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A. Unsold

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Abundance of iron in the photosphere

By A. Unsöld
University of Kiel, Germany

For many years there has been a discrepancy of about a factor of ten between the solar iron abundance obtained from the Fraunhofer spectrum of the photosphere and that obtained from the extreme u.v. lines. Similar inconsistencies with the iron abundance in meteorites, especially carbonaceous chondrites of type I, were pointed out by Urey (1967). Let me describe briefly, how these discrepancies have been removed by recent work and point out some further consequences.

The abundance analysis of the solar photosphere requires:

(1) A sufficiently accurate model solar atmosphere, i.e. the temperature T, the electron pressure P_e and the gas pressure P_g as well as the velocities of microturbulence ξ and macroturbulence Ξ as a function of the optical depth for the Rosseland opacity $\bar{\tau}$ or for the continuous absorption coefficient, e.g. near $\lambda_0 = 500$ nm, called τ_0.

(2) The atomic constants for the relevant elements and lines, especially the transition probabilities or oscillator strengths f.

(1) and (2) must be used in connexion with the general theory of the formation of Fraunhofer lines. Both are strongly interlocked so that we must always follow some kind of iteration procedure.

1. Model solar photosphere

About ten years ago astrophysics was haunted by a nightmare called non-local thermodynamic equilibrium (n.l.t.e.). Some astrophysicists, notably Pecker (1959) and R. N. Thomas, began to doubt whether the well-known formulae for thermal excitation and ionization could be applied with sufficient accuracy to, for example, the solar photosphere. If that contention had been true, it would have meant that all solar abundance determinations were affected by large errors. On the other hand, it would have been a hopeless enterprise to develop a purely statistical theory for the distribution of the atomic states, for example, of neutral iron under the influence of the complicated field of radiation in the photosphere together with all sorts of collisions.

After preliminary studies (Unsöld 1962) had made it probable that in reality deviations from local thermodynamic equilibrium (l.t.e) were quite negligible in the photosphere and the lower chromosphere (but probably not so in the higher chromosphere and certainly not in the corona), Holweger (1967) proceeded to construct an empirical model of the solar photosphere (and lower chromosphere) in l.t.e. Since it was known (Pagel 1959; Unsöld 1962; Lambert & Pagel 1968) that the negative hydrogen ion in any case conformed to the laws of l.t.e., the continuous spectrum and its centre limb variation could be used for obtaining the temperature distribution $T(\tau_0)$ for about $0.05 < \tau_0 < 2$. Just extrapolating this temperature distribution towards smaller τ_0—as many authors have done—would lead to very serious errors. So $T(\tau_0)$ out to $\tau_0 \approx 10^{-6}$ was obtained using the observed intensities within strong lines, where the line absorption coefficient is much larger than the continuous absorption coefficient. This l.t.e. model was then tested by calculating mainly the depths and partly the profiles of lines originating from quite different elements, ionization and excitation potentials, etc. Differences between different elements, which had been interpreted by others as being due to n.l.t.e., were soon recognized as resulting from hyperfine structures. No f values were used in this work, since we felt sceptical about several tables of f values although they had been generally used for three decades. It turned out indeed that the l.t.e. solar model was perfectly consistent with all the relevant solar observations. The 'solar' f values, however, obtained from the egf for different atomic states did not at all agree with the well-known measurements made by King & King (1935; King 1938*a*) in the electric furnace.

2. New measurements of f values in the laboratory

In this situation a group of plasma spectroscopists working in the Institut für Experimentalphysik of the University of Kiel developed improved techniques for measuring f values. In order to avoid systematic errors depending upon the excitation potential of the atomic states it is advisable to work at high temperatures. Furthermore, the problem of having l.t.e. is much more serious in laboratory sources than in stellar atmospheres. Theoretical work by Bates, Kingston & McWhirter (1962) and others shows that in a plasma partial l.t.e. between the high excitation states and the free electrons having an electron temperature is established mainly by electron collisions. How far 'down' in the energy level diagram l.t.e. is realized depends chiefly upon the number density of the free electrons n_e. Equipartition between the free electrons and these high excitation states on the one hand and the low excitation states, especially the ground state, on the other hand, is reached mainly through radiative transitions. Therefore it is important that the plasma be optically thick for these transitions, especially the resonance lines. However, for accurate measurements of the f values one ought to have no self-absorption, i.e. optically thin layers. The narrow path between Scylla and Charybdis was realized by Professor Richter and his colleagues using a wall-stabilized arc burning in argon ($\sim$ 100 kN m^{-2}) (figure 1). In the central part of the arc column, argon containing a small and adjustable amount of the element to be investigated (e.g. $FeCl_3$–vapour) is blown in sideways. In the outer parts pure argon is blown in. Thus one obtains an isothermal part of the arc column containing e.g. iron and no self-reversal by cooler iron vapour in end-on observation. T_e and n_e could be measured accurately using known methods of plasma diagnostics (Bues, Haag (Mrs Garz) & Richter 1969) T_e being in the range of 9000 to 12 000 K, n_e about 10^{16} to 10^{17} electrons/cm^3. The absolute calibration of the whole set of f values was done by means of published atomic beam, lifetime, beamfoil, etc., measurements of selected lines. Comparison of the new measurements (Garz & Kock 1969) with those of King & King (1935; King 1938*a*) showed that the latter were affected by a large systematic error increasing with excitation potential to more than a factor of ten, while the accidental errors in King's tables are quite small. The more recent tables of f values for Fe I lines by Corliss & Warner (1964) and by Corliss & Bozman (1962) have about the same systematic error as King & King but, in addition, also accidental errors of the same order of magnitude, so that these publications should be used only with great precaution. The new scale of f values is confirmed by their agreement with beam-foil and shock-tube measurements of various groups (compare Garz *et al.* 1969) and with all the astrophysical data to be mentioned presently. The error in King & King's measurement, which was taken over in many recent publications, consisted most probably in their measuring the temperature in their furnace about 400 K too low. It was not possible after 35 years to trace down how that happened. The same systematic error is obviously present in the Cr I values by Hill & King (1951) as compared with the shock-tube measurements by Wilkerson (1961) and most probably in the older determinations for Ti I. A lot of new measurements will be necessary before we have satisfactory f values for all the lines of astrophysical interest. In passing I ought to mention that the measurements of Cu I f values made by Kock & Richter (1968) with their wall stabilized arc in argon confirm qualitatively the calculations made by Bates *et al.* (1962) on n.l.t.e. in *some* ranges of T_e and n_e. Here the mentioned nightmare can be watched while being kept in a safe cage!

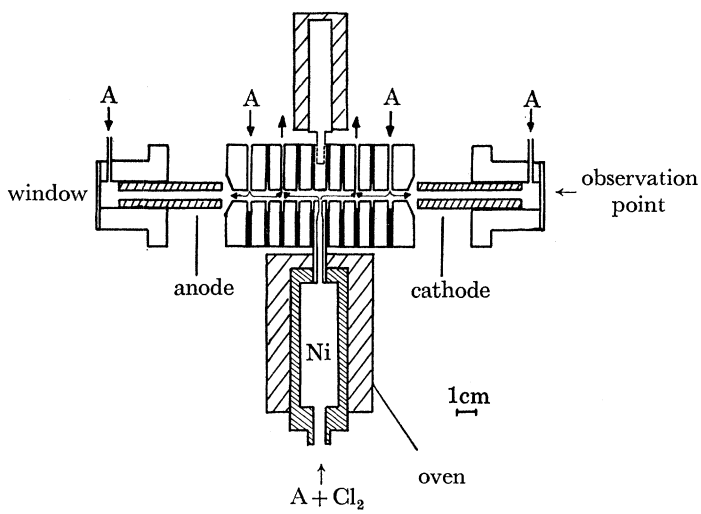

FIGURE 1. Wall stabilized arc used by Richter, Kock, Garz and Heise for measuring f values.

3. THE SOLAR IRON ABUNDANCE

The improved f values for Fe I were used for determining the solar abundance of iron (referred to $\lg \epsilon = 12$ for hydrogen). In doing so it was noticed that now iron becomes important by contributing an essential fraction of the free electrons in the solar atmosphere. Moreover, it became possible to subdivide the total turbulence more accurately into microturbulence ξ and macroturbulence Ξ. The original Holweger model was therefore slightly revised by $\Delta \lg P_e \approx +0.1$; $\Delta \lg P_g \approx -0.1$; $\xi = 1\,\text{km}\,\text{s}^{-1}$ and $\Xi = 1.6\,\text{km}\,\text{s}^{-1}$. Including these second-order corrections the iron abundance now becomes

$$\text{Fe I:} \quad \lg \epsilon(\text{Fe}) = 7.60 \pm 0.15 \quad \text{(Garz, Holweger, Kock \& Richter 1969).}$$

Using the same apparatus, new f values were also determined for many Fe II lines, leading to an independent abundance determination

$$\text{Fe II:} \quad \lg \epsilon(\text{Fe}) = 7.63 \pm 0.20 \quad \text{(Baschek, Garz, Holweger \& Richter 1970).}$$

Both values are in excellent agreement with the earlier determination using forbidden Fe II-lines in the Fraunhofer spectrum

$$\text{[Fe II]:} \quad \lg \epsilon(\text{Fe}) = 7.50 \pm 0.25 \quad \text{(Grevesse \& Swings 1969).}$$

The agreement is just as good with the determinations made from allowed and forbidden transitions of higher stages of ionization in the extreme u.v. region by Pottasch (1963*a*, *b*, 1964*a*, *b*, 1967), Jordan (1966) and others leading to $\lg \epsilon\,(\text{Fe}) = 7.6$ to 7.7. All these $\epsilon(\text{Fe})$ values are about a factor of ten higher than obtained by Goldberg, Müller & Aller (1960), the difference being mostly due to their using King's f values.

Before drawing some general conclusions, we should mention, that using the same method f values have also been measured for Ni I lines, leading to the abundance

$$\lg \epsilon(\text{Ni}) = 6.25 \pm 0.15 \quad \text{(Garz, Heise \& Richter 1970; Garz 1971).}$$

Since the ratio Fe/Ni is very important in connexion with meteorites and the planetary system, the f values of many Fe I and Ni I lines were also measured relative to each other, thus avoiding possible errors in the absolute calibrations. In one experiment, an argon arc was used into which small amounts of Fe and Ni in a known ratio had been introduced. In another experiment a spark between electrodes having a known Fe/Ni ratio was employed. The results for $\lg \epsilon(\text{Fe})/\epsilon(\text{Ni})$ are

electric arc	1.25 ± 0.15	most probable value 1.25 ± 0.15 (Garz 1971).
spark between Fe-Ni electrodes	1.1 ± 0.25	
Absolute determinations for Fe and Ni	1.35 ± 0.20	

The coronal extreme u.v. lines, according to several authors quoted in detail by Mrs Garz, lead to $\lg \epsilon(\text{Fe})/\epsilon(\text{Ni}) = 1.15 \pm 0.10$ in very good agreement with the photospheric value.

4. Further consequences

The new determinations of f values and abundances lead to many interesting consequences.

(i) The mean excitation temperature of the photosphere $T = 4400$ K determined by King (1938*b*) and others obviously carries on the error of $1/T$ made in measuring the furnace temperature. The corrected mean excitation temperature is in excellent agreement with the temperature near $\tau_0 \approx 0.1$ in Holweger's model, i.e. $T = 5260$ K. Similar errors, which indirectly affect also the abundance determinations for other elements, must also be present in earlier work on stellar spectra.

(ii) Slight and still preliminary corrections for the abundance of magnesium and silicon give

$$\lg \epsilon(\text{Mg}) = 7.5 \quad \text{and} \quad \lg \epsilon(\text{Si}) = 7.6.$$

Iron therefore makes now an essential contribution to the free electrons in the photospheres of the Sun and cool stars. This leads roughly to an increase

$$\Delta \lg P_e \approx +0.1 \quad \text{and a decrease} \quad \Delta \lg P_g \approx -0.1$$

for a given optical depth.

(iii) Having removed systematic distortions of the scale of f values—strong (weak) lines mostly having low (high) excitation potential—we can establish the correct relations in the curve of growth between

α, the linear branch, W_λ depending only on $\epsilon g f$;

β, the flat branch, W_λ depending on $\epsilon g f$ and the microturbulent velocity ξ;

γ, the damping part, W_λ depending on $\epsilon g f \Gamma$.

We have already mentioned the new value obtained for the photospheric turbulence. As to the damping constants Γ, it will be interesting to compare empirical values with—admittedly still fairly rough—quantum mechanical calculations. Such investigations have been started by Holweger. Concerning a recent note by Ross (1970) I should like to refer to a clarifying paper by Garz, Richter, Holweger & Unsöld (1970).

(iv) The abundances of the so far investigated elements are the same in the photosphere and in the lower corona. Violent mixing obviously overcomes the tendency towards diffusive separation.

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(v) The new abundances determined for the Sun are in excellent agreement with the abundances in carbonaceous chondrites of type I. As representing the latter we use the values given by Urey (1967) for the meteorite Orgueil, reduced to $\lg \epsilon(\mathrm{Si}) = 7.60$. The new solar determination for copper is due to Kock & Richter (1968):

element	meteorite Orgueil	solar photosphere
Mg	7.62	7.50
Si	7.60	7.60
Fe	7.55	7.60
Ni	6.29	6.25
Cu	4.28	4.16

As this small sample contains essential elements of the lithophile, siderophile and chalcophile groups we are probably justified in stating that in the carbonaceous chondrites I all the non-volatile elements of the original solar matter have been condensed without any separation processes interfering. Since meteoritic matter in general as well as terrestrial and lunar matter must have undergone large-scale separation processes, this is an important datum with regard to theories of the origin of our planetary system.

Somewhat more generally we should note that the solar iron to nickel ratio

$$\lg \epsilon(\mathrm{Fe})/\epsilon(\mathrm{Ni}) = 1.25 \pm 0.15$$

is now in excellent agreement with the value 1.29 ± 0.05 found for chondrites in general (Garz 1971).

(vi) Recently Bertsch, Fichtel & Reames (1969) have found that the abundance ratio of iron-group nuclei relative to oxygen-group nuclei in a solar cosmic ray event agreed with the *former* value of the photospheric iron abundance. Since, on the other hand, a recent determination of the oxygen abundance in the photosphere by Müller, Baschek & Holweger (1968) gave

$$\lg \epsilon(0) = 8.83$$

in close agreement with previous determinations we must conclude *now* that the abundance distribution of the elements in solar cosmic rays differs from that of photospheric matter. Abundance determinations in cosmic rays (and possibly also the solar wind?) should therefore not be mixed with photospheric abundances. They should probably rather be considered in connexion with theories of the acceleration of solar cosmic ray particles.

The work, about which I reported in this lecture, has been done by a group of astrophysicists working in the Institute for Theoretical Physics and the Observatory, Kiel: Dr Baschek and Dr Holweger together with a group of experimental physicists working in the Institut für Experimentalphysik, Kiel (Director: Professor Lochte-Holtgreven): Professor Richter, Dr Garz, Dr Kock and others. I would like to thank all of them for their excellent cooperation and for making available for this lecture much unpublished material.

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