The Solar Oxygen Problem:
Crisis, Catastrophe, or Opportunity?

Thomas R. Ayres
Center for Astrophysics and Space Astronomy, University of Colorado, 389 UCB, Boulder, CO 80309-0389 USA

Abstract. A proposed large reduction in the solar oxygen abundance—motivated by spectral synthesis of weak forbidden O I absorptions using 3D convection models—has provoked consternation in the helioseismology community: the spectacular agreement between measured interior sound speed profiles and predictions based on the historical $\epsilon_O$ completely unravels at the new lower value. In an effort to validate low-O, two generic tests of the 3D models are outlined. A snapshot from the CO$^5$BOLD class of convection simulations is shown to meet some of the requirements, but fail others. Implications for the solar carbon monoxide (CO) spectrum—alternative O tracer—are discussed.

1. Introduction

Recent sharp downward revisions in the solar oxygen abundance, from the previously recommended $\epsilon_O \sim 800$ ppm (parts per million relative to hydrogen) a decade ago to only $\sim 450$ ppm now (e.g., Asplund et al. 2004 [Asp04]), have been met with some dismay by the helioseismology community (e.g. Bahcall et al. 2005); low-O devastates the previous excellent agreement between theoretical descriptions of the internal stratification of the Sun and exquisitely measured seismic oscillation patterns at the surface. Although the state-of-the-art time dependent 3D convection simulations, which partly have lubricated the downward slide of $\epsilon_O$, treat the dynamics and thermal rugosity of the photosphere better than traditional 1D models, they still are subject to the age-old concern in the modeling business: is the digital thermal structure truly an accurate replica of the real photosphere, as far as synthesizing the spectral diagnostic at hand? In particular, the convection simulations must skimp on physical detail—mainly the radiation transport—to accommodate the difficult multidimensional hydrodynamics; and usually are unable to include important subsidiary phenomena, like small scale magnetic flux concentrations, again because of computational limitations. Here I compare predictions of a 3D snapshot from the CO$^5$BOLD collaboration (e.g., Steffan et al. 2002) to: (1) center-limb observations of the visible continuum; and (2) calibrated measurements of Ca II H and K. These experiments test the accuracy of the 3D model, and as a byproduct provide an independent way to check the oxygen abundance, via the strong 5 $\mu$m vibration-rotation bands of carbon monoxide.
2. Continuum Center-Limb Behavior

As discussed by Ayres et al. (2006 [APK06]), matching center-limb behavior of spatially averaged continuum intensities is a fundamental test of any thermal model that hopes to replicate the true physical conditions in the photosphere. 3D simulations can differ noticeably from 1D, because the shallow raypaths near the limb can cut across several different convective structures, mixing a more extreme range of thermal fluctuations along the inclined sightline than would be encountered in a laterally homogeneous situation. Owing to the nonlinear averaging of the Planck function in the visible, the degree of thermal inhomogeneity along the ray is rather critical. Figure 1 depicts a 0.4 \( \mu \text{m} \) disk center intensity pattern from the CO\(^5\)BOLD snapshot, and the foreshortened appearance at the extreme limb (\( \mu = \cos \theta \), where \( \theta \) is the heliocentric angle) for different viewing orientations.

![Figure 1. Simulated continuum center-limb behavior.](image)

The right-hand panel of Fig. 1 compares calculated center-limb behavior for the 3D structure and a 1D mean model derived from the full snapshot by averaging \( T(z) \) and \( P(z) \) on uniform \( \tau_{0.5, \mu \text{m}} \) surfaces. Crosses are measured wavelength dependent limb darkening in the visible and infrared. Smaller dark dots are the 1D simulation; larger open circles (slightly above) are the full 3D model. Solid and dashed curves in the upper part of the panel show the 3D/1D ratios for the two extreme limb positions: horizontal dashed lines are at 5\% and 10\%. The 3D/1D differences are not large, but must be taken into account. CO\(^5\)BOLD performs much better on this test than Asp04 (see APK06). The comparison not only highlights the consequences of the nonlinear averaging mentioned earlier, but the “3D corrections” also provide a practical way to utilize 1D versions of the 3D mean model tweaked to better reproduce some desired spectral property.
3. Ca II Wings

As shown by Ayres (1975), the extensive damping wings of the Ca II 0.393 $\mu$m and 0.396 $\mu$m “H” and “K” resonance lines can be exploited to map photospheric thermal structure in the Sun and other late-type stars.

By the same token, Ca II H and K can be applied to validate a proposed model. Figure 2 illustrates such a test of the CO$^5$BOLD snapshot. Small frames above the tracing are intensity maps marching from the continuum (lightest) down into the extreme line core (darkest): the “reversed granulation” pattern, described by a number of authors, is evident in the latter. The formation of the Ca II lines was treated in a partial coherent scattering approximation, although the key mean intensity $J_\lambda$ was taken locally from the particular vertical column, rather than by a more global average of the surroundings. Again, dark dots are the 1D simulation, open circles are 3D, and the wavelength dependent ratio is depicted relative to the 5% and 10% levels. Although the CO$^5$BOLD intensities are several percent larger than the 1D counterparts, the 3D simulations still fall somewhat below the calibrated profile, indicating that the model generally is too cool in the upper photosphere; similar to the earlier criticism of the Asp04 (mean) model by APK06. The cooler stratification wrecks havoc on molecular diagnostics like CO, which are very temperature sensitive; causing one to derive, in that case, a lower O abundance (or equivalently, low $\epsilon_C$, as did Scott et al. [2006] using the Asp04 approach applied to CO).

It is possible, however, to adjust at least the 1D mean model to produce a better fit to the observed Ca II wings. Such a scaled model is illustrated in Figure 3 (marked the same as the CO$^5$BOLD mean model, but about 100–150 K warmer above $z \sim -200$ km [$z = 0$ is at $\tau_{0.5 \mu m} = 1$]). The scaled model agrees fairly well with the 1D “COmospHERE” profile proposed by APK06 (smaller dark dots), and is significantly warmer than the Asp04 mean model (open circles) in the mid-photospheric layers where the CO lines form. (Shading around the Asp04 model indicates the range of horizontal rms temperature fluctuations along constant $\tau_{0.5 \mu m}$ surfaces; dot-dashed curves are $\Delta T_{rms}$ for CO$^5$BOLD.)
4. Carbon Monoxide

The ubiquitous CO bands in the thermal infrared provide excellent tracers of thermal structure; or C and O abundances if the $T(\tau)$ profile of the atmosphere is known (e.g., APK06). The upper right-hand panel of Fig. 3 compares synthetic spectra of representative CO 5 $\mu$m absorptions (black dots are observations) for the full CO$^5$BOLD (thicker curve, for the $\epsilon_O = 700$ ppm and $C/O = \frac{1}{2}$ favored by APK06) and the 1D mean model (thinner curves). Shallowest profiles are for $\epsilon_O = 400$ ppm, increasing in steps of 100 ppm to the deepest at 800 ppm. Here we find, curiously, that although the 3D synthetic lineshapes apparently are mildly distorted by the convective velocity fields, mirroring the observed profiles, the “3D corrections” are relatively minor. For the original CO$^5$BOLD model, one would conclude—in agreement with Scott et al.’s low $\epsilon_C$—that $\epsilon_O \sim 500$ ppm.

![Figure 3. Thermal models (left); synthetic CO profiles (right).](image1)

The lower right-hand panels depict analogous synthetic profiles for the 1D tweaked CO$^5$BOLD model, with the same range of $\epsilon_O$ (thicker profile is for 700 ppm). One can see that the scaled model favors a higher $\epsilon_O \sim 700$ ppm, compatible with APK06’s extensive 1D analysis, again because of the slightly warmer temperatures in the upper photosphere needed to match the Ca II wings.

5. Discussion

There is clear disagreement between low–$\epsilon_O$ derived from visible O I forbidden lines (Asp04), which form in the deep photosphere, and the higher values inferred
from thermal IR CO lines, which arise in the middle photosphere. Can these disparate $\epsilon_O$'s be reconciled? On the one hand, the O I absorptions, although very weak and partially blended, are expected to be relatively model independent because they are ground state transitions of the majority ionization stage. So, we probably should trust the low-O abundances from that source, if we can be assured that uncertainties due to blending, continuum placement, and atomic parameters have been fully vetted. On the other hand, even though the CO lines have virtually no such ancillary observational distractions, the large temperature sensitivity, and some uncertainty concerning the oscillator strength scales (e.g., APK06), renders them perhaps less robust abundance diagnostics.

At the same time, there are at least two important issues with the 3D models themselves. For one, they lack the fine scale magnetic bright points that are a common feature of filtergrams taken, for example, in the 0.4 $\mu$m “G band” (CH molecule). Such structures cover only a small fraction of the surface, but nevertheless are much warmer than the surrounding photosphere. So, they might have a disproportionately large influence on the near-UV Ca II wings; perhaps accounting for part of the apparent “temperature deficit” of the CO$^5$BOLD 3D model relative to the empirical wing intensities. The bright points would have almost no influence on the CO absorptions, however, because of their small surface coverage. In this event, the equivalent temperature correction for a model appropriate to the CO bands might be smaller than suggested by the CO$^5$BOLD 1D profile scaled to match Ca II, and the derived 700 ppm perhaps then should be considered an upper bound on $\epsilon_O$.

A second 3D issue is the amplitude of horizontal thermal fluctuations in the middle photosphere. Spatial maps of 5 $\mu$m continuum and CO line cores suggest that the $\Delta T$'s of the 3D models are too extreme above about –200 km (APK06). If true, this would have a direct influence on deriving an appropriate temperature correction based on matching the Ca II wings. Muting the $\Delta T_{\text{rms}}$'s would work in the opposite direction to the bright point effect.

Some of these 3D-related questions might be answered soon, based on the spectacular photospheric images being obtained by the recently launched Hinode satellite (formerly Solar–B). For the moment, though, while low $\epsilon_O$ is not yet fully consistent with all the observations, it does look doubtful that any of the existing interpretations can be stretched sufficiently to restore solar oxygen to its former 800 ppm glory.

Acknowledgments. This work was supported by NSF grant AST–0607295.

References