that likely are preferentially sampled at the limb owing to their spatial prevalence. (Note, however, that the C–S time slices used here are from an atypically strong acoustic disturbance, so the spatial average might not be representative.) At the relatively low spatial/spectral resolution of current observations, the C–S model fails to reproduce the CO band off-limb emissions.
Figure 7. Inhomogeneous model: 20% warm + 80% cool.

Figure 8. Carlsson–Stein 1-D radiation-hydro model.
Figure 9. Details of translimb intensity roll-offs.

although it certainly does better than the homogeneous reference model (Fig. 5). The failure to match the weaker lines, in particular, points to too little CO opacity through the low chromosphere; perhaps a consequence of not including in the hydrodynamic simulation important sources of atmospheric cooling at low temperatures (like CO itself).

Indeed, the C–S model strongly resembles the inhomogeneous simulation depicted in Fig. 6 (80% VAL C' + 20% COOL1), except that the weaker transitions, like 7–6 R68 (2142.82 cm⁻¹) show significantly less extension than the stronger features, such as 3–2 R14 (2142.72 cm⁻¹). The stronger features are “saturated” in terms of their transverse optical depths in both simulations, and the off-limb extensions are limited primarily by the chromospheric temperature rises at the tops of both models (static in the case of COOL1; dynamic in the case of the C–S time slices). However, as can be seen from Fig. 3, the C–S model never achieves the sustained low temperatures of COOL1, and thus the CO column through even the coldest cycles of the dynamical simulation will never be as large as through COOL1. Accordingly, the weaker, unsaturated lines have lower transverse optical depths in the C–S over-the-limb simulation, and smaller off-limb extensions.

The final diagram, Figure 9, revisits the calculations depicted in the high spectral resolution (rightmost) columns of Figs. 5–8 for two frequencies (indicated by vertical tick marks in the bottom panels of those figures): one in the core of the strong 3–2 R14 transition, the other in the continuum window at 2142.89 cm⁻¹. Here, the spectral intensities have not been (self-)normalized
(in the manner depicted in Fig. 4), but instead are displayed in units of the disk center continuum intensity \([I_C(\mu = 1)]\). This rendition emphasizes the effects of spatial resolution, which are somewhat hidden in Figs. 5–8 where the CO off-limb extensions are measured as the monochromatic differences between the half-power point intensity roll-off at the translimb edge of the normalized spectrograms relative to the continuum edge, similarly defined. The spatial behavior of the continuum frequency is indicated by the solid curves; that for the line core frequency by the dot-dashed traces. These diagrams show that even though the continuum and line core limbs can be significantly blurred by the low resolving power of the (ideal) 1.5 m telescope, the displacement in effective tangential heights of the limbs can be measured differentially to a small fraction of an arcsecond as long as the limb profiles are well-sampled spatially and the signal-to-noise is sufficiently high.

In the upper panel, one can see the relatively low contrast between the line core and continuum near the limb in the VAL C’ simulation, contrary to the new FTS measurements; and indeed a continued rise of the line core intensity above the limb where the CO feature forms in the initial chromospheric temperature inversion of the model. In the other panels, depicting the various spatially inhomogeneous models, the CO core maintains a larger “absorption” contrast with respect to the continuum out to the limb, and goes into “emission” in the translimb regime only because the background continuum becomes transparent, and fades away, at a lower tangential altitude than the molecular features. In all the simulations, it is clear that both the continuum and line core edges are very sharp (on the scale of 0.’1), and thus cannot be fully resolved short of using a 10 m effective aperture. (Such resolutions can be achieved at the limb during solar eclipses, however, as demonstrated by Clark et al. [1995]; but these are only infrequent opportunities over solar observatories with the proper IR instrumentation, and the issue of spectral resolution would still remain.) Note that, as far as the CO off-limb emissions are concerned, the differences between a 3 m and a 4 m telescope are relatively minor compared with the major step going from 1.5 m to 3 m.

5. Conclusions

The differences between the alternative inhomogeneous models are most readily apparent at the high spatial resolution afforded by a telescope of at least double the aperture of the McMath-Pierce, but are distinguishable to some extent even with the present comparatively low-resolution instrumentation. Boosting spectral resolution is equally important, because it plays a very complementary—even compensatory—role to spatial resolution. Unfortunately, however, the very high resolution capability of the FTS cannot easily be applied to the off-limb CO emissions owing to the long integration times (minutes) required to accumulate a high-resolution scan: even with low-order AO, seeing fluctuations would adversely affect the interferogram in unpredictable ways.

It also is worth noting, from Fig. 2, that the actual performance of the McMath-Pierce is far from the hypothetical ideal 1.5 m in the context of IRIS imaging in the relatively slow (~400 ms exposures) “open” double-pass mode (i.e., without the intermediate slit usually employed in the double-pass config-
uration to control scattered light: the interstil removes the spectral multiplex advantage of the 2-D detector by passing essentially only a single frequency at a time. Experiments are underway to improve the performance of the double-pass mode, while retaining at least some of the multiplex advantage. Planned replacement of the current high-background, small-format (256×256) Amber Engineering device with an astronomical grade “Aladdin” 1K×1K InSb camera will be a major advance; allowing higher S/N in shorter exposures at double-pass spectral resolution. Coupled with improvements in understanding the McMath-Pierce optics, and the planned IR/AO system, the upgraded IRIS should permit substantial progress on the controversy surrounding the existence and role of the solar C0mospheare; even before the ATST comes online later this decade.

Nevertheless, the advent of a large-aperture ATST will finally provide IR solar astronomers with the tool they sorely need to advance to the next level of exploration in this new, challenging, and provocative window on the thermodynamics of the solar outer atmosphere.

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References