Element Stratification in Stars: 40 Years of Atomic Diffusion
G. Alecian, O. Richard and S. Vauclair (eds)
EAS Publications Series, **17** *(2005) 21–30*

THE NEW SOLAR CHEMICAL COMPOSITION

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Abstract. We present our current knowledge of the solar chemical composition based on the recent significant downward revision of the solar photospheric abundances of the most abundant metals very recently reviewed in detail by Asplund *et al.* (2005a). These new solar abundances result from the use of a 3D hydrodynamical model of the solar atmosphere instead of the classical 1D hydrostatic models, accounting for departures from LTE, and improved atomic and molecular data. With these abundances, the new solar metallicity, Z, and Z/X, decrease to $Z = 0.012$ and $Z/X = 0.0165$ respectively, almost a factor of 2 lower than earlier widely used values. While resolving a number of longstanding problems, the new 3D-based solar photospheric composition also poses serious challenges for the standard solar model.

1 Introduction

New generation of three-dimensional (3D) hydrodynamical models of the solar lower atmosphere have been applied, for the first time, to the analysis of the solar photospheric spectrum, instead of the classical 1D photospheric models used during more than four decades. This new technique leads to significant downward revisions of the abundances. Since the main results concerning the most abundant elements have been described in various papers and in a very recent review (Asplund *et al.* 2005a), we shall only briefly describe the main advantages of the use of the new 3D model, combined with calculations of non-LTE effects when possible, *i.e.* when the required atomic data are available. We shall also briefly discuss the abundances of C, N, O, Na to Ca, and Fe as well as Ne and Ar, and comment on the various consequences of the new solar element abundances.

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DOI: 10.1051/eas:2005095

2 Model Atmospheres: 3D *Versus* 1D

The convection zone of the Sun extends to the visible surface layers. We see the solar granulation which strongly influences the emergent spectrum. The 3D model atmosphere of the solar granulation results from the solution of the hydrodynamical equations of mass, momentum and energy conservation coupled to the equation of radiative transfer (see *e.g.* Asplund *et al.* 2000a and references therein). These models do not invoke any free parameters adjusted to agree with observational constraints.

These simulations successfully reproduce key observational diagnostics where 1D models fail, like the granulation topology and statistics, the helioseismological constraints, the emergent flux distribution and limb darkening, the intensity brightness contrast and, last but not least, the shapes, shifts and asymmetries of the photospheric spectral lines. Actually, for the first time, we are able to fit nearly perfectly a predicted line profile with the observed one. We do not need any more artificial parameters like micro- or macro-turbulence, needed with 1D models, to reproduce the observed widths of line profiles.

3 Photospheric Abundances

Table 1 presents a compilation of the most reliable solar and meteoritic abundances; they are given in the logarithmic scale relative to hydrogen adopted by astronomers, $A_{\rm el} = \log N_{\rm el}/N_{\rm H} + 12.0$, where $N_{\rm el}$ is the abundance of a given element by number. Meteoritic values are taken from the compilation of Lodders (2003) but they are placed on a slightly different absolute abundance scale. Since the reference element is silicon in the meteoritic scale and since our recommended Si value is 0.03 lower than that advocated by Lodders (2003), we correspondingly adjusted all meteoritic abundances by that amount ($-0.03\,$dex). Our new results only concern the elements C, N, O, Na to Ca, and Fe (as well as Ne and Ar, see Sect. 3.2). The abundances of the elements not directly reconsidered here have been taken from recent works (see Asplund *et al.* 2005a; Sneden & Lawler 2005).

for Ce and Pr; the value for Sc has been updated from Neuforge 1993). They are not based on 3D models but they nevertheless differ from previous compilations because they have been obtained from new analyses using improved atomic data (in particular transition probabilities and partition functions).

As we already mentioned, the new analyses have been carried out using the 3D hydrodynamical model. In each case, we used as many indicators as possible of the abundance, forbidden and permitted atomic lines as well as molecular lines whenever possible in order to minimize systematic errors. A special effort has also been made to utilize only the very best available solar lines and line data. It is better to retain only a small number of best quality abundance indicators rather than using larger samples of less reliable lines. In several incidences, detailed non-LTE calculations have been carried out when the required atomic data are available.

Table 1. Element abundances in the present-day solar photosphere and in meteorites (C1 chondrites). Indirect solar estimates are marked with [..].

	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 ± 0.25	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	1.70 ± 0.10	1.58 ± 0.02
16	S	7.14 ± 0.05	7.16 ± 0.04	59	Pr	0.58 ± 0.10	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	3.17 ± 0.10	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				

As a result, we are confident that the values we give in Table 1 for the elements mentioned hereabove, result from the most reliable element abundance analyses carried out so far: the predicted line profiles computed with the 3D model agree perfectly with the observed profiles without the use of any artificial parameters and the abundance results from various indicators are in excellent agreement (Sect. 3.1).

3.1 Carbon, Nitrogen and Oxygen

Detailed accounts of our new analyses of these very important elements, which contribute to 2/3 of the metallicity and are depleted in meteorites, have recently been published (C: Asplund *et al.* 2005b; O: Asplund *et al.* 2004); the N results are currently being prepared for publication (Asplund *et al.* 2005c). They are also discussed in detail in our recent review (Asplund *et al.* 2005a).

Table 2 summarizes the results obtained for those three elements with the 3D model and with the widely used for solar studies 1D model of Holweger & Müller (1974). We used quite a large number of abundance indicators, covering a wide wavelength range from the visible to the infrared, including atomic and molecular lines formed in quite different layers of the photosphere and with quite different sensitivities to temperature. For C and O, we see from Table 2 that, in sharp contrast with the analysis using the 1D model where the dispersion of the results is very large (0.31 dex for C, 0.23 dex for O), excellent agreement is found between all abundance indicators when employing the 3D model. This excellent agreement between transitions of very different formation depths and temperature and pressure sensitivities is a very strong argument in favour of our new abundances as well as for the realism of the 3D model. In particular, we note with satisfaction that consistent results are now finally provided by the infrared vibration-rotation CO lines which have previously caused a great deal of troubles when analysed with a 1D model (Grevesse *et al.* 1995; Ayres 2002; Scott *et al.* 2005).

Nitrogen has only a few very faint NI lines, many of them blended with CN lines, and faint vibration-rotation lines of NH in the infrared, to offer as indicators of its abundance (Asplund *et al.* 2005c).

The new solar abundances of C, N, and O are much lower than those recommended in the widely used compilation of Anders & Grevesse (1989): −0.17 dex (C), −0.27 dex (N) and −0.27 dex (O) respectively. They are also much lower than the values recommended by Grevesse & Noels (1993) and Grevesse & Sauval (1998) in more recent compilations: −0.13 dex (C), −0.14 dex (N) and −0.17 dex (O) respectively.

3.2 Neon and Argon

No suitable spectral lines of Ne and Ar are present in the photospheric spectrum and therefore the abundances of these elements can not be determined directly. The values in Table 1 are estimated from the measured abundance ratios,

Table 2. C, N, O abundances as implied from a variety of different atomic and molecular indicators using a 3D hydrodynamical model of the solar atmosphere (Asplund *et al.* 2005a). Results from the semi-empirical model of Holweger-Müller (1974) are given for comparison.

lines	$A_{\mathrm{C,N,O}}$	
	3D	HM
[CI]	8.39	8.45
CI	8.36 ± 0.03	8.39 ± 0.03
CH $\Delta v = 1$	8.38 ± 0.04	8.53 ± 0.04
C_2 Swan	8.44 ± 0.03	8.53 ± 0.03
CH A-X	8.45 ± 0.04	8.59 ± 0.04
CO $\Delta v = 1$	8.41 ± 0.02	8.62 ± 0.02
CO $\Delta v = 2$	8.38 ± 0.02	8.70 ± 0.03
NI	7.85 ± 0.08	7.97 ± 0.08
NH $\Delta v = 1$	7.73 ± 0.05	7.95 ± 0.05
[OI]	8.68 ± 0.01	8.76 ± 0.02
OI	8.64 ± 0.02	8.64 ± 0.08
OH $\Delta v = 0$	8.61 ± 0.03	8.82 ± 0.01
OH $\Delta v = 1$	8.61 ± 0.03	8.87 ± 0.03

Ne/O = 0.15, Ar/O = 0.0033, in the solar corona and solar energetic particles (Reames 1999) with the photospheric abundance for oxygen. The Ne and Ar abundances are therefore directly affected by the revised solar oxygen abundance and are therefore also much lower than the values recommended in the compilations cited hereabove.

During this meeting, we heard from Jean-Paul Zahn that Drake & Testa (2005) suggested that a higher Ne/O = 0.4 might be appropriate for the Sun from the analysis of the coronae of 21 stars using Chandra X-ray spectra. The implication of a high Ne solar abundance will be further mentioned in Section 4.6.

The present authors, in collaboration with Manuel Güdel (Asplund *et al.* 2005d), are not in favour of such a high Ne/O ratio for the Sun. Actually, it is known that highly active stars like those studied by Drake & Testa (2005), show large Ne/O ratios. The solar coronal matter, observed by spectroscopic techniques at various wavelengths, by particle collection techniques (solar wind, solar energetic particles) generally shows low values of the Ne/O ratio in agreement with the value retained here. This value is also observed in the local galactic medium: other nearby objects which have similar overall compositions to the Sun like B stars, HII regions and planetary nebulae also have low Ne/O ratios as well as the values predicted by nucleosynthesis theories in type II supernovae. We know that the problem of the solar abundance of Ne is not yet entirely settled and that much work remains to be done as far as low activity stars are concerned but for all the reasons hereabove (Asplund *et al.* 2005d) we argue that the low Ne/O = 0.15 adopted here is to be preferred for the Sun to the high value Ne/O = 0.4.

3.3 Intermediate Elements: Sodium to Calcium, Iron

3D analyses of Na, Mg, Al, Si, P, S, K, Ca and Fe have also been performed. Detailed results concerning Si and Fe have already been published (Asplund 2000; Asplund *et al.* 2000b). When possible, departures from LTE have also been taken into account. The line list is essentially based on Lambert & Luck (1978). We however rejected the stronger lines and the lines which appeared too much blended for meaningful comparison of theoretical and observed profiles. As for CNO, the 3D-based abundances are lower than the 1D-based results but the impact of the 3D model atmosphere is smaller than for CNO, mainly since the abundances are based on atomic transitions rather than very temperature sensitive molecular lines. The results reported in Table 1 for these elements are actually 0.05 to 0.10 dex lower than those recommended by Anders & Grevesse (1989) and Grevesse & Sauval (1998). Once again, as for CNO, the difference 3D-1D is much larger for the most sensitive indicators to the temperature, like NaI or CaI, which are minor species compared to NaII or CaII, than for PI, SI and CaII, which are major species.

4 Implications of the New Results and Comments

4.1 Solar Metallicity

Because we decreased by rather large amounts the abundances of elements which contribute much to the metallicity (C+N+O $\approx$ 2/3, Ne$\approx$8%, Fe $\approx$ 9%, Si+Mg$\approx$10%), Z will decrease accordingly. With the solar composition given in Table 1, the new present day abundances by mass of hydrogen, X, helium, Y, and, Z, the sum of all the other elements, become

$$X = 0.7393, Y = 0.2485 \text{ and } Z = 0.0122 \text{ with } Z/X = 0.0165.$$

The abundance of helium adopted is obtained from inversion of helioseismic data by Basu & Antia (2004): $Y = 0.2485$. Although this value is independent of the solar model, it depends on the equation of state used. This value corresponds to $A_{\rm He} = 10.9276$ (rounded to 10.93 in Table 1) *i.e.* $N_{\rm He}/N_{\rm H} = 8.5\%$.

The metallicity and Z/X are much lower than the previously recommended and widely used values: $Z = 0.0189$ and $Z/X = 0.0275$ from Anders & Grevesse (1989), $Z = 0.017$ and $Z/X = 0.024$ from Grevesse & Noels (1993) and Grevesse & Sauval (1998). The new metallicity, $Z = 0.012$, should now be used instead of the customary $Z = 0.02$ value.

4.2 Protosolar Chemical Composition

Thanks to the pioneering works of Georges Michaud, we know that the present day chemical composition we derive from the analysis of the solar photospheric spectrum has slightly changed during the solar lifetime. We can now estimate the effects of diffusion at the bottom of the convective zone on the chemical composition of this reservoir, combining the effects of gravitational settling and radiative accelerations (Turcotte *et al.* 1998).

Since the protosolar composition is required in many fields of astrophysics, the values of Table 1 can easily be corrected to give rise to the chemical composition at the birth of the Sun. From the results of Turcotte & Wimmer-Schweingruber (2002), who computed the relative changes in surface abundance of He and the most abundant elements up to Ni during the solar lifetime, using a detailed solar model including some additional mixing just below the convective zone, in the tachocline, additional mixing needed to burn Li, it is easily seen that

- the protosolar metal abundances relative to hydrogen can be obtained from the present day values of Table 1 increased by 0.05 dex, *i.e.* 12%, with an uncertainty of ± 0.01 dex;
- the effect of diffusion on He is very slightly larger: + 0.057 dex (±0.01).

Those numbers and the uncertainties come from the mean values predicted when diffusion alone and diffusion + additional mixing are considered. The uncertainties do not take into account potential uncertainties in the diffusion rates, which might perhaps be larger.

The X, Y, Z corresponding to the protosolar composition become

$$X_0 = 0.7133,\ Y_0 = 0.2735,\ Z_0 = 0.0132 \text{ and } Z_0/X_0 = 0.0185.$$

This is to be compared with the present day values given in Section 4.1.

4.3 The Sun: A Sun-Like Star

The new abundances remove the special nature of the Sun otherwise would have in comparison with its neighbourhood. Previous studies actually suggested that the Sun had too high a metallicity compared to the solar neighbourhood. The new lower solar abundances of C and O show that the Sun is now in agreement with those measured in the interstellar medium for realistic gas-to-dust ratios and with the values measured in nearby B stars (see Asplund *et al.* 2005a, 2005b). Interestingly, while the previous discrepancy has been most often blamed on problems with the analyses of hot stars and nebulae, the most serious shortcoming has rather been on the solar side.

4.4 Comparison with Meteorites

From Table 1 and Figure 1 of Asplund *et al.* (2005a), it is seen that the agreement between photospheric and meteoritic abundances is very good. This is well known since many years. The mean difference is 0.01 ± 0.06 dex, when ignoring the obvious known cases where the elements are depleted in the Sun (Li) or in meteorites or where the photospheric abundances are doubtful because of the lack of unperturbed lines, the lack of accurate transition probabilities and/or the problem of departure from LTE impossible to handle.

4.5 Miscellaneous

We have to be very cautious when comparing our new 3D-based solar results with stellar abundance results for stars having outer convection zones. These stellar abundances could be severely biased because of the use of theoretical 1D models instead of 3D models. We have to keep in mind that stellar element abundances are not observed but interpreted based on models of the stellar atmospheres and line formation.

Abundance measurements in various solar corona types of matter show the well known FIP (First Ionization Potential) effect: elements with low FIP ($\leq$10 eV) are overabundant relative to the photosphere by a factor 4–5 whereas higher FIP elements (like CNO) have photospheric-type abundances. With the new solar abundances, the FIP effect is reduced to a factor 2.2 in the slow solar wind and solar energetic particles, while the FIP effect in the rapid polar solar wind reduces to a factor 1.5. These are the numbers that constrain the theories advocated to explain this effect.

4.6 Problems with the Standard Solar Model

While the new abundances have positive implications as described hereabove, it introduces at least one new problem. Solar interior models computed with our new abundances completely disagree with the extremely precise measurements of the sound speed profile, the convection zone helium abundance ($Y = 0.2485$) and the depth of the convective envelope ($r_{\mathrm{e}} = 0.713\ R_{\odot}$) inferred from helioseismology while the same models computed with older solar abundances agree very well with these measurements. A flurry of papers, too numerous to be cited here, have appeared where solar scientists and others like J.N. Bahcall, S. Basu, H.M. Antia, J.A. Guzik, J. Montalban, A. Miglio, M. Seaton, S. Turck-Chièze... and their collaborators, are rushing around reexamining systematically all the ingredients that enter the models and trying to find a solution. Indeed, no real solution has yet been found: only *ad hoc* parries like artificially increasing the opacity in the region below the convection zone, increasing the diffusion velocities, eventually increasing the neon abundance (Sect. 3.2).

5 Summary and Conclusions

The new solar photospheric abundances of Table 1 lead to a metallicity $Z = 0.012$ and $Z/X = 0.0165$ ($Z_0 = 0.013$ and $Z_0/X_0 = 0.0185$ for the protosolar values).

These are much lower than previously recommended values. We have to forget about the classical metallicity $Z = 0.02$ used as a standard since so many decades.

It should be noted that not the whole difference with previous models is attributed to the use of a 3D model atmosphere over classical 1D models since the adoption of more recent transition probabilities, more realistic non-LTE procedures when possible, better observations (infrared transitions not observed from ground-based facilities) and a proper accounting of blends play also an important role in this respect.

The use of a 3D hydrodynamical model represents however a real step forward in the modelling of the very inhomogeneous ever changing solar atmosphere. This 3D model successfully passed a series of critical exams (Sects. 2 and 3). For the first time, we reproduce key observational diagnostics, granulation topology and statistics, helioseismic properties, emergent flux distribution and limb darkening, and, last but not least, we also reproduce the observed shapes, without artificial parameters like micro- and macro-turbulence required for 1D models, the shifts and asymmetries of spectral lines.

Thanks to these new tools, all the indicators of the abundance of an element (Table 2) do perfectly agree on the contrary to the large dispersions observed when using 1D models. Furthermore, the new results do not show any trend with atomic or molecular properties on the contrary to 1D model based abundances.

All of these reasons and the positive implications described in Sections 4.1 to 4.5 give us much confidence in the reliability of our new lower solar abundances.

The problems encountered (Sect. 4.6) with the Standard Solar Model are not real “trouble in paradise”. Actually, even if no solution has been found, the various researches undertaken are bringing new insights on the solar interior structure. We might eventually with Turck-Chièze *et al.* (2004) question the Standard Solar Model as no longer being representative of the present Sun.

To conclude, let us cite John Bahcall in one of his latest popular paper: “Scientists love a conflict between theory and observations because they are guaranteed to learn something interesting in resolving the conflict. We are puzzled but we are having fun”.

We dedicate this review to John Bahcall, who recently passed away, for his continuous interest in our works and his encouragements to go on refining solar abundances.

We would like to thank various collaborators, including Carlos Allende-Prieto, Paul Barklem, Ronny Blomme, Mats Carlsson, Dan Kiselman, David Lambert, Åke Nordlund, Pat Scott, Bob Stein, and Regner Trampedach.

We also thank Manuel Güdel for his fruitful collaboration on the solar Ne abundance problem and Georges Michaud, Andrea Miglio, Josefina Montalban, Arlette Noels-Grötsch, Andrew Prentice, Gregor Rauw, Don Reames, Ian Stevens, Sylvie Théado and Sylvaine Turck-Chièze for helpful discussions.

NG thanks Sylvie Vauclair for her invitation, the Observatoire Royal de Belgique, Léo Houziaux, Secrétaire Perpétuel of the Belgian Royal Academy of Sciences and the Foundation Ochs-Lefèbvre for financial support; he also appreciated the warm hospitality of the staff of the Uppsala Astronomical Observatory.

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