IV. THE ABUNDANCES OF THE CHEMICAL ELEMENTS IN THE UNIVERSE

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1. THE COMPOSITION OF THE SOLAR ATMOSPHERE

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The analysis of the Sun by spectroscopic methods refers to an exceedingly thin layer, just above the photosphere, which has a thickness of only a few hundreds of kilometers. The deeper layers are inaccessible to our investigations, because there the matter becomes too opaque. The higher layers of the chromosphere and the corona again are less well known, because they are too transparent, so that deviations from thermodynamic equilibrium conditions may occur. So it is understandable that just the layer where the equilibrium is *nearly* established must be the only layer which can be fully investigated. Probably this is the best analysed sample of the universe. Whether the composition here found is really representative for the Sun as a whole depends on the importance of the convection, which tends to stir the gases into one homogeneous mixture.

The analysis of the solar atmosphere is of fundamental importance, because it may be carried out in detail and with a considerable dispersion, so that even very faint lines appear. Moreover, by a judicious comparison between the spectrum of the centre and of the limb, the uncertainties pertaining to the atmospheric structure may be in principle eliminated; or, an atmospheric model being assumed, a very detailed check on its validity may be found. All methodical questions can be especially well elucidated when describing the way in which the solar analysis is made.

The curve of growth is a wonderful method in order to get rapidly a working knowledge of a stellar atmosphere and to interconnect both faint and strong lines. From such investigations has been derived a pretty close, generally accepted description of the solar gases, their temperature, pressure and composition at each height. But for a more refined analysis, the mean curve of growth does not furnish sufficiently exact information. Its run is different from element to element, or rather from line to line: for there are differences in Doppler-effect, differences in damping and differences in the distribution over the height of the atmosphere.

For a more exact analysis we have to investigate individually each Fraunhofer line. This has been done first for *the strong resonance lines* of some metals. This method has several disadvantages for precise work: (1) From such lines the number of absorbing atoms can be found only if we also know the damping of the corresponding atomic transition; however, this damping depends on the conditions and is a rather uncertain coefficient. (2) The exact computation of the relation between the number of atoms and the profile of a strong line is difficult and is often done in an approximate way only. (3) Especially in the core of the line the profile is partially filled up by fluorescent or non-coherent radiation. Of these effects, the damping is the most important; effective progress has been recently made in the understanding of the damping mechanisms, but there remains to ascertain the value of the individual coefficients, which can be found only from theory. It is important that theoretical physicists should give us some help in this respect.

For the reasons just explained, there is now an increasing tendency to base the analysis of the Sun on *the individual investigation of the faint lines* (4). Indeed, their equivalent widths are independent of the damping; the relation between equivalent width and the number of absorbing atoms may be tabulated once for all, taking into account the complete atmospheric structure without schematic models, by what I shall call 'the detailed theory'. Moreover, for these lines it seems that no special processes are involved which could influence the central intensity. The importance of these faint lines is so considerable, that special care ought to be bestowed on the determination of *f*-values for their atomic transitions. This does not necessarily involve great experimental difficulties; but it has been more or less neglected up to now, because nobody expected that these lines would become interesting. I hope that the sub-commission on intensity tables will pay due attention to this category of special lines.

It must be granted that only the very faintest lines are really well described by the simple theory. Stronger lines, however, are easily reduced to this standard case by means of the curve of growth; but then uncertainties come in, first about the state of turbulence and the distribution over the height; and, for still stronger lines, the uncertitude about the damping begins to play a role.

The accuracy of the results obtained either from strong or from faint lines depends on our knowledge of the following fundamental data:

Atmospheric model:

$$\left.\begin{array}{l}\text{He content}\\ \text{turbulence}\\ \text{far U.V. radiation}\end{array}\right\}\rightarrow\left\{\begin{array}{l}\bar{\kappa};\\ \text{possible deviations from Boltzmann and Saha;}\\ \text{relation between } T \text{ and } P.\end{array}\right.$$

Atomic constants:

f-values;
polarization of the atoms (radial eigenfunctions) → damping;
probability of de-excitation by electrons → absorbing or scattering.

From this survey, it will be clear that considerable improvement of our analysis is still possible, partly by ascertaining physical data concerning atomic properties, and partly by obtaining from general astrophysics a more exact picture of the solar atmosphere. The information about *f*-values is certainly of major importance.

We will now consider how the numbers of atoms corresponding to the several lines are converted into *abundances of the elements*. It will be clear from the first, that the most reliable results will be obtained for these elements where absorption lines originating from the most populated levels are observed. On the contrary, the determination becomes dangerous if the abundances must be deduced by means of very great Boltzmann or Saha factors. From this point of view the elements H, C, N, O, Si and S present considerable difficulties, their visible lines having very high excitation potentials. It is well to remember that the excitation temperatures recently found by excellent authors run from 4300° to 5700°. For an element with an E.P. of 9 V., this means that the Boltzmann factor would vary between $[-10{\cdot}5]$ and $[-8{\cdot}0]$: an incertitude by a factor of 300! For such cases all care must be given to the selection of the exact temperature (or equivalent temperature), most appropriate to the line considered. The 'detailed theory' of the solar atmosphere gives automatically the exact equivalent temperature for each individual line without additional assumptions.

Since many lines of low levels originate at a mean depth of only $\tau \approx 0{\cdot}1$ e.V. it is important to ascertain the run of the temperature especially for these high layers, where the blanketing effect may have an important influence.

It is customary to compute 'the number of atoms above the photosphere' for each element. In doing this, we refer to the Schuster-Schwarzschild model, which indeed is very practical and has a direct pictorial value. The sum of all these numbers of atoms may be put equal to 1, and the relative abundances may be derived. A closer analysis shows that this representation should be accepted only with some caution. Strictly speaking, nobody can tell where the photosphere really begins; or rather, for each spectral line there is an equivalent photospheric depth, varying according to the wave-length, the E.P. and the I.P. The effective layers having different thicknesses, it is clear that a clean comparison between the abundances is not well possible. The detailed theory gives a more direct and complete determination of the relative abundances. For each line, the equivalent width determines $\sigma_\nu/\bar{\kappa}$, which is equivalent to the abundance of the H^- ion, or, again, to the abundance of the metal compared with hydrogen. Especially for faint lines, it is easy to take completely into account the variation of $\sigma_\nu/\bar{\kappa}$ over the height of the atmosphere; which means: whether the atoms are concentrated in the higher or in the lower regions, whether the effective layer is shallow or thick, etc. The results are therefore more precise, the relative proportion of the metals is determined according to an equitable standard. Another important advantage of such a theory will be pointed out presently.

The abundance of hydrogen is one of the most important and difficult problems of the solar analysis. It may be obtained by two methods:

(1) The spectrophotometry of the Balmer lines may be carried out by the methods used for strong metal lines. However, these results are uncertain, because the broadening of the Balmer lines is still imperfectly understood: this is demonstrated by the failure of theory to describe the mutual relation between the Balmer profiles and the modifications of profiles, when approaching the limb. It has been tried to measure the last lines of the Balmer series or of the Paschen series; these are so shallow that they may be considered as formed in an optically thin layer. But such measurements are difficult, their equivalent widths as published are not well in mutual agreement (2, 8, 5).

(2) As already explained, the theory of faint lines yields directly for each metal the abundance compared with hydrogen, without any measurement of a hydrogen line. This method, first applied by Strömgren (7) and made more exact since Chandrasekhar's work on the H^- absorption, gives an independent determination only when atoms of strongly ionized elements are used. It entirely avoids the Boltzmann factor, which for hydrogen is of the order of 10^{-9} and is always more or less uncertain; moreover, it is independent of the broadening either of the hydrogen or of the metal lines. Applying our reduction to a few suitable elements, we find that the abundance of hydrogen is in the mean [0·16] greater than found by Strömgren; this last value is thus practically confirmed.

The determination of *the abundances of the atoms C, N and O* is a very important question, because after H and He they are the best represented elements in the solar atmosphere. Their concentration determines the speed of the nuclear transformation in the interior parts of the Sun.

(1) Their abundances may be derived from the atomic lines; unfortunately these belong to the infra-red spectrum and have an excitation potential of 8 to 10 V.; so the Boltzmann reduction is dangerous. Probably more reliable is the reduction by means of the detailed theory.

(2) Bowen and, independently, Cabannes and Dufay have been able to identify the very faint forbidden lines of O in the solar spectrum, which are absorbed by very low levels of the atom. From these follows the abundance, without the danger of a wrong Boltzmann factor (1). Both results are in excellent agreement.

(3) Finally, the abundances of these elements may be found from the molecular bands of CH, OH, CN, NH and C_2, which are observable in the solar spectrum. The abundances of these four atoms determine the concentration of the molecules. You will hear presently how beautifully Dr Hunaerts applied this method.

The results of the three calculations are compared in the general table (11). It is at once clear that there are still divergencies which must urgently be solved.

There remains *the determination of the helium abundance*. As yet this has been derived only from the chromospheric lines and from the prominences (3, 9). Now the analysis of the chromosphere has shown that the abundance of the metals, compared with hydrogen, is distinctly smaller in the chromosphere, and that it still decreases at greater heights (13). The proportion of helium to hydrogen has been found sometimes to vary considerably in different parts of the same prominence (14). This proves that it is still uncertain whether the helium content of the chromosphere may be considered as equal to that of the deeper layers. It seems impossible as yet to derive any information from the line λ10830, which shows as a hazy absorption in the infra-red spectrum: the excitation potential being

19·8 e.V., the Boltzmann factor is enormous and entirely uncertain, the very existence of equilibrium conditions is doubtful. In principle, the helium abundance of the reversing layer could be determined by similar methods as the hydrogen abundance; for the admixture of helium will modify the structure of the atmosphere, especially the relations between T, P, P_e and κ, and this again must have an influence on the line intensities of the other elements. A systematic comparison between the intensities of atom lines and ion lines of the same element, either strong or faint, must yield not only the abundance of hydrogen but also that of helium.

The table of abundances in the solar atmosphere here presented summarizes most of the recent information. Tabulated are the logarithms of the number of particles (atoms or ions) of each element, this logarithm being put equal to 10 for hydrogen. The results of Menzel and his collaborators cannot be critically compared with the others, because details about the computations have not yet been published. The chief differences with Unsöld occur for those elements where the Boltzmann reduction becomes important (S, Si, Zn), apparently because Menzel used a lower temperature. The table shows that Unsöld's temperature is in much better agreement with the detailed theory, which is especially reliable for the deeper atmospheric levels. Since just these are determinant for the special lines in question, the higher temperature seems the best choice. Very striking is the difference between Menzel and Unsöld for Mg. For Fe, the values of Unsöld are probably not reliable, since there is doubt about the absolute f-values of King on which they are based.* The results of Unsöld are the most complete set now available; they have been reduced by himself to the hydrogen value of Strömgren. The next column gives for some elements the results obtained if Unsöld's data are treated by the detailed theory of faint lines, keeping the f-values as used by him; for iron, a value deduced directly from King has been added. The ratio to hydrogen is here determined directly and independently. The following conclusions may be drawn: (1) Compared with Unsöld-Strömgren, a slightly smaller abundance is found for most elements, with respect to hydrogen; the mean factor amounts to [0·16]. (2) The results for the individual metals deviate only in minor respects from those obtained by the Scharzschild-Schuster model; taking into account the changed hydrogen value, the greatest difference amounts to [0·31]; for the metalloids, the divergencies are greater. Consequently for more precise work it is advisable to use the detailed theory. For oxygen, the results of Bowen, Cabannes and Dufay have been first compared with hydrogen via Unsöld-Strömgren; the second number has been computed directly from the detailed theory.

For the rarer elements, the original table of Russell is still now of high value (6).

Especially interesting is the absence of the heavy hydrogen isotope. From our present knowledge of equivalent widths, we may assert rather safely that the ratio of the two isotopes is less than 10^{-5}. Traces of the carbon isotope C^{13} are lacking in the solar spectrum, but in this case it would be difficult to assign an upper limit to the abundance.

Abundance of the Light Elements in the Solar Atmosphere

Element	Menzel c.s.	Unsöld	Minnaert	Hunaerts (molec.)	Bowen, Cabannes and Dufay (forb. l.)
H	10·0	10·0	10·0	10·0	10·0
H^2	—	—	5·0	—	—
He	9·30	9·30 (promin.)	—	—	—
C	5·56	6·29	—	7·06	—
N	6·09	6·61	—	7·02	—
O	6·56	6·73	—	7·23	6·55–6·83 (M.) 6·27–6·73 (M.)

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* Remark made by Menzel at the meeting.

Abundance of the other Elements in the Solar Atmosphere

Element	Menzel c.s.	Strömgren	Rudkjøbing	Unsöld	Unsöld (M.)
Na	4·56	3·96	4·00	4·28	4·09
Mg	6·39	5·60	5·25	5·51	5·48
Al	4·39	—	—	4·33	4·16
Si	5·87	—	—	5·29	—
S	5·57	—	—	4·92	—
K	3·09	3·32	—	3·20	3·00
Ca	4·57	4·23	—	4·23	—
Sc	—	—	—	1·33	0·98
Ti	2·57	—	—	2·96	2·76
V	2·09	—	—	2·06	1·81
Cr	2·87	—	—	3·58	3·00
Mn	3·09	—	—	3·46	—
Fe	4·99	—	—	5·72	5·29–5·59 (King)
Co	2·69	—	—	3·03	—
Ni	4·39	—	—	3·96	—
Cu	2·39	—	—	2·23	—
Zn	3·57	—	—	2·78	—
Sr	—	—	—	1·35	1·00
Y	—	—	—	1·21	—
Zr	—	—	—	0·37	0·10
Mo	—	—	—	0·78–1	—
Ba	—	—	—	0·95	—
Pb	—	—	—	0·6	—

In conclusion, I should like to emphasize some rather obvious recommendations for future work: First, that a high standard of accuracy in the determination of abundances must be reached and can be reached. Secondly, that all data should be published in full, in order to make a detailed discussion possible. Thirdly, that abundances should be determined for each celestial body independently, not trying *a priori* to confirm the uniformity of constitution of the Universe.

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