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DOI: [10.1888/0333750888/1979](https://doi.org/10.1888/0333750888/1979)

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From

Encyclopedia of Astronomy & Astrophysics

P. Murdin

© IOP Publishing Ltd 2005

ISBN: 0333750888

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Bristol and Philadelphia**

Downloaded on Wed Aug 17 17:14:56 BST 2005 [127.0.0.1]

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Solar Abundances

What is the Sun made of? This fundamental question only received an answer about 70 years ago. H N RUSSELL, whose name is associated with much pioneering research in astrophysics during the first half of this century as well as with a series of basic work in atomic spectroscopy, made the first quantitative analysis of the chemical composition of the SOLAR PHOTOSPHERE in 1929. Using eye estimates of solar line intensities, he succeeded in deriving the abundances of 56 elements. He also showed that the Sun and, finally, the universe were essentially made of hydrogen; this observation took some time to be accepted by the whole astronomical community. Many of the remarkable features correlated with nuclear properties (see figure 1), giving clues to the origin of the different elements, were already present in Russell's results.

Is the solar composition unique or does it vary with time and/or from one solar layer to another? The only obvious expected variation is in the central layers, where, because of thermonuclear reactions, the hydrogen content decreases, leading to an increase in the helium content (see NUCLEAR REACTION RATES). More subtle and unforeseen variations in the chemical composition have, however, been observed recently. During the solar lifetime, the convective zone reservoir which fills the outer solar layers is slowly enriched in hydrogen from the radiative zone below it, whereas it slowly loses, through its lower boundary layer, about 10% of all the heavier elements (see SOLAR INTERIOR: CONVECTION ZONE). In the outer atmospheric layers, and particularly in the very heterogeneous solar CORONA, the observed composition is variable in different types of solar matter and a fractionation occurs in the low chromospheric layers: elements of low first ionization potential (≤ 10 eV) show abundances larger than in the photosphere.

In spite of these subtle variations, it is possible to define a standard solar chemical composition, essentially derived from spectroscopic analysis of the solar photosphere.

Interest of solar abundances

The chemical composition of the Sun is obviously a key set of data for modeling the interior as well as the atmosphere of the Sun.

The Sun, being the best-known star, has always been considered as the typical star, the reference to which the abundance analyses of other stars are compared.

The standard abundance distribution as shown in figure 1 is also the basic set of data that have to be reproduced by nucleosynthesis theories; it also plays a key role in modeling the chemical evolution of galaxies and of the universe.

The Sun is also unique because chemical composition data can be measured in other objects of the solar system such as the Earth, Moon, planets, comets, meteorites. These data are very important for modeling the evolution of the solar system (see SOLAR SYSTEM: FORMATION).

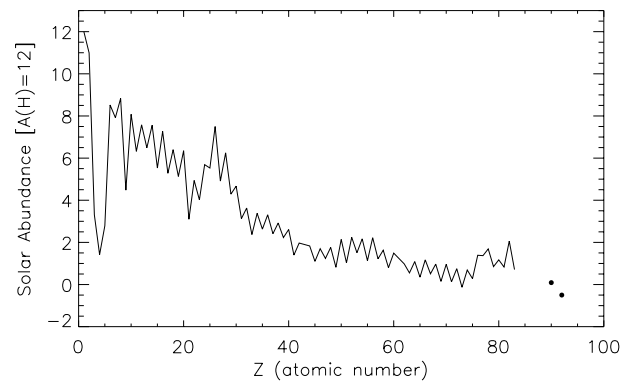


Figure 1. Logarithmic distribution of the abundance of the elements relative to hydrogen as a function of the atomic number, Z .

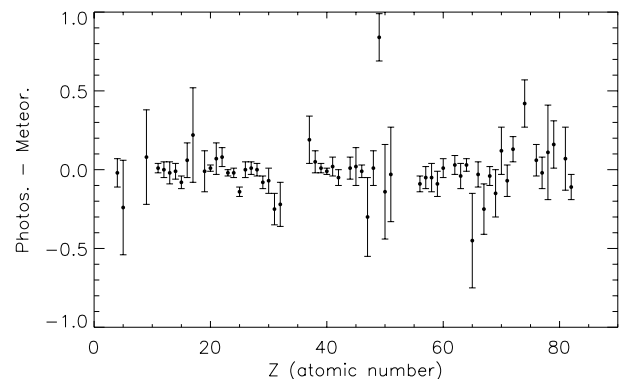


Figure 2. Difference between solar and meteoritic abundances of elements, in the usual logarithmic scale, as a function of Z . Error bars represent the uncertainty of the solar abundance determinations. The point representing Li falls outside of this figure (-2.21).

Sources of solar abundances

Solar abundances can be derived by very different techniques and for very different types of solar matter, from the interior to the outermost coronal layers. Using spectroscopy in a very large wavelength range, we can derive the chemical composition of the photosphere, CHROMOSPHERE and CORONA and also of SUNSPOTS. Particle collection techniques from space allow us to measure the chemical composition of the SOLAR WIND and of SOLAR WIND ENERGETIC PARTICLES, emitted when the Sun is active. We can also obtain information on solar flares from GAMMA-RAY ASTRONOMY. Finally, calibration of theoretical solar models and direct inversion of solar oscillation data allow us to derive the solar abundance of helium. Note also that lunar soils contain a record of the past chemical history of the Sun.

For different reasons and because of the variations in chemical composition, all of these sources of abundance results do not have the same weight. The solar photosphere is actually the layer from which we have

Table 1. Element abundances in the solar photosphere and in meteorites.

Element	Photosphere ^a	Meteorites	Photosphere– meteorite difference	Element	Photosphere ^a	Meteorites	Photosphere– meteorite difference
1 H	12.00	–	–	42 Mo	1.92 ± 0.05	1.97 ± 0.02	–0.05
2 He	[10.93 ± 0.004]	–	–	44 Ru	1.84 ± 0.07	1.83 ± 0.04	+0.01
3 Li	1.10 ± 0.10	3.31 ± 0.04	–2.21	45 Rh	1.12 ± 0.12	1.10 ± 0.04	+0.02
4 Be	1.40 ± 0.09	1.42 ± 0.04	–0.02	46 Pd	1.69 ± 0.04	1.70 ± 0.04	–0.01
5 B	(2.55 ± 0.30)	2.79 ± 0.05	–0.24	47 Ag	(0.94 ± 0.25)	1.24 ± 0.04	–0.30
6 C	8.52 ± 0.06	–	–	48 Cd	1.77 ± 0.11	1.76 ± 0.04	+0.01
7 N	7.92 ± 0.06	–	–	49 In	(1.66 ± 0.15)	0.82 ± 0.04	+0.84
8 O	8.83 ± 0.06	–	–	50 Sn	2.0 ± 0.3	2.14 ± 0.04	–0.14
9 F	[4.56 ± 0.30]	4.48 ± 0.06	+0.08	51 Sb	1.0 ± 0.3	1.03 ± 0.07	–0.03
10 Ne	[8.08 ± 0.06]	–	–	52 Te	–	2.24 ± 0.04	–
11 Na	6.33 ± 0.03	6.32 ± 0.02	+0.01	53 I	–	1.51 ± 0.08	–
12 Mg	7.58 ± 0.05	7.58 ± 0.01	+0.00	54 Xe	–	2.17 ± 0.08	–
13 Al	6.47 ± 0.07	6.49 ± 0.01	–0.02	55 Cs	–	1.13 ± 0.02	–
14 Si	7.55 ± 0.05	7.56 ± 0.01	–0.01	56 Ba	2.13 ± 0.05	2.22 ± 0.02	–0.09
15 P	5.45 ± 0.04	5.56 ± 0.06	–0.11	57 La	1.17 ± 0.07	1.22 ± 0.02	–0.05
16 S	7.33 ± 0.11	7.20 ± 0.06	+0.13	58 Ce	1.58 ± 0.09	1.63 ± 0.02	–0.05
17 Cl	[5.50 ± 0.30]	5.28 ± 0.06	+0.22	59 Pr	0.71 ± 0.08	0.80 ± 0.02	–0.09
18 Ar	[6.40 ± 0.06]	–	–	60 Nd	1.50 ± 0.06	1.49 ± 0.02	+0.01
19 K	5.12 ± 0.13	5.13 ± 0.02	–0.01	62 Sm	1.01 ± 0.06	0.98 ± 0.02	+0.03
20 Ca	6.36 ± 0.02	6.35 ± 0.01	+0.01	63 Eu	0.51 ± 0.08	0.55 ± 0.02	–0.04
21 Sc	3.17 ± 0.10	3.10 ± 0.01	+0.07	64 Gd	1.12 ± 0.04	1.09 ± 0.02	+0.03
22 Ti	5.02 ± 0.06	4.94 ± 0.02	+0.08	65 Tb	(–0.1 ± 0.3)	0.35 ± 0.02	–0.45
23 V	4.00 ± 0.02	4.02 ± 0.02	–0.02	66 Dy	1.14 ± 0.08	1.17 ± 0.02	–0.03
24 Cr	5.67 ± 0.03	5.69 ± 0.01	–0.02	67 Ho	(0.26 ± 0.16)	0.51 ± 0.02	–0.25
25 Mn	5.39 ± 0.03	5.53 ± 0.01	–0.14	68 Er	0.93 ± 0.06	0.97 ± 0.02	–0.04
26 Fe	7.50 ± 0.05	7.50 ± 0.01	+0.00	69 Tm	(0.00 ± 0.15)	0.15 ± 0.02	–0.15
27 Co	4.92 ± 0.04	4.91 ± 0.01	+0.01	70 Yb	1.08 ± 0.15	0.96 ± 0.02	+0.12
28 Ni	6.25 ± 0.04	6.25 ± 0.01	+0.00	71 Lu	0.06 ± 0.10	0.13 ± 0.02	–0.07
29 Cu	4.21 ± 0.04	4.29 ± 0.04	–0.08	72 Hf	0.88 ± 0.08	0.75 ± 0.02	+0.13
30 Zn	4.60 ± 0.08	4.67 ± 0.04	–0.07	73 Ta	–	–0.13 ± 0.02	–
31 Ga	2.88 ± 0.10	3.13 ± 0.02	–0.25	74 W	(1.11 ± 0.15)	0.69 ± 0.03	+0.42
32 Ge	3.41 ± 0.14	3.63 ± 0.04	–0.22	75 Re	–	0.28 ± 0.03	–
33 As	–	2.37 ± 0.02	–	76 Os	1.45 ± 0.10	1.39 ± 0.02	+0.06
34 Se	–	3.41 ± 0.03	–	77 Ir	1.35 ± 0.10	1.37 ± 0.02	–0.02
35 Br	–	2.63 ± 0.04	–	78 Pt	1.8 ± 0.3	1.69 ± 0.04	+0.11
36 Kr	–	3.31 ± 0.08	–	79 Au	(1.01 ± 0.15)	0.85 ± 0.04	+0.16
37 Rb	2.60 ± 0.15	2.41 ± 0.02	+0.19	80 Hg	–	1.13 ± 0.08	–
38 Sr	2.97 ± 0.07	2.92 ± 0.02	+0.05	81 Tl	(0.9 ± 0.2)	0.83 ± 0.04	+0.07
39 Y	2.24 ± 0.03	2.23 ± 0.02	+0.01	82 Pb	1.95 ± 0.08	2.06 ± 0.04	–0.11
40 Zr	2.60 ± 0.02	2.61 ± 0.02	–0.01	83 Bi	–	0.71 ± 0.04	–
41 Nb	1.42 ± 0.06	1.40 ± 0.02	+0.02	90 Th	–	0.09 ± 0.02	–
				92 U	(<–0.47)	–0.50 ± 0.04	–

Abundances are given in the logarithmic scale usually adopted by astronomers $A_{\text{el}} = \log N_{\text{el}}/N_{\text{H}} + 12.0$, where N_{el} is the abundance by number. By definition the abundance of hydrogen is exactly $A_{\text{H}} = 12.0$.

^a Values between square brackets are not derived from the photosphere, but from sunspots, solar corona and solar wind particles. Values between parentheses are less accurate results.

the largest number of data. Actually, 65 elements, out of 83 stable elements, are present in the photospheric spectrum; other sources of solar abundances only concern a limited number of elements. The photosphere, just above the convection zone, is a well-mixed region whereas the outer solar layers show a very heterogeneous and changing structure. Furthermore, it is also the layer that was studied quite a long time before the other layers for an obvious reason: the solar photospheric spectrum has been recorded for quite a long time with high resolution and high signal-to-noise ratio. For all these reasons,

photospheric abundances are adopted as a reference for all the other solar (and stellar) data.

Solar photospheric abundances

The basic data for deriving photospheric abundances are from the photospheric spectrum. Solar photospheric spectra with very high resolution and very high signal-to-noise ratio, obtained from the ground and from space, are now available for quite a large wavelength range, from the ultraviolet to the far infrared.

The strength of a line in the ABSORPTION SPECTRUM is directly related to the abundance of the element producing the line. The exact relation between these two quantities can be obtained if the physical conditions and physical processes of the layers where the line is formed are known. Empirical modelling of the photosphere has now reached a rather high degree of accuracy. Physical processes are also well known. Actually, in the photosphere, collisional processes dominate, which allows us to simplify the treatment. From the line strength, now measured with high accuracy, or directly from the fit of the predicted and observed spectra, the so-called spectral synthesis technique, it is possible to derive rather accurate values for the product of the abundance of the element producing the line, relative to the hydrogen abundance, times the transition probability of the line (see also SOLAR SPECTROSCOPY AND DIAGNOSTICS). The ratio $N_{\text{el}}/N_{\text{H}}$ is a natural measurement of abundance because the continuum is essentially produced by the opacity due to hydrogen species whereas the absorption line is the result of an additional opacity caused locally by a given element.

One of the largest sources of uncertainty of solar photospheric abundances comes from the inaccuracies of the transition probabilities. These data really play a key role in solar spectroscopy. Most of the progress in our knowledge of the solar photospheric chemical composition during the last decades has been mainly, if not uniquely, due to the use of more accurate transition probabilities. Actually, we believe that the dispersion of solar photospheric abundance results reflects the internal accuracy of the transition probabilities used to derive the abundances. Also, unfortunately, too few very accurate transition probabilities are available for the atomic and molecular lines present in the photospheric spectrum.

In table 1, we give the latest data for the solar photospheric abundances relative to hydrogen. The values are given in the logarithmic scale usually adopted by astronomers $A_{\text{el}} = \log N_{\text{el}}/N_{\text{H}} + 12.0$, where N_{el} is the abundance by number. It is to be noted that such a scale was originally adopted in order to avoid negative numbers for the least abundant elements. It is still used nowadays even if two values are now negative numbers i.e. their abundance is less than one millionth that of hydrogen—rather rare!

As may be seen from table 1, the photospheric abundances of a few elements cannot be measured in the photosphere, because these elements do not show lines in the photospheric spectrum, the most important of them being helium. This does not at all mean that these elements are absent in the Sun. Actually, this is purely for basic spectroscopic reasons: under the physical conditions in the photosphere, with a typical temperature around 5000 K, no line of these elements (neutral or once-ionized species) falls within the wavelength range covered by the photospheric spectrum.

Comparison with meteorites

Although most of the matter of the solar system is contained in the Sun, very useful information concerning

the chemical composition of the initial solar nebula and its evolution can be obtained from the observations of other bodies of the solar system. Early terrestrial data very rapidly showed that the Earth suffered from heavy chemical fractionation since its formation but results of measurements made on METEORITES, during the first half of this century, soon showed many regularities, as seen in figure 1.

Most meteorites suffer from differentiation due to melting after condensation in the parent body. However, the so-called CI carbonaceous chondrites, has preserved the bulk composition of the stellar nebula from which they condensed, except for the highly volatile elements (H, C, N, O and the rare gases) which partly escaped.

Meteoritic chemical composition can now be measured with very high accuracy. When compared with photospheric results, there were past discrepancies, for several elements, but the discrepancies have gone away as the photospheric values have become more accurate. Now, as seen from figure 2, the agreement between the photosphere and CI chondrites is remarkably good. The uncertainties essentially come from the photospheric results which cannot be obtained to better than 10–20%. The few discrepant points can be accounted for by the larger uncertainty of some photospheric results, especially for elements which only show very few blended lines in the photospheric spectrum.

Table 1 allows us to define a ‘standard abundance distribution’ (also sometimes called ‘cosmic abundance’ or ‘local galactic abundance’) by combining photospheric results, for elements partly lost by meteorites, with meteoritic results for the other elements.

A few special cases

For different reasons that will become clear in the following, a few elements deserve particular comments.

Helium

In 1868, a new element was discovered in the solar spectrum obtained during an eclipse. The name of the Sun was given to this unknown element, namely helium. It was only discovered on Earth in 1895.

Despite its name and its very high abundance, about one-tenth of hydrogen, the most abundant element, He is not present in the photospheric spectrum, for purely spectroscopic reasons, as explained previously, and it is largely absent from the meteorites. Solar wind and solar energetic particles show a very variable and rather low value when compared with values observed in hot stars and in the interstellar medium from H II regions around us. Coronal values derived from spectroscopy still have too large uncertainties, $N_{\text{He}}/N_{\text{H}} \approx 8 \pm 1.5\%$. Among the giant planets, values are still too uncertain and fractionation might have been at work in some of them.

Progress in our knowledge of the solar helium content has recently come from standard solar models as well as non-standard models and also from the direct inversion of HELIOSEISMIC OBSERVATIONS. The calibration of

solar theoretical models, i.e. the fit of a theoretical model to the presently observed characteristics of the Sun (age, mass, diameter, luminosity), leads to the abundance of helium in the protosolar cloud from which the Sun formed ($N_{\text{He}}/N_{\text{H}} = 9.8 \pm 0.4\%$). Inversion of helioseismic data leads to a very accurate, but smaller, value, $N_{\text{He}}/N_{\text{H}} = 8.5 \pm 0.07\%$; this is the present solar abundance of helium in the outer convection zone. The difference between these two values is now explained by slow element diffusion at the base of the convection zone during the solar lifetime, as already mentioned in the introduction.

Astronomers often use the abundances by mass of hydrogen (X), helium (Y) and all the other elements together, the metallicity (Z), in a scale where $X + Y + Z = 1$. The numbers cited above become $Y = 0.275 \pm 0.01$ or $A_{\text{He}} = 10.99 \pm 0.02$ in our logarithmic scale, at the birth of the Sun, and $Y = 0.248 \pm 0.02$ or $A_{\text{He}} = 10.93 \pm 0.004$, as the present value in the solar outer layers.

Lithium, beryllium, boron

The strikingly low abundances of these light elements are a direct consequence of their low nuclear binding energy; at temperatures of the order of a few million kelvins, these nuclei are destroyed by proton collisions.

In the Sun, meteoritic and photospheric abundances of Be and B agree within the error bars, whereas Li is 160 times less abundant in the (present) photosphere than in the meteorites, i.e. at birth of the Sun. Lithium is the most fragile of these three elements and its solar destruction rate could be explained if the solar convection zone reached a little deeper layers than now deduced from helioseismology. So additional mixing, just below the convection zone, has to be added in order to explain the observed solar lithium depletion.

Carbon, nitrogen, oxygen

These elements which have largely escaped from meteorites are key elements. Because of their large abundances, they are the main contributors to the metallicity (O 47%, C 17%, N 5%) and they are also very important contributors to the opacity which plays a crucial role in modeling the solar interior.

Although coronal measurements of the CNO abundances are certainly very helpful, the solar abundances of these three elements rely heavily on photospheric analyses.

In spite of the fact that the solar photospheric abundances of these elements can be derived from a large number of indicators, atoms as well as diatomic molecules made of C, N, O and H, the uncertainties of the solar results are uncomfortably too large, partly because of the lack of very accurate transition probabilities.

Neon, argon

These two noble gases do not appear in the solar photospheric spectrum, for the reasons already described, and are largely lost by meteorites. It is hoped that values obtained for the outermost solar layers, from

coronal spectra, solar wind and solar energetic particle measurements as well as gamma ray spectroscopy of solar flares, do not suffer from the fractionation mentioned in the introduction and can be used as representative of the present solar photosphere.

Isotopic abundances

Because isotopic shifts in atomic lines are extremely small, it is impossible to obtain isotopic ratios for most of the elements. For a few elements, however, such as C, O and Mg, which appear in diatomic molecules, we can derive estimates of the solar isotopic composition, with rather large uncertainties. Isotopic data can be obtained from solar wind measurements for He, Ne and Mg.

Isotopic ratios for all the elements can be measured with high accuracies for terrestrial material. They agree with the results obtained from meteorites although 'isotopic anomalies' are observed which are, however, confined to a very small fraction of the meteorites. Thus the method is to take solar abundances for the elements together with isotopic ratios as derived on earth in order to obtain the solar abundances of individual nuclides.

Conclusions

With the solar chemical composition presented in table 1, the usual mass abundances are $X = 0.735$, $Y = 0.248$ and $Z = 0.017$ with $Z/X = 0.023$.

The solar abundances are in excellent agreement with the meteoritic abundances derived from CI carbonaceous chondrites. The effects of element migration at the bottom of the convection zone are, however, not observed. This is puzzling although not surprising. Actually, the uncertainties of the photospheric abundance results are still too large to allow such a faint effect to be detected.

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