

## Standard Abundances

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**Abstract.** After a short discussion on the very notion of standard abundances, we present an updated version of the solar chemical composition as derived from the solar photosphere and the meteorites.

### 1. Introduction

The words Standard Abundances are found everywhere in the astrophysical literature where they now replace Cosmic or Solar Abundances, or Local Galactic Abundances, however keeping the same meaning. Actually this meaning has strong implications which are not always kept in mind by the users.

Heavy elements are produced in different types of stars, evolving with very different lifetimes. A homogeneous increase in  $Z$  in the Galaxy would require a similar rate of star formation everywhere, with the same initial mass function and instantaneous recycling of newly-formed elements. It is obvious, both from observations and theory, that there is no single chemical mixture which can be used everywhere in the Galaxy and there is no such idea as a standard chemical composition.

This is however what is generally being done. The solar system chemical composition serves as a standard not only for stars apparently of the same metallicity but also for objects with different  $Z$ , the detailed composition being adjusted following the  $Z$ 's ratio.

The choice of the Sun as a standard is obvious for the following reasons: it is the nearest and best known star, its chemical composition can be derived using various techniques in different outer layers of the star; it has additional reliable indicators like the meteorites and in particular, the CI meteorites, and the planets. It is however questionable whether the Sun is really representative of the mean chemical composition of the Galaxy in the solar environment (see Section 2).

The knowledge of the chemical composition of the different constituents of the Universe is a key data for modelling these objects. The chemical composition is an essential data for testing the nucleosynthesis processes as well as galactic evolution models. It plays also a crucial role in the computation of such important data as the opacities. It is still out of reach to really incorporate in

a stellar evolution code, a precise opacity computation taking into account the slightest changes in one or more of the heavy elements, even if the atomic data are now available. So a compromise is adopted which is to compute opacity tables for the solar chemical composition varying only X and Y and adjusting the Z value. This is one of the reasons why the solar chemical composition has become, mostly for pragmatic reasons, the standard chemical composition.

## 2. Is the Sun a Typical Star?

It has been suggested that the Sun, might be anomalous, i.e. metal rich, and therefore not representative of the local ISM composition at the time of its formation, 4.6 Gyr ago.

The two main reasons are the following:

- The metallicity in the present local ISM region, essentially measured from analyses of the Orion nebula and of nearby B stars, is lower than the value obtained from solar abundances (Gies & Lambert 1992, Cunha & Lambert 1992, Wilson & Rood 1994, Mathis 1996). This is in contradiction with galactic chemical evolution models which predict an increase of metallicity with time. This increase should however vary with the galactocentric position, the highest values being found towards the central regions of the Galaxy.
- The Li abundance measured in the Orion nebula, is very similar to the meteoritic abundance which suggests that it has evolved very little during the last 4.6 Gyr. This observation is also very difficult to reconcile with the theoretical predictions of the variation with time of the Li abundance (Steigman 1993, Cunha et al. 1995).

On the other hand, a very detailed analysis by Edvardsson et al. (1993) of a large number of F and G dwarfs has led to the conclusion that:

- The Sun is indeed a normal star, i.e. it has the same composition as other stars of the same age located at the same galactocentric distance.
- A real dispersion exists among the stars.

## 3. Standard Abundances from the Sun

The outer layers of the Sun show a very heterogeneous structure in the chromosphere and the corona, overlying a well mixed photosphere where most of the absorption lines are formed, just above the convection zone.

Abundances can be derived from all these regions ranging from the photosphere and sunspots to the chromosphere and corona using classical spectroscopic techniques but also  $\gamma$ -ray spectroscopy. Particle measurements are used to obtain data for the solar wind (SW) and solar energetic particles (SEP).

The most reliable results for most of the chemical elements are without any doubt obtained from analyses of the solar photospheric spectrum for which very high quality data exist from UV to IR. Furthermore, physical processes and physical conditions are rather well known in the photospheric layers. This is not the case for other regions like sunspots, chromosphere or corona, the last two layers being extremely heterogeneous and varying with time. In addition, it is now known that a fractionation process is at work in the solar outer layers: elements with first ionization potential (FIP), lower than about 10 eV are systematically overabundant by a factor of 4.5 in the corona, SW and SEP when compared to photospheric values.

Pioneering works by Payne (1925) and Russell (1929) have shown that the Universe is largely dominated by hydrogen. Russell (1929) succeeded for the first time in deriving the solar abundances of a large number of chemical elements and Russell's mixture has been used for about three decades.

Since then, much progress has been done in the field of solar photospheric abundances. On the one hand, solar photospheric spectra are now available with very high resolution and signal over noise ratio for quite a large range in wavelength, from UV to far IR (for a review, see Kurucz 1995). On the other hand, empirical modelling of the photosphere has now reached a high degree of accuracy (see e.g. Grevesse & Sauval 1994). Last, but not least, accurate atomic data, in particular transition probabilities, have been obtained for quite a number of transitions of solar interest although additional spectroscopic work remains to be done.

The most recent results for solar abundances derived from photospheric spectra are given in Table 1 and comments for a few important elements are to be found in Section 5.

#### 4. Standard Abundances

Other sources of abundances exist in the solar system like planets, comets and meteorites. In the planets, however, elements have either evaporated or fractionated; very few reliable data are available for comets. A very rare class of meteorites, CI meteorites, is known to be representative of the matter from which the solar system formed, 4.6 Gyr ago. Except for the very volatile elements, this class of meteorites has retained all the other elements present in the primitive matter of the solar nebula. It is therefore a very reliable source of standard abundances especially because of the high precision of the measurements: most of the results for CI meteorites are known to within 5 to 10 percent.

In the past decades, there were large and unexplained discrepancies between photospheric and meteoritic results, for quite a large number of elements. These past discrepancies have now gone away, mostly thanks to the increased accuracy of the analyses of the photospheric spectra, essentially due to the use of atomic data of better accuracy. It is now generally accepted that the solar photosphere and the CI meteorites have exactly the same composition, even if some small differences still remain (Anders & Grevesse 1989, Grevesse & Noels 1993a, Palme & Beer 1994).

Since Russell's first analysis, other tables of standard abundances have been published. Most of them are essentially based on a combination of data coming from meteorites as well as from the solar photosphere (Goldschmidt 1937, Suess & Urey 1956, Goldberg et al. 1960, Cameron 1968, 1973, 1982, Ross & Aller 1976, Meyer 1979, 1985, 1989, Anders & Ebihara 1982, Trimble 1975, 1991, Anders & Grevesse 1989, Grevesse et al. 1992, Grevesse & Noels 1993a, Palme & Beer 1994).

We summarize in Table 1 what we believe to be the best values for standard abundances as derived from the photosphere and the meteorites. Abundances are given in the logarithmic scale usually used by astronomers,  $A_{el} = \log N_{el}/N_H + 12.0$ , where  $N_i$  is the abundance by number.

Photospheric abundances are essentially those given in Grevesse et al. (1992) and Grevesse & Noels (1993a), updating results recommended in Anders & Grevesse (1989). Values in parentheses are uncertain and values in brackets are based on other solar or astronomical data. The solar photospheric abundances of S, Sr, La and Ce have been remeasured recently and their values have slightly changed (Delalic et al. 1990, Biéumont et al. 1993, Gratton & Sneden 1994).

Meteoritic abundances have been taken from Anders & Grevesse (1989) and Palme & Beer (1994). We took the straight mean between those two tables, the differences being very small for most of the elements. For a few elements however, new measurements led us to adopt revised values. For boron, we took the recent data of Zhai & Shaw (1994) who found a meteoritic abundance of boron about 25 % smaller than the value recommended by Anders & Grevesse (1989). For S, P, Se and Au, we chose the new values obtained by Palme & Beer (1994). The conversion factor from the meteoritic scale,  $N_{Si} = 10^6$ , to the solar abundance scale,  $\log N_H = 12$ , has been derived as usual by comparing the solar meteoritic ratio,  $R = \log(\text{sol/met})$ , for a series of elements which abundances have been accurately measured both in the photosphere and in the meteorites. We now adopt  $R = 1.560 \pm 0.013$ . The uncertainty in coupling the two scales is thus only of the order of 3 %.

It is still obvious from the results presented in Table 1 that the uncertainties on the photospheric results are much larger than those on the meteorites. Within the uncertainty limits, there is a complete agreement between both sources of solar abundances, except for some elements which photospheric values are still very dubious. We also give in Table 1 the differences between photospheric and meteoritic results.

## 5. Comments on a Few Elements

### 5.1. Helium

Helium is a very peculiar element in the sense that its primordial abundance is known with a great accuracy,  $Y_p = 0.23 \pm 0.01$  ( $Y$  is the usual mass abundance of He; see Wilson & Rood 1994 for detailed references), whereas its solar abundance is unknown. Despite its name and its high abundance, this element is unfortunately undetectable in the photospheric spectrum and in the meteorites. SW and SEP measurements show a very variable but rather low value, with a

Table 1. Element Abundances in the Solar photosphere and in Meteorites

El.	Photosphere	Meteorites	Ph-Met	El.	Photosphere	Meteorites	Ph-Met
01 H	12.00	—	—	42 Mo	1.92 ±0.05	1.97 ±0.02	-0.05
02 He	[10.99 ±0.035]	—	—	44 Ru	1.84 ±0.07	1.83 ±0.04	+0.01
03 Li	1.16 ±0.10	3.31 ±0.04	-2.15	45 Rh	1.12 ±0.12	1.10 ±0.08	+0.02
04 Be	1.15 ±0.10	1.42 ±0.04	-0.27	46 Pd	1.69 ±0.04	1.70 ±0.04	-0.01
05 B	(2.6 ±0.3)	2.79 ±0.05	(-0.19)	47 Ag	(0.94 ±0.25)	1.24 ±0.04	(-0.30)
06 C	8.55 ±0.05	—	—	48 Cd	1.77 ±0.11	1.76 ±0.04	+0.01
07 N	7.97 ±0.07	—	—	49 In	(1.66 ±0.15)	0.82 ±0.04	(+0.84)
08 O	8.87 ±0.07	—	—	50 Sn	2.0 ±(0.3)	2.14 ±0.04	-0.14
09 F	[4.56 ±0.3]	4.48 ±0.06	+0.08	51 Sb	1.0 ±(0.3)	1.03 ±0.04	-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	—	2.23 ±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)	5.53 ±0.04	-0.08	57 La	1.17 ±0.07	1.22 ±0.02	-0.05
16 S	7.33 ±0.11	7.20 ±0.04	+0.13	58 Ce	1.58 ±0.09	1.63 ±0.02	-0.05
17 Cl	[5.5 ±0.3]	5.28 ±0.06	0.22	59 Pr	0.71 ±0.08	0.80 ±0.04	-0.09
18 Ar	[6.52 ±0.10]	—	—	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 ±0.04	(-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 ±0.04	(-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 ±0.04	7.50 ±0.01	0.00	69 Tm	(0.00 ±0.15)	0.15 ±0.04	(-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 ±0.01	6.25 ±0.01	0.00	71 Lu	(0.76 ±0.30)	0.13 ±0.02	(+0.63)
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 ±0.04	—
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	—	3.38 ±0.02	—	77 Ir	1.35 ±(0.10)	1.37 ±0.01	-0.02
35 Br	—	2.63 ±0.04	—	78 Pt	1.8 ±0.3	1.69 ±0.04	+0.11
36 Kr	—	3.23 ±0.07	—	79 Au	(1.01 ±0.15)	0.87 ±0.02	(+0.14)
37 Rb	2.60 ±(0.15)	2.41 ±0.02	+0.19	80 Hg	—	1.17 ±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 ±0.06	—
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	—

ratio  $N_{\text{He}}/N_{\text{H}}$  of the order of 4 %. Other sources from solar spectroscopy give very uncertain results (see e.g. Laming & Feldman 1994). The giant planets do not help very much as they do show very different and rather small helium contents, whereas the outermost planets are more helium abundant, with large uncertainties however (Grevesse et al. 1992).

The so-called solar helium abundance is therefore derived from calibrations using theoretical stellar evolution models. The most recent calibration, with an adopted value of  $Z/X = 0.0244$ , from Table 1, leads to a helium mass abundance of  $Y = 0.27$ . This value is somewhat smaller than the previously found  $Y$  value using the same procedure but with an older  $Z/X$  ratio of 0.0286 from Anders & Grevesse (1989). In those calibrations,  $Y$  is the helium abundance of the nebula

from which the solar system formed and the standard theoretical evolutions do not change the  $Y$  value in the outer layers during the whole central hydrogen burning phase.

There are now strong indications that this value of  $Y = 0.27$  is too large. On the one hand, the inversion of the observed helioseismic data leads to a value of about 0.23 (Kosovichev et al. 1992). On the other hand, observations from Spacelab recently published (Gabriel et al. 1995), although they are limited to the solar corona, suggest a value of  $N_{\text{He}}/N_{\text{H}}$  of  $0.07 \pm 0.011$ , which means a  $Y$  value of about 0.22.

This puzzling difference could be easily explained if helium diffusion has been at work during the 4.6 Gyr of the Sun's evolution. Actually, theoretical evolutions taking helium diffusion into account have shown that a 10 % reduction in the photospheric helium abundance can be expected (Proffitt & Michaud 1991, Christensen-Dalsgaard et al. 1993, Pinsonneault 1995).

## 5.2. Lithium - Beryllium - Boron

These elements are the only ones for which large differences exist between meteoritic and photospheric abundances. This is easily understandable as those elements are burned at low temperatures; if the convection envelope is deep enough, the surface abundances will be lowered. There are however theoretical uncertainties about the extent of the outer convection zone; here again, the inversion of helioseismic data suggests a convective envelope somewhat deeper than what is found in the models (Christensen-Dalsgaard et al. 1993). Depletion rates to be explained by theoretical models are 140 for Li and 1.9 for Be, the photospheric abundance for B being too uncertain to allow giving a depletion rate for B.

## 5.3. Carbon - Nitrogen - Oxygen

These elements contribute for about 70 % to the metallicity. As they are partly lost in meteorites, the knowledge of their photospheric abundances is of particular interest. A comprehensive discussion is given in Grevesse & Noels (1993a) and Grevesse & Sauval (1994). The uncertainties are still uncomfortably large because of their crucial role in the metallicity. They essentially come from the lack of accuracy in the atomic and molecular data.

## 5.4. Neon - Argon

The abundances of these two noble gases can only be derived from the coronal spectrum, SW and SEP, which explains the rather large uncertainties given in Table 1. The abundance values quoted in Table 1 are weighted means between SW and SEP values and measurements from impulsive flare spectra (see Grevesse et al. 1992, Grevesse & Noels 1993a).

### 5.5. Iron

The longstanding puzzling problem of the difference between the photospheric and the meteoritic abundance of iron now seems to be solved. Recent works (Holweger et al. 1990, Holweger et al. 1991, Biémont et al. 1991, Hannaford et al. 1992, Milford et al. 1994, Blackwell et al. 1995a,b, Holweger et al. 1995, O'Mara 1995, Kostik et al. 1996) do show that the abundance derived from Fe II lines nicely agrees with the meteoritic value. These lines are the best indicators of the solar Fe abundance because iron is essentially once ionized in the solar photosphere. Moreover, accurate transition probabilities have recently been determined for some of these lines. A problem still remains with the abundance derived from Fe I lines which shows a dependence on the excitation energy. Low excitation lines lead to a somewhat higher abundance whereas high excitation lines give an abundance in agreement with the meteorites. We do believe this problem has its origin in solar spectroscopy. High excitation Fe I lines are on the whole faint lines in the solar photospheric spectrum whereas low excitation lines are medium strong lines. High excitation lines are also much less sensitive to temperature as well as to possible departures from local thermodynamic equilibrium. Corrections to the low excitation line results, coming from slight temperature modifications, effects of microturbulence, non-LTE effects and collisional broadening effects might explain the difference between the results derived from low excitation and high excitation lines of Fe I.

### 5.6. Thorium

This element is a radioactive element used as a chronometer for constraining the age of the Galaxy (Butcher 1987). In Table 1, we have not indicated any value for the photospheric abundance of Th for the following reasons. The only line that can be used is a line of Th II at 4019.136 Å. The abundance derived from this line is much larger than the accurately known meteoritic value. Such a discrepancy is unexplainable because Th is a refractory element and its meteoritic abundance is representative of the Th abundance in the original nebula (Anders & Grevesse 1989). It has been shown that the Th II line is blended with a Co I line (Lawler et al. 1990) and also with a V I line (Grevesse & Noels 1993b). As the transition probability of the V I line is still somewhat uncertain, it is impossible to predict its contribution to the Th II line and thus to derive an accurate value for the photospheric abundance of thorium.

## 6. Conclusions

Much progress has been made during the last two decades in the solar abundance accuracies. They have been due to the availability of high quality spectra covering a large range in wavelength but essentially to definite progress in the accuracy of transition probabilities. The solar photosphere is never *at fault*. Past *errors* have been shown to be due to errors in atomic or molecular data.

The new solar abundances are now in excellent agreement with the meteoritic abundances derived for CI carbonaceous chondrites, the mean difference

between photospheric and meteoritic results having vanish to zero. With the results presented in Table 1, i.e. the photospheric data for C, N, O; Ne and Ar, largely lost by the meteorites and the more accurate meteoritic data for the other elements, the classical mass abundances are  $X = 0.708$ ,  $Y = 0.275$  and  $Z = 0.017$ .

Very small differences exist for some elements. They are essentially due to the uncertainties of the photospheric results. Meteoritic data have now reached very high accuracies, e.g. a few percent.

The least well known data are the data for CNO which contribute the most to the metallicity ( $\sim 70\%$ ) and are largely lost from meteorites. Progress is expected in the near future provided the accuracy of molecular data needed to interpret the best solar indicators of the abundances of C, N and O is improved.

Progress is also to be expected concerning a more realistic description of the heterogeneous outer solar layers through hydrodynamical modelling of the matter motions just above the solar convection zone.

Diffusion seems to be at work in the solar outer layers. The present day solar photospheric He content which we cannot unfortunately measure directly is about 10% smaller than it was when the Sun was born. Such an effect is not seen in other elements because photospheric and meteoritic abundances are in very good agreement.

Even if the Sun is not a standard or typical star, it is and will remain a unique source of chemical element abundances because it is the best known star to which other stars are compared.

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