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CO isotopologue ratios in the solar photosphere

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Abstract. We re-evaluate the CO dipole moment function in order to obtain more accurate isotope ratios for the solar photosphere using previous infrared observations. We used a new set of dipole moments from HITEMP which were accurately determined by both semi-empirical and ab initio methods. Preliminary values of isotope ratios using the new dipole moments are in better agreement with the inferred photosphere values from Genesis, showing that the solar photosphere is isotopically similar to primitive inclusions in meteorites.

Keywords. solar photosphere, solar system formation, solar abundances

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1. Introduction

Determination of the oxygen isotope ratios in the bulk Sun is essential for understanding the formation environment of the solar system (Clayton 2003). The oxygen isotope composition of the photosphere is most readily determined from the infrared absorption lines of the isotopologues of CO. The solar CO fundamental (Δv=1) and first-overtone (Δv=2) bands were previously recorded by the shuttle-borne ATMOS Fourier transform spectrometer (FTS) (Abrams *et al.* 1996), and with the National Solar Observatory's FTS on the McMath-Pierce telescope at Kitt Peak. Analysis of the rovibrational bands from these photospheric spectra by 1D simulation models yielded a wide range of oxygen isotope ratios (Ayres *et al.* 2006), (Scott *et al.* 2006) none of which were consistent with the solar wind isotope ratios measured by the Genesis spacecraft (McKeegan *et al.* 2011). More recently, a CO5BOLD 3D convection model (Freytag *et al.* 2012) was employed to calculate ratios with lower uncertainties, $^{16}O/^{17}O = 2738 \pm 118$ and $^{16}O/^{18}O = 511 \pm 10$, which fall between terrestrial values and those reported by Genesis (Ayres *et al.* 2013). In that analysis a discrepancy in published CO dipole moment functions yielded a range of isotopic ratios spanning $\sim 30‰$ in $\delta^{18}O$. Here we re-evaluate the CO dipole moment function in order to obtain more accurate isotope ratios for the photosphere.

2. CO spectroscopy

In order to determine isotopologue abundances from the observations, the f-values (oscillator strengths) are needed for the rovibrational transitions of the ground electronic state of different isotopic C^xO for x=16, 17, 18. The two most commonly used oscillator strength scales are Hure & Roueff (1996) and Goorvitch (1994)(HR96 and G94, respectively). For a given rovibrational transition the f-value is proportional to the square of rovibrational dipole moment. According to Ayres *et al.* (2013), the derived $^{16}O/^{18}O$ ratios were 528 ± 11 for HR96 and 496 ± 7 for G94, respectively. The difference introduced by the two sets of dipole moments was too high to make a meaningful comparison to the Genesis values. Here, we have used a new set of dipole moments from Li *et al.* (2015)(LG15) which were accurately determined by both semi-empirical and ab initio methods. Using the spectroscopically determined potential energy function (Coxon & Hajigeorgiou 2004) of the electronic ground state of CO in the LEVEL 8.0 code, we employed the dipole moment function of LG15 to calculate the rovibrational dipole moments of $^{12}C^{16}O$, $^{12}C^{17}O$, and $^{12}C^{18}O$ isotopologues. Comparison of the f-value ratios of G94, HR96, and LG15 for Δv=1 for both $^{12}C^{16}O$, and $^{12}C^{18}O$ reveals a several percent difference between f-values of G94 and HR96 (Gharib-Nezhad *et al.* 2015). This difference produced a systematic offset in the 3D convection model results of Ayres *et al.* (2013). Our revised set of f-values is much closer to HR96 than G94, and thus the results of 3D simulations will be much be closer to the HR96 results of Ayres *et al.* (2013).

3. Implications

Using our revised f-values the new $\delta^{18}O$ values are within about 5‰ of the results obtained in Ayres *et al.* (2013) using the HR96 f-values. 3D radiative transfer calculations using the more accurate set of CO f-values are in progress. These new results are significant because the photospheric $\delta^{18}O$ using HR96 is the same, within uncertainties, as the Genesis inferred photospheric $\delta^{18}O$ value. To infer photospheric isotope ratios, the Genesis solar wind isotope ratios must be corrected for fractionation during acceleration of coronal ions to form the solar wind. The primary fractionation process is believed to be inefficient Coulomb drag, in which protons collide repeatedly with heavier ions, such as OVI and OVII, imparting a mass-dependent preference for escape of the lightest O ions (Bodmer & Bochsler 1998). McKeegan *et al.* (2011) estimated the mass-dependent fractionation of O ions to be ≈ 40‰ in $\delta^{18}O$. Thus, the observed Genesis solar wind $\delta^{18}O$ value of -102‰ corresponds to a photosphere $\delta^{18}O \sim -60$‰. Using our revised f-value, the photosphere $\delta^{18}O \sim -50$‰, with an uncertainty of about $10 - 15$‰. Direct observation of the solar photosphere is now consistent in $\delta^{18}O$ with the inferred values from Genesis, and suggests that inefficient Coulomb drag is the primary source of fractionation for heavy isotopes during formation of the solar wind.

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