CO (x=16,17,18) ISOTOPOLOGUE RATIOS IN THE SOLAR PHOTOSPHERE

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Introduction: Determination of the CO isotopologue ratios in the solar photosphere is important for understanding the oxygen chemical evolution of the solar system[1]. The solar CO fundamental (Δν=1) and first-overtone (Δν=2) bands have been recorded by the shuttle-borne ATMOS Fourier transform spectrometer (FTS)[2], and with the National Solar Observatory’s FTS on the McMath-Pierce telescope at Kitt Peak. Analyzing the rovibrational bands from these photospheric spectra by 1D simulation models, oxygen isotopic ratios had been estimated as 16O/18O=1700±220 and 16O/17O=440±6, but these results were significantly lower than terrestrial values [3]. Later, Scott et al. used a prototype 3D conventional model to obtain 16O/18O=479±28.5 [4], closer to the terrestrial value, but still differing from the Genesis inferred solar isotopic ratios (i.e. 16O/18O=2798 and 16O/17O=530) [5]. More recently, a CO5BOLD 3D convection model [6] has been employed to calculate ratios with lower uncertainties 16O/18O=2738±118 and 16O/17O =511±10, which fall between the terrestrial values and those reported by Genesis [7], [8]. However, differences in published CO dipole moment functions yielded a range of isotopic ratios spanning ~ 30 % in δ18O. Here we re-evaluate the CO dipole moment function in order to obtain more accurate isotope ratios for the photosphere.

CO f-values and 3D convective model: Crucial input data to the 3D convection simulations are the f-values (oscillator strengths) for the rovibrational (rotation-vibration) transitions of the ground electronic state of different isotopic CO (x=16, 17, 18). Examples of commonly-used oscillator strength scales are Hure and Roeff (1996) [9] and Goorvitch (1994) [10] (HR96 and G94, respectively). For a given rovibrational transition, involving a lower level (ν", J") and an upper one (ν', J'), the f-value is calculated as follows:

\[ f_{ν',J'} = \frac{8 \pi^2 n_e}{3 \hbar^2 \sigma^2} \left( \frac{\sigma}{2 J' + 1} \right) S_{HL} |D_{ν,J}|^2 \]

where, σ is the frequency of the transition, D_{ν,J} is the rovibrational dipole moment, and S_{HL} is the HönL-London factor that determines the intensity of rotational-transitions. According to Ayres et al.[8], the derived 16O/18O ratios were 528±11(HR96) and 496±7(G94) respectively (Table 3 in [8]). Even though the results fall between the terrestrial values and the inferred Genesis ratios, the uncertainty between the two sets of dipole moments was too high to make a meaningful comparison with the Genesis values.

Building on the previous work, we have used a new set of dipole moments from Li et al.[11],[12] (LG14) which were accurately determined by both semi-empirical and ab initio methods. Using the spectroscopically-determined potential energy function[13] of the electronic ground state of CO in the LEVEL code[14], we employed the semi-empirical coefficients of the power series expansion of the dipole moment function (Table 4 in [12]) to calculate the rovibrational dipole moments of 12C16O, 12C17O, and 12C18O isotopologues.

Fig. 1 represents the f-value ratios of G94, HR96, and LG for Δν=1 (IR fundamental transitions) of both 12C16O, and 12C18O respectively. The several percent differences between f_{16O} and f_{18O} (Figs. 1 and 2) significantly affect the accuracy of isotopic ratios computed by a 3D convection model. The new set of f-values, f_{LG}, are closer to HR96 than G94, and thus the results of 3D simulations (in progress) should be closer to HR96.

Conclusion: 3D radiative transfer calculations the more accurate set of CO f-values are in progress. In Figs. 3, the predicted locations of new δ18O and δ17O values are shown as red diamonds, in between the HR 96 and G94 results, close to the former, and now in better agreement with Genesis. Results of the 3-D hydrodynamic simulation will be presented.

Fig. 1. f-value ratios calculated by rovibrational dipole moments of G96[10], HR96[9], and LG[12] for $^{12}\text{C}^{16}\text{O}$ (top), $^{13}\text{C}^{17}\text{O}$ (bottom) ($\Delta v=1$). Red curves are $f_{LG}/f_{HR96}$ and black curves are $f_{G94}/f_{HR96}$.

Fig. 2. f-value ratios calculated by rovibrational dipole moments of G96[10], HR96[9], and LG[12] for $^{12}\text{C}^{18}\text{O}$ ($\Delta v=2$). Red curves are $f_{LG}/f_{HR96}$ and black curves are $f_{G94}/f_{HR96}$.

Fig. 3. Computed oxygen isotope ratios of the solar photosphere using different sets of dipole moments. The horizontal axis is oxygen abundance ($\varepsilon_0$) in ppm. (Top) $^{17}\text{O}/^{16}\text{O}$; (bottom) $^{18}\text{O}/^{16}\text{O}$; the white/red circles and the green/blue circles represent the G94[9] and HR96[10] isotope ratios, respectively. The new oxygen ratios (red diamonds) are predicted to fall between the HR96 and G94 results. The yellow/black region represents the isotopic ratios resulting from the average f-values of G94 and HR96 including various modelization and observational errors, and the thick blue and red bands refer to the Genesis and Earth oxygen isotopes, respectively. Formed error bars will be added after the 3D simulation work is completed.