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The 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. These new solar abundances result from the use of a 3D hydrodynamic 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, decreases to $Z = 0.012$, almost a factor of two lower than earlier widely used values. We compare our values with data from other sources and analyse a number of impacts of these new photospheric abundances. While resolving a number of longstanding problems, the new 3D-based solar photospheric composition also poses serious challenges for the standard solar model as judged by helioseismology.

Keywords Sun: abundances, photosphere, corona

1 Introduction

New generation of three-dimensional (3D) hydrodynamic models of the solar lower atmosphere have been applied, for the first time, to the analysis of the solar photospheric

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spectrum, rather than the classical 1D photospheric models used during more than four decades. This new approach, combined with considerations of non-LTE effects in the line formation, leads to significant downward revisions of the abundances. This is a totally new situation. Indeed, the reasons for abundance changes among older abundance tables, for example Grevesse and Sauval (1998) versus Grevesse and Noels (1993) versus Anders and Grevesse (1989), were essentially due to the use of more accurate atomic data, especially transition probabilities rather than improved models of the solar atmosphere.

The main results of the new analyses, concerning the most abundant elements, have been described in detail in a series of papers entitled "Line formation in solar granulation" (Asplund et al. 2000a, 2000b; Asplund 2000; Asplund et al. 2004; Asplund 2004; Asplund et al. 2005b; Scott et al. 2006) and in two recent reviews (Asplund et al. 2005a; Grevesse et al. 2005). We shall therefore describe the main advantages of the use of the new 3D model only briefly, and then discuss the new photospheric abundance results of C, N, O, Na to Ca and Fe as well as Ne and Ar, compare these results with data from other sources and comment on the various consequences of these new solar element abundances.

2 Model Atmospheres: 3D Versus 1D

The visible surface layer of the Sun is just on top of the convection zone. Therefore the solar granulation strongly influences the photospheric spectrum. We not only see the solar granulation but spectral lines do show, through their shapes (widths, shifts and asymmetries), that matter motions are present in the photosphere as well.

The 3D model atmosphere of the solar granulation results from the solution of the hydrodynamic 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 as was earlier the case with the micro- and macro-turbulence parameters required with the 1D models.

The simulations using the 3D model successfully reproduce key observational facts, such as the granulation topology and statistics, the helioseismological constraints, the 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.

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, $A_{\mathrm{el}} = \log N_{\mathrm{el}}/N_{\mathrm{H}} + 12.0$, where N_{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 dex lower than that advocated by Lodders (2003), we correspondingly adjusted all meteoritic abundances by that amount (−0.03 dex).

The present-day photospheric abundance of helium adopted is obtained from inversion of helioseismic data by Basu and Antia (2004): Y, the abundance by mass of He, is $Y = 0.2485$. Although this value is independent of the solar model, it depends on the equation of state. This He abundance corresponds to $A_{\mathrm{He}} = 10.93$ i.e. $N_{\mathrm{He}}/N_{\mathrm{H}} = 8.5\%$.

Table 1 Element abundances in the present-day solar photosphere and in meteorites (C1 chondrites). Indirect solar estimates are marked with [..]. For He, see 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	1.66 ± 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	[2.24 ± 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	1.00 ± 0.03	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	1.11 ± 0.03	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	1.25 ± 0.11	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	[3.25 ± 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	2.58 ± 0.02	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				

Our new results only concern the elements C, N, O, Na to Ca, and Fe, as well as Ne and Ar. The abundances of all the elements not directly reconsidered here have been taken from our most recent compilation (Grevesse et al. 2005) updated with very recent works for Zr (Ljung et al. 2006), Pd (Xu et al. 2006), Sm (Lawler et al. 2006), Gd (Den Hartog et al. 2006) and Os (Quinet et al. 2006). All of these results do not use 3D models but rather the classical 1D models. However, they use improved atomic data, in particular transition probabilities.

As already mentioned the new solar analyses for C, N, O, Na to Ca and Fe have been carried out using the 3D hydrodynamic model discussed in Sect. 2. In each case, and whenever possible, we used as many indicators as possible of the abundance—forbidden and permitted atomic lines as well as molecular lines—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 after the required atomic data had become available.

3.1 Carbon, Nitrogen and Oxygen

Detailed accounts of our new analyses of these very important elements have recently been published (Asplund et al. 2005b; Asplund et al. 2004; Scott et al. 2006); the N results are currently being prepared for publication. They are also discussed in our recent reviews (Asplund et al. 2005a; Grevesse et al. 2005).

Table 2 summarizes the results obtained for the three elements with the 3D model and with the 1D model of Holweger and Müller (1974), which has been widely used for solar studies. We used a large number of abundance indicators: atomic and molecular lines covering the wide wavelength range from the visible to the infrared, and formed in different layers of the photosphere and having 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 spread of the results is very large (0.31 dex for C, 0.23 dex for O), excellent agreement is found

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

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. 2006).

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 direct indicators of its abundance.

The new solar abundances of C, N, and O are much lower than those recommended in the widely used compilation of Anders and Grevesse (Anders and 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 and Noels (1993) and Grevesse and 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

It is well known that no spectral lines of Ne and Ar are present in the photospheric spectrum. The "photospheric" abundances of these elements, Ne being the most important one because of its high abundance, have therefore to be estimated from measurements made in coronal matter of various types. Ratios Ne/O and Ar/O are generally measured using X-ray and vacuum ultraviolet spectroscopy of various types of active centers and in the quiet corona, in the solar wind (SW) and in solar energetic particles (SEP). As these ratios refer to oxygen, the Ne and Ar abundances are directly affected by the new solar abundance of oxygen.

Measurements of the coronal Ne/O abundance ratio show however a very broad scatter by a factor of about 5, from very low, $\mathrm{Ne/O} \sim 0.1$, to very high values, $\mathrm{Ne/O} \sim 0.5$. In spite of these variations, a large number of analyses, using the various techniques mentioned above, applied to quite different types of coronal matter, lead to values around $\mathrm{Ne/O} = 0.15$ and $\mathrm{Ar/O} = 0.033$. We shall adopt the SEP values published by Reames (1999). Therefore the solar abundances of Ne and Ar become $A_{\mathrm{Ne}} = 7.84$ and $A_{\mathrm{Ar}} = 6.18$, much lower than older values around 8.1 and 6.4, respectively.

Since increasing Ne might possibly help reconciling the standard solar model and the observations of helioseismology (see Sect. 4.7), many new analyses have been devoted to the abundance of Ne: some confirm the low Ne/O ratio adopted here but others lead to higher values of this ratio.

Recently, Schmelz et al. (2005), analysing X-ray spectra of different coronal features and of the full-sun, and Young (2005a), from XUV spectra of the quiet sun, confirmed the low Ne/O value.

Drake and Testa (2005) however suggested, from X-ray analyses of a sample of highly active stars, that the Sun should have a much higher ratio, $\mathrm{Ne/O} = 0.41$. Recently, Liefke and Schmitt (2006) showed that these highly active stars are not at all representative of solar-type stars because, as Güdel (2004) already found, those stars exhibit the inverse FIP effect: elements with high first ionization potential (FIP) are enhanced rather than low FIP elements (see Sect. 4.5). Neon, having a very high FIP (21.6 eV), much larger than O (13.6 eV), is therefore enhanced and large Ne/O ratios are observed. We suggest, with Güdel (2004), that the solar corona, in some highly magnetically active centers, might perhaps also exhibit such an inverse FIP effect. This could maybe explain some of the high Ne/O ratios observed in various coronal structures (see also Sect. 4.5).

More puzzling are the solar results of Feldman and Widing (2007 and references therein) and Bochsler (2007 and references therein). Feldman and Widing derived the Ne/O and Mg/Ne ratios in different types of solar matter. Ne/O remains rather constant, around 0.15, whereas Mg/Ne varies tremendously because of the FIP effect (Sect. 4.5). Adopting the lowest value for the ratio Mg/Ne, corresponding to no FIP effect, they derive a high value of the abundance of Ne and, from Ne/O, a high value of O, in agreement with the older values of both Ne, $A_{\mathrm{Ne}} = 8.1$, and O, $A_{\mathrm{O}} = 8.9$. The only way to reconcile those results with ours is to suspect that FIP effects smaller than 1 can occur for the low FIP element Mg (see Sect. 4.5).

On the other hand, Bochsler (2007) derived the abundances of Ne and O from solar wind data. We note that the pioneer aluminum foil experiment by Johannes Geiss and collaborators, during the Apollo missions on the Moon, are still considered to give the best solar wind data ever obtained. From the very variable He/Ne and ^{4}He/^{3}He ratios, Bochsler finally derived a ratio He/Ne independent of any fractionation. Combined with the value for He in the solar convection zone reported in Table 1, he found a high value of the abundance of Ne, $A_{\mathrm{Ne}} = 8.10$. With the rather stable Ne/O ratio observed in the solar wind, he also found a high value for O, $A_{\mathrm{O}} = 8.92$.

Also very puzzling is the recent analysis of Cunha et al. (2006) of a sample of B stars. While they confirm the low solar abundances of CNO described here, they, on the contrary, find a high abundance of Ne, $A_{\mathrm{Ne}} = 8.11$, in agreement with the old solar value.

Although we still believe the low Ne/O ratio and the low Ne abundance reported in Table 1, to be representative of the present Sun, we have to keep these last results in mind and wait for additional analyses of the Sun, stars and interstellar medium.

3.3 Intermediate Elements: Na to Ca, Fe

3D analyses of Na, Mg, Al, Si, P, S, K, Ca and Fe have also been performed. Detailed results have been published (Si: Asplund 2000; Fe: Asplund et al. 2000b; Na, Mg, Al, P, S, K, Ca: Asplund et al. 2005a). When possible, departures from LTE have also been taken into account. 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 on 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 and Grevesse (1989) and Grevesse and Sauval (1998). Once again, as for CNO, the difference 3D−1D is much larger for the most sensitive indicators of temperature, like NaI or CaI, which are minor species compared to NaII or CaII, or to PI and SI, which are also 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, Z will decrease accordingly. With the solar composition given in Table 1, the new present day solar metallicity is $Z = 0.0122$.

This metallicity is much lower than the previously recommended and widely used values, $Z = 0.0189$ (Anders and Grevesse 1989) and $Z = 0.017$ (Grevesse and Noels 1993; Grevesse and Sauval 1998).

4.2 Protosolar Chemical Composition

The well known diffusion of the elements at the bottom of the solar convection zone slowly depletes this reservoir as well as the photosphere on top of it (see e.g. Turcotte et al. 1998; Turcotte and Wimmer-Schweingruber 2002). Corrections to the present day abundances as in Table 1 in order to obtain the protosolar abundances can be estimated: the values in Table 1 have to be increased by 0.05 dex for all the so-called metals and the abundance of He has to be increased by 0.057 dex (Grevesse et al. 2005).

The protosolar values for Y, the abundance by mass of He, and the metallicity, Z, become $Y_0 = 0.2735$ and $Z_0 = 0.0132$.

4.3 The Sun is a Sunlike Star

Previous studies suggested that the Sun had too high abundances of O and C compared to the solar neighbourhood. The new lower solar abundances of C and O show that the Sun is now in agreement with the surrounding interstellar medium and nearby B-stars (Turck-Chièze et al. 2004; Asplund et al. 2005a, 2005b).

4.4 Comparison with Meteorites

Since many years, it is well known that the agreement between photospheric and meteoritic abundances is very good. 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 Photospheric Versus Coronal Abundances: the FIP Effect

Abundance measurements in various types of coronal matter, like different coronal structures, solar wind (SW), solar energetic particles (SEP), show the well known FIP (First Ionization Potential) effect. Elements with low FIP (<10 eV) are overabundant in the corona relative to the photosphere whereas higher FIP elements (>10 eV) have photospheric-type abundances. This highly variable phenomenon is discussed at large in different papers of this Volume. In spite of the rather large variations of this FIP effect, canonical mean enhancement factor values (or FIP factors, i.e. ratios of photospheric versus "coronal" abundances) can be derived: they amount to $\sim$2.7 (slow SW) and $\sim$1.8 (rapid SW, Bochsler 2006), $\sim$3.25 (SEP, Reames 1999) and 1.25 to 1.66 for the quiet corona (Young 2005b). With our new photospheric abundances, these values are reduced to $\sim$2.0 (slow SW), $\sim$1.4 (rapid SW), $\sim$2.4 (SEP) and 0.8 to 1.1 (quiet sun). The last numbers show that there exists coronal matter which shows no FIP effect i.e. which has photospheric-type composition. This is true as well for the polar plumes (Del Zanna et al. 2003). Possibly also FIP factors smaller than 1 could exist: this has also been suggested during this symposium.

A further remark needs to be made. The low FIP elements are well represented, by 14 elements from Na to Zn with FIP ranging from 5.1 to 9.4 eV, but the high FIP side is really underpopulated. Actually, only 3 elements have accurate photospheric as well as coronal abundances: C (FIP: 11.3 eV), O (13.6 eV) and N (14.5 eV). The uncertainties of the abundances of Cl (13.5 eV) and F (17.5 eV) both in the photosphere and corona are much too large and these two elements cannot be considered among the high FIP elements. Furthermore, Ar (15.8 eV) and Ne, with a very high FIP of 21.6 eV, cannot be taken into account because their photospheric abundances are not directly derived from the photosphere itself. Therefore we do not really know if neon does not behave differently from the other high FIP elements, such as C, N and O, which do however have a much lower FIP than Ne.

4.6 Miscellaneous

As the stellar abundances are generally referred to the solar values, the new solar scale will alter the cosmic yardstick. This has important impacts in various fields of astrophysics like stellar modeling as a whole, giant planets, T-Tauri models, Herbig Ae/Be, gas/dust ratio in dense interstellar clouds, …

We have also 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 (Asplund 2005). 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.

4.7 Problems with the Standard Solar Model

While the new abundances have positive implications as described hereabove, they introduce 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 ($r_e = 0.713\ \mathrm{R}_\odot$) inferred from helioseismology while the same models computed with older solar abundances agree very well with these measurements. Since O, C and Ne, by order of decreasing importance, are very important contributors to the opacity in the layers just below the convection zone where the problems arise, the revised solar abundances of these elements decrease the opacity and this significantly alters the structure of these layers.

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, M.H. Pinsonneault, J.A. Guzik, J. Montalban, A. Miglio, A. Noels, M. Seaton, S. Turck-Chièze, M. Castro, S. Vauclair, and their collaborators, have been 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 measures such as artificially increasing the opacity in the region below the convection zone, increasing the diffusion velocities, increasing the neon abundance, accreting low Z matter, …, currently exist.

5 Conclusions

The new solar abundances presented here are systematically lower, for the elements Na to Ca and Fe, to much lower, for C, N, O, as well as Ne and Ar, than previously recommended values.

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 hydrodynamic model represents however a real step forward in the modelling of the very inhomogeneous ever changing solar atmosphere. For the first time, we can reproduce the observed photospheric line profiles including their widths, shifts and asymmetries, the atomic- and molecular-based abundances now finally agree, there are no more significant trends with line strengths or excitation potentials in the derived abundances, very different lines, probing very different layers of the solar atmosphere with greatly different sensitivities to the physical conditions, now lead to the same results.

Although efforts should be continued in refining the 3D models, in the non-LTE calculations, in improving the number and accuracy of the atomic and molecular data, in extending the work to many more elements, we believe that the arguments hereabove mentioned are very strong in favour of our new results as well as for the realism of the 3D model.

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