The solar chemical composition

Martin Asplund [a] Nicolas Grevesse [b] and A. Jacques Sauval [c]

[a] *Research School of Astronomy and Astrophysics, Australian National University, Cotter Road, Weston 2611, Australia*

[b] *Centre Spatial de Liège, Université de Liège, avenue Pré Aily, B-4031 Angleur-Liège, Belgium and Institut d'Astrophysique et de Géophysique, Université de Liège, Allée du 6 Août, 17, B5C, B-4000 Liège, Belgium*

[c] *Observatoire Royal de Belgique, avenue circulaire, 3, B-1180 Bruxelles, Belgium*

Abstract

We present what we believe to be the best estimates of the chemical compositions of the solar photosphere and the most pristine meteorites.

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1 The solar photospheric elemental abundances

As we have recently published a detailed account of the solar chemical composition (Asplund et al. 2005a), we do not provide a lengthy discussion here. Our best estimates of the solar photospheric abundances are listed in Table 1, which are identical to those given in Asplund et al. (2005a). The abundances $A_{\rm X}$ are given on the logarithmic scale relative to hydrogen usually used by astronomers, where $A_{\rm X} \equiv \log \epsilon_{\rm X} \equiv \log(N_{\rm X}/N_{\rm H}) + 12$, where $N_{\rm X}$ is the number density of element X. If the cosmochemical scale relative to silicon is preferred which is normalized to $N_{\rm Si} = 10^6$, abundances are obtained from $10^{A_{\rm X}-1.51}$.

We would like to stress the recent significant downward revisions of the solar C, N and O abundances compared with our previous solar abundance compilations (e.g. Anders & Grevesse 1989; Grevesse & Sauval 1998). These large changes follow from the application of a 3D, time-dependent, hydrodynamical solar model atmosphere (Stein & Nordlund 1998; Asplund et al. 2000a) instead of previous 1D modelling but also from accounting for departures from LTE for certain transitions and a careful consideration of the best possible atomic data like transition probabilities (Allende Prieto et al. 2001, 2002; Asplund et al. 2004, 2005b). Similar 3D analyses have been performed for the other elements up to Ca (Asplund 2000; Asplund et al. 2005a) and Fe (Asplund et al. 2000b). For these elements the differences between the 3D and 1D results are much smaller, since the abundances are based on excited, permitted atomic lines which are less temperature-sensitive (Asplund 2005). The meteoritic abundances listed in Table 1 are identical to the critical compilation of Lodders (2003) for C1 chondrites with an exception of a -0.03 dex normalization adjustment due to the revised photospheric Si abundance (Asplund 2000). Abundances of individual nuclides can be derived by combining our elemental values and the isotopic ratios of Lodders (2003; Table 6 and Sect. 2.5).

With the elemental abundances presented in Table 1, the solar mass fraction of metals is $Z = 0.0122$ ($Z/X = 0.0165$), which is significantly smaller than the corresponding values using the Anders & Grevesse (1989, $Z/X = 0.0274$) or Grevesse & Sauval (1998, $Z/X = 0.0231$). The agreement between the photospheric and meteoritic abundances is in general very good with a mean difference of 0.01 ± 0.06 when ignoring the volatile and/or depleted elements (e.g. Li, C, N, O and the noble gases) as well as a few highly discrepant elements (e.g. Rb, Ag, W). Unfortunately the C1 chondrites can not shed light on the correctness of the new low solar photospheric abundances on C, N and O as these elements are depleted in the meteorites.

As the Sun often functions as a standard reference point for the elemental abundances of all types of cosmic objects, the here presented solar chemical composition should be a useful resource for many areas of astronomy with a large number of implications. The low solar C, N and O abundances agree much better with the corresponding abundances in the local interstellar medium and nearby B stars as well as the values measured in the solar corona/wind (e.g. André et al. 2003; Sofia & Meyer 2001).

A major challenge for these revised solar abundances, however, is that the excellent agreement achieved until now with helioseismology using standard solar evolution modelling is destroyed (e.g. Bahcall et al. 2004; Basu & Antia 2004). The solution to this problem has not yet been identified but much work stimulated by this discrepancy is currently ongoing. New calculations by the Opacity Project suggest that missing opacity can not provide the answer (Badnell et al. 2005). It has been suggested that the problem would disappear if the solar Ne abundance was about 0.5 dex higher (Bahcall et al. 2005); we remind the reader that our indirect estimate of the photospheric Ne abundance is based on the derived Ne/O ratio in the solar corona together with our determined photospheric O abundance under the assumption that the Ne/O is the same in the solar corona and photosphere (Asplund et al. 2004). Very recently Drake & Testa (2005) have claimed that the solar Ne abundance is indeed much higher than given in Table 1 based on an analysis of the Ne/O ratio in the coronae of 21 stars determined using *Chandra* X-ray spectra. If the Sun would have the same Ne/O as indicated by these stellar coronae, the discrepancy with helioseismology with the low C, N and O abundances listed in Table 1 would essentially be removed. More work is clearly needed to confirm this, including whether such high Ne/O values are consistent with expectations from Galactic chemical evolution modelling and measurements of Galactic B stars, planetary nebulae and H II regions.

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Table 1
Element abundances in the present-day solar photosphere and in meteorites (C1 chondrites). Indirect solar estimates are marked with [..]. Note in particular the current debate regarding the Ne abundance, as discussed in the text.

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.25 ± 0.05	44	Ru	1.84 ± 0.07	1.77 ± 0.08
2	He	[10.93 ± 0.01]	1.29	45	Rh	1.12 ± 0.12	1.07 ± 0.02
3	Li	1.05 ± 0.10	3.25 ± 0.06	46	Pd	1.69 ± 0.04	1.67 ± 0.02
4	Be	1.38 ± 0.09	1.38 ± 0.08	47	Ag	0.94 ± 0.24	1.20 ± 0.06
5	B	2.70 ± 0.20	2.75 ± 0.04	48	Cd	1.77 ± 0.11	1.71 ± 0.03
6	C	8.39 ± 0.05	7.40 ± 0.06	49	In	1.60 ± 0.20	0.80 ± 0.03
7	N	7.78 ± 0.06	6.25 ± 0.07	50	Sn	2.00 ± 0.30	2.08 ± 0.04
8	O	8.66 ± 0.05	8.39 ± 0.02	51	Sb	1.00 ± 0.30	1.03 ± 0.07
9	F	4.56 ± 0.30	4.43 ± 0.06	52	Te		2.19 ± 0.04
10	Ne	[7.84 ± 0.06]	-1.06	53	I		1.51 ± 0.12
11	Na	6.17 ± 0.04	6.27 ± 0.03	54	Xe	[2.27 ± 0.02]	-1.97
12	Mg	7.53 ± 0.09	7.53 ± 0.03	55	Cs		1.07 ± 0.03
13	Al	6.37 ± 0.06	6.43 ± 0.02	56	Ba	2.17 ± 0.07	2.16 ± 0.03
14	Si	7.51 ± 0.04	7.51 ± 0.02	57	La	1.13 ± 0.05	1.15 ± 0.06
15	P	5.36 ± 0.04	5.40 ± 0.04	58	Ce	1.58 ± 0.09	1.58 ± 0.02
16	S	7.14 ± 0.05	7.16 ± 0.04	59	Pr	0.71 ± 0.08	0.75 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.45 ± 0.05	1.43 ± 0.03
18	Ar	[6.18 ± 0.08]	-0.45	62	Sm	1.01 ± 0.06	0.92 ± 0.04
19	K	5.08 ± 0.07	5.06 ± 0.05	63	Eu	0.52 ± 0.06	0.49 ± 0.04
20	Ca	6.31 ± 0.04	6.29 ± 0.03	64	Gd	1.12 ± 0.04	1.03 ± 0.02
21	Sc	3.05 ± 0.08	3.04 ± 0.04	65	Tb	0.28 ± 0.30	0.28 ± 0.03
22	Ti	4.90 ± 0.06	4.89 ± 0.03	66	Dy	1.14 ± 0.08	1.10 ± 0.04
23	V	4.00 ± 0.02	3.97 ± 0.03	67	Ho	0.51 ± 0.10	0.46 ± 0.02
24	Cr	5.64 ± 0.10	5.63 ± 0.05	68	Er	0.93 ± 0.06	0.92 ± 0.03
25	Mn	5.39 ± 0.03	5.47 ± 0.03	69	Tm	0.00 ± 0.15	0.08 ± 0.06
26	Fe	7.45 ± 0.05	7.45 ± 0.03	70	Yb	1.08 ± 0.15	0.91 ± 0.03
27	Co	4.92 ± 0.08	4.86 ± 0.03	71	Lu	0.06 ± 0.10	0.06 ± 0.06
28	Ni	6.23 ± 0.04	6.19 ± 0.03	72	Hf	0.88 ± 0.08	0.74 ± 0.04
29	Cu	4.21 ± 0.04	4.23 ± 0.06	73	Ta		-0.17 ± 0.03
30	Zn	4.60 ± 0.03	4.61 ± 0.04	74	W	1.11 ± 0.15	0.62 ± 0.03
31	Ga	2.88 ± 0.10	3.07 ± 0.06	75	Re		0.23 ± 0.04
32	Ge	3.58 ± 0.05	3.59 ± 0.05	76	Os	1.45 ± 0.10	1.34 ± 0.03
33	As		2.29 ± 0.05	77	Ir	1.38 ± 0.05	1.32 ± 0.03
34	Se		3.33 ± 0.04	78	Pt		1.64 ± 0.03
35	Br		2.56 ± 0.09	79	Au	1.01 ± 0.15	0.80 ± 0.06
36	Kr	[3.28 ± 0.08]	-2.27	80	Hg		1.13 ± 0.18
37	Rb	2.60 ± 0.15	2.33 ± 0.06	81	Tl	0.90 ± 0.20	0.78 ± 0.04
38	Sr	2.92 ± 0.05	2.88 ± 0.04	82	Pb	2.00 ± 0.06	2.02 ± 0.04
39	Y	2.21 ± 0.02	2.17 ± 0.04	83	Bi		0.65 ± 0.03
40	Zr	2.59 ± 0.04	2.57 ± 0.02	90	Th		0.06 ± 0.04
41	Nb	1.42 ± 0.06	1.39 ± 0.03	92	U	<-0.47	-0.52 ± 0.04
42	Mo	1.92 ± 0.05	1.96 ± 0.04				