STANDARD SOLAR COMPOSITION

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Abstract. We review the current status of our knowledge of the chemical composition of the Sun, essentially derived from the analysis of the solar photospheric spectrum. The comparison of solar and meteoritic abundances confirms that there is a very good agreement between the two sets of abundances. They are used to construct a Standard Abundance Distribution.

Key words: Sun: abundances, Meteorites: abundances, Solar spectroscopy

Abbreviations: CI – Carbonaceous Chondrite; SW – Solar Wind; SEP – Solar Energetic Particles; SAD – Standard Abundance Distribution

1. 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 was essentially made of hydrogen, an observation which took some time to be accepted by the whole astronomical community. When one looks at his abundance distribution, many of the remarkable features correlated to nuclear properties, and that gives clues to the origin of the different elements, were already present in Russell's results.

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. Minnaert and his collaborators (Minnaert and Slob, 1931; Minnaert and Mulders, 1931) developed the curve of growth technique, Wildt (1939) showed that the continuous opacity in the solar atmosphere was essentially due to H^- ions and Strömgren (1940) constructed the first photospheric model.

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Goldberg *et al.* (1960; GMA) using the curve of growth technique together wit a photospheric model, and a careful examination of the observed equivalent width and, for the first time, of the oscillator strengths of the lines, succeeded in gettin the abundances for 42 elements. The results of GMA have been considered as th standard reference work for more than 10 years.

In the last 25 years different groups all over the world have been very activ in photospheric abundance works: L.H. Aller and his co-workers, D.E. Blackwel and his co-workers, O. Engvold and O. Hauge, H. Holweger and his co-workers D.L. Lambert, B. Warner, and our Belgian group including E. Biémont and A Noels.

2. 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 ver 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* (Ramaty, 1996) Finally, *calibration of solar models and inversion of helioseismic data* allow us t *derive the solar abundance of helium* (see section 4.1). Note also that lunar soil also record the past chemical history of the Sun (see Wieler, 1998).

In addition to the expected abundance changes in the central layers of the Sun *we now observe more subtle and unforeseen variations in the chemical compositio which varies with time and from place to place*: this is the subject of this Workshop

Below the convection zone, element migration is at work (we prefer to us migration instead of segregation as proposed during this Workshop). Since its birth the reservoir that fills the solar outer layers, could have lost about 10 % of He and al the heavier elements: this has been discussed in many reviews and contributions a this Workshop (see e.g. Turck-Chièze, 1998; Turcotte and Christensen-Dalsgaard 1998; Vauclair, 1998).

In the outer solar layers, all the indicators show that the observed composition is variable in different types of solar matter and that *a fractionation occurs*, a low chromospheric level, leading to the *FIP* or *FIT* effect: elements of low firs ionization potential show abundances larger than in the photosphere. This phenomenon is also discussed at large in many reviews and contributions presente at this Workshop (see e.g. Bochsler, 1998; Feldman, 1998; Geiss, 1998; Hénoux 1998; Peter, 1998; Raymond, 1998; Reames, 1998; Zurbuchen *et al.*, 1998).

The solar photosphere is actually the layer from which we have the largest number of data. A very large number of elements are present in the photospheric spectrum whereas the other sources of solar abundances only concern a limited num ber of elements. 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 (see also section 4).

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. The role of the opacities and the crucial contributions of elements like Fe in the central layers and of O and Ne at the bottom of the convective zone has been stressed by Rogers (1998) and Turck-Chièze (1998).

Standard chemical composition is also the basic data that has to be reproduced by nucleosynthesis theories (see also section 5) and it plays also a key role in the chemical evolution of galaxies (see e.g. Pagel, 1997).

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 (see section 5). It has been suggested that the Sun might be somewhat anomalous (see Grevesse *et al.*, 1996, for the references) but Gustafsson (1998) has convinced us at this Workshop 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.

When studying solar abundances we have access to important tracers of the structure and of the physical processes in the outer solar layers.

The *Sun* is also *unique* because *chemical composition* data *can be acquired for other types of matter in different objects of the solar system like the Earth, Moon, planets, comets, 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 rendez-vous mission. *A very rare class of meteorites, the so-called CI carbonaceous chondrites, is of particular interest.* 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 (see section 5).

4. 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 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). Empirical modelling of the photosphere has now reached a high degree of accuracy [see also section 4.5 and the reviews in this volume by 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.

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 hereabove mentioned papers. Large discrepancies previously found between the Sun and CI meteorites (see section 5) 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.

Two recent papers on atomic transition probabilities and the solar abundance of Lu better illustrate the role of atomic data on solar abundances (Den Hartog *et al.*, 1998; Bord *et al.*, 1998). The solar photospheric abundance of Lu was 4 times larger than the very accurate meteoritic value. New accurate measurements of atomic transition probabilities for Lu II lines of solar interest have allowed to get the photospheric result down to the meteoritic value (see Table I).

In Table I, we give the best solar photospheric abundances taken from our latest review (Grevesse *et al.*, 1996). Values are given in the logarithmic scale usually adopted by astronomers, $A_{e\ell} = \log N_{e\ell}/N_H + 12.0$, where $N_{e\ell}$ is the abundance by number. We now comment on a few elements.

4.1. HELIUM

In 1868, a new element is discovered in the solar spectrum obtained during an eclipse. The name of the Sun was given to the new element, helium. Helium is only discovered on Earth in 1895. Nowadays, its primordial abundance is known

Table I

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	[10.93 ±0.004]	–	–	44 Ru	1.84 ±0.07	1.83 ±0.04	+0.01
03 Li	1.10 ±0.10	3.31 ±0.04	−2.21	45 Rh	1.12 ±0.12	1.10 ±0.04	+0.02
04 Be	1.40 ±0.09	1.42 ±0.04	0.02	46 Pd	1.69 ±0.04	1.70 ±0.04	−0.01
05 B	(2.55 ±0.30)	2.79 ±0.05	(−0.24)	47 Ag	(0.94 ±0.25)	1.24 ±0.04	(−0.30)
06 C	8.52 ±0.06	–	–	48 Cd	1.77 ±0.11	1.76 ±0.04	+0.01
07 N	7.92 ±0.06	–	–	49 In	(1.66 ±0.15)	0.82 ±0.04	(+0.84)
08 O	8.83 ±0.06	–	–	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 ±0.07	−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	[5.5 ±0.3]	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	–

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 – For He, see section 4.1; for Th, see Grevesse *et al.* (1996).

to a high degree of accuracy (see e.g. Pagel, 1997). As many data concerning solar He are discussed at length in many of the review papers presented in this volume, we shall only give a brief summary of the present state-of-the-art.

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_{He}/N_H = 7.9 ± 1.1 % (Gabriel *et al.*, 1995) and 8.5 ± 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 ± 1.7 %) are found for Uranus and Neptune. Note that the recent Galileo spacecraft has recently measured an intermediate value on Jupiter, Y = 0.234, or N_{He}/N_H = 7.85 % (von Zahn and Hunten, 1996).

Progress in our knowledge of *the solar He content* has recently come *from solar standard 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 ± 0.01 (N_{He}/N_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 ± 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 (see e.g. Vauclair, 1998; Turcotte and Christensen-Dalsgaard, 1998).

In Table I, we give the present value in the outer layers, Y = 0.248 ± 0.002, or N_{He}/N_H = 8.5 %, or A_{He} = 10.93 ± 0.004. The value at birth of the Sun is Y = 0.275 ± 0.01, or N_{He}/N_H = 9.8 %, or A_{He} = 10.99 ± 0.02.

4.2. LITHIUM, BERYLLIUM, BORON

Since our latest review (Grevesse *et al.*, 1996), things have changed for Be. Very recently, Balachandran and Bell (1998) have shown that *the solar abundance of Be* should be increased because an extra opacity source has to be introduced in the near UV region of the Be II lines and their result *is now in perfect agreement with the meteoritic value* (see Table I).

The Li Be B problem is now reduced to explaining how the Sun can deplete Li by a factor 160 whereas Be and B are not destroyed. Although conventional models fail to do that, mixing just below the bottom of the convection zone seems to be successful (see Blöcker *et al.*, 1998; Vauclair, 1998; Zahn, 1998).

We also note that the solar abundances of lithium and boron have been very slightly decreased because of slight non-LTE effects (Carlsson *et al.*, 1994; Kiselman and Carlsson, 1996).

4.3. 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 (see also Turck-Chièze, 1995). 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).

We have revisited all the lines of all the CNO solar abundance indicators and redone some computations playing with different photospheric models (see section 4.5). 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 (Sauval and Grevesse, 1998); we estimate the uncertainties to be of the order of 0.06 dex. These values are slightly smaller than the previously recommended values.

4.4. 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 for 10 % to the metallicity. Furthermore, it is an important contributor to the opacity at the bottom of the convection zone (Rogers, 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, $A_{Ne} = 8.08 \pm 0.06$, is in excellent agreement with the SEP value (Reames, 1998).

The solar abundance of argon has recently been redetermined by Young *et al.* (1997) from the coronal spectra (see also Young, 1998). The value proposed by Young, $A_{Ar} = 6.47 \pm 0.10$, is in agreement with the accurate SEP value (Reames, 1998). We shall adopt the SEP value, $A_{Ar} = 6.40 \pm 0.06$, because of its smaller uncertainty.

4.5. IRON

The longstanding *puzzling problem of the 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 recent papers by Anstee *et al.* (1997), Kostik *et al.* (1996), Holweger (1996) and Grevesse *et al.* (1996) give a detailed account of the problem and its possible solutions as well as all the references to the original recent analyses. 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 well summarized in the first two papers cited above. 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. One very important progress has however been made very recently: O'Mara's Australian group has computed accurate cross-sections for the broadening of s-p, p-s, p-d, d-p, d-f and f-d transitions by collisions with neutral atomic hydrogen (Anstee and O'Mara, 1995; Barklem and O'Mara, 1997; Barklem *et al.*, 1998). This is an important parameter which is now known. Our results obtained with the Holweger and Müller (1974) model [the temperature distribution of this model is the same as that of the original model of Holweger (1967); this model last for three decades which is a tremendously good performance] are plotted in Figure 1. As can be seen, *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* (see Grevesse *et al.*, 1995). *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 model in the deeper layers ($\log\tau \approx -1$). With this new model, Figure 2 *shows that 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. A complete discussion of the problem will be given in a forthcoming paper (Grevesse and Sauval, 1998).

5. Standard Abundance Distribution

The first real table of abundances of the chemical elements results from the pioneer work of the Norvegian cosmochemist Goldschmidt (1937). Prior to Goldschmidt,

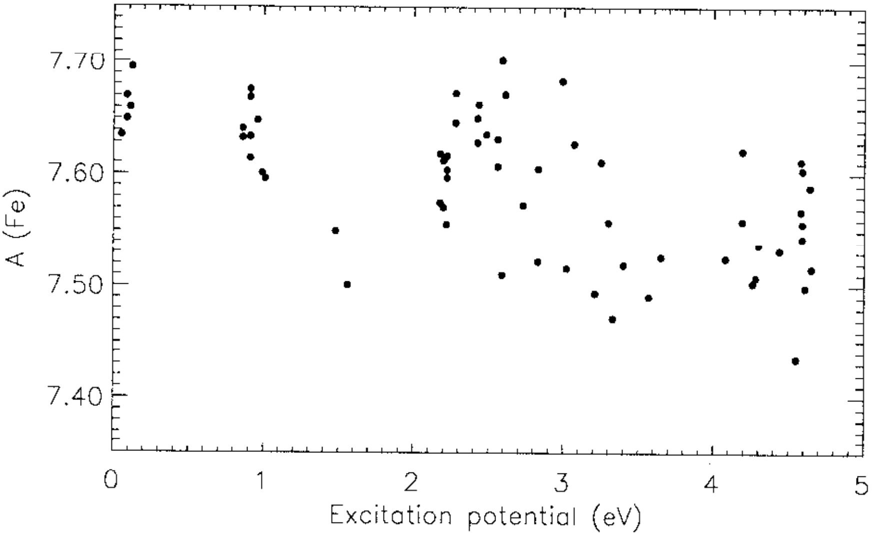

Figure 1. Solar abundance of iron as a function of the line excitation potential; this result is based on 65 Fe I lines adopting the Holweger-Müller (1974) model

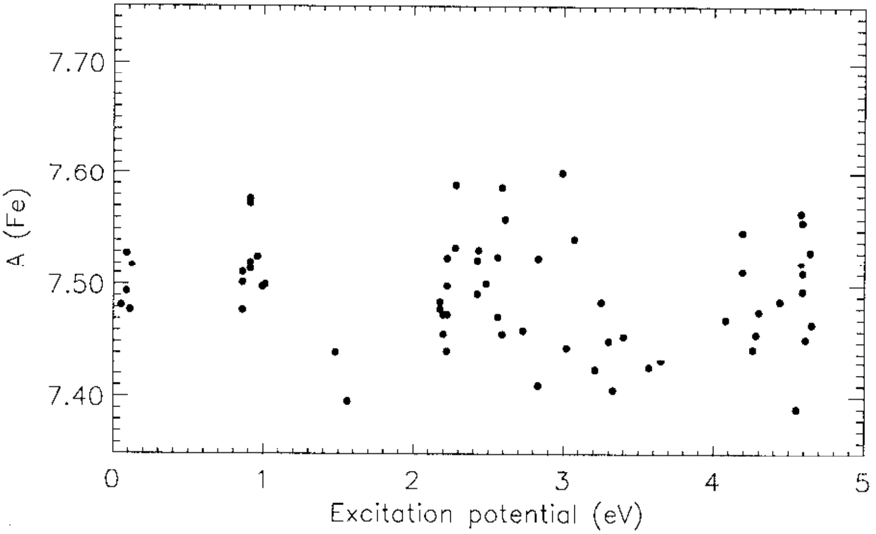

Figure 2. Solar abundance of iron as a function of the line excitation potential; this result is based on the same 65 Fe I lines as in Figure 1, but adopting the new photospheric model (see text)

early attempts to build such tables have not been very successful; except for the important solar results of Russell (1929), the data were essentially based on the (fractionated) Earth. Goldschmidt's careful analysis of about 80 elements based on solar, stellar and meteoritic data, had a great impact on further studies of "cosmic" abundances (see e.g. a very interesting historical note by Suess, 1988). The word "cosmic" abundances has often been used for such data because it was thought that solar system abundances could represent most of the other objects in the universe.

Goldschmidt's data show much better than Russell's data most of the remarkable features seen in the modern abundance curve. Unfortunately the knowledge in nuclear physics as well as in astrophysics was too fragmentary at that time to allow the discovery of the origin of the elements.

After Goldschmidt, and inspired by his results, progress led to the abundance table of Suess and Urey (1956). This table was the key data for 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 term "standard abundance distribution" (or SAD) has been introduced by Pagel (1973); it is equivalent to "cosmic abundances" or "local galactic abundances" found in different papers. The SAD is essentially based (see Anders and Grevesse, 1989; Palme and Beer, 1993; Cowley, 1995; Grevesse *et al.*, 1996, for recent reviews on the subject together with analysis of previous works; see also the excellent reviews by Trimble, 1975, 1991, 1996) on *CI carbonaceous chondrites data*, which *are now measured* in our Earth laboratory with a variety of sophisticated techniques leading *to very high accuracies* (5 to 10 percent; see Table I). The data for the most volatile elements, partly lost from meteorites, are taken from the Sun, as shown in section 4.

We know that the solar system based standard abundance distribution 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. Even in the solar system itself, we observe isotopic anomalies showing material of very different origin but these anomalies are confined in a very small mass fraction. These anomalies probably result from incomplete mixing in the primordial solar nebula. But, nevertheless, 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.

Table I is an update of the standard abundance distribution: it has been build according to Anders and Grevesse (1989) and Grevesse *et al.* (1996) taking into account the most recent values for the 83 stable or long lived elements. Meteoritic values are taken from Anders and Grevesse (1989) and Palme and Beer (1993). These two tables of abundances agree perfectly; slight disagreements come from differences in selection of literature data. We therefore took a straight mean between values in these two works except for S, Se, Kr and Xe where we followed the recommendations of Palme and Beer (1993).

As can be seen from Figure 3, *photospheric and meteoritic results agree perfectly*. The few discrepant points can be accounted for by the uncertainty of the photospheric results, much larger than the small uncertainties of the meteoritic data. Lack of space does not allow us to reproduce the same table as Table I but for the 264 stable nuclei. It is available from the authors. Actually, isotopic abun-

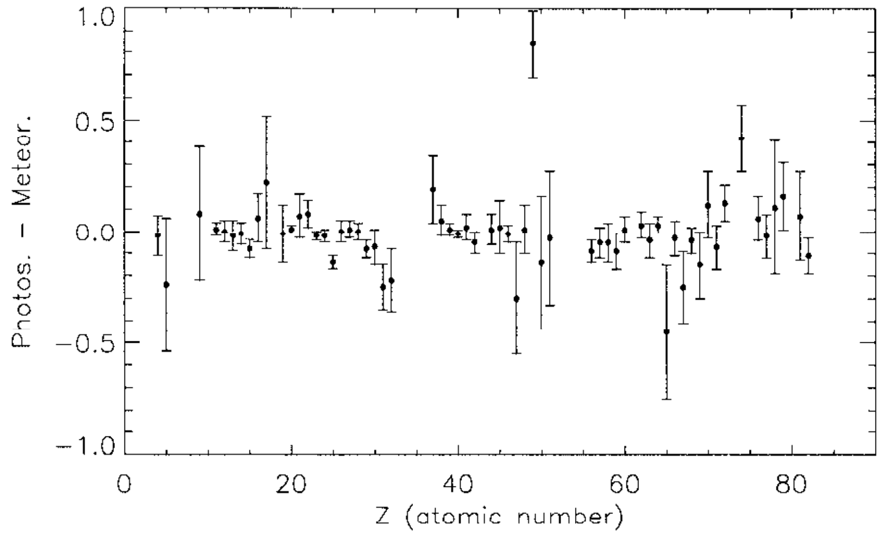

Figure 3. Difference between Solar and Meteoritic abundances of elements as a function of Z. Error bars represent the uncertainty of the solar abundance determinations. The point representing Li falls largely outside of this figure (-2.21)

dances can hardly be obtained from solar data. As meteoritic and terrestrial data nicely agree, isotopic ratios are adopted as measured in terrestrial materials.

6. Conclusions

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 (which predict that present day abundances, given by photospheric values, should be smaller by 10 to 15 percent than the values in the solar nebula at the time of formation of the solar system, as given by meteorites) *are not observed. This is puzzling although not surprising.* Actually, the uncertainties of the photospheric abundance results are unfortunately still much too large to allow such a faint effect to be detected. Furthermore, hydrogen, the reference element, is largely lost in meteorites.

With the data presented in Table I, i.e. the solar values for He, C, N, O, Ne, Ar and the more accurate meteoritic data for the other elements measured in CI meteorites, the classical mass abundances are: $X = 0.735$, $Y = 0.248$ and $Z = 0.017$ with $Z/X = 0.023$. The uncertainty on the metallicity might be of the order of 10 percent. These values are slightly smaller than the ones we proposed earlier (Grevesse *et al.*, 1996) because the new preliminary values of the CNO abundances have slightly decreased.

Efforts should be done to reduce the uncertainties of the photospheric abundances because the abundance uncertainties (e.g. of C, O, Ne) now introduce uncertainties in the opacity that are similar in magnitude to those of the physics (Rogers, 1998).

Progress should come from the use of more accurate atomic and molecular data. It is also expected from a more realistic description of the heterogeneous outer solar layers through 3D modelling of these layers.

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