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ABUNDANCES OF THE RARE EARTHS IN THE SUN

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Abstract. We have determined the solar abundances of the rare earths (La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Tm, Yb, Lu) on the basis of measurements made on new high-resolution tracings of the solar spectrum obtained at the International Scientific Station of the Jungfraujoch (Switzerland) by L. Delbouille, L. Neven and G. Roland. Our results (Table XV) are compared with those of other authors for the sun and meteorites as well as with the abundances predicted by nucleosynthesis theories.

1. Introduction

The importance of the presence of the rare earths, as well as the intensities of their lines, as indicators of certain peculiarities in stellar spectra (Ap, Am, Ba and CH stars) has been recognized by numerous authors since the works of Struve and Swings (1943). Furthermore the importance of the abundances of the rare earths, from the point of view of the nucleosynthesis, as tests of the s- and r-processes, has been stressed by Burbidge *et al.* (1957) and, more recently, by Seeger *et al.* (1965).

In recent years, many efforts have been devoted to the spectroscopic analysis of the first and second spectra of these elements (principally at the National Bureau of Standards), to the determination of the absolute oscillator strengths of their lines (Corliss and Bozman, 1962) and to the determination of their ionization potentials (Sugar and Reader, 1965; Reader and Sugar, 1966). However, up to now, several of these spectra are not yet completely known. The progress that has been made in the spectroscopic knowledge of these elements has led to the determination of the solar abundances of part of them: La, Ce, Pr, Nd, Sm, Eu and Gd (Wallerstein, 1966); Ce, Pr, Nd, Sm, Eu, Gd and Dy (Righini and Rigutti, 1966).

Since these works, new high-resolution solar spectra have been obtained allowing more accurate measurements of equivalent widths and of profiles of the Fraunhofer lines.

On the basis of these new observations, we have determined the solar abundances of all the lanthanides present in the photospheric spectrum, from La (Z = 57) up to Lu (Z = 71). The solar abundances of Er, Tm and Lu are determined for the first time.

2. Methods

For lines whose equivalent widths (W_λ) are easily measurable, we used the method of direct integration of the line profiles. We iterate on the abundance until a theoretical profile is obtained whose W_λ is equal to the observed equivalent width.

Different models of the solar photosphere have been used: Mutschlecner (1963),

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HOLWEGER (1967), LAMBERT (1968), B.C.A. (GINGERICH and DE JAGER, 1968) and ELSTE (1968). The lines of the rare earths are generally faint; they are formed in layers where the different solar models are in relatively good agreement. As the deviations between the abundances computed from the different models are of the order of 0.05 in the logarithm of the abundance, we shall only give the results obtained for Elste's model.

The continuous absorption coefficients published by BODE (1965) have been used in our analysis. For each of the elements Er, Yb and Lu, only one badly blended line is available. In such cases, a more elaborate method to determine the abundance had to be used. The profile of the spectral region in the neighbourhood of the line is computed, taking into account the contribution of all the lines. This profile is then compared to the observed one. The abundance of the element concerned is varied and the computations are repeated until observed and computed profile agree. Once this agreement obtained, it gives us the contribution of the line of the rare earth to the observed spectrum and the corresponding abundance.

3. Experimental Data

The measurements of the equivalent widths of the lines have been made on new tracings of the solar spectrum obtained at the International Scientific Station of the Jungfraujoch (Switzerland; altitude 3580 m) by L. Delbouille, G. Roland and L. Neven. The high resolution of these spectra permits a more accurate determination of the profiles and equivalent widths of the lines than before. The observed profiles are very close to the true profiles and, in most of the spectral regions considered, the solar continuum can be drawn with accuracy.

The lines have been selected with the help of the tables published by MOORE *et al.* (1966) (M.M.H.). The elements La, Ce, Pr, Nd, Sm, Gd and Dy show a large number of lines in the solar spectrum. For these elements, it has been possible to eliminate blended lines. For the other rare earths, it has been necessary to include blended lines in our study because of the relatively small number of lines of these elements in the solar spectrum (MOORE, 1963; MOORE *et al.*, 1966). The ionization potentials have been determined by READER and SUGAR (1966) (atoms) and by SUGAR and READER (1965) (ions).

We used the only available oscillator strengths for these elements; those of CORLISS and BOZMAN (1962). Their absolute and relative scales have been doubted many times recently (COWLEY and WARNER, 1967; HUBER and TOBEY, 1968). Nevertheless, according to WARNER and COWLEY (1967), the normalization factor adopted by Corliss and Bozman should be correct for the rare earths and the oscillator strengths should therefore be free of systematic errors.

The rare earths being mostly once-ionized in the solar photosphere, it is easy to show that the abundances are practically directly proportional to the partition functions of the ions (u_1) and almost insensitive to the partition functions of the neutral elements (u_0). We recomputed the partition functions for different temperatures and from the most recent available spectroscopic data. Our partition functions do not differ appreciably from those given by CORLISS (1962).

We should also point out that the profiles of the lines of the rare earths (with the exception of La, Pr, Tm, Tb and Ho) must be affected by isotopic effects. Since there are only few data available for these elements, we did not take this effect into account. We believe, however, this approximation does not introduce errors in the abundances because most of the lines used are faint.

4. Results and Discussion

A. LINES OF ONCE-IONIZED RARE EARTHS

The results obtained from the study of the lines of once-ionized elements are given in Tables I to XII. For each of the rare earths we give the atomic number (Z), the ionization potential of the atom (X_{I}) and of the ion (X_{II}), and, for each line, the solar wavelength (M.M.H., 1966), the equivalent width (W_λ), in mÅ given by M.M.H., the W_λ measured on the tracings obtained at the Jungfraujoch, the multiplet number, the excitation potential (E.P.), the oscillator strength (log *gf*), the weight we shall give to the result obtained from this line and, in the last column, our value of the abundance ($A_{\mathrm{el}} = \log N_{\mathrm{el}}$ in the scale where $\log N_{\mathrm{H}} = 12.00$). The weight given to each line varies between 1 and 4; weight 4 corresponds to a line whose wings are free from blends and to a spectral region where the continuum can be determined accurately; weight 1 is attributed to a line whose W_λ cannot be measured with accuracy; weights 2 and 3 represents intermediate cases.

At the bottom of each table, we also give the weighted mean abundance and the standard deviation.

It can be seen that the dispersion of the results is rather important in certain cases. This may be due to random errors in the oscillator strengths and to the presence of some unidentified lines at the wavelengths of the lines of the rare earths.

It should also be noted that for certain elements we used lines which were not identified with certainty by M.M.H. (these lines have been marked with asterisks in the tables). The good agreement between the abundance deduced from these lines with the final abundance of a given element enables us to ascertain their identification.

On the contrary the lines λ 3313.304, 4129.724, 6645.127 and 6173.065 Å which were identified as Eu II lines by M.M.H. lead to much higher abundances than the other Eu II lines (Table VIII). We therefore did not take these lines into account in the computation of the Eu abundance, where we only considered the lines giving rise to the smaller abundance. We believe that the 4 above-mentioned lines are only partly due to Eu II.

For Yb, Lu and Er, the abundances have been derived from only one line for each element. Furthermore, each of these lines is badly blended and located in the ultraviolet, when the true continuum cannot be determined with accuracy. In the case of Er II, the line is even not identified with certainty. Our results, for these three elements, have to be considered with caution.

Tables I-XII: Spectroscopic data and results

TABLE I

La II $Z = 57$ $X_{\text{I}} = 5.58$ $X_{\text{II}} = 11.06$

λ	$W_\lambda^{\text{M.M.H.}}$	W_λ^{Joch}	No. Mult.	E.P.	$\log gf$	weight	A_{el}
5797.601	1.5	4.5	4	0.24	−2.30	1	2.17
4086.712	42.0	41.8	10	0.00	−0.60	3	1.46
4333.763	35	42.4	24	0.17	−0.60	1	1.61
4322.505	12	18.5	25	0.17	−1.62	4	2.17
3713.554	7.5	11.1	26	0.17	−1.18	1	1.55
5123.006	11	9.3	36	0.32	−1.78	3	2.09
4123.234	–	45.7	41	0.32	−0.40	2	1.62
4748.737	4	3.8	65	0.93	−1.20	1	1.72
4619.897	2.5	3.6	76	1.75	−0.24	2	1.51
5188.238	5.0	2.2	95	2.45	0.05	3	1.63
5377.064	4.0	2.3	95	2.30	−0.43	3	1.99

$\text{Log}\, A_{\text{La}} = 1.81 \pm 0.27$

TABLE II

Ce II $Z = 58$ $X_{\text{I}} = 5.65$ $X_{\text{II}} = 10.85$

λ	$W_\lambda^{\text{M.M.H.}}$	W_λ^{Joch}	No. Mult.	E.P.	$\log gf$	weight	A_{el}
4562.367	17	19.6	1	0.48	−0.07	4	1.74
4382.167	8	7.9	2	0.68	−0.17	1	1.63
4523.080	12	12.2	2	0.52	−0.45	4	1.93
4560.966	4.5	5.5	2	0.68	−0.70	3	1.97
4073.486	18	15.4	4	0.48	0.05	2	1.55
4127.376	16	20.5	4	0.68	−0.04	2	1.97
4593.935	12	12.2	6	0.70	−0.26	2	1.90
4560.278	13	13.5	8	0.91	−0.15	2	2.05
5187.457	5.5	4.5	15	1.21	−0.07	2	1.72
5274.236	6.5	8.1	15	1.04	−0.30	4	2.05
4773.959	8.5	8.8	17	0.92	−0.56	3	2.26
4444.401	5.5	4.0	19	0.92	−0.23	1	1.61
5117.166*	3	2.6	23	1.40	−0.24	2	1.84
5472.304	3	1.9	24	1.25	−0.51	3	1.79
5512.062	9	8.5	24	1.01	−0.49	4	2.22
4053.491	7	9.7	36	0.00	−0.83	2	1.76
4222.602	22	29.2	36	0.12	−0.44	2	2.00
3942.155	10	13.0	37	0.00	−0.34	1	1.41
3534.064	14	11.1	44	0.52	−0.01	2	1.61
3999.243	16	19.3	57	0.30	0.09	1	1.46
4486.914	11	14.6	57	0.30	−0.62	3	1.97
4083.226	26	25.6	60	0.70	−0.04	2	2.11
3501.466	12	11.7	67	0.23	−0.84	1	2.19
4399.224	5.5	6.6	81	0.33	−0.78	3	1.82
4068.834	3.5	5.2	82	0.70	−0.36	1	1.68
3417.486*	6	5.4	100	0.70	−0.08	1	1.55
4031.340	12	16.5	108	0.32	−0.43	1	1.91
4120.838	13	10.4	112	0.32	−0.74	2	1.99
3539.076	12	11.5	118	0.32	−0.11	1	1.54

* lines identified as Ce II? by M.M.H.

(Table II continued)

Ce II $Z = 58$ $\chi_{\text{I}} = 5.65$ $\chi_{\text{II}} = 10.85$

λ	$W_\lambda^{\text{M.M.H.}}$	W_λ^{Joch}	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3246.684*	12	7.8	130	0.42	−0.40	2	1.79
4364.663	12	13.9	135	0.50	−0.35	4	1.88
4042.592	13	10.2	140	0.50	−0.22	3	1.65
4361.668	2	4.3	157	0.53	−1.17	2	2.21
3989.452*	5	3.7	240	0.90	−0.20	1	1.56
4943.448*	1.5	2.2	–	1.21	−0.55	2	1.90

$\log A_{\text{Ce}} = 1.88 \pm 0.21$

* lines identified as Ce II? by M.M.H.

TABLE III

Pr II $Z = 59$ $\chi_{\text{I}} = 5.42$ $\chi_{\text{II}} = 10.55$

λ	$W_\lambda^{\text{M.M.H.}}$	W_λ^{Joch}	No. Mult.	E.P.	$\log gf$	weight	A_{el}
4651.511	5	3.1	6	0.20	−1.63	2	1.84
3994.810	15	11.7	11	0.05	−0.65	1	1.37
5259.735	3	4.4	35	0.63	−0.83	4	1.56
5173.911	3.5	3.9	35	0.97	−0.52	1	1.54
5322.819	2	3.0	35	0.48	−1.19	2	1.60
5219.028	2.5	3.3	37	0.79	−0.93	3	1.70
5509.114*	0.5	0.5	–	0.48	−2.02	1	1.64
5352.405*	–	1.9	–	0.48	−1.52	1	1.73

* lines identified as Pr II? by M.M.H.

$\log A_{\text{Pr}} = 1.63 \pm 0.12$

TABLE IV

Nd II $Z = 60$ $\chi_{\text{I}} = 5.49$ $\chi_{\text{II}} = 10.73$

λ	$W_\lambda^{\text{M.M.H.}}$	W_λ^{Joch}	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3990.104	27	17.3	19	0.47	−0.46	1	1.78
4018.836	9	5.5	19	0.06	−1.46	1	1.85
4069.272	8.5	13.0	20	0.06	−1.01	2	1.78
3952.201	14	13.2	23	0.00	−1.16	1	1.90
4021.338	16	12.9	36	0.32	−0.77	4	1.80
5255.517	7	6.3	43	0.20	−1.43	3	1.90
5212.346	4.5	4.4	44	0.20	−1.49	2	1.80
5089.831*	1.5	3.0	46	0.20	−1.79	2	1.94
5092.803*	6.5	5.8	48	0.38	−1.22	3	1.84
4446.399	8.5	9.8	49	0.20	−1.29	4	2.04
4385.670	15	12.1	50	0.20	−1.18	2	2.02
4059.966	6	7.2	63	0.20	−0.98	2	1.63
5293.169	10	9.4	75	0.82	−0.55	4	1.82
5319.820	11	9.3	75	0.55	−0.96	3	1.95
5311.476	2.5	2.4	80	0.99	−0.89	3	1.71
5356.991*	2	2.9	80	1.26	−0.70	2	1.86
5276.878	1.5	1.5	81	0.86	−1.19	3	1.67
5842.385*	1.5	1.0	86	1.28	−1.11	2	1.80

* lines identified as Nd II? by M.M.H.

$\log A_{\text{Nd}} = 1.82 \pm 0.12$

TABLE V

Sm II $Z = 62$ $\chi_{\mathrm{I}} = 5.63$ $\chi_{\mathrm{II}} = 11.07$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
4606.511	3	2.1	1	0.00	−1.96	2	1.62
4777.850	1.5	1.7	3	0.04	−1.97	2	1.54
4719.856	5.5	7.2	3	0.04	−1.80	3	2.04
4791.597	2.5	2.5	7	0.10	−1.83	1	1.64
3511.217	11	6.3	12	0.10	−1.23	1	1.65
4815.816	2.5	3.5	14	0.18	−1.49	3	1.53
4329.038	12	9.4	15	0.18	−0.91	1	1.45
4577.694	4	4.4	23	0.25	−1.40	1	1.63
4499.501*	2	3.2	23	0.25	−1.58	2	1.68
3712.767	6	3.9	25	0.25	−1.24	1	1.52
4318.936	10	10.7	27	0.28	−0.78	3	1.46
4420.526	14	9.2	32	0.33	−0.87	2	1.53
4642.245	7.5	10.6	36	0.38	−1.12	2	1.86
4854.352	2.5	1.3	36	0.38	−1.87	1	1.66
4523.924	11	11.2	41	0.43	−1.16	4	1.99
4537.970	4.5	5.7	45	0.48	−1.08	1	1.66
4615.456	2.5	2.2	49	0.54	−1.42	1	1.63
4467.339	8	9.8	53	0.66	−0.39	3	1.40

* line identified as Sm II? by M.M.H.

$\log A_{\mathrm{Sm}} = 1.66 \pm 0.21$

TABLE VI

Gd II $Z = 64$ $\chi_{\mathrm{I}} = 6.16$ $\chi_{\mathrm{II}} = 12.1$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3894.713	11.0	7.7	1	0.00	−0.68	2	1.12
3697.747	8.5	8.4	4	0.03	−0.39	1	0.93
3549.371	26	25.1	7	0.24	0.20	2	1.15
3712.717	9	9.9	20	0.38	0.06	1	0.89
3916.521	11	11.0	20	0.60	0.06	1	1.12
4037.913	4.5	3.8	49	0.56	−0.53	1	1.18
4085.574	10	6.1	50	0.73	−0.04	2	1.06
5733.891	0.5	0.7	94	1.37	−0.93	1	1.49

$\log A_{\mathrm{Gd}} = 1.12 \pm 0.15$

TABLE VII

Dy II $Z = 66$ $\chi_{\mathrm{I}} = 5.93$ $\chi_{\mathrm{II}} = 11.67$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3434.376	11	10.2	–	0.00	−0.46	1	1.03
3546.832	6.5	8.3	–	0.10	−0.55	1	1.12
3757.368	16	14.4	–	0.10	−0.18	1	0.92
3563.159	20	21.1	–	0.10	−0.37	1	1.39
4103.315	12	12.6	–	0.10	−0.43	2	1.06
3694.817	24	16.7	–	0.10	−0.14	2	0.96
3983.666	10	10.8	–	0.54	−0.34	1	1.34
4073.125	5	7.4	–	0.54	−0.19	2	1.01
3672.316	10	6.6	–	0.59	−0.32	2	1.19
3996.697	7	7.4	–	0.59	−0.30	2	1.18

$\log A_{\mathrm{Dy}} = 1.11 \pm 0.14$

TABLE VIII

Eu II $Z = 63$ $\chi_{\mathrm{I}} = 5.68$ $\chi_{\mathrm{II}} = 11.25$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3724.949	19	20.6	2	0.00	−0.23	1	0.48
3819.688	43	45.9	1	0.00	0.02	2	0.67
3724.949	19	17.6	1	0.00	−0.23	1	0.40
3907.114	28	26.7	5	0.21	0.03	2	0.52
3971.994	17	14.5	5	0.21	−0.08	2	0.32
3313.304	9	3.0	24	3.00	0.58	1	1.70
4129.724	54	57.5	1	0.00	−0.31	1	1.12
6645.127	4	4.5	8	1.38	−0.59	2	1.26
6173.065	1.5	0.9	9	1.32	−1.46	1	1.38

$\log A_{\mathrm{Eu}} = 0.49 \pm 0.14$

TABLE IX

Tm II $Z = 69$ $\chi_{\mathrm{I}} = 6.18$ $\chi_{\mathrm{II}} = 12.05$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3462.213	11	16.4	–	0.00	−0.35	1	0.60
3701.375	9	3.3	2	0.00	−0.89	2	0.31
3362.593	8	13.1	–	0.03	−0.58	1	0.77
3700.269	–	4.0	6	0.03	−0.77	2	0.31

$\log A_{\mathrm{Tm}} = 0.43 \pm 0.20$

TABLE X

Er II $Z = 68$ $\chi_{\mathrm{I}} = 6.10$ $\chi_{\mathrm{II}} = 11.93$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3896.248*	–	(20.70)	–	0.05	−0.15	–	0.76

* line identified as Er II? by M.M.H.

$\log A_{\mathrm{Er}} = 0.76$

TABLE XI

Yb II $Z = 70$ $\chi_{\mathrm{I}} = 6.25$ $\chi_{\mathrm{II}} = 12.17$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3694.199	67	(58.00)	1	0.00	−0.82	–	0.81

$\log A_{\mathrm{Yb}} = 0.81$

TABLE XII

Lu II $Z = 71$ $\chi_{\mathrm{I}} = 6.1$ $\chi_{\mathrm{II}} = 13.9$

λ	$W_\lambda^{\mathrm{M.M.H.}}$	$W_\lambda^{\mathrm{Joch}}$	No. Mult.	E.P.	$\log gf$	weight	A_{el}
3397.062	28	(16.00)	4	1.46	−0.22	–	0.84

$\log A_{\mathrm{Lu}} = 0.84$

B. LINES OF NEUTRAL RARE EARTHS

In Table XIII, we indicate the lines of the neutral rare earths reported by M.M.H. The identifications of these lines in the solar spectrum are principally based on their presence in sunspots spectra where the lowering of the temperature favours the recombination of ions into atoms.

The abundances have been determined from the equivalent widths quoted in the third column. The sixth column has been directly adopted from M.M.H. It indicates the strengthening of the lines in sunspots spectra. The oscillator strengths come from the work of CORLISS and BOZMAN (1962) except for Yb I where we used the results of BAUMANN and WANDEL (1966) based on life-time measurements.

The abundance obtained for La is of the order of 5.5 greater than the value obtained from the La II lines.

The Eu I line, λ 4661.92 Å is invisible in the photospheric spectrum but it appears in sunspots spectra (M.M.H.). It falls in the near wing of the Fe I λ 4661.979 Å line. Its equivalent width should be of the order of 0.1 mÅ in the photospheric spectrum, on the basis of the abundance derived from Eu II lines (Table XIII, col. 8). The line λ 4594.126 Å (Eu I) coïncide with a V I line. The abundance of vanadium determined from the observed W_λ (58 mÅ) is in excellent agreement with the solar abundance of V. The Eu abundance obtained for W_λ (Eu I) = 1 mÅ permits us to conclude that the contribution of Eu I to the observed line is of the order of 0.1 mÅ. The Eu I line, λ 4627.221 Å leads to an abundance which is about 50 times greater than the abundance deduced from the Eu II lines.

The two Tm I lines are only identified as Tm I? by M.M.H. They also lead to abundances much greater than the results obtained for the Tm II lines.

The line λ 5556.478 Å is a blend between a Yb I line and a C_2 line. The contribution of Yb I should be less than 0.1 mÅ, the C_2 contributing practically to the whole observed W_λ. The Yb I resonance line, λ 3987.966 Å, also lead to too high an abundance for Yb.

We believe the only way to explain these disagreements is to doubt the identification of lines of La I, Eu I, Tm I and Yb I in the solar photospheric spectrum.

To be in a position to test this statement, we made the predictions of the equivalent widths of all these lines in sunspots spectra, using ZWAAN's (1965) sunspots model. Our results are included in the last two columns of Table XIII, where the predicted W_λ correspond, respectively to the abundances deduced from the lines of once-ionized elements (Tables I, VIII, IX, XI) and to the abundances deduced from the lines of the neutral elements (Table XIII, col. 7). Unfortunately, the actual values of the W_λ's, in the sunspots spectra, of the lines given in Table XIII are not known. But we believe that the predicted values indicated in column 9 are more likely than the rather high values obtained in column 10 from the abundances deduced from the neutral lines.

TABLE XIII

Neutral rare earths lines in the solar spectrum

λ	Identification (M.M.H.)	W_λ (mÅ)	E.P. (eV)	log *gf*	Spots [1]	Abundance	W_λ predicted (mÅ)		
							Photosphere [2]	Spots [2]	Spots [3]
6249.91	La I	0.5	0.51	−0.25	s	2.55	$\leqslant 0.1$	29*	99
4661.92	Eu I	–	0.00	0.17	s	1.64 (for $W_\lambda = 1.0$ mÅ)	$\leqslant 0.1$	32	147
4594.126	VI (Eu I)	58.0	0.00	0.33	S	1.49 (for $W_\lambda = 1.0$ mÅ)	$\leqslant 0.1$	41	146
4627.221	Eu I	4.3	0.00	0.25	s	2.21	$\leqslant 0.1$	36	295
4094.20	Tm I?	4.0	0.00	0.12	–	1.90	0.16	50	270
4105.828	Tm I?	4.0	0.00	0.08	S	1.94	0.16	50	270
3987.966	Yb I	17.5	0.00	0.114	s	1.59	3.1	228	544
5556.478	Yb I, C_2	2.2	0.00	−1.775	s?	1.75 (for $W_\lambda = 0.5$ mÅ)	0.06	29*	113

[1] s = line strengthened in sunspot; S = line greatly strengthened in sunspot.

[2] Values obtained for the abundances deduced from the study of the lines of once-ionized elements (Tables I, VIII, IX, XI).

[3] Values obtained for the abundances deduced from the study of the lines of neutral rare earths (this table, column 7).

* Dr. C. Zwaan kindly communicated to us that the observed sunspots equivalent widths of these two lines were in general agreement with the values quoted in this column.

5. Search for Tb II and Ho II Lines in the Solar Spectrum

The identification of the lines of Tb II and Ho II in the solar spectrum is still problematic because no analysis of the second spectra of these elements has as yet been made. It is still impossible to make theoretical predictions of the behaviour of the lines of these elements in the sun. Nevertheless, M.M.H. suggested that the following solar lines could be due to Tb II: λ 3568.550, 3600.454, 3658.864 (CN+Tb II?), 3702.825 and 4278.551 Å. These tentative identifications are based on the very peculiar behaviour of the lines of once-ionized rare earths in the chromospheric spectrum. MENZEL (1931) showed that lines of La, Ce, Pr, Nd, Sm, Eu, Gd, Dy and Tb (Er probably present, Ho absent or too faint) were present in the chromospheric spectrum. He also noted, when going from the chromosphere through the solar limb, that the lines of these elements were still observed as emission lines instead of changing into absorption lines. This phenomenon has recently been interpreted by CANFIELD (1968) in the case of Ce II lines. He was able to reproduce the behaviour of the Ce II lines by admitting that these lines are formed by non-coherent scattering.

We searched for other Tb II lines in the solar spectrum. It may be that the following faint lines λ 3703.94 Å ($W_\lambda = 1.5$ mÅ), λ 3755.23 Å ($W_\lambda = 1.0$ mÅ) and λ 4144.484 Å ($W_\lambda = 8.0$ mÅ) are also due to Tb II (the last line only partly). In spite of the fact that there is a chromospheric line at 4144.56 Å (MOORE, 1968) these three lines are dubious. The first identification of Ho II lines in a stellar spectra was made by PRZYBYLSKI (1963). Other authors (MENZEL, 1931; STRUVE and SWINGS, 1943; DAVIS, 1947) had already suggested its presence in the sun and in certain stellar spectra. Przybylski identified 31 lines of Ho II (from λ 3700 to 4800 Å) in the peculiar star HD 101065. This star seems to show the results of a very strong r-process. He also concluded that the Ho II lines were absent from the solar spectrum.

We looked for the strongest Ho II lines (MEGGERS *et al.*, 1961) in the solar spectrum. All these Ho II lines are masked by well-identified lines except for the lines given in Table XIV. From the coïncidences mentioned in this table, it can be concluded that it is still premature to say that these lines are due to Ho II. In certain cases the discrepancies in λ are too large. Further spectroscopic data (accurate wavelengths, term values, oscillator strengths) have to be await before this question can be settled.

TABLE XIV

Search for Ho II lines in the solar spectrum

λ_{lab}	I_{lab}	λ	W_λ(mÅ)	Observation
3796.72	1000	−.803	33.0	unidentified line
3416.46	600	−.409	6.0	unidentified line
3474.26	600	−.273	5.5	unidentified line
4045.44	600	−.508	9.0	unidentified line
3515.59	460	−.647	4.5	unidentified line
3425.34	220	−.316	2.8	unidentified line
3546.05	180	−.023	2.5	unidentified line

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6. Conclusions

Our results for the solar abundances of the rare earths are summarized in column 7 of Table XV, where they are compared with those obtained by Russell (1929), Wallerstein (1966), Righini and Rigutti (1966), Goldberg *et al.* (1960) and with the meteoritic abundances taken from Urey (1967). It should be mentioned that the abundances obtained by Wallerstein are values relative to Sc. The numbers given in Table XV, column 3 have been computed from the relative abundances of Wallerstein and normalized to $\log N_{\mathrm{sc}} = 3.00$, which probably represents a mean value for the solar scandium abundance.

TABLE XV

Comparison of the abundances of the rare earths

Z	Element	R.	W.	R.R.	G.M.A.	This Work	Meteorites
57	La	2.3	1.92	–	–	1.81 ± 0.27	1.11
58	Ce	2.9	1.53	1.78	–	1.88 ± 0.21	1.62
59	Pr	1.1	1.37	1.45	–	1.63 ± 0.12	0.78
60	Nd	2.5	1.78	1.93	–	1.82 ± 0.12	1.44
61	Pm	Unstable – Absent in the solar spectrum (Moore, 1963)					
62	Sm	2.0	1.27	1.62	–	1.66 ± 0.21	0.91
63	Eu	1.9	0.97	0.96	–	0.49 ± 0.14	0.51
64	Gd	1.6	0.99	1.13	–	1.12 ± 0.15	1.15
65	Tb	see text					0.27
66	Dy	2.1	–	1.00	–	1.11 ± 0.14	1.11
67	Ho	see text					0.50
68	Er	0.6	–	–	–	0.76	0.87
69	Tm	–	–	–	–	0.43 ± 0.20	0.09
70	Yb	–	–	–	1.53 (Yb I)	0.81	0.87
71	Lu	–	–	–		0.84	0.09

R. = Russell (1929)
W. = Wallerstein (1966)
R. R. = Righini and Rigutti (1966)
G. M. A. = Goldberg *et al.* (1960)

Our results are in general agreement with those obtained by Righini and Rigutti (1966) by the curve-of-growth method, except for Pr and Eu. The disagreement between our values and those of Wallerstein (1966) for Ce, Pr, Sm and Eu can be explained as follows:

Wallerstein used a rapid, but rather inaccurate method to determine the abundances;

part of the lines he used are now known to be blended.

The comparison of our solar abundances with the meteoritic abundances leads to the following conclusions:

the solar abundances of La, Ce, Pr, Nd, Sm, Tm and Lu are greater (much greater for La, Pr and Sm) than the meteoritic values;

there is agreement between solar and meteoritic abundances for Eu, Gd, Dy, Er and Yb.

The disagreement noted for Lu is perhaps not meaningful because our result relies upon only one blended ultraviolet line.

The rare earths abundances are important for testing the s- and r-processes (Seeger *et al.*, 1965; Fowler, 1968). The theoretical predictions by Seeger, Fowler and Clayton are in agreement with the meteoritic abundances. Our abundances, quite different from the meteoritic values, lead to a situation difficult to explain. Actually, if one plots the product σN_s (where σ represents the neutron capture cross-section and N_s the abundance of the s-only isotopes) against the atomic weight A, one obtains quite curious results. The rapid drop off of the $\sigma N_s = f(A)$ curve, usually occurring at $A = 140$ (see e.g. Fowler, 1968), due to the small σ of the isotopes with magic number of neutrons ($N = 82$), seems to take place at $A = 150$ when using our solar abundances rather than the meteoritic abundances (because of the high solar abundances of La and Sm). Such a situation seems to be unexplainable. Much work remains to be done in the field of the determination of the neutron capture cross-sections but it would be quite surprizing they would be responsible for the observed behaviour of the elements between $A = 140$ and 150. We therefore believe the solar abundances to be too great. This could only be due to the transition probablities used in our study.

If we admit that the solar abundances are erroneous because of the *gf*-values and that the meteoritic abundances represent the solar abundances at the origin of the solar system, we can have an idea of the uncertainty of the *gf*-values. The transition probabilities used in this study (Corliss and Bozman, 1962) would have to be multiplied by a factor about 5 for the elements between La and Sm; they would be correct for the elements heavier than Sm. If we take into account the selective diffusion of the elements at the basis of the solar convection zone (Delcroix and Grevesse, 1968), the correction factors could become as large as about 15 (La→Sm) and about 5 (elements heavier than Sm). We must point out that such high correction factors for *gf*-values are not so unlikely to be true.

To conclude, we shall say that, unfortunately, the solar abundances found in this study seem unexplainable on the basis of nucleosynthesis theories. Our results, presented in detail in Tables I to XII and summarized in Table XV, will be easily adapted to new *gf*-values absolute scales.

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