Comparing the Chemical Compositions of the Sun and Earth

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Abstract.   We compare the solar and terrestrial bulk elemental compositions. We show that the Sun and Earth share the same refractory elemental abundances, and that, to first order, the Earth is a devolatilized piece of the Sun left over from the Sun's formation. We discuss the advantages of an aluminium normalization for this comparison over the traditional silicon normalization.

1.   Introduction

If we did not know which star (from a group of stars) was our own, a comparison of the refractory (not volatile) elemental abundances of each star and the Earth's, would identify our Sun from the stellar lineup. Conversely, we can infer the elemental compositions of extrasolar earths from spectroscopic measurements of the elemental compositions of other stars. An important part of this procedure is to quantify as accurately as possible the chemical fractionation that occurred in our Solar System 4.5 billion years ago. We do this by comparing the bulk elemental abundances of the Sun and Earth.

2.   The Sun's Bulk Composition

The mass fractions of H, He and other elements in the Sun and elsewhere in the universe, are referred to as X, Y and Z respectively, where $X + Y + Z = 100\%$. After big bang nucleosynthesis (BBN) the universe can be described by $(X, Y, Z) = (75.2, 24.8, 0)\%$ (Spergel et al. 2007). After ~ 13.8 billion years of burning H into He and Z, we have a current cosmic baryonic average of approximately $(X, Y, Z) = (74.2, 25.3, 0.5)$. The 0.5% increase in Y after BBN is from Figure 1b of Fukugita & Kawasaki (2006). This 0.5% increase in Z is a crude estimate based on the idea that the net result of stellar fusion produces about as much He as it does everything else. This is also plausible because the Sun may have about twice as much Z as the cosmic baryonic average, since the material in the Sun has probably been more processed in stellar interiors than has most of the baryonic material in the universe. Also, the Sun is more metal-rich than $65 \pm 2\%$ of near-by stars of a variety of ages (Robles et al. 2008).

The difference between the proto-Sun and the current Sun is that as the Sun burns H to He, X has gone down by $\sim 4.6\%$ and Y has gone up by the same amount. The equivalent mass loss of the Sun due the Sun's luminosity over the 4.5 Gyr lifetime of the Sun ($\delta m = L_\odot t/c^2$ where $L_\odot$ is the solar luminosity and

Table 1.   Cosmic and Solar Mass Fraction Estimates [%]

X	Y	Z	Reference
75.2	24.8	0	cosmic values after big bang nucleosynthesis ((Spergel et al. 2007)
74.2	25.3	0.5	current cosmic baryonic average ((Fukugita & Kawasaki 2006)
71.2	27.4	1.4	proto-solar ((Lodders 2003, Grevesse et al. 2005)
66.6	32.0	1.4	current bulk Sun
73.9	24.9	1.2	solar photosphere ((Grevesse et al. 2005, Asplund et al. 2005)

t is the age of the Sun) is negligible, since $\delta m \approx 0.03\%$ of the Sun's mass. These numbers are summarized in Table 1.

There is an on-going controversy over the precise value of the solar Z. Helioseismological estimates of ~ 1.8 (Antia & Basu 2006, Chaplain et al. 2007) are hard to reconcile with recent photospheric estimates of ~ 1.2 (Asplund et al. 2005, Grevesse et al. 2005). However, the investigation of the systematic errors of these techniques is still in its infancy.

The $\sim 1.5\%$ of the mass of the Sun that is not H and not He, consists of oxygen (43.0%), carbon (17.3%), iron (9.7%), neon(8.2%), silicon(5.7%), magnesium(5.1%), nitrogen(5%), sulfur(2.9%), (Lodders 2003, Grevesse et al. 2005). These elements are unsurprisingly, just the right ingredients to form life (= C, H, O, N, S) and terrestrial planets (= Fe, O, Si, Mg).

The solar Z value and the abundances of the individual elements which scale with Z, depend to some degree on whether we are talking about the proto-solar nebula (= current bulk = proto bulk Sun) or the Solar photospheric values. To avoid this ambiguity in future work, when we compare the Sun to other stars, we use the solar photospheric values, because our observations of other stars are limited to their photospheres. When we compare the elemental abundances of the Sun to those of the Earth, we use the proto-solar values which are estimates of the bulk composition of the Sun.

In Figure 1 we compare the bulk elemental composition of the Sun to that of the Earth. The solar abundances plotted are the protosolar abundances from Lodders (2003, Table 2, p. 1224), with the exception of oxygen, nitrogen, and neon which are photospheric abundances from Asplund et al. (2005, Table 1) using the Lodders (2003) protosolar correction factor = 0.074 dex (see p. 1235).

3.   Normalization

The relative elemental abundances of the Sun and Earth can be compared only after normalization. For example, it has been traditional to normalize to the element silicon. The normalization can be described as follows: take an average piece of the Sun that contains 10^6 atoms of silicon and then count how many atoms of the other elements are contained in that piece. Then take an average piece of the Earth that also contains 10^6 atoms of silicon and then count how many atoms of the other elements are contained in that piece. When plotted, this provides a comparison of the Sun and Earth, normalized to silicon.

We normalize to aluminium because it is a more refractory element than silicon. Silicon is about 10 times more abundant in the Earth than is aluminium,
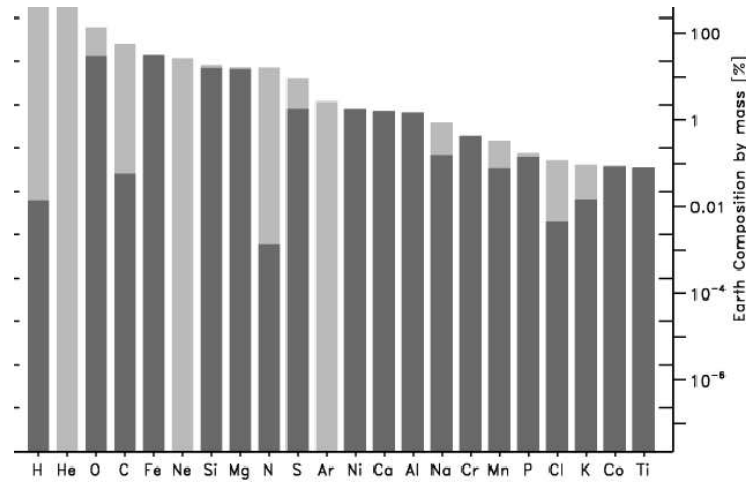
Figure 1.   Comparison between the elemental abundances of the Sun (Lodders 2003, Asplund et al. 2005) and bulk Earth (Morgan & Anders 1980, McDonough 2003) (non-weighted averages from these two references) normalized to aluminium. To first order, the Earth is a devolatilized piece of the protosun. The x-axis shows the elements arranged in decreasing abundance in the Sun by mass.

so in the past, when measurement accuracy was low, Si was the preferred normalization. However, as precision has increased to parts-per-billion levels, the rational to use Si has disappeared. For example, with a silicon normalization, the Earth is enriched relative to the Sun in all the elements which are more refractory than Si (e.g. Fe, Mg, Ni, Ca, Al, Cr, Ti, V, Sr Zr). However, when normalized to Al we see that the Earth is not enriched in anything, but depleted in the volatile elements and has maintained solar abundances of the refractory elements.

Our preferred normalization is an element that has not been depleted in either the Sun or the Earth. Volatile loss is not an issue for the Sun because the Sun's gravitational field is strong enough to hold all elements. This is not true for the Earth. Thus, we normalize the Earth-Sun comparison to the most refractory elements — elements that have not been lost during Earth's formation. Thus, Figure 1 has been normalized to the same number of aluminium atoms and then converted to percent mass. Thus, for Al, the light grey Sun histogram bar and dark grey Earth histogram bar are of equal height).

Notice that the blue bars of the histogram are always lower or equal to the yellow bars. The difference between the bars is the degree to which the Earth has lost its volatiles. Any element that can only appear in a gaseous state will be severely depleted on Earth (e.g. He, Ne, Ar). Other elements that are largely, but not exclusively found in gaseous state (H, O, C, N) have been partially depleted. Gaseous states that have led to their depletion include: H_2, O_2, CO, CH_4 and N_2. In the protoplanetary disk that formed our Solar System, H_2O was a volatile

within about 4 AU (the snowline) and a more refractory solid beyond 4 AU. Similar consideration of the ices NH_3 and CH_4 explain why H, C and N are only partially depleted. Fe, Mg Ni,Ca, Al, Cr, Ti, V, Sr and Zr are refractory elements and have relative abundances that have not changed since the Earth's formation. These relative abundances closely track the solar abundances for these elements and would be the abundances used in the thought experiment described above to identify the host star of the Earth. Of these refractory elements, aluminium seems to be the most abundant refractory element, so we use it to normalize the Sun-Earth comparison. This allows us to meaningfully quantify the pattern of volatiles that have been lost from the Earth. We will extend this work to quantify the range of devolatilization that led to the bulk compositions of the rocky planets of our Solar System. This will yield our best estimate of the devolatilization that has led to formation of rocky planets orbiting other stars. Thus, the chemical compositions of extrasolar rocky planets, can be extracted from the spectra (and elemental abundances) of their host stars.

References

Antia, H.M. & Basu, S. 2006 Determining Solar Abundances Using Helioseismology, Apj 644, 1292-1298

Asplund, M., Grevesse, N. and Sauval A. J., 2005. The Solar Chemical Composition in "Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis" ed xxx, ASP Conf. Series 336, 25

Chaplain, W.J. et al. 2007 Solar Heavy-element abundance: constraints from frequency separation ratios of low-degree p-modes. ApJ, 670, 872-884

Fukugita, M. Kawasaki, M, 2006 Primordial Helium Abundance: A Reanalysis of the Izotov-Thuan Spectroscopic Sample ApJ 646, 2, 691-695

Grevesse, N., Asplund, M. and Sauval A. J., 2005. The New Solar Composition. in "Element Stratification in Stars, 40 years of Atomic Diffusion", ed. Alecian, G., Richard, O. and Vauclair S., EAS Publications Series

Lodders, K. 2003. Solar System Abundances and Condensation Temperatures of the Elements. ApJ, 591:1220–1247,.

Lodders, K. & Fegley, B. 1997. An Oxygen Isotope Model for the Composition of Mars. Icarus, 126:373–394.

McDonough, W. 2003. Compositional Model for the Earth's Core, volume 2. Elsevier-Pergamon, Oxford.

Morgan, J. W. & Anders, E. 1980. Chemical composition of earth, Venus, and Mercury. In National Academy of Sciences, Proceedings, vol. 77, Dec. 1980, p. 6973-6977., pages 6973–6977.

Robles, J. A., Lineweaver, C. H., Grether, D., *et al.* 2008, A comprehensive comparison of the Sun to other stars: searching for self-selection effects, ApJ 689, 1457

Spergel, D. et al. 2007, Three-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology ApJSS, 170, 377-408