ISOTOPIC CO IN THE SOLAR PHOTOSPHERE, VIEWED THROUGH THE LENS OF 3D SPECTRUM SYNTHESIS T. R. Ayres[1], J. R. Lyons[2], H.-G. Ludwig[3], E. Caffau[3], S. Wedemeyer-Bohm[4], [1]Center for Astrophys. and Space Astronomy, University of Colorado, Boulder, CO 80309; Thomas.Ayres@colorado.edu; [2]Earth & Space Sciences, UCLA, Los Angeles, CA 90095; [3]Zentrum fur Astronmie der Universitat Heidelberg, Heidelberg, Germany; [4]Institute of Theorestical Astrophysics, Univeristy of Oslo, Oslo, Norway.

Introduction: Comparison of the oxygen isotope composition of the Sun to the terrestrial planets is essential to understanding the early evolution of the solar system. Previous measurements of CO isotopic absorption lines in the solar photosphere using 1D photospheric reference models yielded photospheric oxygen isotope ratios highly enriched in ^{17}O and ^{18}O (e.g.,^{16}O/^{17}O=1700±220 and ^{16}O/ ^{18}O=440±6) compared to terrestrial values [1], [2]. Using a prototype 3D convection model resulted in isotopic ratios closer to terrestrial, but still with large error bars (^{16}O/^{18}O=480±30) [3]. By contrast, analysis of *Genesis* collection plates found δ^{18}O = −102.3±3.3 ‰ and δ^{17}O = −80.8±5.0 ‰, which implied photospheric values of −59 ‰ for both isotopes, after accounting for fractionation due to inefficient Coulomb drag during solar wind particle acceleration [4]. Clearly, a reconciliation of the *Genesis* and photospheric data sets is needed.

Photospheric spectra and convective model: We consider the formation of solar infrared (2–6 μm) rovibrational bands of carbon monoxide (CO) as observed by ATMOS in the latest generation of 3D convection models (CO5BOLD [5]). The aim is to refine existing abundances of the heavy isotopes of carbon (^{13}C) and oxygen (^{18}O, ^{18}O), to compare with direct capture measurements of solar wind light ions by the *Genesis* Discovery Mission. We have taken special precautions, on the one hand to control and narrow the random (mainly observational) uncertainties of the analysis; and on the other to quantify a variety of systematic effects related to the models, and equally so the laboratory molecular line parameters. We are attempting to perform precision "forensic" spectroscopy of the solar plasma with uncertainties ideally below 1%, in order to compare to the very precise *Genesis* findings (with ~1% quoted errors). That goal was partly frustrated by uncertainties in the atomic physics (f-value scales [6], [7]) and more subtle aspects of the modelization, even though state-of-the-art 3D convective snapshots were utilized. Nevertheless, we demonstrate that especially for ^{13}C, but ^{18}O as well, the observational uncertainties can be controlled to the desired level or better, so that in principle future comparisons of higher precision can be carried out, once the external atomic physics and modelization issues are resolved. We also confirm that the 1D spectrum synthesis approach is essentially useless for this particular molecular problem, although there are other less pathological cases where a careful 1D analysis can produce similar results to a full 3D study (see, e.g., Ayres 2008 [8]).

Results: We find that previous, mainly 1D, analyses were systematically biased toward lower isotopic ratios, suggesting an isotopically "heavy" Sun contrary to accepted fractionation processes thought to have operated in the primitive solar nebula. The derived 3D ratios for ^{13}C and ^{18}O are as follows (where $R_{23} \equiv {}^{12}C/{}^{13}C$, etc.): R_{23} = 91.4±1.3 (R_{Earth} = 89.2); and R_{68} = 511±10 (R_{Earth} = 499), where the uncertainties are 1-σ and "optimistic" (Fig 1a shows a typical C^{18}O line). We also obtained R_{67} = 2738±118 (R_{Earth} = 2632), but we caution that the observed ^{12}C^{17}O features are extremely weak (Fig. 1b). The new solar ratios for the oxygen isotopes fall between the terrestrial values and those reported by *Genesis* (R_{68} = 530, R_{67} = 2798), although including both within 2-σ error flags, and go in the direction favoring recent theories for the oxygen isotope composition of Ca–Al inclusions (CAI) in primitive meteorites [9]-[11]. Figure 2 summarizes the range of C and O isotopic ratios determined here. While not a major focus of this work, we derive an oxygen abundance, ε_O ~ 603±9 ppm (relative to hydrogen; log ε_O ~ 8.78 on the H = 12 scale), well above recently suggested low O abundances [12]. The results presented here are in press [13].

References: [1] Harris et al. (1987) MNRAS 224, 237. [2] Ayres et al. (2006) ApJS 165, 618. [3] Scott et al. (2006) A&A 456, 675. [4] McKeegan et al. (2011) Science 332, 1528. [5] Freytag et al. (2012) J. Comput. Phys. 231, 919. [6] Goorvitch (1994) ApJS 95, 535 (G94). [7] Hure & Roueff (1996) A&AS 117, 561 (HR96). [8] Ayres (2008) ApJ 686, 731. [9] Clayton (2002) Nature 415, 860. [10] Yurimoto & Kuramoto (2004) Science 305, 1763. [11] Lyons & Young (2005) Nature 435, 317. [12] Grevesse et al. (2010) ApJSS 328, 179. [13] Ayres et al. (2013) ApJ (in press). [14] Caffau et al. (2008) A&A 488, 1031.

Fig 1 (next page) (a, *top*) 'Hybridization' (i.e. co-adding) of ^{12}C^{18}O rovibrational lines ('28') from ATMOS spectra, for four representative Δv = 1 transitions. Abscissa is temperature in Kelvin; ordinate is line strength times absorption. Inset shows absorption

depth versus line width. In the lower parts of the panels, temperature-dependent factors for the line opacities are shown by thin curves and the average at discrete temperatures by large blue dots. **(b, *bottom*)** Same as *(a)* for $\Delta v = 1$ $^{12}C^{17}O$ transitions. Thick orange curves are synthetic spectra for this isotopomer ('27'). Blending by other isotopomers is particularly conspicuous since the $^{12}C^{17}O$ line depths are only a few tenths of a percent at best.

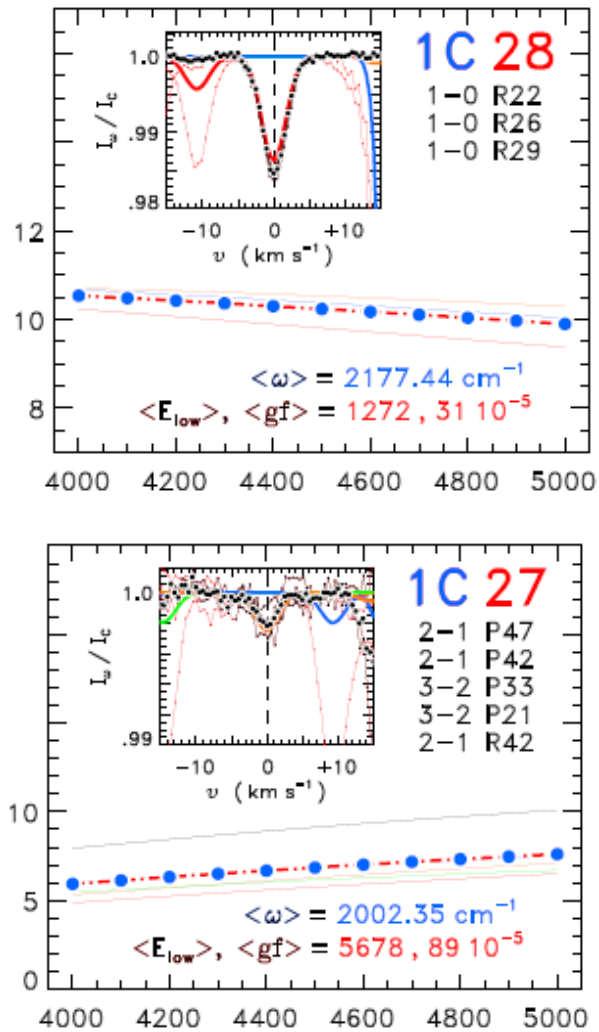

Fig. 2. (right column) Summary of measured photospheric isotopic ratios for various model assumptions. Abscissa is oxygen abundance (ε_O) in ppm. ***(top)*** $^{12}C/^{13}C$; ***(middle)*** $^{12}O/^{18}O$; ***(bottom)*** $^{12}O/^{17}O$. Included are the three reference snapshots, and three temperature perturbation scenarios for each snapshot, for both the G94 [6] (white/red) and HR96 [7] (blue/green) f-value scales; and the full 3D model and its three scenarios, for the average f-values (yellow/black). Thin red horizontal hatched lines refer to terrestrial standard values; upper blue lines are for *Genesis* oxygen. Overlapping vertical hatched regions show preferred ε_O from [12] (black), from [14] (red), and from seismology (blue).