

# SOLAR ABUNDANCES : THE REFERENCE SYSTEM

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**ABSTRACT.** We summarize the recent critical compilation and analysis of the solar and meteoritic abundances by Anders and Grevesse (1989). We also update a few solar photospheric results and present a detailed discussion of the problem of the solar abundance of iron.

## 1 - Introduction

The important stages in the evolution of the chemical composition of the sun, since the first quantitative analysis of Russell (1929), have been recalled by Ross and Aller (1976) and Grevesse (1984).

The sun is the only star for which we have redundant informations concerning the abundances of the elements as derived from analyses of the photosphere, sunspots, chromosphere, corona and active regions, and from particle composition measurements in the solar wind (SW) and solar energetic particles (SEP).

Photospheric studies provide without any doubt the most reliable and most accurate set of solar abundances for the following reasons. We have now at our disposal very high quality solar spectra from the ultraviolet to the infrared. The structure and physical processes are better known in the photosphere than anywhere else in the sun. Furthermore, it is well mixed by convection and turbulence.

Results derived from other solar layers are described briefly by Grevesse (1984) and Anders and Grevesse (1989, abbr. AG), and in more details by Meyer (1985), Gloeckler and Geiss (1989), Stone (1989) and Ramaty (1989). Sunspots analyses are only used to derive the abundances of F(HF), Cl(HCl) and Tl(TII) which are not represented in the solar photospheric spectrum. Chromospheric results are derived from eclipse spectra. The interpretation of the data is difficult (deviations from local thermodynamic equilibrium, uncertainties in the chromospheric structure, very heterogeneous medium, ...) and within rather large error bars, the chromospheric results agree with the photospheric values. Coronal values, derived from forbidden lines of highly ionized atoms in the visible or permitted lines in the EUV and X-ray ranges, also suffer from rather large uncertainties (30 to 100 %; see table 4 of AG). Solar wind measurements only cover a few elements (H, He, C, N, O, Ne, Si, Ar, Fe) with better accuracies whereas SEP measurements allow to determine the abundances of all the elements up to  $Z = 30$  (Zn) with very good accuracies (see table 4 of AG).

Comparison of the photospheric and coronal abundances (as derived from the coronal spectrum and from SW and SEP measurements) show that separation processes fractionate the gas supplied to the corona (see *e.g.* AG and references therein; see also section 4.2).

More details concerning these different sources of solar abundances can be found in the hereabove mentioned references.

## 2. Interest of Solar Abundances

Although much progress has been made during the last decade [see *e.g.* Gehren (1988), Lambert (1989), Smith (1989), Aller (1989), Meyer (1989), and the many reviews in this volume] as far as stellar abundances are concerned, the sun is still by far the more precise source for the abundances of a very large number of nuclei (71). It is used as the standard or reference system to which stellar abundances are compared.

Comparison between solar abundances and values from other members of the solar system gives important informations concerning the formation and evolution of the solar system. Comparison between solar and meteoritic results is especially important and allow to derive an accurate table of the solar system abundances of the elements (see AG and sect. 4.1).

Solar system abundances are also basic data in solar and stellar structure calculations through X, Y and Z (mass fraction of H, He and all the other elements).

Solar abundances are severe constraints for testing nucleosynthesis theories.

They also allow to study detailed physical conditions and processes in the outer solar layers, not only in the photosphere but also in the chromosphere and corona from a comparison between photospheric and coronal results.

## 3. Solar Photospheric Abundances

### 3.1 SOLAR, ATOMIC AND MOLECULAR DATA

Solar spectra of very high quality, high resolution and high signal over noise ratio, exist from 300 nm to 16  $\mu\text{m}$  (Delbouille *et al.*, 1973; Farmer and Norton, 1989). Equivalent widths ( $W_\lambda$ ) and profiles of atomic and molecular lines can be measured with very high accuracy, even for very faint features. From these data, it is a straightforward procedure to derive the abundances. We only need to know the solar photospheric model, the physical processes (LTE or non-LTE) and the required atomic and molecular data.

The solar photospheric model is now well known and the temperature structure is known with accuracy from indicators like CO, very sensitive to T (see *e.g.* Grevesse 1984b, Grevesse and Sauval, 1990).

Slight departures from LTE are found for low excitation lines of neutrals of the iron group; they should not play an important role if the abundance can be derived from lines of the once ionized species of these elements, by far the dominant stage of ionization (see *e.g.* Grevesse, 1990).

There is no doubt that present precision in the solar abundances is a matter of precision in the atomic and molecular data and, essentially, the transition probabilities (even, if other basic data, like the ionization potentials, dissociation energies, hyperfine structures and partition functions, also play a role). During the last decade or so, atomic spectroscopists have made substantial progress in the number and accuracy of transition probabilities they have been able to measure or compute for lines of solar interest. Thanks to these improvements, the dispersions in the solar abundance results have decreased to the 10 % level for many elements (in many cases, it is easily seen that the dispersion in the solar results reflects the quality of the transition probabilities used; see Grevesse, 1990). Furthermore, large changes in the absolute scales of the transition probabilities have led to the same modifications in the solar abundances. In each case, past discrepancies between meteoritic and solar results have gone away (see AG).

### 3.2 SOLAR RESULTS

Since our latest compilation of the solar photospheric abundance results [AG; see also Grevesse (1984a, b) and the references therein] a few elements have been revised. The new results are given hereafter.

C : Grevesse *et al.* (1990b) derived the abundance of carbon from different indicators : CH vibration-rotation lines, C<sub>2</sub> Swan and Phillips bands, CH electronic transition (A-X), CI and [CI] lines. All these indicators lead to a remarkable agreement :  $A_C = 8.60 \pm 0.05$  (where  $A_C = \log N_C/N_H$  in the usual scale where  $\log N_H = 12.00$ ).

N : Grevesse *et al.* (1990a) derived the abundance of nitrogen from vibration-rotation lines of NH in the infrared and from NI lines. Both results agree :  $A_N = 8.00 \pm 0.05$ .

Cd :  $A_{Cd} = 1.77 \pm 0.11$  (Youssef *et al.*, 1990).

Sm :  $A_{Sm} = 1.01 \pm 0.06$  (Biémont *et al.*, 1989).

Th :  $A_{Th} = 0.23 \pm 0.08$  (Lawler *et al.*, 1990).

All of the other elements have kept their solar abundance unchanged (see AG, their table 2). The problem of the solar iron abundance is discussed with some detail in sect. 4.3.

## 4. Discussion

### 4.1. METEORITIC versus SOLAR ABUNDANCES

The accuracy of meteoritic measurements has improved and analyses of C1 chondrites, which have escaped fractionation processes during their formation, have converged to the point where most elements are known to better than 10 %. Thanks to improved transition probabilities, the solar abundances have also become more accurate. The agreement between meteoritic and solar results is now remarkably good. If we retain only 29 accurately known elements in the photosphere, whose abundances can be derived using a sufficient number of good quality lines with accurate transition probabilities, then the data agree perfectly : the mean difference is  $0.000 \pm 0.036$  dex, *i.e.* 9 %. A more detailed discussion of this comparison is given by AG. However, there are many elements (see AG) for which the data disagree by more than 0.10 to 0.15 dex. If, for many of them (B, F, Cl, Ga, Rb, Ag, In, Sn, Tb, Ho, Tm, Yb, Lu, Hf, Pt, Au) the solar abundance is poorly determined due to severe blending of their few available lines and/or lack of accurate transition probabilities, some discordant elements that seem to be well-determined in the photosphere are very puzzling [ $\Delta(\text{phot.-met.}) = -0.22$  dex (Ge),  $-0.14$  (Mn),  $+0.06$  (Ti),  $+0.16$  (Fe),  $-0.20$  (Pb),  $+0.15$  (Th)]. The problem of iron is discussed in sect. 4.3.

### 4.2 PHOTOSPHERIC versus CORONAL ABUNDANCES

Comparison between the photospheric and coronal abundances (for elements with  $Z \leq 30$ , Zn being the heaviest element measured in SEP) shows (see AG, their table 4, figure 3 and references therein) that separation processes at relatively low temperature ( $\sim 10000$  K) fractionate the gas supplied to the corona. Elements with high first ionization potentials (FIP  $\geq 10$  eV; C, N, O, Cl, F, Ar, Ne) are depleted by a factor 4.4 (0.64 dex as obtained with the new photospheric abundances of C and N) relative to elements of lower FIP (iron group elements, K, Ca, Na, Al, Si, Zn). H and He do probably not behave exactly in the

same way. Although the mechanism and site of the separation process are not yet entirely known, promising scenarios have been developed by Vauclair and Meyer (1985 and private communication) and by von Steiger and Geiss (1989). As the abundances of Ne and Ar cannot be determined from the solar photospheric spectrum and as they are known with good accuracies from the SEP, one can correct their coronal values for the depletion factor and derive "photospheric" abundances of these two important elements (see AG). The same procedure cannot be applied to F and Cl which are too poorly determined both from the SEP and from the sunspot spectra.

#### 4.3. THE IRON PROBLEM

The actual solar photospheric abundance of iron, as derived from low excitation lines of FeI (Blackwell *et al.*, 1984; Blackwell *et al.*, 1986) with the very accurate Oxford transition probabilities (Blackwell *et al.*, 1982),  $A_{Fe} = 7.67 \pm 0.03$ , is 40 % higher than the very accurate meteoritic value,  $A_{Fe} = 7.51 \pm 0.01$  (AG).

Because of the high abundance of iron, because of the richness of its spectrum in the sun and stars and because of its role, in stellar abundances, as representing the metallicity,  $Z$ , it is crucial to know if this difference is real or not.

The best indicator for the solar abundance of Fe is undoubtedly the FeII spectrum. In the photosphere, the ratio  $n(\text{FeII})/n(\text{FeI})$  is about 93/7. Therefore FeII lines are much less sensitive than FeI lines to possible temperature uncertainties. Furthermore, Steenbock, quoted by Holweger (1988), does not find any departures from LTE in FeII whereas slight departures (up to 15 %) are predicted in FeI, the low excitation lines having larger departures from LTE than the high excitation lines. Unfortunately, very accurate  $gf$ -values are still very rare for FeII lines of solar interest (see hereafter).

The results from the low excitation FeI lines, for which we have very accurate  $gf$ -values measured at Oxford, obtained by Simmons and Blackwell (1982) and by Blackwell *et al.* (1984) show that departures from LTE exist in excitation. The lines with  $E_{exc} \cong 2.2$  eV lead to an abundance which is 0.07 dex smaller ( $A_{Fe} = 7.60$ ) than the result derived from lower and higher (up to 2.6 eV) excitation lines ( $A_{Fe} = 7.67 \pm 0.03$ ; note the very small dispersion which essentially reflects the high accuracy of the Oxford  $gf$ -values). Fe I lines of higher excitation would be better indicators of the solar abundance of Fe because they are less sensitive to  $T$  than lower excitation lines and non-LTE effects should decrease if not disappear. It is only very recently that accurate  $gf$ -values have been measured for FeI lines with  $E_{exc}$  up to 5.0 eV (O'Brian *et al.*, 1990). These new results obtained with a different technique in emission (lifetimes + branching ratios) are in excellent agreement with the Oxford absorption measurements (Blackwell *et al.*, 1982):  $\Delta \log gf$  (abs.-em.) =  $0.022 \pm 0.036$  dex. They will allow to see how these lines behave as compared to the lower excitation lines, but it would be surprising to find so large (40 %) non-LTE effects in excitation.

Milford *et al.* (1989) also measured  $gf$ -values for FeI lines of rather high excitation,  $2.2 < E_{exc} < 5.0$  eV, with a claimed high accuracy of 0.01 to 0.04 dex. Using most of these 30 lines, for which we measured the  $W_\lambda$  on the atlas of Delbouille *et al.* (1973), leads to  $A_{Fe} = 7.61 \pm 0.14$ . This very large dispersion in the results is certainly due to errors in the oscillator strengths (compare this dispersion with the dispersion of 0.03 dex found with the Oxford oscillator strengths of the same claimed accuracy). Therefore, we may obviously cast some doubt on the accuracy of the oscillator strengths of Milford *et al.* (1990). They unfortunately cannot help to settle the question of the iron abundance.

Very few accurate transition probabilities exist for good solar FeII lines, the best indicator of the solar abundance of iron. Recent works by Kurucz (1981), Moity (1983), Whaling

(1985), Kroll and Kock (1987), Heise and Kock (1990) and Pauls *et al.*(1990) still show large disagreements between lines in common. The highest accuracy is claimed by Heise and Kock (1990; 15 to 23 %), and Pauls *et al.*(1990; 15 to 20 %) who measured a few good solar lines only, 13 and 3 respectively.

Whaling (1985), from his accurate  $gf$ -values ( $\sim 5$  to 15 %) for lines with  $\lambda < \sim 490$  nm, showed that Kurucz (1981) and Moity (1983)'s results were too large and that the corrections depend on the  $\log gf$  for Kurucz and on the excitation potential of the upper level for Moity. We corrected those  $gf$ -values and used them to derive  $A_{Fe}$  from strong and faint FeII lines and got the following results (Grevesse, unpublished) :  $A_{Fe} = 7.73 \pm 0.08$  (from 12 rather strong FeII lines with  $gf$ -values from Moity as corrected by Whaling) and  $A_{Fe} = 7.66 \pm 0.14$  (from 55 faint FeII lines with  $gf$ -values from Kurucz as corrected by Whaling). The large dispersions once again cast some doubt on the correction procedure and cannot help solving the problem of the solar abundance of iron even if these values agree with the high photospheric value derived from FeI lines.

Very recently, Pauls *et al.*(1990; PGH) used 3 very good infrared FeII lines for which they measured the  $gf$ -values with accuracies of 15 to 20 %. They found  $A_{Fe} = 7.66 \pm 0.06$ . Also, very recently, Holweger *et al.*(1990; HHK) using 13 FeII lines (faint and medium strong), together with  $gf$ -values from Heise and Kock (1990), derived  $A_{Fe} = 7.48 \pm 0.09$ .

The explanation of this difference is not entirely clear although part of the difference can be explained as follows. We have redone the computations, using our computer code and the same data as HHK *i.e.* same model, same microturbulence, 1 km/s and same enhancement factor of the damping parameter, 2.5. We found  $A_{Fe} = 7.53 \pm 0.09$  *i.e.* 12 % higher than HHK. This might perhaps be explained by the differences in continuous opacities used in both computer codes (we checked that our results for the FeI lines agree perfectly with those of Blackwell *et al.*(1984) and Blackwell *et al.*(1986)). Now, with the same solar data, but using slightly lower values for the microturbulent velocity, 0.85 km/s (Blackwell *et al.*, 1984), and enhancement factor for the damping parameter (1.5; this value seems more appropriate to explain the observed wings of the stronger lines than the value 2.5 used by HHK), we find  $A_{Fe} = 7.58 \pm 0.11$ . Among the 13 lines used by HHK only 5 lines are really faint *i.e.* independent of the microturbulence and of the damping parameter. The rather large uncertainties in all these results do certainly come from inaccuracies in the  $gf$ -values. Therefore, I have some doubt about these transition probabilities. When comparing the  $gf$ -value scales of PGH and Heise and Kock (1990; used by HHK), if the difference is small,  $\Delta(\text{Pauls-HK}) = -0.013$  dex, the dispersion is large,  $\pm 0.12$  dex. And for two lines used by HHK, the differences are rather large :

$$\begin{aligned} & \lambda 4576.3 \text{ \AA}, \Delta = -0.03 \text{ i.e. } A_{Fe} (gf \text{ PGH}) = 7.63 \\ \text{and } & \lambda 7515.8 \text{ \AA}, \Delta = -0.12 \text{ i.e. } A_{Fe} (gf \text{ PGH}) = 7.63. \end{aligned}$$

So, a large part of the difference between the solar abundances of iron derived by PGH and HHK might come from differences in the  $gf$ -values.

We also recently revised the solar abundance of iron as derived from the very faint low excitation forbidden lines of FeII. These lines should be very good indicators of the solar abundance of Fe because they are nearly model-independent and they should be formed in LTE. Furthermore, their theoretical oscillator strengths should be better known than the corresponding data for permitted lines. Actually, Hanssen and Biémont (private communication) recomputed the  $gf$ -values for a few [FeII] lines and found their new data to be 10 % smaller than Garstang (1962)'s values. Using such  $gf$ -values (Garstang -10 %), we now find  $A_{Fe} = 7.68 \pm 0.05$  from 10 [FeII] lines.

In summary, we believe the high iron abundance of Fe ( $A_{Fe} = 7.67$ ) to be the correct one. However, this has to be confirmed from an analysis of FeII lines. We urgently need very accurate  $gf$ -values for the numerous very good faint FeII lines that are present in the solar spectrum.

#### 4.4. X, Y and Z

With the abundances of AG, updated with the revised values for the photospheric abundances of C and N (sect. 3.2), the mass fractions of H, He and heavier elements become :

$$\begin{aligned} X &= 70.67 \quad (70.63) \% \\ Y &= 27.43 \quad (27.41) \% \\ Z &= 1.90 \quad (1.96) \% \end{aligned}$$

where the first values have been calculated with the meteoritic abundance of Fe (7.51) and the values between parentheses with the high photospheric result (7.67).

#### 5. Conclusions

We have summarized the recent critical compilation and analysis of the solar and meteoritic abundances by Anders and Grevesse (1989). A few solar photospheric results (C, N, Cd, Sm, Th) which have been revised since 1989 have been reported. The problem of the solar iron abundance has been discussed with some details. We conclude that, even if different indicators seem to converge towards the high value [ $A_{Fe} = 7.67$  as compared to  $A_{Fe}$  (meteorites) = 7.51] of the solar abundance of iron, we cannot yet decide definitely if this difference is real. Very accurate oscillator strengths are urgently needed for FeII lines of solar interest. These lines only will provide a definite test and solution to the problem of the solar abundance of iron.

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