

# Abundances of the Elements in the Sun

N. Grevesse<sup>1</sup> and A. J. Sauval<sup>2</sup>

<sup>1</sup>*Institut d'Astrophysique et de Géophysique, Université de Liège, B-4000 Liège, Belgium*

<sup>2</sup>*Observatoire Royal de Belgique, B-1180 Bruxelles, Belgium*

*nicolas.grevesse@ulg.ac.be*

**Abstract:** We review the current status of our knowledge of the chemical composition of the sun and its evolution from core to corona. In spite of subtle variations, it is possible to define a standard chemical composition (Table 1), essentially derived from the analysis of the solar photospheric spectrum, together with important contributions from helioseismology as well as from observations of the solar upper atmosphere.

## 1. INTRODUCTION

What is the sun made of? The answer to this fundamental question is of crucial importance not only for modelling the sun itself but more generally for modelling the great variety of stellar objects and the universe as a whole.

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. 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, from the photosphere to the corona, 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. In the outer atmospheric layers, and essentially in the very heterogeneous solar corona, the observed composition is very variable in different types of solar coronal structures and a fractionation occurs in the low chromospheric layers: elements of low first ionization potential  $\leq 10$  eV generally show abundances larger than

in the photosphere. In the outermost coronal structures, additional gravitational settling acts to further modify the chemical composition.

We shall nevertheless see that in spite of these subtle variations, it is possible to define a standard solar chemical composition, essentially derived from analyses of the solar photospheric spectrum, but with important contributions from other sources.

## 2. HISTORICAL INTRODUCTION

H.N. Russell, whose name is associated with a large number of pioneer researches in astrophysics during the first half of this century (for example the Hertzsprung-Russell diagram) as well as to a series of basic works in atomic spectroscopy (for example the LS or Russell-Saunders coupling), also made the first quantitative analysis of the chemical composition of the solar atmosphere (Russell, 1929). Using eye estimates of solar line intensities measured on the Revised Rowland Atlas of the solar spectrum together with the reversing layer hypothesis, he succeeded to derive the abundances of 56 elements. Russell's mixture was used by almost two generations of astronomers. He also showed that the solar atmosphere and, finally, the universe were essentially made of hydrogen, an observation which took some time to be accepted by the whole astronomical community. Many of the remarkable features correlated to nuclear properties (Figure 1), giving clues to the origin of the different elements, were already present in Russell's results.

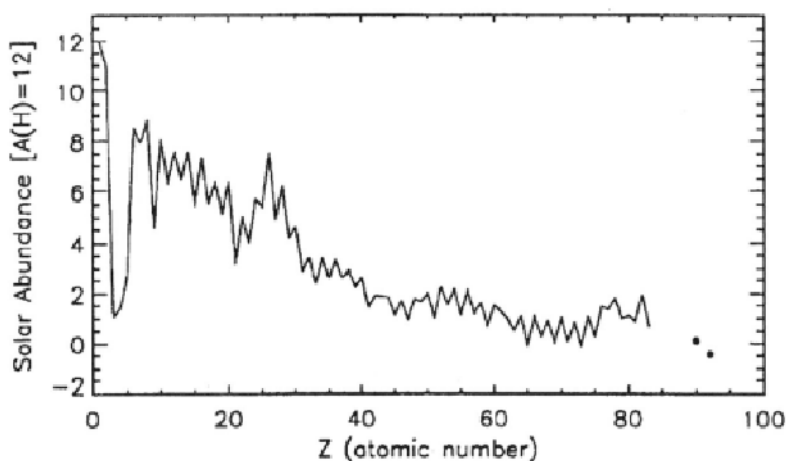


Figure 1. Distribution of the abundance of the elements as a function of the atomic number, Z.

Twenty years later, Unsöld (1948) using better observations and better techniques obtained abundance results for 25 elements and noticed that his results were not much different from Russell's values. He concluded that this was not surprising because Russell had an "unvergleichliches spektroskopisches Fingerspitzengefühl" (an incomparable spectroscopic flair).

In the meantime important works of great interest for our understanding of stellar atmospheres have been published, allowing progress in the accuracy of abundance analyses.

Goldberg *et al.* (1960; hereafter GMA) using the curve of growth technique together with a photospheric model, and a careful examination of the observed equivalent widths and, for the first time, of the oscillator strengths of the lines, succeeded in getting the abundances for 42 elements. The results of GMA have been considered as the standard reference work for more than 10 years. In the last 25 years different groups all over the world have been very active in photospheric abundance works: L.H. Aller and his co-workers, D.E. Blackwell and his co-workers, O. Engvold and O. Hauge, H. Holweger and his co-workers, D.L. Lambert, B. Warner, B.J. O'Mara and his co-workers, and our Belgian group including E. Biémont and A. Noels.

Chemical composition data concerning the solar outer layers above the photosphere slowly accumulated during the last 30 years or so. These data, obtained from the ground as well as from space, revealed a great variability from one layer to another, from one event to another. In spite of these variabilities and sometimes large differences with photospheric results, these data play an important role in defining the solar chemical composition and, more importantly, in explaining the physical processes that allow these outermost layers to exist (see different reviews in Fröhlich *et al.*, 1998).

### 3. INTEREST OF SOLAR ABUNDANCES

The chemical composition of the sun is a key data for modelling the sun, the interior as well as the atmosphere. In the photosphere, elements like Mg, Si and Fe, play a particular role because they provide most of the electrons in this layer. The critical role of the opacities and the crucial contributions of the most abundant elements like Fe in the central solar layers and of O and Ne at the bottom of the convective zone has been stressed by many authors (Rogers and Iglesias, 1998; Turck-Chièze, 1998; Turcotte and Christensen-Dalsgaard, 1998; Guzik and Neuforge, this volume).

Progress in the opacity computations allow to say that uncertainties in the opacities due to uncertainties in the abundances are now similar in magnitude to those due to uncertainties in the physics of opacity computations. With the tremendous new achievements of solar seismology, solar interior

layers can now be empirically tested (Guzik and Neuforge, this volume). Very slight changes in the abundance profile of the interior layers have profound and observable effects on the sound speed profile obtained with very high accuracy from solar seismic observations.

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. We know that the solar system based standard abundance distribution (SAD) is not universal. Outside of the solar system we obviously observe quite a large number of peculiarities (*i.e.*, differences from the SAD) among different stellar objects. In the solar system itself, we observe the so-called "isotopic anomalies" showing material of very different origins, but these anomalies are confined in a very small mass fraction (See *e.g.*, Ott and many other papers in this volume). These anomalies probably result from incomplete mixing in the primordial solar nebula (See however Manuel, this volume). It has also been suggested that the sun might be somewhat anomalous (See Grevesse *et al.*, 1996 for references), but Gustafsson (1998) has convincingly shown that the sun is like many other stars of the same age in our galaxy and that the claimed slight metal richness of our sun is well within the real cosmic scatter. Abundances are remarkably similar to some extent to the SAD, everywhere we look, and the deviations from the SAD are to be explained by secondary but very important processes.

When studying solar abundances in different solar layers (See section 4), we have also access to important tracers of the structure as well as of the physical processes in the outer solar layers.

The sun is also unique because chemical composition data can be acquired from different objects in the solar system like the earth, moon, planets, comets and meteorites. Few data come from planets; for the terrestrial planets, including the Earth, elements have either evaporated or fractionated. Very few reliable data are available for comets. This is one of the main goals of a future comet rendezvous mission. A very rare class of meteorites, the so-called CI carbonaceous chondrites, is of particular interest (See *e.g.*, Ebihara *et al.*, this volume; Larimer, this volume). These meteorites have preserved the bulk composition of their parent bodies (planetesimals) and have thus retained most of the elements present in the primitive matter of the solar nebula, except for the few most volatile elements. Chemical composition data among these various bodies are important tracers of the origin and evolution of the solar system.

And, last but not least, the standard chemical composition as derived from meteorites is also the basic data that has allowed Burbidge *et al.* (1957) and Cameron (1957) to build the firm basis of the theory of element nucleosynthesis explaining how, where and when all the nuclides are formed. The remarkable pattern seen in Figure 1 is in timely related to nuclear stability.

The different nuclear processes giving rise to this distribution of the chemical elements have been identified: big-bang nucleosynthesis, spallation by galactic cosmic rays, thermonuclear fusion and neutron captures in stars during stationary evolution and supernova explosions (Burbidge, this volume). The standard chemical composition also plays a key role in the chemical evolution of galaxies and the universe (Pagel, 1997).

## **4. SOURCES OF SOLAR ABUNDANCES**

Because of its proximity, our sun is unique and, by far, the best known star. Actually, 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 to measure the chemical composition of the solar wind (SW) and of solar energetic particles (SEP). We can eventually get informations on solar flares from gamma-ray spectroscopy. Finally, calibration of solar models and inversion of helioseismic data allow us to derive the solar abundance of helium (See section 5.1). Using similar techniques, we might hope, in the future, to be able to get empirical abundance profiles in the solar interior (Turck-Chièze, 1998; Takada and Shibahashi, 1998; Guzik and Neuforge, this volume) in order to test the selective element migration which takes place in the radiative zone just below the convective zone (See hereafter). Note also that lunar soils also record the past chemical history of the sun (Wieler, 1998).

Below the convective zone, in the radiative zone, selective element settling is at work, thanks to the effects of gravitation, thermal diffusion and radiative acceleration (Vauclair, 1998; Turcotte and Christensen-Dalsgaard, 1998; Guzik and Neuforge, this volume). Although this is a very slow phenomenon, since the birth of the sun, computations show that the reservoir that fills the solar outer layers, could have lost about 10% of He and of all the heavier elements. A varying metallicity profile is thus building up in the radiative zone that has profound effects on the models. Of course, strictly speaking, the chemical composition of the photosphere should be about 10% lower than the composition of the interstellar cloud from which the sun formed 4.6 GY ago.

In the solar outer layers, all the indicators (coronal spectra, SW and SEP measurements, gamma-ray spectroscopy, various measurements in very different coronal structures) show that the observed chemical composition (involving the most abundant elements up to Ge) is very variable in different

types of solar matter and that a fractionation occurs, at low chromospheric level, leading to the so-called FIP (First Ionization Potential; or FIT: First Ionization Time) effect: elements of low first ionization potential ( $\leq 10$  eV) show abundances about 4 times larger than in the photosphere whereas elements with higher ionization potential (except for helium; see section 5.1), have the same abundance in the corona and in the photosphere. It has to be mentioned that the FIP effect strongly depends on the observed coronal structure: it can vary from 1, *i.e.*, photospheric abundances, in coronal holes and impulsive flares, up to very large values (15) in long lasting coronal plumes. In the outermost coronal layers, far away from the sun further gravitational settling occurs. The variation in chemical composition among very different coronal structures and the FIP effect are discussed in detail in many recent papers (*e.g.*, Fröhlich *et al.*, 1998; Reames, 1999).

The solar photosphere is without any doubt the layer from which we have the largest number of chemical composition data. Actually, 65 elements, out of 83 stable elements, are present in the photospheric spectrum. The few elements which cannot be measured in the photosphere, the most important being helium, are not absent however. These elements do not show lines in the photospheric spectrum 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. The other sources of solar abundances only concern a limited number of elements: in the SEP, the richest source of elemental abundances, only 21 elements have been measured.

Just above the convection zone, the photosphere is a well mixed region (See, however, Solanki, 1998) whereas the outer solar layers show a very heterogeneous and changing structure. The structure and the physical processes of the photosphere are also rather well known allowing to reach good accuracies. It is also the layer that has been studied quite a long time before the other layers for obvious reasons: the solar photospheric spectrum has been recorded since quite a long time. For all these reasons, photospheric abundances will be adopted as a reference for all the other solar data.

## 5. SOLAR ABUNDANCES

For many reasons given above, the solar chemical composition, to which the results for the other layers will be compared, is the composition derived from the analysis of the solar photospheric spectrum.

Much progress has been made during the last decades. Solar photospheric spectra, the basic data for deriving photospheric abundances, with very high resolution and very high signal over noise ratio, obtained from the ground and

from space, are now available for quite a large wavelength range, from the UV to the far IR (See Kurucz, 1995, for a recent review). The strength of an absorption line is directly related to the product of the abundance of the element producing the line and of the transition probability of the line. The exact relation between these two quantities can easily 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 high degree of accuracy [See section 5.5 and Solanki (1998) and Rutten (1998)]. And, last but not least, accurate atomic and molecular data, in particular transition probabilities, have progressively been obtained for transitions of solar interest; these data play a key role in solar spectroscopy.

*Table 1. Element abundances in the solar photosphere\**

| Element | $A_{el}$            | Element | $A_{el}$          | Element | $A_{el}$          |
|---------|---------------------|---------|-------------------|---------|-------------------|
| 01 H    | 12.00               | 29 Cu   | $4.21 \pm 0.04$   | 58 Ce   | $1.58 \pm 0.09$   |
| 02 He   | $[10.93 \pm 0.004]$ | 30 Zn   | $4.60 \pm 0.08$   | 59 Pr   | $0.71 \pm 0.08$   |
| 03 Li   | $1.10 \pm 0.10$     | 31 Ga   | $2.88 \pm (0.10)$ | 60 Nd   | $1.50 \pm 0.06$   |
| 04 Be   | $1.40 \pm 0.09$     | 32 Ge   | $3.41 \pm 0.14$   | 62 Sm   | $1.01 \pm 0.06$   |
| 05 B    | $2.70 \pm 0.16$     | 33 As   | -                 | 63 Eu   | $0.51 \pm 0.08$   |
| 06 C    | $8.52 \pm 0.06$     | 34 Se   | -                 | 64 Gd   | $1.12 \pm 0.04$   |
| 07 N    | $7.92 \pm 0.06$     | 35 Br   | -                 | 65 Tb   | $(-0.1 \pm 0.3)$  |
| 08 O    | $8.83 \pm 0.06$     | 36 Kr   | -                 | 66 Dy   | $1.14 \pm 0.08$   |
| 09 F    | $[4.56 \pm 0.3]$    | 37 Rb   | $2.60 \pm (0.15)$ | 67 Ho   | $(0.26 \pm 0.16)$ |
| 10 Ne   | $[8.06 \pm 0.10]$   | 38 Sr   | $2.92 \pm 0.05$   | 68 Er   | $0.93 \pm 0.06$   |
| 11 Na   | $6.33 \pm 0.03$     | 39 Y    | $2.24 \pm 0.03$   | 69 Tm   | $(0.00 \pm 0.15)$ |
| 12 Mg   | $7.58 \pm 0.05$     | 40 Zr   | $2.60 \pm 0.02$   | 70 Yb   | $1.08 \pm (0.15)$ |
| 13 Al   | $6.47 \pm 0.07$     | 41 Nb   | $1.42 \pm 0.06$   | 71 Lu   | $0.06 \pm 0.10$   |
| 14 Si   | $7.55 \pm 0.05$     | 42 Mo   | $1.92 \pm 0.05$   | 72 Hf   | $0.88 \pm (0.08)$ |
| 15 P    | $5.43 \pm 0.05$     | 44 Ru   | $1.84 \pm 0.07$   | 73 Ta   | -                 |
| 16 S    | $7.33 \pm 0.11$     | 45 Rh   | $1.12 \pm 0.12$   | 74 W    | $(1.11 \pm 0.15)$ |
| 17 Cl   | $[5.5 \pm 0.3]$     | 46 Pd   | $1.69 \pm 0.04$   | 75 Re   | -                 |
| 18 Ar   | $[6.40 \pm 0.10]$   | 47 Ag   | $(0.94 \pm 0.25)$ | 76 Os   | $1.45 \pm 0.10$   |
| 19 K    | $5.12 \pm 0.13$     | 48 Cd   | $1.77 \pm 0.11$   | 77 Ir   | $1.35 \pm (0.10)$ |
| 20 Ca   | $6.36 \pm 0.02$     | 49 In   | $(1.66 \pm 0.15)$ | 78 Pt   | $1.8 \pm 0.3$     |
| 21 Sc   | $3.17 \pm 0.10$     | 50 Sn   | $2.0 \pm (0.3)$   | 79 Au   | $(1.01 \pm 0.15)$ |
| 22 Ti   | $5.02 \pm 0.06$     | 51 Sb   | $1.0 \pm (0.3)$   | 80 Hg   | -                 |
| 23 V    | $4.00 \pm 0.02$     | 52 Te   | -                 | 81 Tl   | $(0.9 \pm 0.2)$   |
| 24 Cr   | $5.67 \pm 0.03$     | 53 I    | -                 | 82 Pb   | $1.95 \pm 0.08$   |
| 25 Mn   | $5.39 \pm 0.03$     | 54 Xe   | -                 | 83 Bi   | -                 |
| 26 Fe   | $7.50 \pm 0.05$     | 55 Cs   | -                 | 90 Th   | -                 |
| 27 Co   | $4.92 \pm 0.04$     | 56 Ba   | $2.13 \pm 0.05$   | 92 U    | $(< -0.47)$       |
| 28 Ni   | $6.25 \pm 0.04$     | 57 La   | $1.17 \pm 0.07$   |         |                   |

\*Elements for which no photospheric value is given are not necessarily absent from the photosphere; see section 4 – Values between square brackets are not derived from the photosphere, but from sun spots (F, Cl), solar corona and solar wind particles (Ne, Ar) – Values between parentheses are less accurate results – For He, see section 5.1; for Th, see Grevesse, *et al.* (1996).

We have recently reviewed in detail this key role and, in particular, the role of transition probabilities in solar spectroscopy, not only in improving the abundance results but also as tracers of the physical conditions and processes in the solar photosphere (Grevesse and Noels, 1993; Grevesse *et al.*, 1995). Most of the progress in our knowledge of the solar photospheric chemical composition during the last decades has been essentially, if not uniquely, due to the use of more accurate transition probabilities as seen in the examples given in the here above mentioned papers. Large discrepancies previously found between the sun and CI meteorites have progressively disappeared as the accuracy of the transition probabilities has been increased. Actually, the dispersion of solar photospheric abundance results reflects the internal accuracy of the transition probabilities used to derive the abundances. The sun is rarely (never?) at fault but unfortunately, older sets of transition probabilities were too often at fault! Hopefully, the techniques now allow to measure transition probabilities with high accuracy, even for rather faint lines. It has to be mentioned that many analyses of solar abundances have resulted from close collaborations between atomic spectroscopists and solar spectroscopists. Too rare groups, however, work to fill the gaps in the many data still needed by the astronomers.

In Table 1, we give the best solar photospheric abundances taken from our latest review (Grevesse and Sauval, 1998). Recent results obtained by Cunha and Smith (1999; B), by ourselves on P (unpublished), by Barklem and O'Mara (1998; Ca), by Barklem and O'Mara (1999; Sr) have been taken into account. Values are given in the logarithmic scale usually adopted by astronomers,  $A_{\text{el}} = \log N_{\text{el}}/N_{\text{H}} + 12.0$ , where  $N_{\text{el}}$  is the abundance by number. Such a scale was originally adopted in order to avoid negative numbers for the least abundant elements. It is still used nowadays even if one value is now negative. We now comment on a few elements.

## 5.1 Helium

In 1868, a new element was discovered in the solar spectrum obtained during an eclipse. The name of the sun was given to the new element, helium. Helium was only discovered on earth in 1895. Nowadays, its primordial abundance is known to a high degree of accuracy (Pagel, 1997).

Despite its name and its very high abundance, He is not present in the photospheric spectrum and is largely lost by the meteorites. Solar wind and solar energetic particles show a very variable and rather low value (*i.e.* low when compared to values observed in hot stars and in the interstellar medium from H II regions around us). Coronal values derived from spectroscopy have large uncertainties:  $N_{\text{He}}/N_{\text{H}} = 7.9 \pm 1.1\%$  (Gabriel *et al.*, 1995) and  $8.5 \pm 1.3\%$  (Feldman, 1998). Giant planets, as observed by the Voyager spacecraft, do not allow to settle the question: Jupiter and Saturn



show anomalously low values whereas higher values ( $9.2 \pm 1.7\%$ ) are found for Uranus and Neptune (Conrath, *et al.*, 1989). Note that the recent Galileo spacecraft has recently measured an intermediate value on Jupiter,  $Y = 0.234$ , or  $N_{\text{He}}/N_{\text{H}} = 7.85\%$  (von Zahn and Hunten, 1996).

Progress in our knowledge of the solar He content has recently come from standard solar models as well as non standard models and the inversion of helioseismic data. While the calibration of the standard models leads to an abundance of He by mass of  $Y = 0.27 \pm 0.01$  ( $N_{\text{He}}/N_{\text{H}} = 9.5\%$ ) in the protosolar cloud (Christensen-Dalsgaard, 1998), non standard models (*i.e.*, taking element migration, for example, into account) start with an helium abundance of  $Y = 0.275$  (Gabriel, 1997). Inversion of helioseismic data leads to a very accurate, but smaller, value,  $Y = 0.248 \pm 0.002$  (*i.e.*, 8.5%) as the value of the present solar abundance of He in the outer convection zone (Dziembowski, 1998). The difference of 10 percent between these two values is now interpreted as due to element migration at the basis of the convection zone during the solar lifetime (Vauclair, 1998; Turcotte and Christensen-Dalsgaard, 1998). The problem of the solar He is also discussed in Guzik and Neuforge (this volume).

In Table 1, we give the present value in the outer layers,  $Y = 0.248 \pm 0.002$ , or  $N_{\text{He}}/N_{\text{H}} = 8.5\%$ , or  $A_{\text{He}} = 10.93 \pm 0.004$ . The value at birth of the sun is  $Y = 0.275 \pm 0.01$ , or  $N_{\text{He}}/N_{\text{H}} = 9.8\%$ , or  $A_{\text{He}} = 10.99 \pm 0.02$ .

## 5.2 Lithium, Beryllium, Boron

Recent results obtained for the solar abundances of beryllium (Balachandran and Bell, 1998) and boron (Cunha and Smith, 1999) show that solar data for Be and B now perfectly agree with the meteoritic values.

The Li Be B problem is now reduced to explaining how the sun can deplete Li by a factor 160 (the ratio between the meteoritic and photospheric values) whereas Be and B are not destroyed. Although standard solar models fail to do that, mixing just below the bottom of the convection zone seems to be successful (Blöcker *et al.*, 1998; Vauclair, 1998; Zahn, 1998; Guzik and Neuforge, this volume).

## 5.3 Carbon, Nitrogen, Oxygen

These elements which have largely escaped from meteorites are key elements. Because of their large abundances, they are main contributors to the metallicity (O: 47%, C: 17%, N: 5%); they are also important contributors to the opacity, especially O (Guzik and Neuforge, this volume). Although coronal measurements of the CNO abundances are certainly very helpful, the solar abundances of these three elements will nevertheless heavily rely upon the photospheric values.

The abundances of C, N and O can be derived from a large number of indicators, atoms as well as diatomic molecules made of C, N, O and H. The problems encountered when analyzing all these indicators have been described by Grevesse and Sauval (1994).

Recently, Reetz (1998) has redetermined the solar abundance of oxygen on the basis of the A–X transition of OH, of the O I triplet around 777.3 nm and of vibration-rotation and pure rotation lines of OH in the infrared. He finds  $A_O = 8.80 \pm 0.06$ .

We have revisited all the lines of all the CNO solar abundance indicators and redone some computations playing with different photospheric models. Unfortunately, our new analysis is not yet finalized because we believe that there are, among other things, many uncleared problems with the atomic as well as molecular data. We can only suggest preliminary values for the revised solar C, N and O abundances:  $A_C = 8.52$ ,  $A_N = 7.92$  and  $A_O = 8.83$ , respectively; we estimate the uncertainties to be of the order of 0.06 dex (Sauval *et al.*, 1999). These values are slightly smaller than the previously recommended values. Even small, these modifications have profound effects on the solar model as shown by Guzik and Neuforge (this volume).

## 5.4 Neon, Argon

These two noble gases do not appear in the solar photospheric spectrum and are largely lost by meteorites. Therefore we have to rely on coronal data as obtained from the coronal spectrum, SW, SEP and gamma-ray spectroscopy.

Ne is an important element because it contributes 10% to the metallicity. Furthermore, it is an important contributor to the opacity at the bottom of the convection zone (Rogers and Iglesias, 1998; Turck-Chièze, 1998).

For Ne, an accurate value has recently been obtained by Widing (1997) who measured the Ne/Mg ratio in photospheric material observed in emerging flux events. His value has been slightly revised by Feldman (1998),  $A_{Ne} = 8.12 \pm 0.10$ . On the other hand, gradual SEP events lead to a very accurate Ne/O ratio (0.152). If we adopt the hereabove mentioned solar oxygen abundance, we find  $A_{Ne} = 8.01 \pm 0.07$ , the uncertainty being essentially due to the uncertainty of the photospheric abundance of oxygen. We shall therefore recommend a mean between these two results:  $A_{Ne} = 8.06 \pm 0.10$ .

The solar abundance of argon has been rediscussed by Young *et al.* (1997) who, mostly on the basis of SW and SEP results, together with B-type stars, as well as lunar soils results, recommended a value  $A_{Ar} = 6.47 \pm 0.10$ , smaller than the value recently proposed by Feldman (1998),  $A_{Ar} = 6.62 \pm 0.12$ , from the impulsive flare Ar/Mg ratio. Now recent SEP based Ar abundance results (Reames, 1998) lead to a much smaller value,  $A_{Ar} = 6.35 \pm 0.09$ , adopting the solar oxygen abundance,  $A_O = 8.83$ , quoted

hereabove. We shall therefore suggest to adopt  $A_{Ar} = 6.40 \pm 0.10$ , keeping in mind these very different values.

## 5.5 Iron

The longstanding puzzling problem of the possible difference between the photospheric and the meteoritic abundance of iron has been the subject of numerous works by different research groups during the last decade. The debate between the Oxford group (D.E. Blackwell and his co-workers) and the Kiel-Hannover group (H. Holweger and co-workers) as to whether the solar abundance of Fe derived from Fe I lines is high,  $A_{Fe} = 7.63$  (Oxford), *i.e.*, larger than the meteoritic value,  $A_{Fe} = 7.50$ , or low (Kiel-Hannover), *i.e.*, in agreement with the meteorites, is summarized in Grevesse and Sauval (1999) where we give a complete discussion of the problem. Apparently, the cumulative effects on the abundance results of slight differences between the equivalent widths, gf-values absolute scales, microturbulent velocities and empirical enhancement factors of the damping constants, could partly explain the two different abundance results.

We have also rediscussed the problem using most of the lines retained by the two different groups cited hereabove. Our results obtained with the usually adopted Holweger and Müller (1974) photospheric model show that low excitation lines lead to higher abundance values than higher excitation lines. As the low excitation lines are more sensitive to the temperature than the high excitation lines and as they are, on the whole, formed higher in the atmosphere, an easy way to solve for this dependence is to change very slightly the temperature of the photospheric model in the *ad hoc* layers. The new solar model we built has a temperature about 200 K lower at  $\log \tau \approx -3$  and has the same T of the Holweger and Müller (1974) model in the deeper layers ( $\log \tau \approx -1$ ). With this new model results from low and high excitation Fe I lines lead to the same abundance value:  $A_{Fe} = 7.50 \pm 0.05$ , in pretty good agreement with the very accurate meteoritic result (7.50). This value also agrees with results obtained from the analyses of Fe II lines.

## 6. COMPARISON WITH METEORITES

Solar abundance results are generally compared with the very accurate results obtained from a very rare class of meteorites, the CI carbonaceous chondrites (Ebihara *et al.*, this volume; Larimer, this volume). As can be seen from Figure 2, photospheric and meteoritic results agree now perfectly well. It was shown (See section 5, also Anders and Grevesse, 1989) that past discrepancies have gone away as the solar values have become more accurate, especially

thanks to transition probabilities of much better accuracy. The few discrepant points can be accounted for by the uncertainty of the photospheric results, much larger than the very small uncertainties of the meteoritic data.

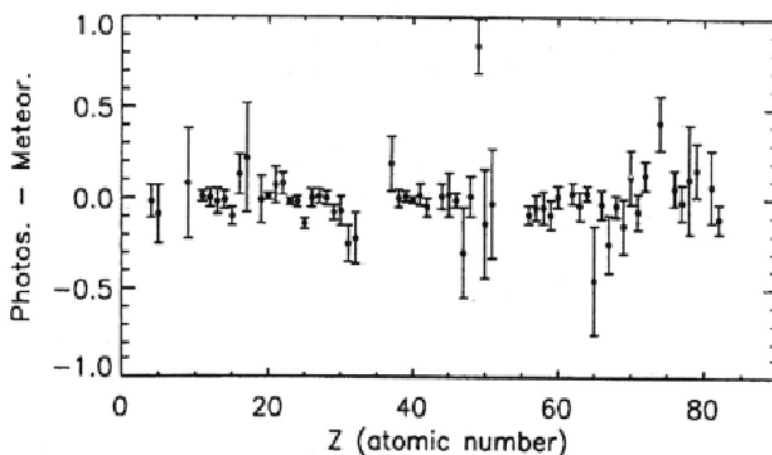


Figure 2. Difference between Solar and Meteoritic abundances of elements as a function of  $Z$  (Grevesse and Sauval, 1998). Error bars represent the uncertainty of the solar abundance determinations. The point representing Li falls largely outside of this figure (-2.21).

We do believe that this is not just by chance that photospheric and meteoritic abundances agree so well (Figure 2), from refractories to rather highly volatile elements (See Figure 4 of Anders and Grevesse, 1989). This is a strong argument in favor of the CI carbonaceous chondrites as a good representative sample of the well mixed solar nebula.

Meteoritic abundances are generally combined with solar abundances to build the "standard abundance distribution" (SAD; See *e.g.*, Grevesse and Sauval, 1998). For a large number of elements, values from CI's are used rather than solar values because of the higher accuracies of the CI results and because CI and solar data nicely agree. However, for the most abundant elements and the most important ones as far as solar modelling is concerned (H, He, O, C, Ne and N by order of decreasing abundances), the SAD will always rely on solar data.

## 7. SOLAR ISOTOPIC RATIOS

It is very difficult to get any very accurate isotopic ratios from the analysis of the solar photospheric spectrum. Results obtained from the spectroscopic analysis of molecular lines lead to isotopic ratios for C, O and

Mg only: within the rather large error bars, the solar photospheric values agree with the reference terrestrial isotopic abundances (Sauval *et al.*, 1999 for C and O).

Recent solar wind and solar energetic particles measurements of very different coronal structures and events, from various ongoing space experiments (Ulysses, WIND, SOHO, ACE), have allowed to obtain very interesting sets of isotopic data ranging from the  $^3\text{He}/^4\text{He}$  ratio up to nickel, including only the most abundant elements. Data also come from lunar surface material which record implanted solar matter since the birth of the Moon. Different review papers concerning these subjects have recently been published by Bochsler (1998), Kallenbach *et al.* (1998), Wieler (1998), Williams *et al.* (1998), Wimmer-Schweingruber *et al.* (1999) and Zurbuchen *et al.* (1998).

It would be out of the scope of the present review to make an exhaustive discussion in a field in very rapid evolution. Helium plays a special role because from the solar  $^3\text{He}/^4\text{He}$  ratio, a value of D/H can be obtained which has important consequences for galactic evolution and the big-bang model (Geiss and Gloeckler, 1998). Although this ratio,  $^3\text{He}/^4\text{He}$ , is extremely variable, from event to event and from the slow to the fast solar wind, accurate long term averages can be obtained.

The isotopic abundances of refractory elements generally show little variations among different solar system objects including the solar sources. Solar values generally agree with the terrestrial ratios within a few percent, but the slow solar wind could be slightly fractionated (depletion in the heavier isotopes) and some SEP events show large variations probably related to a charge/mass fractionation occurring in SEP.

The situation is quite different and, actually, very complicated for volatile elements like the noble gases Ne, Ar, Kr and Xe (these last two elements have only been observed in lunar soils). For the isotopic ratio  $^{20}\text{Ne}/^{22}\text{Ne}$ , for example, very different values are observed: 13.7 (SW), 11.0 (SEP, but with large variations down to 6.6 in some events), 9.8 in the terrestrial atmosphere and at least two kinds of "planetary" Ne in meteorites, 8.6 and 10.7, respectively. Although the origin of these rather large differences is unknown, various physical processes (related to acceleration and transport) could lead to these isotopic fractionations in the outer solar layers as well as during the different phases of formation of the planetary bodies (Bochsler, 1998; Williams *et al.*, 1998). Isotopic fractionations in the high speed solar wind do not seem to be very efficient (Wimmer-Schweingruber *et al.*, 1999).

Manuel and Hwaung (1983; Manuel, this volume) took another point of view in order to explain the differences in isotopic composition of noble gases between the solar wind and planetary solids. They suggest that a very

efficient fractionation process is operating inside the sun enriching light mass nuclei at the surface, *i.e.*, the photosphere. When the photospheric abundances are corrected for this hypothetical fractionation process, the sun's interior turns out to be essentially made of iron! Hydrogen and helium, the most abundant elements in the universe, become very minor contributors to solar bulk matter. With such a sun, they eventually suggested that the sun formed on the iron core of a precursor supernova which exploded about 5 billion years ago.

We do believe that solar modellers will have tremendous difficulties to compute a shining sun with such a mixture and that helioseismic observations are not in favor of such exotic matter (Guzik and Neuforge, this volume). Furthermore, wherever we look around us, other stellar objects do show, to within important but explainable differences, about the same composition as the solar photospheric one.

In the standard abundance tables, because a large number of isotopic ratios cannot be measured from solar sources, it is generally assumed that the solar isotopic abundances are the same as in terrestrial and meteoritic material, except for very rare cases (Anders and Grevesse, 1989; Ebihara *et al.*, this volume).

## 8. CONCLUSIONS

We have come to a point where photospheric and meteoritic abundances agree pretty well. Does this necessarily mean that there are no real small differences? Probably not because the uncertainties of the photospheric data are still too large. To reduce these uncertainties and make progress in our understanding of the solar photosphere, better and many more atomic data of high precision are required. We have also seen that 1D classical photospheric models have really reached their limits. Progress is now expected if we now turn to more realistic 3D modelling of the photosphere. We could dream to be able to see very slight but meaningful differences between photospheric and meteoritic abundances which would tell us about subtle physical processes at work in the sun.

Progress in our knowledge of the outermost solar layers is obviously going on very rapidly nowadays thanks to very powerful and sensitive instruments already at work in space or to be launched soon. Accumulating data using very different techniques and for extremely different solar structures and dynamic events will allow to better understand these changing solar structures as well as the various fractionations which modify elemental as well as isotopic abundances.

Finally, from progress in helioseismology and solar modelling, we might dream to have direct access to the chemical composition of the interior layers of the sun.

## ACKNOWLEDGEMENTS

We are grateful to P. Bochsler, R.A. Mewaldt and D.V. Reames for helpful discussions. We thank J. Vandekerckhove for his help with the figures. This research has made use of NASA's Astrophysics Data System Abstract Service. N.G. thanks the Belgian Fonds National de la Recherche Scientifique as well as the organizers of the OESS Symposium for financial support.

## REFERENCES

- Anders, E. and Grevesse, N.: 1989, "Abundances of the elements: Meteoritic and solar", *Geochim. Cosmochim. Acta* **53**, 197-214.
- Balachandran, S.C. and Bell, R.A.: 1998, "Shallow mixing in the solar photosphere inferred from revised beryllium abundances", *Nature* **392**, 791-793.
- Barklem, P.S. and O'Mara, B.J.: 1998, "The broadening of strong lines of  $\text{Ca}^+$ ,  $\text{Mg}^+$  and  $\text{Ba}^+$  by collisions with neutral hydrogen atoms", *Mon. Not. Royal Astron. Soc.* **300**, 863-871.
- Barklem, P.S. and O'Mara, B.J.: 1999, "Broadening of lines of Be II, Sr II and Ba II by collisions with hydrogen atoms and the solar abundance of strontium", *Mon. Not. Royal Astron. Soc.*, in press.
- Blöcker, T., Holweger, H., Freytag, B., Herwig, F., Ludwig, H.-G. and Steffen, M.: 1998, "Lithium depletion in the sun: A study of mixing based on hydrodynamical simulations", *Space Sci. Rev.* **85**, 105-112.
- Bochsler, P.: 1998, "Structure of the solar wind and compositional variations", *Space Sci. Rev.* **85**, 291-302.
- Burbidge, E.M., Burbidge, G.R., Fowler, W.A. and Hoyle, F.: 1957, "Synthesis of the elements in stars", *Rev. Mod. Phys.* **29**, 547-650.
- Cameron, A.G.W.: 1957, "Nuclear reactions in stars and nucleogenesis", *Publ. Astron. Soc. Pac.* **69**, 201-222. See also "Stellar evolution, nuclear astrophysics and nucleosynthesis", Chalk River Report CRL-41, Atomic Energy of Canada, Ltd.
- Christensen-Dalsgaard, J.: 1998, "The 'standard' sun", *Space Sci. Rev.* **85**, 19-36.
- Conrath, B., Flasar, P.M., Hanel, R., Kunde, V., Maguire, W., Pearl, J., Pirraglia, J., Samuelson, R., Gierasch, P., Weir, A., Bezaud, B., Gautier, D., Cruikshank, D., Horn, L., Springer, R. and Schaffer, W.: 1989, "Infrared observations of the Neptunian system", *Science* **246**, 1454-1459.
- Cunha, K. and Smith, V.V.: 1999, "A determination of the solar photospheric boron abundance", *Ap. J.* **512**, 1006-1013.
- Dziembowski, W.: 1998, "Shortcomings of the standard solar model", *Space Sci. Rev.* **85**, 37-48.
- Feldman, U.: 1998, "FIP effect in the solar upper atmosphere: Spectroscopic results", *Space Sci. Rev.* **85**, 227-240.

- Fröhlich, C., Huber, M.C., Solanki, S.K. and von Steiger, R.: 1998, eds., *Solar Composition and its Evolution – From Core to Corona*, Kluwer Academic Publishers, Norwell, MA, (also *Space Sci. Rev.* **85**, R11-R12, 1998).
- Gabriel, A.H., Culhane, J.L., Patchett, B.E., Breevelt, E.R., Lang, J., Parkinson, J.H., Payne, J. and Norman, K.: 1995, “Spacelab 2 measurement of the solar coronal helium abundance”, *Adv. Space Res.* **15**, 63-67.
- Gabriel, M.: 1997, “Influence of heavy element and rotationally induced diffusions on the solar models”, *Astron. Astrophys.* **327**, 771-778.
- Geiss, J. and Gloeckler, G.: 1998, “Abundance of Deuterium and  $^3\text{He}$  in the protosolar cloud”, *Space Sci. Rev.* **84**, 239-250.
- Goldberg, L., Müller, E.A. and Aller, L.H.: 1960, “The abundances of the elements in the solar atmosphere”, *Ap. J. Suppl. Ser.* **5**, No 45, 1-137.
- Grevesse, N. and Noels, A.: 1993, “Atomic data and the spectrum of the solar photosphere”, *Physica Scripta* **T47**, 133-138.
- Grevesse, N. and Sauval, A.J.: 1994, “Molecules in the sun and molecular data”, in *Molecular Opacities in the Stellar Environment*, ed., Jørgensen, U.G., Lecture Notes in Physics, Springer-Verlag, New York, NY, **428**, pp. 196-209.
- Grevesse, N., Noels, A. and Sauval, A.J.: 1995, “Atomic and molecular data in solar photospheric spectroscopy”, in *Laboratory and Astronomical High Resolution Spectra*, eds., Sauval, A.J., Blomme, R. and Grevesse, N., ASP Conference Series **81**, pp. 74-87.
- Grevesse, N., Noels, A. and Sauval, A.J.: 1996, “Standard abundances”, in *Cosmic Abundances*, eds., Holt, S.S. and Sonneborn, G., ASP Conference Series **99**, pp. 117-126.
- Grevesse, N. and Sauval, A.J.: 1998, “Standard solar composition”, *Space Sci. Rev.* **85**, 161-174.
- Grevesse, N. and Sauval, A.J.: 1999, “The solar abundance of iron and the photospheric model”, *Astron. Astrophys.* **347**, 348-354.
- Gustafsson, B.: 1998, “Is the sun a sun-like star?”, *Space Sci. Rev.* **85**, 419-428.
- Holweger, H. and Müller, E.A.: 1974, “The photospheric barium spectrum: Solar abundance and collision broadening of Ba II lines by hydrogen”, *Solar Physics* **39**, 19-30.
- Kallenbach, R., Ipavich, F.M., Kucharek, H., Bochsler, P., Galvin, A.B., Geiss, J., Gliem, F., Gloeckler, G., Grünwaldt, H., Hefti, S., Hovestadt, D. and Hilchenbach, M.: 1998, “Fractionation of Si, Ne and Mg isotopes in the solar wind as measured by SOHO/CELIAS/MTOF”, *Space Sci. Rev.* **85**, 357-370.
- Kurucz, R.L.: 1995, “The solar spectrum: atlases and line identifications”, in *Laboratory and Astronomical High Resolution Spectra*, eds., Sauval, A.J., Blomme, R. and Grevesse, N., ASP Conference Series **81**, pp. 17-31.
- Manuel, O.K. and Hwaung, G.: 1983, “Solar abundances of the elements” *Meteoritics* **18**, 209-222.
- Pagel, B.E.J.: 1997, *Nucleosynthesis and chemical evolution of galaxies*, Cambridge University Press, Cambridge, UK, 378 pp.
- Reames, D.V.: 1998, “Solar energetic particles: sampling coronal abundances”, *Space Sci. Rev.* **85**, 327-340.
- Reames, D.V.: 1999, “Particle acceleration at the sun and in the heliosphere”, *Space Sci. Rev.*, in press.
- Reetz, J.: 1998, “Oxygen abundances in cool stars and the chemical evolution of the galaxy”, Ph.D. Thesis, Ludwig-Maximilians-Universität München.
- Rogers, F.J. and Iglesias, C.A.: 1998, “Opacity of stellar matter”, *Space Sci. Rev.* **85**, 61-70.
- Russell, H.N.: 1929, “On the composition of the sun’s atmosphere”, *Ap. J.* **70**, 11-82.
- Rutten, R.J.: 1998, “The lower solar atmosphere”, *Space Sci. Rev.* **85**, 269-280.



- Sauval, A.J., Grevesse, N. and Blomme, R.: 1999, "Revised solar abundances of C, N and O", in preparation.
- Solanki, S.: 1998, "Structure of the solar photosphere", *Space Sci. Rev.* **85**, 175-186.
- Takada, M. and Shibahashi, H.: 1998, "The refined seismic solar model and the abundance of the heavy elements", in *Structure and Dynamics of the Interior of the Sun and Sunlike Stars*, eds., Korzennik, S.G. and Wilson, A., ESA Special Publications, SP--418, ESTEC, Noordwijk, The Netherlands, pp. 543-548.
- Turck-Chièze, S.: 1998, "Composition and opacity in the solar interior", *Space Sci. Rev.* **85**, 125-132.
- Turcotte, S. and Christensen-Dalsgaard, J.: 1998, "Solar models with non-standard chemical composition", *Space Sci. Rev.* **85**, 133-140.
- Unsöld, A.: 1948, "Quantitative Analyse der Sonnenatmosphäre", *Z. Astrophys.* **24**, 306-326.
- Vauclair, S.: 1998, "Element settling in the solar interior", *Space Sci. Rev.* **85**, 71-78.
- von Zahn, U. and Hunten, D.M.: 1996, "The helium mass fraction in Jupiter's atmosphere", *Science* **272**, 849-851.
- Widing, K.G.: 1997, "Emerging active regions on the sun and the photospheric abundance of neon", *Ap. J.* **480**, 400-405.
- Wieler, R.: 1998, "The solar noble gas record in lunar samples and meteorites", *Space Sci. Rev.* **85**, 303-314.
- Williams, D.L., Leske, R.A., Mewaldt, R.A. and Stone, B.C.: 1998, "Solar energetic particle isotopic composition", *Space Sci. Rev.* **85**, 379-386.
- Wimmer-Schweingruber, R.F., Bochsler, P. and Wurz, P.: 1999, "Isotopes in the solar wind: new results from ACE, SOHO and WIND", in *Solar Wind Nine*, eds., Habbal, S.R., Esser, R., Hollweg, J.V. and Isenberg, P.A., The American Institute of Physics, College Park, MD, pp. 147-152.
- Young, P.R., Mason, H.E., Keenan, P.P. and Widing, K.G.: 1997, "The Ar/Ca relative abundance in solar coronal plasma", *Ap. J.* **323**, 243-249.
- Zahn, J.-P.: 1998, "Macroscopic transport", *Space Sci. Rev.* **85**, 79-90.
- Zurbuchen, T.H., Fisk, L.A., Gloeckler, G. and Schwadron, N.A.: 1998, "Element and isotopic fractionation in closed magnetic structures", *Space Sci. Rev.* **85**, 397-406.