The Chemical Composition of the Solar System

Katharina Lodders

Washington University, Saint Louis, MO 63130, USA
lodders@wustl.edu

Abstract. Elemental abundances in CI-chondrites are compared to recent photospheric data. Resulting issues for solar system abundances are noted.

Keywords: elemental abundances, Sun, meteorites, CI-chondrites, solar system.

1 Historical Developments

The modern stage for studying element and isotopic distributions with the goal of understanding the origin of the chemical elements was set about a century ago when it was already known that meteorite compositions can provide clues. Russell did the first comprehensive quantitative analyses of elements in the solar photosphere and found that abundances of non-volatile elements in meteorites compared reasonably well. By the 1950s, improvements in geochemical analyses and solar spectroscopy gave abundance data that served as testbeds for nucleosynthesis models. For a description of the historical developments, see [1].

1.1 Elemental Abundances from Meteorites

Meteorites are divided into chondrites, achondrites, and irons, and for elemental abundance studies, the chondrites are important. Chondrites never melted so their metal, silicate, and sulfide portions, occurring in different proportions in different chondrite types never fractionated, and chondrites are considered "primitive". The most common chondrites are ordinary chondrites, followed by enstatite and carbonaceous chondrites. Abundances in the common ordinary chondrite were employed by Harkins 1917, Goldschmidt, and the Noddacks in the 1920s and 30s, but assumptions about the metal, silicate and troilite proportions had to be made. In the early 1950s Urey pointed to the carbonaceous CI-chondrites as solar system standards for non-volatile elements. By the 1970s consensus was reached that the abundances in CI-chondrites are indeed the least affected by chemical volatility fractionations. On the downside, only 5 CI chondrite falls were collected (out of >1,000 observed falls), and less than 25 kg total of them remains. Optimal CI chondritic abundances require multiple well-determined elemental analysis. Recently new elemental and isotopic measurements provided improvements, but also some problems. The abundances for all 83 naturally occurring elements and their isotopes can be evaluated statistically, see

Lodders 2003 (L03) [2], Lodders, Palme & Gail 2009 (LPG09) [3], and Palme, Lodders & Jones 2014 (PLJ14) [4] for which updates are in progress.

1.2 Elemental Abundances in the Solar Photosphere

By now, only 68 of 83 elements have been analyzed in the sun's photosphere because issues with line strengths, number of lines, line accessibility in the spectrum and blending hamper detection and/or quantitative measurements of all elements.

Allende Prieto gives a comprehensive review of spectroscopic abundance determinations [5]. Abundance determinations require a model for the solar atmosphere, and the 1D-atmospheric models (e.g., [6,7]) and 3D-atmospheric models (e.g. [8-13]) are often employed. Differences among different 3D-models are small if the same line selections and NLTE corrections are applied, and line selection and NLTE considerations remain major issues when 3D results are compared.

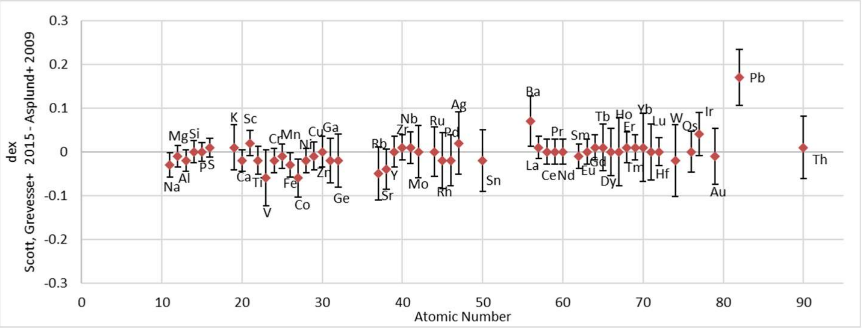

Fig. 1. Differences between 3D-photospheric abundances reported by Scott et al. 2015ab, Grevesse et al. 2015 [11-13] - Asplund et al. 2009 [8].

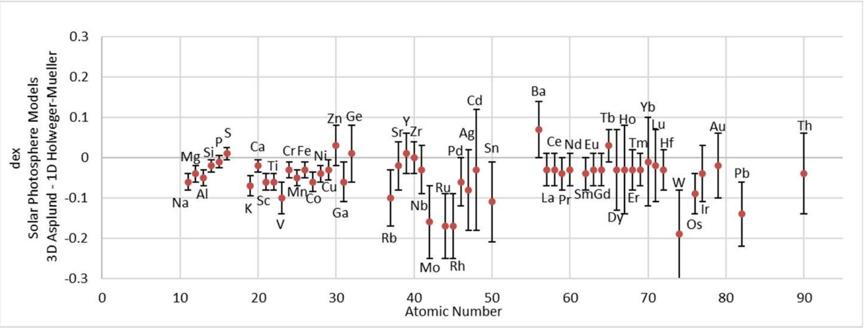

Fig. 2: Differences in photospheric abundances: 3D model (Asplund) – 1D model (Holweger), other parameters constant, see data & discussion in SSG15 [11-13].

Asplund et al. 2009 (A09) [8] reported 3D abundances and details for the heavy element analyses and revised values are in Scott et al. 2015ab, and Grevesse et al. 2015 (henceforth referred to collectively as SSG15, [11-13]). Their updates are mainly NLTE corrections and line selections. Differences are smaller than 0.05 dex for most elements, and tend to increase heavy element abundances slightly (see Fig. 1). Larger differences between A09 and SSG15 are for Ba, Tb, Os, Ir, Pb, and Th.

SSG15 [11-13] computed abundances using the 1D-Holweger and 3D-Aplund model atmospheres, leaving other parameters constant. In 3D models, many abundances are lower than in the 1D models (Fig. 2). The 3D corrections reduce abundances by 0.05-0.10 dex for most elements, they increase by $\leq$ 0.05 dex for B, Ge, Tb, Y, and Zn, the increase is somewhat larger for Ba. Large decreases over 0.1 dex occur for Mo, Ru, Rh, W, Sn, and Pb.

Photospheric abundances in L03 (2) were compiled from different papers and literature updates are in LPG09, PLJ14 [3,4]. This approach relies on the recommendations given in the papers, sometimes averages of several studies were used. This approach may not have a self-consistent base for atmospheric models, since 3D results from different groups, as well as 1D and 3D model results were included. PLJ14 [4] did not adopt A09 [8] because at the time detailed descriptions for the solar abundance determinations were pending.

1.3 Elemental Abundances: Solar and Meteoritic

The difference between meteoritic and photospheric abundances are shown in Figures 3 & 4. Both Figures use the same meteoritic data [4]. Fig. 3 uses photospheric data from SSG15 [11-13], and Fig. 4 photospheric data from PLJ14 [4]. The meteoritic values were converted to a logarithmic atomic scale so that log Si = 7.52 to match the photospheric Si abundance in [4]. A different choice for scaling will shift the differences between photospheric and meteoritic abundances by a constant for all elements in Figs 3 & 4, which is irrelevant for the comparison but would be relevant for linking meteoritic abundances to absolute abundance on the photospheric abundance scale (see [2] for details about the scale factor).

Very volatile elements (C, N, O) are depleted in meteorites and differences are off the scale in Figs. 3 & 4. Differences between meteoritic and solar abundances are less than 10% (~0.05dex) for many elements. Some previous discrepancies between solar and meteoritic abundances in Mn, Ga, Rb, In, and W were partially resolved in SSG15. Differences are notably large for elements with atomic numbers around $40 < Z < 50$, and for $Z > 70$. For some elements the differences between 3D photospheric and meteoritic abundances (Fig. 3) are larger than those calculated with photospheric data from PLJ14 (Fig. 4). The differences between solar and photospheric abundances outside uncertainty limits need to be understood. However, neither comparison reveals obvious systematic trends with chemical properties that would suggest element fractionations between CI-chondrites and the photosphere.

The 3D results indicated dramatic downward revisions in C,N,O, Ne and other elemental abundances, which led to the “oxygen crisis”, e.g., [14]. Standard solar models now missed opacity from C,N,O and Ne for the solar interior and models no longer matched with helioseismology results. A surge of investigations has not yet solved these problems completely. Meteorite studies cannot help to resolve this because meteorites did not retain the full solar complement of volatile C, N, and O.

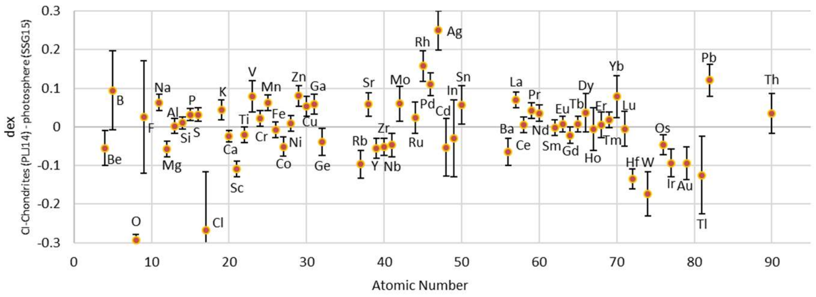

Fig. 3: Differences between meteoritic (Palme et al. 2014, [4]) and photospheric 3D abundances (Scott et al., Grevesse et al. 2015 [11-13]) vs. atomic number. Meteoritic abundances were scaled to log (Si)= 7.52

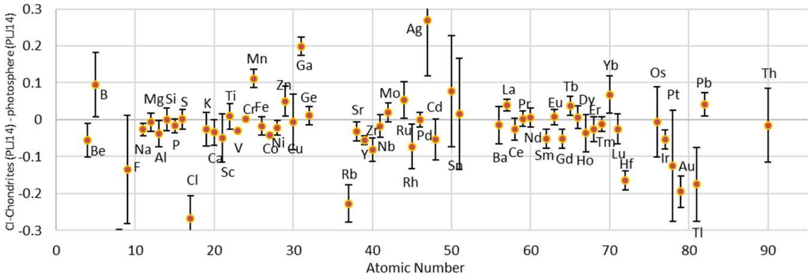

Fig. 4: Differences between meteoritic and photospheric abundances from Palme et al. 2014 [4] vs. atomic number. Meteoritic abundances were scaled to log (Si)= 7.52

2 Solar System Abundances

In [2-4], solar system abundances were determined from present photospheric and meteoritic abundances. C, N, and O were adopted from solar data, for elements lacking or with uncertain solar data, CI-chondrite data were adopted, for elements with plausible agreements, averages could be used. Noble gas data are usually estimated from compositions of the solar wind, B-stars, and/or nucleosynthesis systematics. The data must be adjusted for heavy element settling from the solar photosphere, and abundances of elements with long-lived radioactive nuclides must be calculated to the time of solar system formation (4.567 Ga ago). Given the larger differences between meteoritic and photospheric data from SSG15, deriving the solar system abundances becomes more challenging. Abundances for elements with similar chemistries and/or nucleosynthesis origins from other meteorite groups and from other astronomical objects can be compared to uncover inconsistencies in solar abundances. For example, preliminary Genesis solar wind abundances show non-systematic variations of elements with low First Ionization Potential (FIP) (e.g., Al, Ca, Cr, Mg) relative to the photospheric abundances in A09, whereas comparisons to CI chondrites in PLJ14 indicate systematic variations with FIP, which could indicate that CI-chondrites provide better approximations of the solar composition [15,16]. The updates on meteoritic, photospheric, and solar abundances are in progress.

Acknowledgements: Work supported by NSF AST1517541.

References

1. Lodders, K., Fegley B. 2011, Chemistry of the Solar System, Oxford Univ. Press
2. Lodders, K. 2003, Solar system abundances and condensation temperatures of the elements. Astrophys. J. 591: 1220-1247
3. Lodders, K., Palme H., Gail, H.P. 2009, Abundances of the elements in the solar system. In Landolt-Börnstein, New Series, Vol. VI/4B, Chap. 4.4, J.E. Trümper (ed.), Berlin: Springer-Verlag, p. 560-630.
4. Palme, H., Lodders, K., Jones, A. 2014, Solar system abundances of the elements. In Treatise on Geochemistry, Elsevier, Vol. 2, pp 15-36
5. Allende Prieto, C. 2016, Solar and stellar photospheric abundances, Living Rev. Sol. Phys. 13: 1-40
6. Holweger, H., Mueller, E.A. 1974, The photospheric barium spectrum - Solar abundance and collision broadening of BA II lines by hydrogen, Solar Phys. 39: 19-30
7. Holweger, H. 2001, Photospheric abundances: Problems, updates, implications. In: Solar and Galactic Composition. AIP Conference Proceedings, 598: 23-30
8. Asplund M., Grevesse N., Sauval A.J., Scott P. 2009, The chemical composition of the Sun. Annu. Rev. Astron. Astrophys. 47: 481–522
9. Caffau, E., Ludwig, H.-G., Steffen, M., Ayres, T. R., Bonifacio, P., Cayrel, R., Freytag, B., Plez, B. 2008, The photospheric solar oxygen project. I. Abundance analysis of atomic lines and influence of atmospheric models, Astron. Astrophys. 488: 1031-1046
10. Caffau, E., Ludwig H.G., Steffen, M., Freytag B., Bonifacio P. 2011 Solar chemical abundances determined with a CO5BOLD 3D model atmosphere. Solar Physics 268: 255–269
11. Scott, P., Grevesse, N., Asplund, M., Sauval, A.J., Lind, K., Takeda, Y., Collet, R., Trampedach, R., Hayek, W., 2015, The elemental composition of the Sun. I. The intermediate mass elements Na to Ca Astron. Astrophys., 573: A25
12. Scott, P., Asplund, M., Grevesse, N., Bergemann, M., Sauval, A.J. 2015, The elemental composition of the Sun. II. The iron group elements Sc to Ni, Astron. Astrophys. 573: A26
13. Grevesse, N., Scott, P., Asplund, N., Sauval, A.J. 2015, The elemental composition of the Sun. III. The heavy elements Cu to Th, Astron. Astrophys, 573: idA27
14. Basu, S., Anita, H.M. 2008. Helioseismology and solar abundances, Physics Reports 457: 217-283
15. Heber, V. S., McKeegan, K. D., Bochsler, P., Duprat, J., Burnett, D. S. 2014, The Elemental composition of solar wind with implications for fractionation processes during solar wind formation, LPSC 45: 2117
16. Burnett, D.S., Guan, Y., Heber, V.S., et al. 2017, Solar nebula composition based on solar wind data, LPSC 48: 1532