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ORIGINAL ARTICLE

The chemical composition of the Sun

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Abstract We present a redetermination of the solar abundances of all available elements. The new results have very recently been published by Asplund et al. (Annu. Rev. Astron. Astrophys. 47:481, 2009). The basic ingredients of this work, the main results and some of their implications are summarized hereafter.

Keywords Solar abundances

1 Introduction

When one examines the evolution of our knowledge of the solar chemical composition during the last 3 decades, looking at different reviews, one sees that the progress, during the last 25 years, has essentially been due to progress in the accuracy of the atomic data, mostly the transition probabilities.

The situation has, however, changed recently with the rather severe downward revision of the abundances of a few elements, including the very important O, C and N (Asplund et al. 2005). There are three main reasons for these changes: the use of new 3D hydrodynamical solar model atmospheres, the relaxation of the assumption of local thermodynamic equilibrium (LTE) and the improvements in the atomic and molecular data.

In our new work (Asplund et al. 2009), we have redetermined the abundances of all the elements present in the photospheric spectrum. We also discuss the abundances of elements like He, Ne, Ar, Kr, Xe, . . . , which are not present in the photospheric spectrum. The end product is the first comprehensive and homogeneous analysis since many decades.

The basic ingredients of this new analysis are discussed hereafter. We used a new 3D hydrodynamical solar model atmosphere instead of the classical 1D models of the photosphere. We have made a very careful and very demanding selection of the spectral lines. We have replaced the often used LTE hypothesis by non-LTE analyses, when possible. In the cases of C, N and O, we have used all the indicators of the abundances, atoms as well as molecules. And we have made a careful choice of the atomic and molecular data among the available data.

There is no doubt about the realism of 3D models. The new 3D model we use reproduces very well the topology of the heterogeneous solar upper layers, the observed shapes (widths, shifts and asymmetries) of the spectral lines, the observed spectral distribution of the flux and of the intensity and the center to limb variation of the intensity versus wavelength, as well as the observed wings of the hydrogen lines. 1D models generally fail to reproduce all of these observational diagnostics. Furthermore, with the 3D model, mole-

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cules and atoms, as well as lines of different intensities or excitation energies, lead to results in pretty good agreement; this is not the case with 1D models.

The new very demanding selection of spectral lines we have made is not trivial. Actually we wanted to avoid, as much as possible, the use of spectral lines that are blended. Including such lines leads, without any doubt, to an increase in the abundance scatter and skews the result to higher abundances. So we examined carefully each line we have retained, looking carefully for hidden blends which show up in the widths and/or shapes of the lines.

Relaxing the LTE hypothesis is also a great step forward because many spectral lines of important elements, for example the important O I lines, can only be successfully interpreted in non-LTE. NLTE analyses are, however, very demanding in the number and quality of atomic data like transition probabilities, cross-sections for collisions with electrons and with neutral hydrogen atoms. Such data are unfortunately only available for a limited number of atoms and ions.

In deriving the abundances of C, N and O, we have used all the indicators, atoms as well as molecules. We have shown that molecules are as good indicators of the abundances as atoms because they are not more sensitive to temperature than the very high excitation permitted lines of C I, N I and O I, traditionally used in abundance analyses.

The careful choice of atomic and molecular data is obvious but not trivial. Of course one has to use the most precise of these data. But these atomic and molecular data are not only the obvious and well-known transition probabilities but also, for example, the cross sections for collisions with the neutral hydrogen atoms and, in some cases, the partition functions themselves, which have to be carefully selected.

2 Results and discussion

Our new solar abundances are given in Table 1, in the usual astronomical scale relative to hydrogen where $\log N_{\mathrm{H}} = 12.0$. They are compared with the very recent meteoritic values of Lodders et al. (2009). In order to estimate the uncertainties of the photospheric results, we have added, to the statistical errors derived from the scatter of the results and traditionally used to represent the uncertainty of the solar results, possible systematic errors introduced by the model (mean atmospheric stratification and homogeneities) and by the physical processes (NLTE vs. LTE).

One of the main characteristic of our results is that all indicators of the abundances lead to the same results and no dependence is observed with the strength or excitation energy of the lines. This was not the case with 1D models which lead to large variations of the abundance results among the indicators and dependences with the above parameters. For the C and O elements, for example, we do not have any more differences between the abundance results obtained from the low excitation forbidden lines formed in LTE, the very high excitation permitted lines formed in NLTE and the various molecular transitions from the visible to the infrared.

Caffau et al. (2008) and Caffau et al. (2009) found abundances of O and N larger than our values, also using their own 3D model, but applied to the forbidden and permitted atomic lines only. A full discussion of the reasons why the results of Caffau et al. (2008) are larger than ours would be out of the scope of the present review. We suggest three main reasons for explaining these differences. We better estimated the contributions of the atomic and molecular lines that blend the forbidden O I lines by deriving them in a purely empirical way, independent of the photospheric model and of the abundances. We better derived the important NLTE effects on the high excitation O I lines by estimating very precisely the cross sections of the collisions with the hydrogen atoms from center to limb observations of a sample of these lines. And, finally, equivalent widths for the main permitted O I lines due to Caffau et al. (2008) are systematically larger than our values and also larger than all previously published values. The larger N abundance found by Caffau et al. (2009) is certainly due to their selection of N I lines; some of the near infrared lines they retained being blended. This explains why, because of these blends, their result is larger than ours and the dispersion of their result is also 3 times larger than ours (0.12 dex vs. 0.04 dex).

All the details concerning these problems will be given in forthcoming papers mentioned at the end of this presentation. The differences due to the use of different 3D models is of the order of 5 to 10% at most.

The other main characteristic of our new photospheric results is that they are significantly smaller, for the most abundant elements like C, N, O, Ne and Fe, than those recommended in the widely used compilations of Anders and Grevesse (1989) and Grevesse and Sauval (1998) (Fig. 1). They are generally only somewhat smaller for the other elements as seen from Fig. 1. If we now compare with our most recent compilation (Asplund et al. 2005), already based on the same rules as the present one, but for a few elements only, the new results, for C, N and O, are about 10% larger. This is essentially due to the present use of a new, still more realistic version, of the 3D model.

3 A few implications of the new solar abundances

With the solar chemical composition we recommend in Table 1, the mass fractions of hydrogen, X, helium, Y, and metals, Z, the metallicity, become $X = 0.7380$, $Y = 0.2485$ and $Z = 0.0134$ with $Z/X = 0.0181$. The solar metallicity does not any more have the canonical 2% value recom-

Table 1 Element abundances in the solar photosphere where log $N_{\mathrm{H}} = 12$. Meteoritic values are from Lodders et al. (2009). Indirect photospheric estimates are marked with [...]

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93±0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93±0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24±0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40±0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25±0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

mended by Anders and Grevesse (1989), and largely used by astronomers, but it has the much smaller value of 1.34%.

In order to derive the bulk composition of the sun, 4.56 Gyr ago, we have to take into account the effects of diffusion at the bottom of the convection zone. The bulk composition is therefore higher by 0.05 dex for He and 0.04 dex for the heavier elements, and X, Y and Z become 0.7154, 0.2703 and 0.0142 respectively.

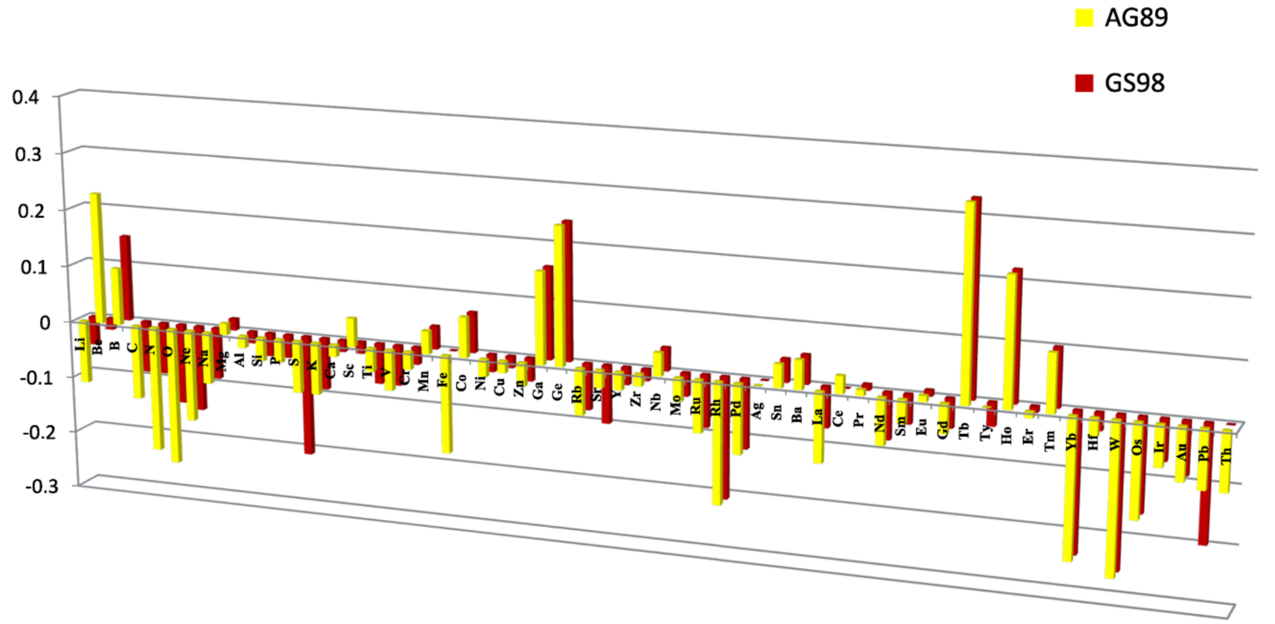

Fig. 1 Comparison of the present photospheric results with those of Anders and Grevesse (1989) (AG89) and Grevesse and Sauval (1998) (GS98). Plotted are the differences (this work—AG89) and (this work—GS98)

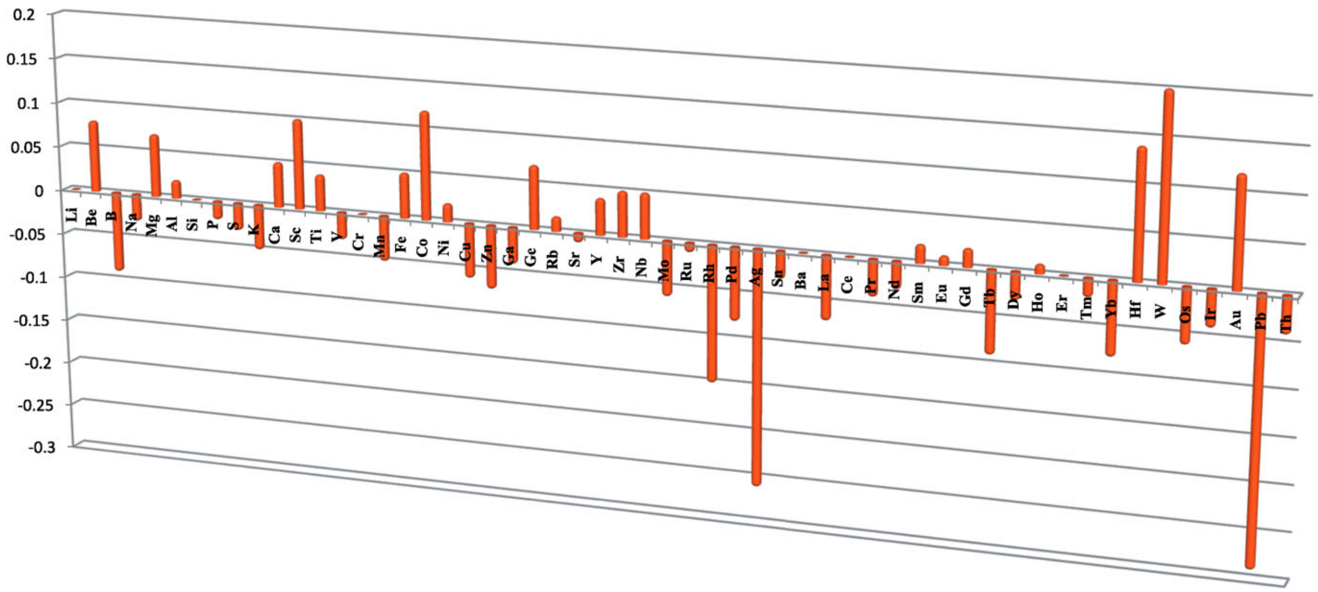

Fig. 2 Differences between our photospheric results and the meteoritic abundances from Lodders et al. (2009)

A comparison between our photospheric results and the recent meteoritic values of Lodders et al. (2009) is shown in Fig. 2. For the elements with an uncertainty less than 25%, the agreement is perfect, the mean photosphere–meteorites difference being 0.00 ± 0.05 dex. A few elements, however, show a rather large disagreement. We do believe that the photospheric results for these few exceptions are to be blamed for unidentified blends or NLTE effects that are impossible to estimate because of the lack of the required atomic data.

In the past, the sun appeared to be metal-rich compared with observations of the solar neighborhood. With our new solar abundances, the sun is "back to normal". There is now a good agreement between the sun and solar-type stars, OB stars, H II regions and the interstellar medium in the solar neighborhood. More details are given in Asplund et al. (2009).

One problem, however, remains unsolved: the disagreement between the solar standard model and the results of helioseismology, even if the situation is somewhat alleviated owing to our new abundances of O, C and Ne, being somewhat larger than the ones of Asplund et al. (2005). Discussions of this problem are to be found in the contributions of Basu (2010) and Serenelli (2010).

4 Conclusions

The main part of this new redetermination of the abundances of the elements in the Sun has recently been published by Asplund et al. (2009). The full description of this analysis, with line lists and all the relevant data for each line, will appear in a forthcoming series of articles soon to be submitted to Astronomy & Astrophysics. They will include detailed discussions of the photospheric abundances of carbon, nitrogen, oxygen, the light elements (Na to Ca), the iron group elements (Sc to Ni) and the neutron-capture elements (Cu to Th).

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