ABUNDANCES OF HEAVY ELEMENTS IN THE SUN*

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Abstract. Solar abundances have been derived for Pb, Bi, Th and U. For the three first elements, the abundances are determined from the profiles of their lines obtained with the high resolution solar spectrometer installed at the Jungfraujoch Scientific Station (Switzerland) and from new oscillator strengths based on life-time measurements (Pb and Bi). The possible presence of U in the solar spectrum is also examined.

Our results are (in the $\log N_H = 12.00$ scale): $\log N_{Pb} = 1.83$, $\log N_{Bi} \leqslant 0.80$, $\log N_{Th} = 0.82$, and $\log N_U \leqslant 0.60$.

The meaning of these new solar abundances is discussed from the point of view of the nucleosynthesis theories.

1. Introduction

The particular role played by Pb, Bi, Th and U in nucleosynthesis theories has been stressed by BURBIDGE *et al.* (1957). The abundances of these elements are strongly interdependent. For Pb and Bi, s-process contributions are complicated by the cycling among Pb^{206}, Pb^{207}, Pb^{208} and Bi^{209} (end of s-process) and r-process contributions arise from radioactive decay of U and Th (radiogenic contributions). Among these radiogenic contributions we have to distinguish cosmoradiogenic ones, taking place before the formation of the solar system, and georadiogenic contributions, occurring after the formation of the sun. U and Th are only formed by the r-process. But heavier r-process elements (progenitors) decay by successive emission of α particles to the U and Th isotopes and, therefore, strongly contribute to the abundances of these elements.

All these processes are strongly dependent on the rate of stellar activity in the history of the galaxy, on the galactic and solar system time scale and on the radioactive decays [see e.g. FOWLER and HOYLE (1960); CLAYTON *et al.* (1961); FOWLER (1962); CLAYTON (1963, 1964, 1967); HOYLE and FOWLER (1964); SEEGER *et al.* (1965)].

These reasons led us to group these elements together in this study.

2. Solar Abundance of Lead

2.1. INTRODUCTION

The solar abundance of lead has been studied by numerous authors. In Table I, we give, for each author, the method, the references concerning the oscillator strengths and the lines selected and, in the last column, the abundance in the scale $\log N_H = 12.00$.

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TABLE I

Abundance of lead in the sun

Authors	Method[a]	f-Values	Lines[b]	log N_{Pb}
Russell (1929)	–	–	UV	1.20
Unsöld (1948)	W_λ	Unsöld (1948)	UV	2.55
Khokhlov (1959b)	W_λ	Khokhlov (1959a)	UV	1.25
Khokhlov (1960)	W_λ	Khokhlov (1960)	IR	< 1.30
Goldberg *et al.* (1960)	W_λ	Allen (1957)	UV	1.33
Helliwell (1961)	W_λ	Helliwell (1961)	UV	1.82–1.90
De Jager and Neven (1962)	W_λ	Khokhlov (1960)	IR	1.15
Mutschlecner (1963)	W_λ	Helliwell (1961); Bell and King (1961)	UV	1.64
Grevesse (1967)	W_λ	Lawrence (1967)	UV	2.00
Ross *et al.* (1968)	Profiles	Helliwell (1961)	UV	1.76
		Brown (1966)		2.08
Peach (1968)	W_λ	Peach (1968)	IR	1.93

[a] W_λ: curve of growth or any method which does not compare observed and computed profile.
[b] UV: 4 lines between λ3639 Å and λ4057 Å. IR: 1 line at λ7229 Å.

As can be seen, the dispersion of the results is rather large. This can be explained as follows. The equivalent widths of the lead lines are difficult to measure with accuracy in the solar spectrum. Four faint lead lines, λ3639.580, 3683.480, 3739.944 and 4057.813 Å appear in the solar UV spectrum. Another very faint line has been detected in the IR, at λ7229.036 Å. All these lines, the spectroscopic characteristics of which are given in Table V, are blended. Furthermore, the absolute oscillator strengths of these lines were not known with high precision, up to 1967.

New solar tracings obtained under high resolution and with low noise enable us to make more accurate measurements of the equivalent widths and of the profiles of the lines. Accurate values of the oscillator strengths can now be obtained from reliable life-time measurements.

These two reasons led us to redetermine the solar lead abundance.

2.2. Lead lines in the solar spectrum

We took new tracings of the solar spectrum around the lead lines with the double-pass solar spectrometer installed, by L. Delbouille and G. Roland, at the Jungfraujoch Scientific Station (Switzerland; elevation 3580 m). The spectra finally obtained are represented in Figures 2–6. The equivalent widths (W_λ) have been measured graphically. The results of these measurements are compared, in Table II, with those obtained by other authors.

As can be seen from Figures 2–6, the line λ3683.480 Å is slightly blended, all the others being strongly blended. The measurement of the W_λ is very difficult and leads to a rather large dispersion in the results (Table II).

2.3. Oscillator strengths

The analysis of the different publications concerning the oscillator strengths of the Pb I lines (Table III) shows poor agreement between the different results.

TABLE II

Equivalent widths of the Pb I lines in the solar spectrum

λ(Å) /	3639	3683	3740	4057	7229	Authors
	8.0	7.0	2.0	5.0	–	GOLDBERG *et al.* (1960)
	–	10.0	3.0	16.0	–	MOORE *et al.* (1966)
	–	11.0	–	17.0	–	HELLIWELL (1961)
	48.3[a]	8.3	1.9	10.8	–	MUTSCHLECNER (1963)
W_λ(mÅ)	–	–	–	–	0.26	DE JAGER and NEVEN (1962)
	–	6.5	–	19.5	< 2.0	KHOKHLOV (1959b, 1960)
	–	–	–	–	0.29	PEACH (1968)
	6.5	7.8	2.0	6.0	≈ 0.35	This work

[a] This value is, in fact, the equivalent width of the Fe I λ3639.525 Å line. The Pb I line falls on the blue wing of this line.

To obtain absolute oscillator strengths, the most accurate method consists in measuring the life-times of certain states of the atom and then in computing the f absolute from the relative 'f-values' which are more easy to determine.

In Figure 1, we reproduce part of the level scheme concerning Pb I. The life-time of the $^3P_1^0$ level has recently been measured by different authors. The results are as following:

	$\tau \times 10^9$ sec
NOVIK *et al.* (1964)	5.6 ± 0.5
SALOMAN and HAPPER (1966)	5.75 ± 0.2
CUNNINGHAM and LINK (1967)	6.05 ± 0.3
DE ZAFRA and MARSHALL (1968)	5.58 ± 0.72

TABLE III

Oscillator strengths for the lead lines

λ						
2833	3639	4057	7229	3683	3740	References
–	0.25	0.35	–	0.41	1.00	ALLEN (1957)
0.21	0.089	0.365	–	0.170	–	HELLIWELL (1961)
0.23	–	–	–	–	–	BELL and KING (1961)
0.60	0.28	0.85	0.19	0.49	1.08	KHOKHLOV (1961)
0.22	0.086	0.46	0.01	0.213	1.06	CORLISS and BOZMAN (1962)
0.212	0.063	0.153	–	0.116	–	PENKIN and SLAVENAS (1963)
0.102	0.042	0.172	–	–	–	SALOMAN (1965)
0.190	–	–	–	–	–	LVOV (1965)
–	0.063	0.139	–	0.070	–	BROWN (1966)
0.169	0.040	0.155	–	–	–	SALOMAN and HAPPER (1966)
0.260	0.037	0.083	0.002	0.068	0.063	LAWRENCE (1967)
0.190	0.056	0.137	0.032	0.104	0.184	LAMBERT (1967)
0.169	0.040	0.155	0.034	0.116	0.194	PEACH (1968)
0.197	0.059	0.142	–	–	–	DE ZAFRA and MARSHALL (1968)
0.189	0.056	0.136	0.030	0.103	0.173	This work

The excellent agreement between these different measurements led us to adopt De Zafra and Marshall's value (and its error). The life-time is related to the oscillator strengths by the following relations:

$$\tau = \frac{1}{\sum_{l} A_{lu}}, \tag{1}$$

where

$$A_{lu} = \frac{1}{1.499} \frac{f_l g_l}{\lambda_{lu}^2 \,(\mathrm{cm})\, g_u}.$$

The different symbols have their usual meanings; the indices l and u refer to the lower and upper levels.

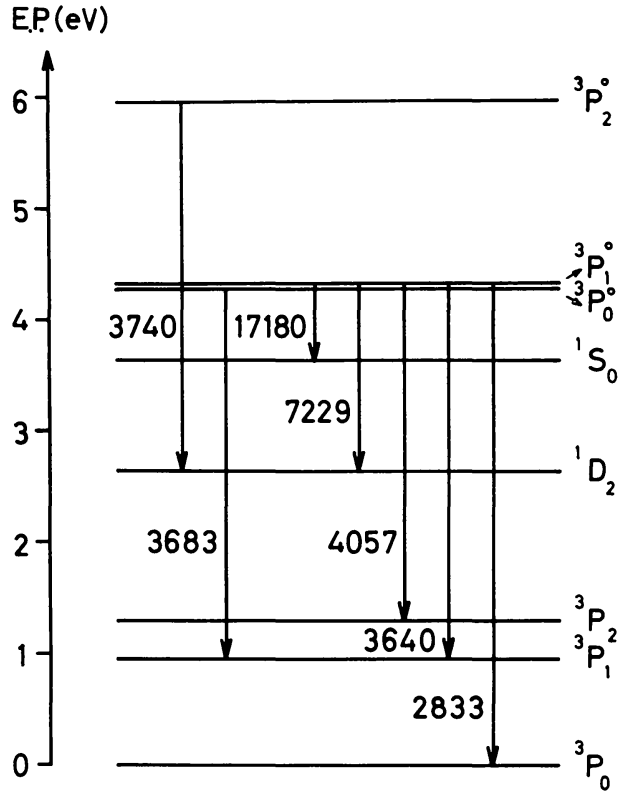

Fig. 1. Part of the level scheme of Pb I.

The relative oscillator strengths have to be adopted from the theoretical results of HELLIWELL (1961) and LAWRENCE (1967) or from the experimental works of CORLISS and BOZMAN (1962), KHOKHLOV (1961), PENKIN and SLAVENAS (1963), and BROWN (1966). The results of HELLIWELL (1961) are erroneous (DE ZAFRA and MARSHALL, 1968). The oscillator strengths of CORLISS and BOZMAN (1962) have been excluded since they are subject to rather important random errors. Those of LAWRENCE (1967) are not reliable since they predict a branching ratio in disagreement with the observed value. We, finally, retain for our discussion of the relative oscillator strengths, the values given in Table IV. These values have been normalized for the λ4058 Å line,

as suggested by DE ZAFRA and MARSHALL (1968). For absorption lines arising from the lower levels $^3P_0$ and $^3P_1$, we adopted the higher values. The reason for this choice is that self-absorption may sometimes perturb the measurements of lines arising from low excitation levels and lead to too low values of f. The adopted values lead to a branching ratio, towards the fundamental level, of 30%, in agreement with the experimental value of $27 \pm 3\%$, found by SALOMAN and HAPPER (1966). The transition $^1S_0$–$^3P_1^0$ has not been taken into account because its contribution in (1) is quite negligible.

The oscillator strengths of the lines λ3683 and 3740 Å have been normalized to the same absolute scale as that obtained from the life-time measurement of the $^3P_1^0$ level and the relative 'f-values' adopted in Table IV.

Our results are to be found in Table III. They are in excellent agreement with recent values derived in the same way by LAMBERT (1967), PEACH (1968) and DE ZAFRA and MARSHALL (1968).

TABLE IV

Relative f-values for the Pb I lines

λ(Å)	PENKIN and SLAVENAS (1963)	KHOKHLOV (1961)	BROWN (1966)	Adopted values
2833	139	70.6	–	139
3640	41.25	32.9	28.06	41.25
4058	100	100	100	100
7229	–	22.35	–	22.35
3683	75.83	57.65	50.4	75.83
3740	–	127.06	–	127.06

2.4. ANALYSIS OF THE Pb I LINES AND DISCUSSION

The abundance has been determined by two methods. First, it has been derived by the classical method based on the equivalent widths of the Pb I lines. The abundance is obtained by computing line profiles of the Pb I lines, until agreement is obtained between W_λ observed and computed. The second method is based on the comparison between observed and theoretical profiles of the lines or of rather large spectral region when the lines are blended.

The computations have been made with the photospheric model given by ELSTE (1968). The continuous absorption coefficients have been taken from BODE (1965).

At each wavelength, we have to take into account the opacity due to the different lines, before integrating the profile. Sometimes, lines contributing to the opacity are unidentified. Such lines have generally been treated as metallic lines. Furthermore, the damping constant has to be considered as a parameter which is adjusted, in each case, to fit the computed line wings with the observed ones. Generally, the empirical damping constant appears to be greater than the computed one even when rigorous treatment, such as given by WARNER (1967), is used (DE JAGER and NEVEN, 1968). This method has been used recently by ROSS *et al.* (1968) for the Pb I solar lines and by GREVESSE (1968) in the case of the Be II solar lines. We have to point out that the

method of comparison between observed and computed profiles, needs, in certain cases, numerous trials.

We shall now describe, in detail, the results obtained for each Pb I line.

2.4.1. λ3683.480 Å

Figure 2 shows the solar spectrum around this line. The profile has been computed including the different lines indicated in Figure 2. We also took into account the absorption by the line λ3683.063 Å (Fe I + V I + Co I). This line is not represented in

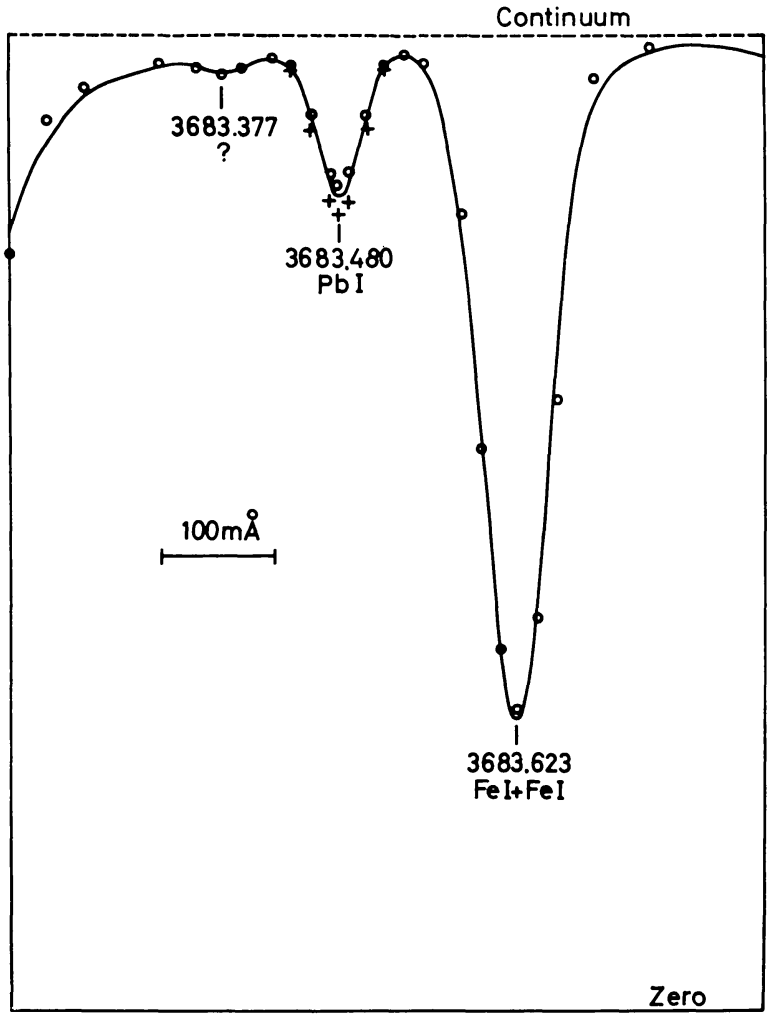

Fig. 2. Solar spectrum around the Pb I λ3683.480 Å line (full line). Open circles represent the spectrum computed for $\log N_{Pb} = 1.65$ and crosses for $\log N_{Pb} = 1.75$.

Figure 2. As already stated, unidentified lines have been handled as metallic lines. This method is not a source of error because we only have, for such lines, to compute their contribution to the line opacity at the wavelengths around the Pb I line. As can be seen, the agreement between the observed and computed spectra is excellent.

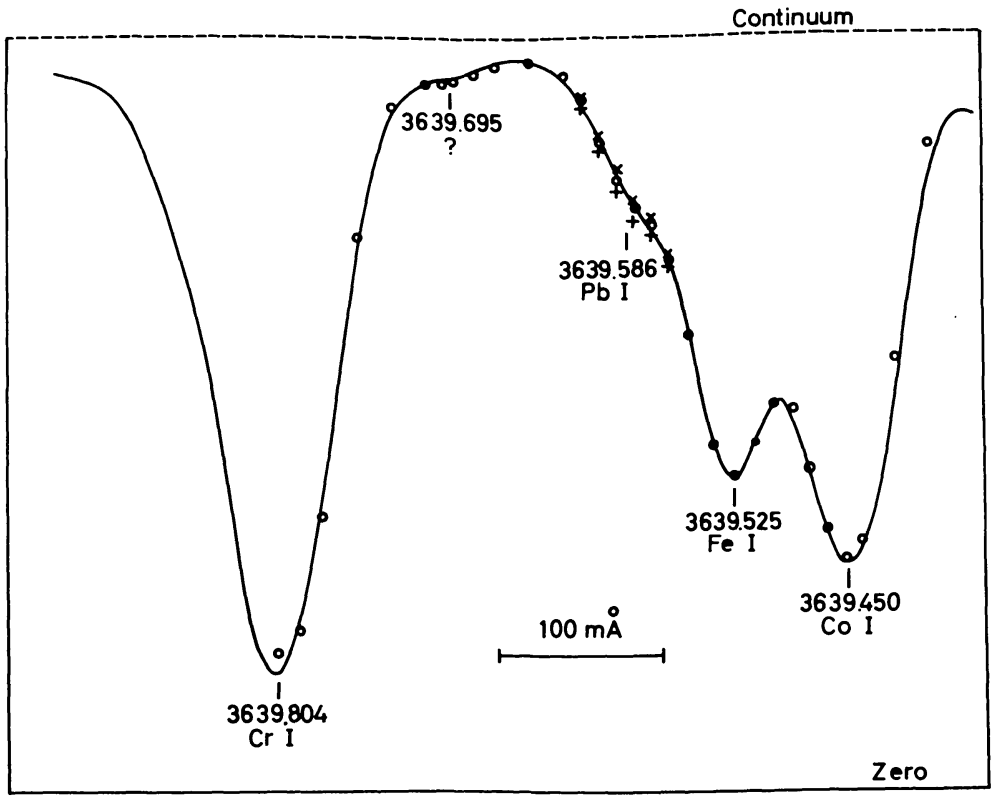

Fig. 3. Solar spectrum around the Pb I λ3639.586 Å line. ○ $\log N_{Pb} = 2.07$; + $\log N_{Pb} = 2.12$ and × $\log N_{Pb} = 2.02$.

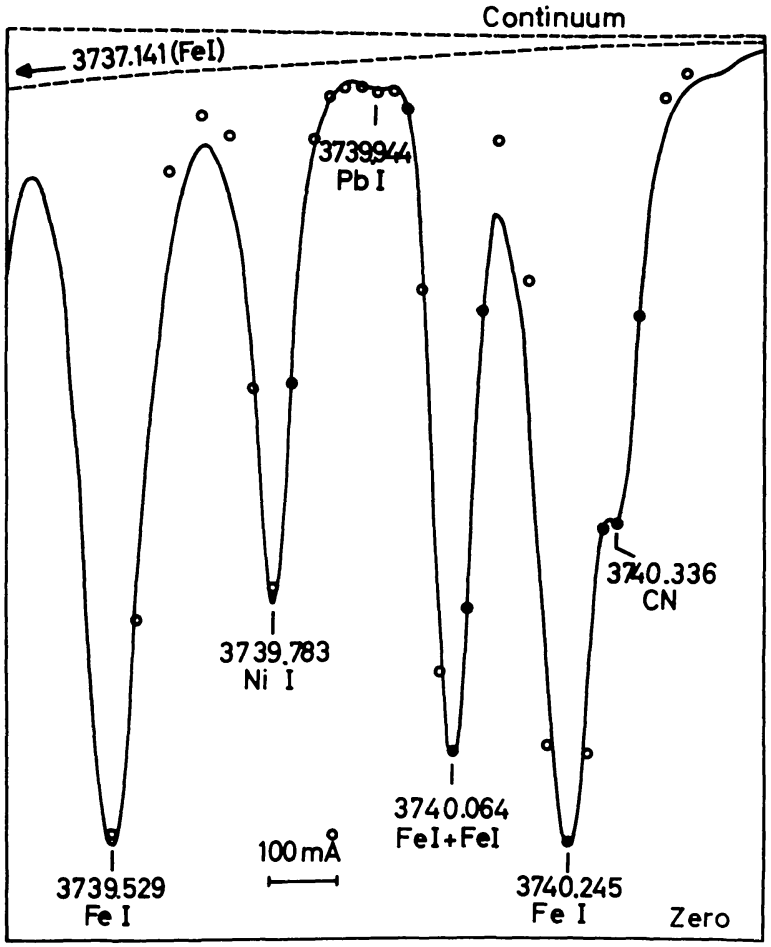

Fig. 4. Solar spectrum around the Pb I λ3739.944 Å line. ○ $\log N_{Pb} = 1.79$.

2.4.2. λ3639.586 Å

Here also, the agreement between observed and computed spectra (Figure 3) is excellent. The lines taken into account are indicated.

2.4.3. λ3739.944 Å

The analysis of this line (Figure 4) is more difficult. This is due to the numerous lines which have to be taken into account and to the faintness of this line. We have also included the opacity due to the strong Fe I line, λ3747.141 Å. Numerous trials have been necessary to obtain the agreement between the observed and computed spectra as shown in Figure 4.

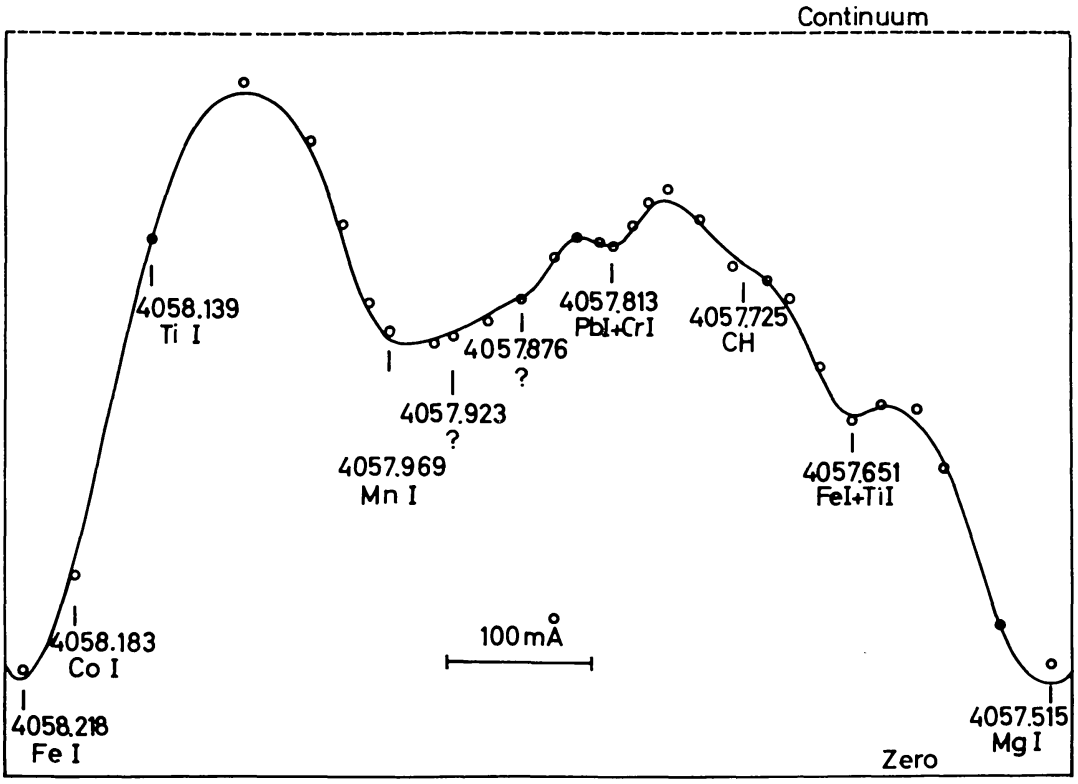

Fig. 5. Solar spectrum around the Pb I λ4057.813 Å line. ○ $\log N_{Pb} = 1.72$.

2.4.4. λ4057.813 Å

This line (Figure 5) is very difficult to analyse. It is strongly blended by neighbouring lines. Furthermore a Cr I (multiplet no. 251) is directly superimposed on the Pb I line. We estimated the oscillator strength of this Cr I line to be $\log gf = -1.43$, on the basis of the Cr I oscillator strengths given by WOLNIK *et al.* (1968) and of the tables of WHITE and ELIASON (1933). The contribution of this line has been computed for $\log N_{Cr} = 5.70$. This chromium abundance has been obtained from a new study of the solar chromium lines, using the oscillator strengths of WOLNIK *et al.* (1968). The final agreement between observed and computed spectra is good. Nevertheless, we shall

give less weight to the result obtained from this line. This is due to the contribution, rather uncertain, of the Cr I line.

2.4.5. λ7229.036 Å

Many authors have discussed the presence of this line in the solar spectrum.

KHOKHLOV (1960) was the first to investigate its possible presence in the solar spectrum. He suggested also that atmospheric water vapour absorption could play a role in this region.

DE JAGER and NEVEN (1962) showed that the atmospheric absorption was less than 0.2% in new spectra they obtained at the Jungfraujoch. They found a line of $W_\lambda = 0.26$ mÅ at λ7229.019 Å which they attributed to Pb I.

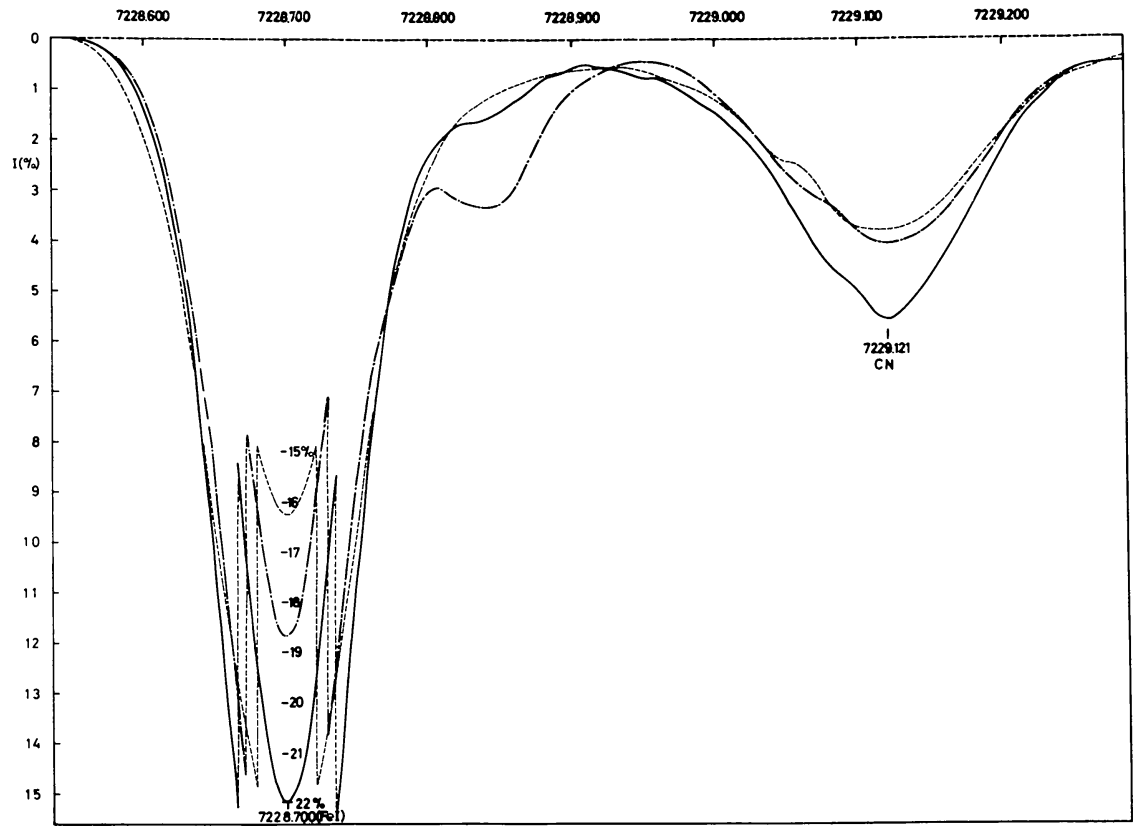

Fig. 6. Comparison of different solar tracings in the region of the Pb I λ7229 Å line; full line: this work; dashed line: DE JAGER and NEVEN (1962); dot-dashed line: PEACH (1968) for sec Z = 1.75.

Recently, PEACH (1968) took new spectra in this region, with the Oxford spectrometer and for numerous different elevations of the sun. He showed that there was absorption by water vapour around the wavelength of the Pb I line. He took this absorption into account and found that the residual absorption feature at λ7229.030 Å had an equivalent width, $W_\lambda = 0.29$ mÅ.

We also observed this spectral region at the Jungfraujoch for different heights of the sun. No variation of the spectra with sec Z was detectable.

In Figure 6, we compare our tracing with the spectra obtained by De Jager and Neven and by Peach. If we look at the central intensities of the lines, it is evident that a greater resolution is reached in our spectrum. We have also to point out that the continuum given by De Jager and Neven and by Peach has been drawn between λ7228.55 Å and λ7229.29 Å. On each of our spectra we found a perfectly flat continuum between λ7228.55 Å and λ7229.75 Å, the absorption at λ7229.29 Å being in each case of the order of 0.5%. If we did not find, like De Jager and Neven, any variation of the spectrum with sec Z, this is due to the fact that these spectra have been obtained at high altitude on rather dry days and in a rather small range of sec Z (1.35 to 1.75). Nevertheless, the absorption by H_2O is still present and difficult to take into account quantitatively. By decomposition of the absorption between 7228.8 and 7229.1 in three components (as De Jager and Neven and Peach did) we would obtain too high a value for the contribution of the lead line. This is what we erroneously did previously (GREVESSE, 1967).

We shall admit the equivalent width derived by PEACH (1968), keeping in mind that this equivalent width has to be slightly increased to $\approx$0.35 mÅ following the remark we made about the continuum.

2.5. RESULTS

The abundances obtained from the study of the five Pb I lines are given in Table V.

The uncertainties mentioned in the last column of Table V, are derived from the probable errors in the '*gf* values' ($\pm$0.05) and from the quality of the fit between observed and computed spectra.

TABLE V

The abundance of lead derived from five Pb I lines

λ(Å)	Transition	E.P.(eV)	log *gf*	Weight	$\log N_{Pb}$	
					[a]	[b]
3639.580	$^3P_1$–$^3P_1^0$	0.97	−0.77	2	1.97	2.07 ± 0.10
4057.813	$^3P_2$–$^3P_1^0$	1.31	−0.17	1	1.56	1.72 ± 0.15
3683.480	$^3P_1$–$^3P_0^0$	0.97	−0.51	3	1.74	1.67 ± 0.07
3739.944	$^1D_2$–$^3P_2^0$	2.65	−0.06	1	2.30	1.79 ± 0.15
7229.974	$^1D_2$–$^3P_1^0$	2.65	−0.82	0.5	2.08	–

[a] Classical method (W_λ).
[b] Method by fitting observed and computed profiles.

It can be seen that the two methods lead to rather different results. These discrepancies increase with the difficulty of measuring the equivalent width, i.e. with the degree of blending of the spectral region. This shows how careful one has to be when graphically deriving equivalent width of lines which are blended. Only the method of fitting observed and computed profiles may lead to better results. The weights we give to the different lines only depend on the degree of perturbation of the spectral region.

The weighted mean of the solar lead abundance is:

$$\log N_{Pb} = 1.83 \pm 0.10 .$$

Let us remark that we did not take an extra-opacity into account below the Balmer discontinuity. This extra-opacity seems to be necessary to explain the discrepancies between the observed and predicted continuous intensity at the centre of the solar disk, below 3647 Å. This would only very slightly affect the result obtained for the first line of Table V.

Our result slightly disagrees with the recent value obtained by Ross *et al.* (1968), using the same technique. Their value is $\log N_{Pb} = 2.02$ (revised by using our '*gf*-values' scale). Nevertheless, our result is in good agreement with the value given by Lambert *et al.* (1968), $\log N_{Pb} = 1.90 \pm 0.10$, a value which has been obtained by rediscussing the results of Ross *et al.* (1968) and Grevesse (1967) from the point of view of the oscillator strengths' absolute scale.

3. Solar Abundance of Bismuth

3.1. Introduction

A tentative identification of Bi I lines in the solar spectrum, between 2200 and 3100 Å, was made by Kachalov (1963). He identified the Bi I lines λ3067.712 Å and λ2730.51 Å on solar spectra, obtained by means of rockets, with a resolution varying between 600 mÅ (at 2200 Å) and 150 mÅ (at 3000 Å). Kachalov derived the abundance of bismuth from the equivalent width of the λ3067.716 Å line: $\log N_{Bi} = 1.20$.

We showed (Grevesse, 1966) that the identification of this line is erroneous. In Figure 7, we reproduce the solar spectrum, between 3066.3 and 3069.3 Å, obtained at the Jungfraujoch International Scientific Station by L. Delbouille, G. Roland and L. Neven. The theoretical resolution is of the order of 3 mÅ at that wavelength. As can be seen, there is no trace of the Bi I line at λ3067.712 Å. We then reduced the resolution of the spectrometer by making the convolution of our spectrum with gaussian instrumental profiles with half-widths equal to 150 mÅ and 240 mÅ. The spectra obtained after convolution are represented by the curves C1 (150 mÅ) and C2 (240 mÅ). C2 is in agreement with Kachalov's spectrum (curve K). The depression at the wavelength of the Bi I line is clearly visible on C2 as on K. It results from the convolution of two OH lines, λ3067.655 Å and λ3067.777 Å, with the instrumental profile used. It cannot be attributed to Bi I, as proposed by Kachalov. The agreement between Kachalov's bismuth abundance and the meteoritic abundance is a pure coincidence.

3.2. Determination of the upper limit of the solar bismuth abundance

We recomputed the profile of the spectral region between 3066.750 Å and 3068.040 Å, taking into account the contributions of the following lines: λ3067.246 (Fe I), 3067.665 (OH), 3067.777 (OH), 3067.920 (Fe I) and 3067.946 Å (Fe I). These computations were made with the B.C.A. photospheric model (Gingerich and De Jager, 1968). The

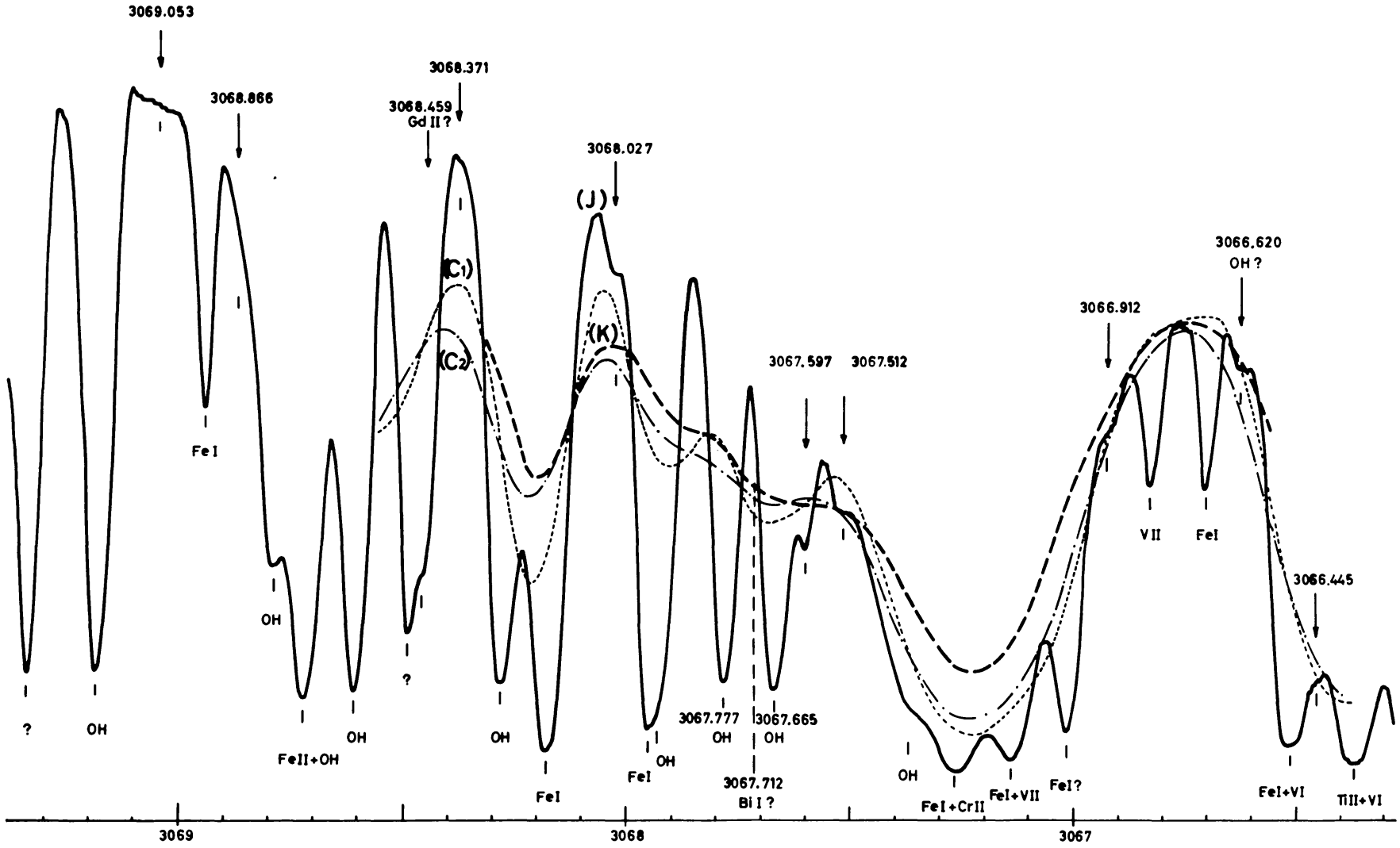

Fig. 7. Solar spectrum around the Bi I λ3067.712 Å. See text.

differences between this model and ELSTE's 1968 model used for the Pb I lines, are not significant from the point of view of abundances determinations. After many trials, we obtained the agreement shown in Figure 8. We have to point out that the continuum cannot be drawn with high precision in this spectral region. We did not take faint lines into account because these lines do not play a role, as far as the opacity at the wavelength of the Bi I line is concerned.

We then added the contribution of the Bi I line, λ3067.712 Å, for different values of the bismuth abundance. The spectra (1), (2), (3) and (4) of Figure 8 are thus obtained for $\log N_{Bi} = 1.73$, 1.13, 0.83 and 0.53.

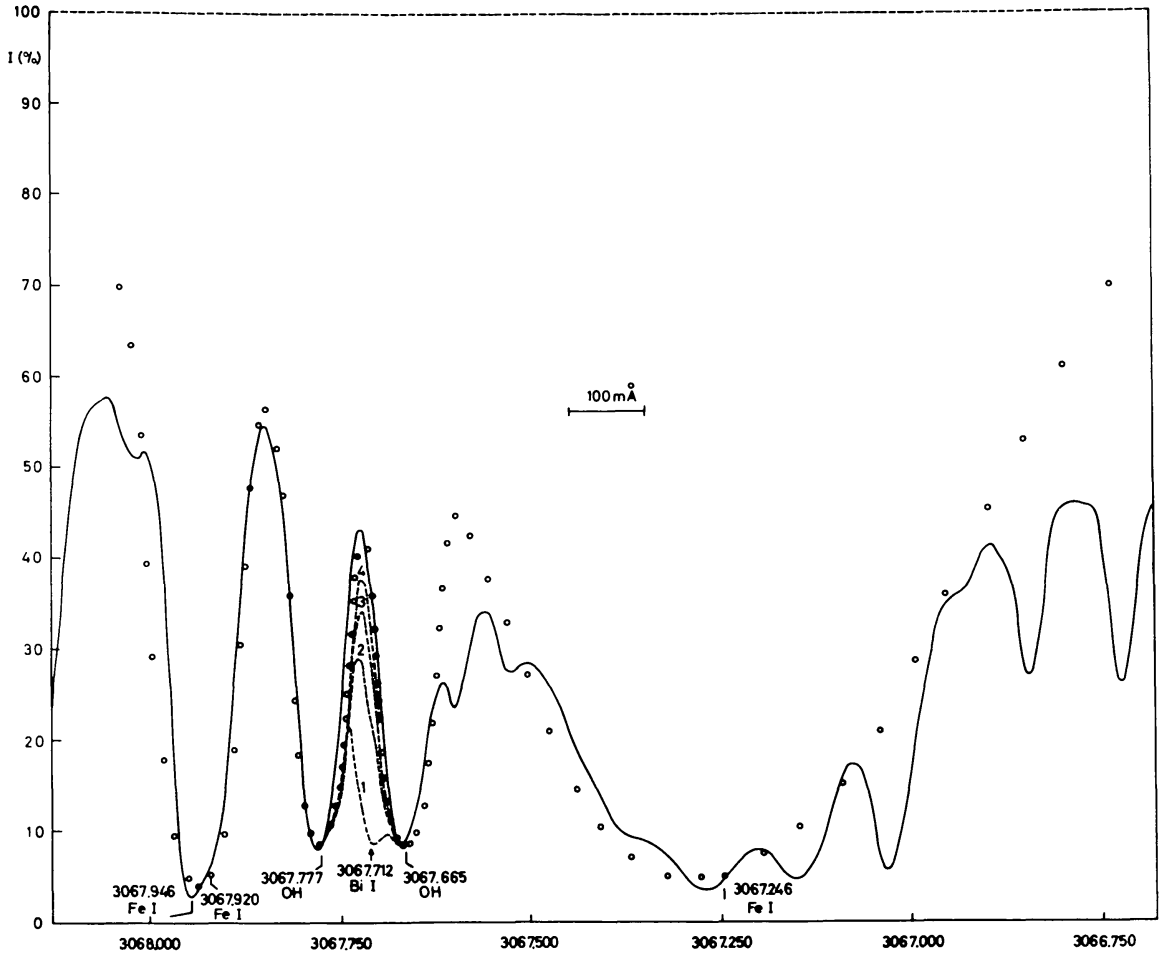

Fig. 8. Comparison of the observed and computed spectra around the Bi I λ3067.712 Å. Open circles represent the spectrum computed without bismuth. Curves (1)–(4) are obtained after taking bismuth into account (see text).

The oscillator strength was computed from the life-time of the level $7s^4P_{1/2}$, $\tau = 5.9 \times 10^{-9}$ sec, given by CUNNINGHAM and LINK (1967) and from the only relative oscillator strengths available, those of CORLISS and BOZMAN (1962) for the lines λ3067.7 Å and λ4722.5 Å. The contribution of the line λ9149 Å is negligible. We found $f(3067.712) = 0.116 \pm 0.008$. This value is in agreement with the experimental values derived by RICE and RAGONE (1965), $f = 0.132$, and LVOV (1965), $f = 0.077$.

After examination of Figure 8, it seems to us reasonable to admit, because of the uncertainty on the continuum and on the continuous opacity in this spectral region, that

$$\log N_{Bi} \leqslant 0.80 .$$

4. Solar Thorium Abundance

4.1. Introduction

Sitterly and King (1943) were the first to suggest the presence of the *raie ultime* of Th II, λ4019.137 Å [$(6d7s^2)\, a^2D_{3/2}$–$(5f\, 6d^2)\, 4F^0_{5/2}$, E.P. = 0.00 eV], in the solar spectrum.

Severny (1958) measured the equivalent width of this line, $W_\lambda = 4.97 \pm 2.16$ mÅ. From this value, he derived $N_{Th}/N_{Pb} \leqslant \approx 0.01$. This would lead to $\log N_{Th} = -0.17$. This value, anomalously low, of the N_{Th}/N_{Pb} ratio is quite unexplainable on the basis of the nucleosynthesis theories.

Khokhlov (1959b) already suggested that the ratio $N_{Th}/N_{Pb} \cong 0.01$ found by Severny (1958) should be increased to 0.25.

4.2. Determination of the solar thorium abundance

We recorded the solar spectrum around the Th II line. The tracing obtained is represented in Figure 9. The equivalent width was derived graphically; we found $W_\lambda =$

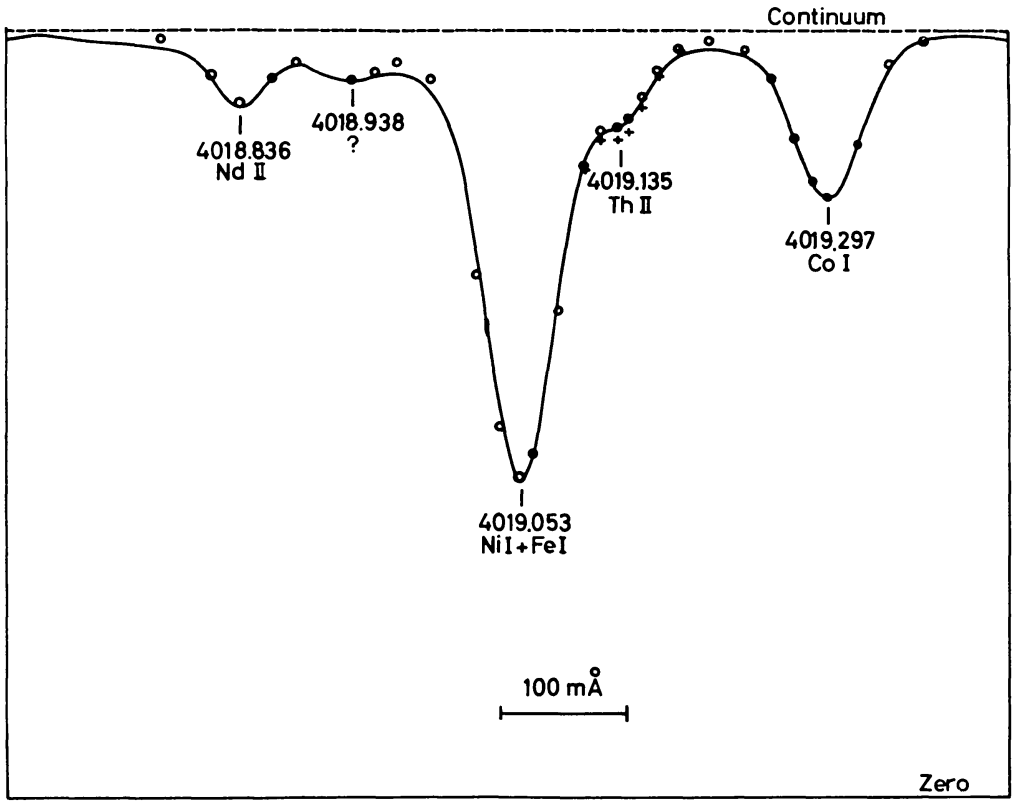

Fig. 9. Solar spectrum around the Th II λ4019.137 Å. ○ $\log N_{Th} = 0.80$ and + $\log N_{Th} = 0.90$.

5.0 mÅ. The abundance was determined by the two methods already used in the Pb I case. The profile of the spectral region around the Th II line, computed with Elste's model is represented in Figure 9.

The oscillator strength of the *raie ultime* of Th II is not well known. CORLISS and BOZMAN (1962) give $\log gf = -0.80$. VAN RENSBERGEN (1967) computed this "gf value" and found $\log gf = -1.22$. We adopted $\log gf = -1.00$.

The ionization potentials of thorium are not yet known with high accuracy. We adopted the following values:

$$\text{I.P. (Th I)} = 6.95 \text{ eV (IONOV and MITTSEV, 1961)}$$
$$\text{I.P. (Th II)} = 12.00 \text{ eV (ALLEN, 1963).}$$

This last value has never been determined in the laboratory. In any case, the abundance of thorium is not very sensitive to the value of the I.P. (Th II).

The solar thorium abundance computed from the fit of the observed and theoretical spectra is

$$\log N_{\text{Th}} = 0.82 \pm 0.05 .$$

The error quoted is based on the quality of the fit. From the equivalent width of the line, we found $\log N_{\text{Th}} = 0.87$. This agreement is easily explained if we notice that the Th II line is not too much blended in the solar spectrum.

4.3. Search for other thorium lines in the solar spectrum

Because of the low ionization potential, Th II is more likely to be present in the solar spectrum than is Th I.

The Th II laboratory spectrum (ZALUBAS, 1960) shows a great number of lines with almost the same intensity. The equivalent widths and profiles of the most intense of these lines, between 3000 Å and 4000 Å, was computed using the oscillator strengths of CORLISS and BOZMAN (1962) and the abundance determined from the λ4019.137 Å line. The W_λ obtained varies between 1 and 3 mÅ. Unfortunately, all of these lines, which are in principle detectable, are strongly blended. Thus, it seems to be hopeless that any other thorium line than the *raie ultime* could be detected in the visible solar spectrum.

5. Search for Uranium in the Solar Spectrum

If present at all, uranium has to be detectable under the form of U II lines. We proceeded as for Th II. The U II laboratory spectrum has also numerous lines of approximately equal intensity. The *raie ultime*, λ3859.58 Å should be about 3 times more intense than the other U II lines. All the lines of U II which could be detectable lie in the spectral range from 3500 Å to 4500 Å. From a systematic search for U II in the high resolution solar tracings obtained by L. Delbouille, G. Roland and L. Neven, we found many very faint lines coinciding with U II lines. The most sensitive U II line, λ3859.58 Å is, unfortunately, strongly blended. From the coincidences, it is premature

to conclude that uranium is present in the solar spectrum but we can estimate that the abundance of uranium in the sun cannot be greater than $\log N_U \cong 0.60$. This last value is, indeed, rather uncertain.

We have to point out that this result is in agreement with the value predicted by SEEGER *et al.* (1965). They found that, at the start of the solar system, the uranium abundance is 0.445 (in the scale where $N_{Si} = 10^6$). This value gives N_U (now) $= 0.093$ (in the same scale) or $\log N_U = 0.52$ in the $\log N_H = 12.00$ scale.

The search for uranium lines in the solar spectrum will be pursued in the future.

6. Conclusions

It is interesting to compare our results with the meteoritic abundances and with the values predicted on the basis of nucleosynthesis theories. In Table VI, all these values are given in the scale where $N_{Si} = 10^6$. The adopted Si abundance is $\log N_{Si} = 7.55$ (in the $\log N_H = 12.00$ scale) (LAMBERT and WARNER, 1968; GREVESSE, unpublished). We put the solar values for Bi and U in brackets as they are rather uncertain.

TABLE VI

Comparison of heavy elements abundances (Si = 10^6)

	Sun	Meteorites	Nucleosynthesis
Pb	1.91 [2.86]	1.6	6.5 ±3
Bi	(≤ 0.18) [≤ 0.27]	0.17	0.46
Th	0.19 [0.28]	0.027	0.24 ±0.06
U	(≤ 0.11) [≤ 0.16]	0.009	0.093 ± 0.023

The solar abundances of these elements could have been affected by thermal and gravitational diffusion (ALLER and CHAPMAN, 1960; DELCROIX and GREVESSE, 1968) at the bottom of the convection zone. From the results of DELCROIX and GREVESSE (1968) we estimated, taking into account the relative diffusion velocities of Si and the Pb, Bi, Th and U group, that to be comparable to meteoritic or predicted abundances the solar abundances of the latter group should be increased by a factor ~1.5, leading to the values given in square brackets in Table VI.

The meteoritic abundances have been taken from UREY (1967). We have to point out here that direct comparison between solar and meteoritic data is not at all meaningful for Pb and Bi. It is well known (UREY, 1964; CLAYTON *et al.*, 1961) that, because of their low melting points, these elements are easily removed in the formation of the meteorites. This fractionation seems to be the lowest in carbonaceous meteorites.

The abundances predicted by the nucleosynthesis have been adopted from CLAYTON *et al.* (1961) for Pb and Bi and from SEEGER *et al.* (1965) for Th and U. Here also, it must be emphasized that:

(1) s-process contribution (for Pb and Bi only) are difficult to predict because the cross-sections for neutron capture by these elements are not yet known with accuracy (see e.g. CLAYTON, 1964).

(2) r-process contributions are computed on a relative scale; absolute values rely upon normalization to observed abundances for heavy elements; these observed abundances are themselves rather uncertain. The so-called normalization factor, r or $r' = 0.30$ (see e.g. FOWLER and HOYLE, 1960; CLAYTON, 1963, 1964), by which the predicted values for the r-process contributions have to be multiplied to give absolute abundances, appears to be correct. Our new solar abundance of lead gives, using CLAYTON's (1963) relation, $r' = 0.325 \pm 0.03$, very close to the adopted value.

When comparing the values given in Table VI, we have to keep in mind the above mentioned remarks.

Better than comparing absolute abundances is to compare relative abundances, the predicted values of which should be more reliable (Table VII). From this comparison, it can be seen that the solar ratios are in agreement with those predicted by the nucleosynthesis theories. For Th and U our results disagree with the meteoritic abundances.

TABLE VII

Comparison of relative abundances

	Sun	Meteorites	Nucleosynthesis
Bi/Pb	$\leqslant 0.094$	0.106	$0.07\ ^{+0.06}_{-0.02}$
Th/Pb	0.1	0.017	$0.06\ ^{+0.03}_{-0.04}$
U/Pb	$\leqslant 0.057$	0.0056	$0.014\ ^{+0.019}_{-0.007}$

We feel confident to say that the agreement between solar and predicted abundances make good sense for the s-process, the r-process, the rate of stellar activity and the galactic and solar time scales adopted in nuclear cosmochronology (FOWLER and HOYLE, 1960; FOWLER, 1967).

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