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THE ABUNDANCE OF THE ELEMENTS IN THE SOLAR PHOTOSPHERE—IV

The Iron Group

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Summary

Abundances of the iron group elements are derived from ionic lines in the photospheric absorption spectrum. There is very good agreement with abundances found from neutral species for all except Co and Ni. The latter discrepancies are thought to arise from uncertainty in the absolute scales of the *f*-values and from difficulties in interpretation of ultra-violet line strengths.

The general good agreement supports the assumption of local thermodynamical equilibrium for the calculation of the ionization state of the solar photosphere.

1. *Introduction*. Over the past few years there have been numerous studies of iron group abundances in the solar atmosphere. Recent reviews have been given by Müller (1966, 1967). Most of this activity has derived from the wealth of approximate *f*-values now available, especially those given by Corliss & Bozman (1962) (CB). In addition, there have been various *f*-value measurements of high accuracy, mostly lifetime or atomic beam experiments (Bell *et al.* (1958), Lawrence *et al.* (1965)), of just a few lines in the iron group elements and this has led to a number of ' re-normalizations ' of the CB *f*-values. In fact, there are almost as many different sets of iron group abundances as there are research and review papers on the subject. In order to say anything new we must either determine many more *f*-values of high accuracy for the neutral iron group, or turn completely from this approach and use an independent line of investigation. It is well known that analyses of coronal and chromospheric emission lines (Pottasch 1963a, b) have complicated rather than clarified the issue.

One straight-forward way of checking the photospheric abundances obtained from neutral iron group lines is to study the ion lines. Only preliminary attempts (Aller *et al.* 1964, Letfus 1965) at this have been made, owing to the general absence of appropriate *f*-values. However, the *f*-values for the once-ionized iron group elements recently published by the writer (Warner 1967a), and whose absolute scales are entirely independent of those for the neutral species, are idealy suited for our purpose. The remainder of this paper is a discussion of solar abundances derived from this source of *f*-values.

The methods of analysis follow the same lines as adopted in the first paper of this series (Lambert 1968). Damping constants for the iron group ions are in general small (Warner 1967b) and the abundances are insensitive to their precise values. The equivalent width *W* of an unsaturated line, which is the abscissa of

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15§

the curve of growth, is given by

$$\left.\frac{W}{\lambda}\right|_{\text{weak}} = C \cdot \frac{N_i}{N_H}$$

where N_i/N_H is the element-to-hydrogen ratio and C contains the f-value and the factors depending on the model atmosphere (Goldberg *et al.* 1960).

TABLE I

Lines of Sc II in the Sun

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
3535·73	11	0·31	4·64	−0·34	5·68	
3567·70	3	0·00	4·45	−0·45	5·88	
3572·57	3	0·02	4·20	0·15	6·46	RRT: Sc II + (Fe I)
3576·33	3	0·01	4·47	0·01	6·33	
3580·93	3	0·00	4·27	−0·15	6·19	
3589·63	3	0·01	4·53	−0·63	5·70	
3590·49	3	0·02	4·34	−0·62	5·70	
3613·81	2	0·02	4·23	0·45	6·77	Double in RRT
3630·75	2	0·01	4·21	0·28	6·61	RRT: Ca I + Sc II
3642·81	2	0·00	4·34	0·09	6·43	
3645·31	2	0·02	4·37	−0·38	5·94	
3651·80	2	0·01	4·41	−0·67	5·67	
3923·50	9	0·31	5·32	−2·22	3·88	
4246·84	7	0·31	4·39	0·19	6·29	
4294·78	15	0·61	4·84	−1·27	4·55	
4305·71	15	0·60	4·81	−1·20	4·63	
4314·09	15	0·62	4·60	−0·10	5·70	
4320·75	15	0·61	4·66	−0·22	5·60	
4325·00	15	0·60	4·53	−0·37	5·46	RRT: Sc II + Fe I + Cr I
4354·61	14	0·61	4·79	−1·50	4·32	
4374·47	14	0·62	4·60	−0·45	5·35	RRT: Sc II + Fe I
4384·82	14	0·60	4·96	−1·65	4·18	
4400·40	14	0·61	4·71	−0·72	5·10	
4415·56	14	0·60	4·66	−0·84	4·99	
4420·67	14	0·62	5·47	−2·32	3·48	
4431·36	14	0·61	5·17	−2·13	3·69	
4670·41	24	1·37	4·91	−0·51	4·59	
5031·04	23	1·36	4·89	−0·38	4·72	RRT: Sc II + Fe I
5239·82	26	1·45	4·98	−0·50	4·50	
5318·36	22	1·36	5·66	−1·82	3·27	
5334·22	30	1·50	6·15	−1·88	3·08	
5337·19	30	1·51	6·15	−1·87	3·08	
5526·82	31	1·77	4·86	0·03	4·73	
5552·24	25	1·45	6·00	−2·38	2·61	
5640·99	29	1·50	5·16	−1·17	3·78	
5657·88	29	1·51	4·91	−0·68	4·16	
5658·35	29	1·50	5·26	−1·29	3·66	
5667·15	29	1·50	5·36	−1·35	3·60	
5669·04	29	1·50	5·19	−1·23	3·72	
5684·20	29	1·51	5·16	−1·09	3·85	
6245·62	28	1·51	5·30	−1·05	3·89	
6279·74	28	1·50	5·43	−1·51	3·44	
6300·68	28	1·51	6·00	−1·98	2·96	
6320·84	28	1·50	6·05	−1·96	2·98	
6604·60	19	1·39	5·25	−1·54	3·52	

Equivalent widths were taken from the revised Rowland solar line tables (RRT) of Moore *et al.* (1966). Wherever possible we restrict discussion to lines longward of about 4000 Å, but in the case of Mn II, Co II and Ni II we have to include ultra-violet lines and in the case of Sc II it is helpful to use a few strong lines below 4000 Å. Initially we considered blended lines as well as unblended, and here we retain only those that do not stand above the mean curve of growth by a significant amount. In this way it is possible to show that certain contributors to blends are in fact unimportant.

All abundances are logarithmic and on a scale where log N(H) = 12·00.

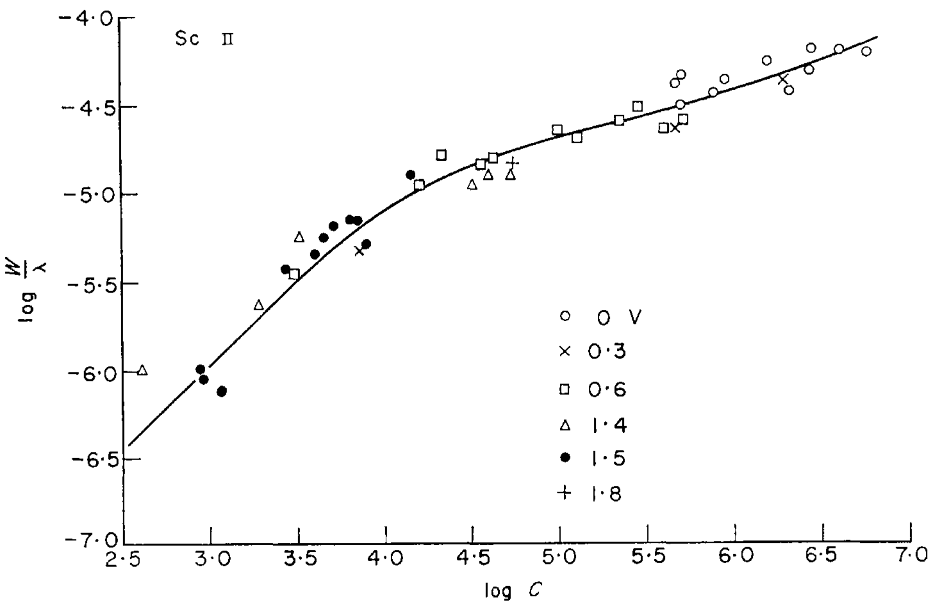

FIG. 1. *Solar curve of growth for Sc* II.

2. *Scandium.* The 45 Sc II lines used in the analysis are given in Table I, and the curve of growth is displayed in Fig. 1. The theoretical curve is for 4500 Å and low excitation potential χ = 0·6 V. A pleasingly small amount of scatter is evident and there are no systematic departures as a function of χ. The abundance derived from Fig. 1 is

$$\log N(\mathrm{Sc}) = 3{\cdot}04$$

The absolute scale of the f-values (Warner 1967a) for Sc II is from theoretical calculations, but in view of the relative simplicity of the electron configurations should be very reliable.

Using the CB f-values the Sc abundance from neutral lines is (Aller 1965) log N(Sc) = 2·80. Using theoretical f-values and a different solar model, Goldberg, Muller & Aller (1960) (GMA) had obtained 2·82 and Unsöld (1948) found 3·33 from Sc I lines.

3. *Titanium.* The 54 Ti II lines employed here are listed in Table II and the composite curve of growth shown in Fig. 2. It has not been possible to reach very far down towards the weak line portion of the curve of growth. Further laboratory measurements and an extension of the analysis of the Ti II spectrum will be needed in order to reach log $W/\lambda \sim -6$.

TABLE II

Lines of Ti II in the Sun

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
3913·47	34	1·12	4·40	−0·24	4·72	
3932·02	34	1·13	4·46	−1·37	3·58	
4012·39	11	0·57	4·63	−1·68	3·79	RRT: Ti II + Ce II
4025·13	11	0·61	4·68	−1·95	3·48	RRT: Ti II + Ni I
4028·35	87	1·89	4·65	−0·65	3·60	
4163·65	105	2·59	4·58	0·20	3·81	RRT: Ti II + Cr I + Fe I
4173·54	21	1·08	4·66	−1·70	3·29	
4174·08	105	2·60	5·01	−0·84	2·76	RRT: Ti II + Ti I
4184·31	21	1·08	4·74	−1·56	3·43	
4290·23	41	1·16	4·56	−0·79	4·13	
4300·05	41	1·18	4·41	−0·46	4·44	
4301·93	41	1·16	4·46	−1·11	3·81	
4314·98	41	1·16	4·55	−1·02	3·90	
4316·80	94	2·05	4·99	−1·07	3·03	
4337·93	20	1·08	4·62	−0·90	4·10	
4341·37	32	1·12	4·71	−1·76	3·20	
4344·29	20	1·08	4·74	−1·67	3·32	
4350·84	94	2·06	4·85	−1·32	2·78	
4367·68	104	2·59	4·65	−0·39	3·21	
4374·83	93	2·06	5·02	−1·04	3·11	
4386·85	104	2·60	4·87	−0·46	3·14	
4391·03	61	1·23	4·89	−2·03	2·83	
4394·07	51	1·22	4·74	−1·47	3·39	
4395·04	19	1·08	4·51	−0·50	4·49	
4395·85	61	1·24	4·82	−1·53	3·31	
4399·78	51	1·24	4·58	−1·06	3·78	RRT: Ti II + (Cr I)
4409·25	61	1·24	5·17	−2·07	2·77	
4409·53	61	1·23	5·10	−2·07	2·78	
4411·93	61	1·22	4·92	−2·11	2·73	RRT: Ti II + (Fe I?)
4417·72	40	1·16	4·65	−1·88	3·73	
4418·34	51	1·24	4·80	−1·67	3·17	
4421·94	93	2·06	4·94	−1·14	2·95	
4443·81	19	1·08	4·51	−0·74	4·25	
4444·56	31	1·12	4·91	−1·86	3·09	
4450·49	19	1·08	4·75	−1·41	3·58	
4464·46	40	1·16	4·82	−1·66	3·24	RRT: Ti II + unknown
4468·50	31	1·13	4·53	−0·65	4·29	
4469·15	18	1·08	4·96	−1·84	3·15	
4470·86	40	1·16	4·90	−1·80	3·10	RRT: Ti II + unknown
4488·33	115	3·12	4·97	0·01	3·14	
4501·28	31	1·12	4·54	−0·79	4·16	
4529·49	82	1·57	4·89	−1·52	3·01	
4533·97	50	1·24	4·62	−0·64	4·20	
4544·02	60	1·24	5·11	−2·08	2·76	RRT: Ti II + unknown
4545·14	30	1·13	4·97	−1·61	3·33	
4549·64	82	1·58	4·49	−0·22	4·30	RRT: Ti II + (Co I)
4563·77	50	1·22	4·55	−0·86	4·00	
4571·98	82	1·57	4·53	−0·34	4·19	
4589·95	50	1·24	4·80	−1·61	3·23	RRT: Ti II + unknown
4805·10	92	2·06	4·69	−0·76	3·31	
5129·16	86	1·89	4·87	−0·93	3·29	
5188·70	70	1·58	4·69	−0·82	3·69	
5226·55	70	1·57	4·74	−0·97	3·55	
5336·80	69	1·58	4·89	−1·35	3·16	

The theoretical curve in Fig. 2 is for 4300 Å and $\chi = 1{\cdot}2$ V. Changes in the shape of the curve for other values of χ are negligible. The abundance derived from Fig. 2 is

$$\log N(\mathrm{Ti}) = 4{\cdot}50$$

From the CB Ti I *f*-values Müller & Mutschlecner (1964) derived log *N*(Ti) = 4·58, and using the *f*-sum rule absolute scale they found log *N*(Ti) = 4·78. The former value is probably the more reliable.

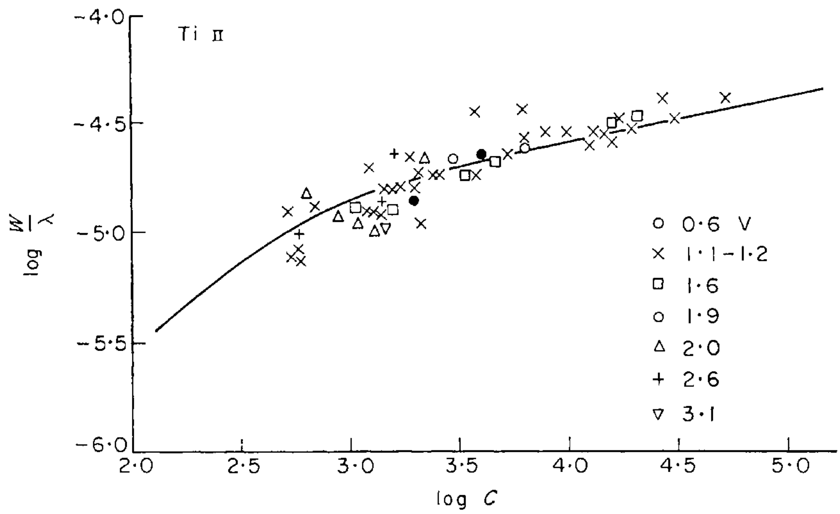

FIG. 2. *Solar curve of growth for Ti* II.

4. *Vanadium.* 31 lines of V II, including four new identifications, are listed in Table III and the curve of growth shown in Fig. 3. The theoretical curve is for 4000 Å and 1·8 V, the changes in the curve for other χ within the wavelength

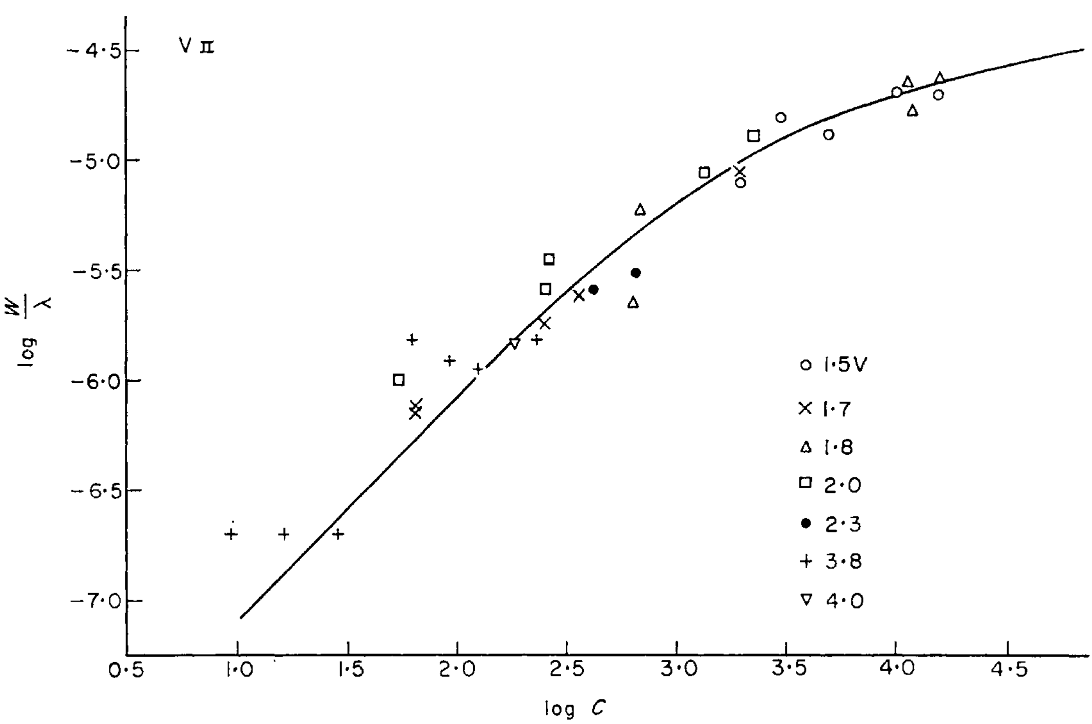

FIG. 3. *Solar curve of growth for V* II.

TABLE III

Lines of V II in the Sun

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
3899·14	33	1·80	4·65	−0·37	4·06	
3903·26	11	1·48	4·71	−0·72	4·00	
3951·96	10	1·48	4·72	−0·52	4·20	
3985·79	202	3·75	5·82	−0·33	2·37	
3997·11	9	1·48	4·89	−1·03	3·69	
4002·93	9	1·43	4·82	−1·28	3·49	
4005·71	32	1·82	4·64	−0·22	4·19	
4008·17	32	1·79	5·22	−1·61	2·83	
4023·38	32	1·80	4·78	−0·35	4·08	RRT: V II+(Co I)
4035·61	32	1·79	4·73	−0·42	4·02	
4036·77	9	1·48	5·11	−1·42	3·30	
4039·57	32	1·82	5·66	−1·60	2·81	
4164·02	37	2·04	5·44	−1·77	2·42	
4190·40	25	1·67	5·62	−1·98	2·57	
4190·89	37	2·03	5·59	−1·81	2·40	
4195·83	19	1·67	6·15	−2·71	1·84	New identification
4202·35	25	1·70	4·78	−1·23	3·29	
4205·07	37	2·04	4·89	−0·85	3·35	
4225·22	37	2·03	5·06	−1·07	3·13	
4231·20	25	1·70	6·15	−2·68	1·83	
4232·04	225	3·97	5·85	−0·23	2·27	
4234·22	24	1·69	5·74	−2·11	2·41	
4242·90	200	3·76	5·92	−0·72	1·97	
4349·96	36	2·04	6·00	−2·46	1·73	New identification
4464·34	199	3·76	5·96	−0·55	2·10	
4517·37	211	3·80	6·70	−1·63	0·98	New identification
4556·76	198	3·76	6·70	−1·44	1·21	New identification
4564·58	56	2·27	5·51	−1·15	2·83	
4590·49	210	3·79	6·70	−1·13	1·47	RRT: V II?
4600·20	56	2·26	5·59	−1·36	2·62	
4884·05	197	3·76	5·82	−0·83	1·80	

range studied are negligible. The abundance of V derived from Fig. 3 is

$$\log N(\mathrm{V}) = 3{\cdot}92.$$

Müller & Mutschlecner (1964) found 4·12 from the CB f-values for V I and 4·02 from an application of the f-sum rule to V I.

5. *Chromium.* 28 lines of Cr II are available, including one new identification, and these are listed in Table IV. The curve of growth is given in Fig. 4, where the theoretical curve is for 4600 Å and χ = 4·0 V. The abundance given by Fig. 4 is

$$\log N(\mathrm{Cr}) = 5{\cdot}47.$$

The writer expressed some uncertainty in his absolute scale (Warner 1967a) for Cr II and suggested that his f-values may be 0·25 dex* too small. If this is found to be correct then the abundance will be changed to 5·22.

Müller & Mutschlecner (1964) found $\log N(\mathrm{Cr})$ = 5·07 from the CB Cr I f-values and 5·43 from the f-values determined by Allen & Asaad (1957).

* ' dex ' is equivalent to ' in the ten-based logarithm '.

TABLE IV

Lines of Cr II *in the Sun*

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
4082·28	165	5·32	5·70	−1·13	1·00	RRT: Cr II?
4086·13	26	3·71	5·11	−2·22	1·28	
4087·60	19	3·10	5·70	−3·03	1·00	
4088·85	19	3·10	5·70	−3·43	0·60	RRT: Cr II?
4098·43	165	5·33	5·74	−1·32	0·80	New identification
4111·00	18	3·10	4·96	−1·86	2·17	
4112·57	18	3·10	5·64	−2·96	1·07	
4113·22	18	3·10	5·14	−2·58	1·45	
4132·41	26	3·76	5·25	−2·16	1·29	
4246·42	31	3·85	6·10	−3·05	0·32	RRT: Cr II+unknown
4252·63	31	3·86	5·14	−1·85	1·51	
4261·93	31	3·86	4·84	−1·21	2·15	
4269·29	31	3·85	5·05	−2·06	1·30	
4275·56	31	3·86	5·00	−1·33	2·03	
4554·99	44	4·07	5·07	−1·44	1·71	
4558·65	44	4·07	4·81	−0·31	2·84	
4588·20	44	4·07	4·84	−0·65	2·49	
4592·06	44	4·07	5·01	−1·37	1·77	
4616·63	44	4·07	5·10	−1·51	1·63	
4618·79	44	4·07	4·77	−0·98	2·16	RRT: Fe I+Cr II
4634·08	44	4·07	4·95	−1·19	1·95	
4824·14	30	3·87	4·71	−1·01	2·30	RRT: Cr II+Fe I
4836·24	30	3·86	5·71	−1·89	1·43	RRT: Cr II+Ni I
4848·25	30	3·86	4·95	−1·13	2·19	
4856·20	30	3·85	5·41	−2·06	1·27	
4864·32	30	3·86	4·93	−1·46	1·86	
4876·40	30	3·85	5·08	−1·56	1·77	
4876·49	30	3·86	5·29	−1·94	1·38	

Accurate atomic beam *f*-values for three lines in multiplet one and three lines in multiplet four (all at 3600 Å) have been determined by Lawrence *et al.* (1965) for Cr I. A comparison of their *f*-values with those of CB shows that the latter are too small by 0·11 dex. This does not necessarily mean, however, that all of the

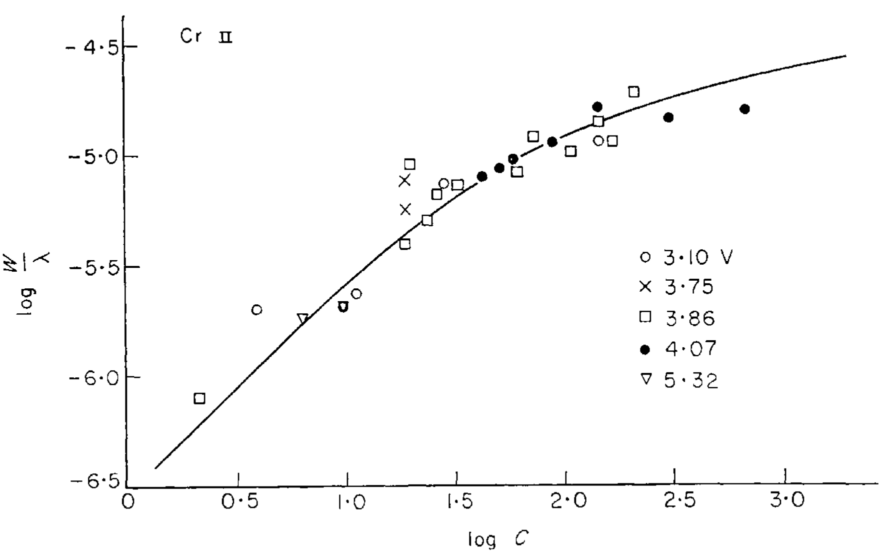

FIG. 4. *Solar curve of growth for Cr* II.

CB Cr I f-values are systematically too small by this amount. The lines measured in the atomic beam are extremely strong in arc emission experiments and very difficult to measure without systematic error. Self-absorption may also be important. The above six lines have not been used in a determination of the solar Cr abundance because they are so strong in the solar spectrum as to demand accurate damping constants for their interpretation.

TABLE V

Lines of Mn II in the Sun

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
3438·96	1	1·17	4·57	−1·75	3·96	
3441·98	3	1·78	3·97	0·05	5·15	
3460·04	1	1·17	4·44	−1·47	4·25	RRT: Mn II + unknown
3460·33	3	1·81	4·27	−0·23	4·85	
3474·06	3	1·81	4·22	−0·44	4·64	
3474·15	3	1·83	4·31	−0·50	4·56	
3482·91	3	1·83	4·36	−0·32	4·74	
3488·68	3	1·85	4·44	−0·51	4·53	
3496·81	3	1·83	4·62	−1·04	4·03	RRT: Mn II + (Co I)
3497·53	3	1·85	4·59	−0·73	4·32	
4174·32	2	1·81	5·37	−3·32	1·84	RRT: Mn II + unknown
4200·29	—	6·18	7·00	−1·12	0·21	New identification
4285·75	—	5·37	6·70	−1·72	0·33	RRT: Fe I? New identification

6. *Manganese.* Only 13 lines of Mn II are available, including two new identifications, and all but three lines fall shortward of 3500 Å. They are listed in Table V and the curve of growth given in Fig. 5. The theoretical curve is for 3500 Å and χ = 1·8 V. The scatter among the group of strong lines is rather large, probably

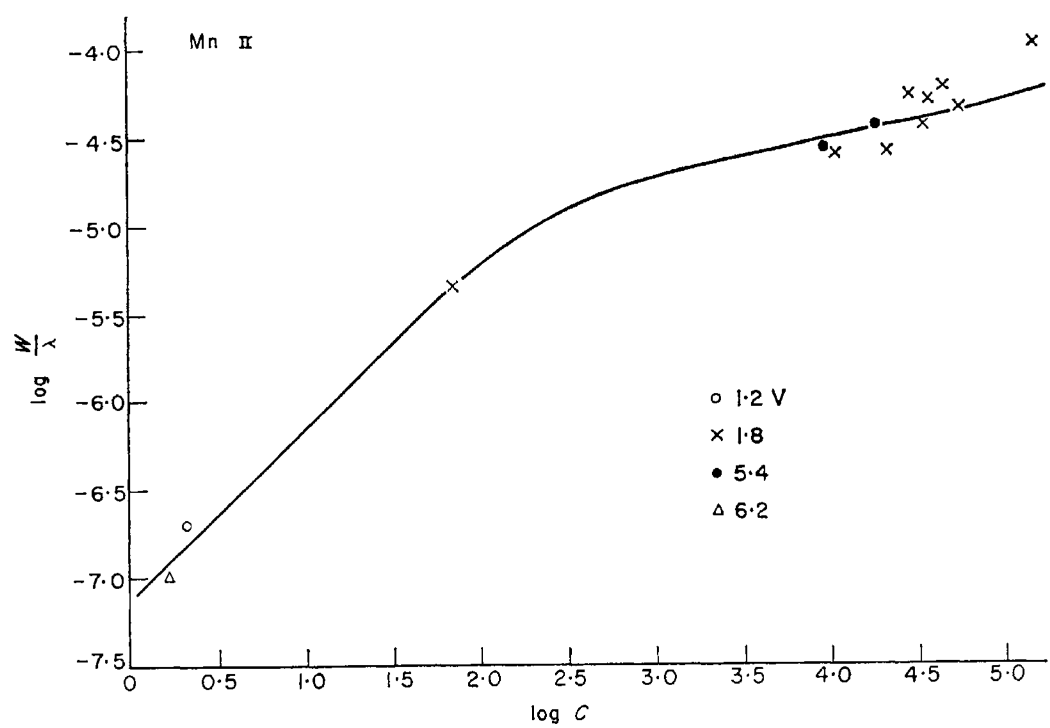

FIG. 5. *Solar curve of growth for Mn II.*

due to the difficulty of measuring equivalent widths in the region of 3450 Å. The Mn abundance derived from Fig. 5 is

$$\log N(\mathrm{Mn}) = 4{\cdot}88$$

In the derivation of this value considerable weight has been given to the three lines longward of 4000 Å, so uncertainties in the ultra-violet opacity (see Section 8) will not greatly affect the Mn abundance. Being based essentially on only three lines the above determination is not of high reliability.

Müller & Mutschlecner (1964) derived log N(Mn) = 4·80 from the CB *f*-values and 4·95 from the Allen & Asaad data.

7. *Iron.* The *f*-values for Fe II in the writer's list do not extend to faint lines of Fe II so we are restricted to the use of strong solar lines if we depend solely on laboratory data. In order to supplement this data and so extend the solar Fe II curve of growth to weaker lines we have made use of some ' astrophysical ' *f*-values derived from model atmosphere analyses of Sirius (Warner 1966a) and Deneb (Groth 1961). These *f*-values have been placed on the same absolute scale as the laboratory measurements (Warner 1966b).

TABLE VI

Lines of Fe II *in the Sun*

Wave-length	Mult	χ	$-\log W/\lambda$	log *gf* Warner	log *gf* Deneb	log *gf* Sirius	log *C*	Remarks
3974·17	29	2·70	4·85		−2·76		0·86	
4002·08	29	2·78	5·02			−3·17	0·38	
4031·45	151	4·73	5·92			−2·51	−0·62	
4070·04	22	2·54	5·57		−3·79		−0·04	RRT: Fe I
4122·66	28	2·58	4·83		−2·73		0·99	
4124·79	22	2·54	5·14	−3·15	−3·52		0·60	
4128·74	27	2·58	4·92	−2·76	−3·04		0·95	
4173·47	27	2·58	4·67	−2·01	−1·95		1·70	
4177·70	21	2·54	4·87		−2·94		0·81	
4178·86	28	2·58	4·72	−2·00	−1·64	−2·02	1·71	
4233·17	27	2·58	4·50	−1·43	−1·30		2·28	
4258·17	28	2·70	4·84	−2·59	−2·73		1·01	
4278·16	32	2·69	5·31		−3·15		0·46	
4303·18	27	2·70	4·62	−2·00	−1·90	−2·07	1·60	
4369·41	28	2·78	5·02		−2·87	−3·09	0·55	
4385·39	27	2·78	4·73	−2·02	−1·88	−2·04	1·50	
4416·83	27	2·78	4·76	−2·09	−1·96	−2·19	1·43	
4472·93	37	2·84	5·06		−2·85	−2·76	0·65	
4489·18	37	2·83	4·87	−2·23	−2·26		1·24	
4491·41	37	2·85	4·80	−2·09	−2·15	−2·00	1·36	
4508·30	38	2·85	4·76	−1·76	−1·74	−1·65	1·69	
4515·34	37	2·84	4·75	−1·91	−1·84	−1·72	1·55	
4520·23	37	2·81	4·79	−1·87	−1·91	−1·90	1·62	RRT: Fe II + Fe I
4522·64	38	2·84	4·73	−1·51	−1·52	−1·48	1·95	RRT: Fe II + (Eu II)
4541·52	38	2·85	4·89	−2·29	−2·34	−2·42	1·16	RRT: Fe II + (Cr I)
4555·89	37	2·83	4·77	−1·79	−1·68	−1·78	1·67	
4576·34	38	2·84	4·91	−2·22	−2·35	−2·61	1·23	
4582·83	37	2·84	4·97	−2·44	−2·48	−2·37	1·01	
4583·84	38	2·81	4·62	−1·25	−1·28	−1·18	2·23	
4595·69	38	2·85	5·74			−3·67	−0·22	
4620·52	38	2·83	4·98	−2·63	−2·65	−2·65	0·83	
4635·31	186	5·95	5·52	−0·95	−0·88	−0·83	−0·17	

TABLE VI (*continued*)

Wave-length	Mult	χ	$-\log W/\lambda$	log *gf* Warner	log *gf* Deneb	log *gf* Sirius	log *C*	Remarks
4656.98	43	2.89	5.18	−2.53	−2.79		0.87	
4666.75	37	2.83	5.02	−2.64	−2.68	−2.75	0.82	
4731.47	43	2.89	4.78	−2.26	−2.46	−2.42	1.14	RRT: Fe II + Fe I
4893.82	36	2.83	5.66			−3.48	−0.01	
4923.93	42	2.88	4.48		−0.93		2.47	
4954.02	168	5.57	6.10			−1.85	−0.63	RRT: Fe II?
4993.35	36	2.81	5.17		−2.89	−2.79	0.64	
5018.45	42	2.89	4.38		−0.82	−0.90	2.53	
5074.07	205	6.81	6.52			−0.95	−0.60	New identification
5132.67	35	2.81	5.33			−3.29	0.18	
5169.05	42	2.89	4.51		−0.72		2.67	
5197.58	49	3.23	4.81		−1.81	−1.73	1.31	
5234.63	49	3.22	4.79		−1.74	−1.75	1.34	
5264.81	48	3.23	5.07		−2.23	−2.25	0.84	
5272.40	185	5.95	5.74		−1.21	−1.07	−0.18	
5276.00	49	3.20	4.67		−1.61		1.49	
5325.56	49	3.22	5.08		−2.72	−2.46	0.46	
5362.87	48	3.20	4.85		−1.95		1.23	
5414.08	48	3.22	5.24		−2.75	−2.85	0.26	
5425.26	49	3.20	5.06		−2.75	−2.58	0.40	
5525.14	56	3.27	5.62			−3.13	−0.11	RRT: Fe II? p
5534.85	55	3.24	4.94		−2.16	−2.21	0.86	
5544.77	166	5.57	6.40			−1.71	−0.48	RRT: C_2
5813.67	163	5.57	6.10			−1.63	−0.40	
5823.18	164	5.57	6.40			−1.67	−0.42	
5826.11	182	5.91	7.00			−1.56	−0.57	RRT: Fe II? p
5952.52	182	5.95	6.15			−1.39	−0.40	RRT: Fe II? p
5991.38	46	3.15	5.28		−2.93	−2.77	0.27	
6045.49	200	6.29	6.22			−1.20	−0.83	
6084.11	46	3.20	5.44		−3.33	−2.79	−0.03	
6103.59	200	6.21	6.40			−1.25	−0.81	New identification
6113.33	46	3.22	5.55			−2.99	0.06	
6149.25	74	3.89	5.24			−1.96	0.48	
6175.16	200	6.22	6.30			−0.97	−0.55	
6179.39	163	5.57	6.40			−1.58	−0.60	
6238.39	74	3.89	5.16		−1.64	−1.96	0.64	RRT: Fe II + (Si I)
6247.56	74	3.89	5.08		−1.55	−1.55	0.89	
6416.93	74	3.89	5.14		−2.14	−1.98	0.37	
6432.68	40	2.89	5.23		−3.02	−2.73	0.45	
6446.40	199	6.22	6.10			−1.03	−0.63	
6456.39	74	3.90	5.03		−1.44		0.97	
6516.08	40	2.89	5.03		−2.71	−2.46	0.75	
7449.34	73	3.89	5.49			−2.22	0.19	
7711.73	73	3.90	5.21		−2.00	−1.97	0.40	

As a result, we are able to use the 76 lines listed in Table VI, of which only 25 have laboratory *f*-values. There are four new identifications. The curve of growth in Fig. 6 shows a moderately small amount of scatter, independent of χ. The theoretical curve is for 4500 Å and $\chi = 2.8$ V. The one weak line falling well below the others is at 5826.11 Å and is assigned $W = 0.5$ mÅ in the RRT, which is probably uncertain.

The abundance derived from Fig. 6 is

$$\log N(\mathrm{Fe}) = 6.51.$$

To select a value of the Fe abundance from the several investigations on Fe I lines using the Corliss & Warner (1964) (CW) *f*-values (which are on the same absolute scale as CB) we have to take into account several effects. Firstly: the question of the absolute scale. Some authors (e.g. Müller (1967), Müller & Mutschlecner (1964)) have pointed out that a comparison of the *f*-value for λ 3720 of Fe I, as measured in the atomic beam by Bell *et al.* (1958), with that given by CW shows that the latter is too large by about 0·20 dex. If this is assumed to be true of the entire set of Fe I *f*-values then the Fe abundance derived from application of the CW data will be 0·20 dex too small.

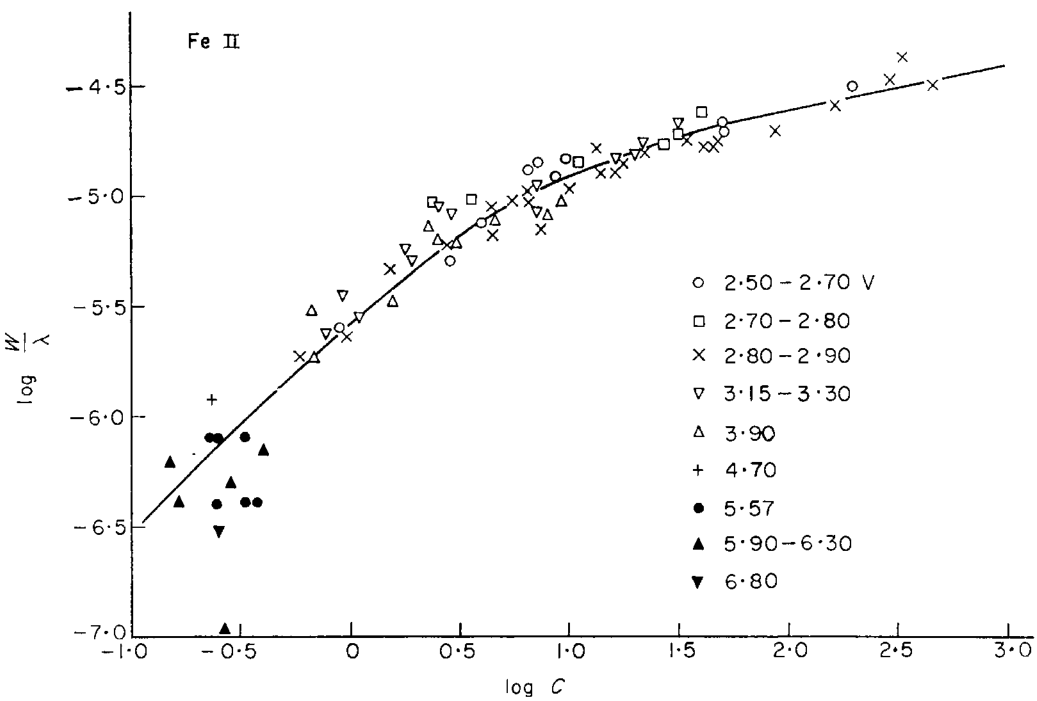

FIG. 6. *Solar curve of growth for Fe* II.

Apart from the obvious difficulties attendant on measuring the intensity of 3720—so that it should not be treated as a typical line—there is a strong argument against the above assumption. Karstensen and Richter (see Corliss & Warner (1966)) have measured the lifetimes of the z^3F_4 and z^3D_1 levels in Fe I. By summing over all downward transitions they also calculated the lifetimes from the CW *f*-values. The results are (lifetimes in 10^{-9} s):

	z^3F_4	z^3D_1
Karstensen & Richter	220 ± 70	100 ± 25
Corliss & Warner	240 ± 90	80 ± 30.

The principal downward transitions from these levels are lines lying in the region 5000–5500 Å. Thus it appears that, at least as far as *f*-values near the above wavelength region are concerned, the CW absolute scale is extremely close to the correct one. Hence if the solar Fe abundance is determined from lines in the general region of 5000–6000 Å there should be no question of adjusting the CW absolute scale.

Secondly there is the question of the influence of known systematic errors in the f-values (as a function of upper excitation potential). These have been discussed by Warner & Cowley (1967) and Cowley & Warner (1967) and it was concluded that lines with upper excitation potential greater than 6·0 V should either be adjusted or rejected. This mainly affects lines in the red and infra-red. There is also a suspicion that lines with χ in the range 0–0·5 V give an anomalously high abundance. This latter is probably not caused by errors in the f-values.

The abundance of Fe derived by Goldberg *et al.* (1964) from the CW data for lines with $1 < \chi < 3$ V lying in the range 4500–6000 Å is $\log N(\text{Fe}) = 6{\cdot}54$. This is 0·11 smaller than the average of all lines used by Goldberg *et al.*, the difference being due to the effects discussed in the previous paragraph. Aller *et al.* (1964) derived $\log N(\text{Fe}) = 6{\cdot}57$ from an average of several hundred Fe I lines (using CW data) and $\log N(\text{Fe}) = 6{\cdot}59$ from a few strong Fe II lines.

The evidence appears strongly for an Fe abundance in the region of 6·55.

TABLE VII

Lines of Co II in the Sun

Wavelength	Mult	χ	$-\log W/\lambda$	$\log gf$	$\log C$	Remarks
3352·82	2	2·24	5·25	−0·88	3·13	
3387·72	2	2·27	4·82	−0·31	3·67	
3415·79	2	2·20	5·03	−0·43	3·65	
3446·40	2	2·24	4·88	−0·02	4·04	RRT: Co I+K I
3501·73	2	2·24	4·82	0·10	4·20	
3514·24	1	2·27	5·48	−1·86	2·22	
3545·05	1	2·20	5·37	−1·16	2·95	
3555·95	1	2·27	5·35	−1·55	2·53	
3578·00	1	2·24	5·35	−0·71	3·37	

8. *Cobalt.* All of the 9 Co II lines listed in Table VII lie shortward of 3600 Å and are thus in a region where equivalent widths are difficult to measure. Additional uncertainty arises because of the observed excessive continuous absorption of unknown origin in the ultra-violet (Matsushima & Terashita 1967) which is not taken into account here. This will tend to make our abundance too small, possibly by a factor ~2. The curve of growth in Fig. 7 is far from satisfactory. The theoretical curve, for 3500 Å and $\chi = 2{\cdot}2$ V, is shown in a position giving

$$\log N(\text{Co}) = 3{\cdot}53.$$

Several lines, not known to be blends, give a substantially higher abundance.

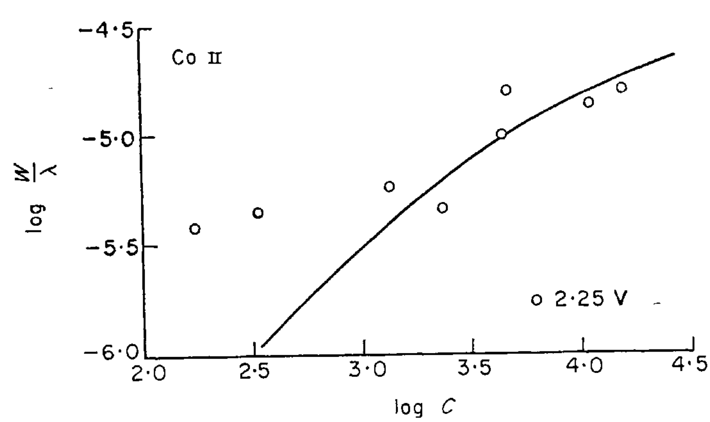

FIG. 7. *Solar curve of growth for Co II.*

Müller & Mutschlecner found log N(Co) = 4·40 from the CB f-values for Co I. Comparison of the CB data with the four lines (3044–3527 Å) measured by Lawrence *et al.* shows that the CB f-values are too large by 0·30 dex. For the same reasons as discussed in Sections 5 and 6 we are hesitant to say that the CB f-values for the lines used in the solar analysis are also too large, but it may be noted that with the Allen & Asaad (1957) f-values a value log N(Co) = 4·71 is derived (Müller & Mutschlecner 1964).

We are inclined to blame the Co II f-values for the discrepancy in Co abundance between ion and neutral lines. A large part may however be due to the use of ultraviolet lines. Until independent measurements are made of Co II f-values and a survey of the effects of additional continuous opacity and uncertainty in continuum placing on the strengths of solar ultra-violet lines (especially ion lines) we can only disregard the abundance found from the Co II lines.

TABLE VIII

Lines of Ni II *in the Sun*

Wavelength	Mult	χ	$-\log W/\lambda$	log gf	log C	Remarks
3397·84	8	3·60	4·96	−1·59	1·64	
3401·77	4	3·07	4·96	−1·29	2·42	
3407·31	4	3·08	4·58	−0·39	3·32	
3454·17	1	2·95	4·76	−0·56	3·23	
3608·73	4	3·09	4·88	−0·81	2·92	RRT: Ni I + unknown
3769·46	4	3·10	4·58	−0·03	3·72	
4015·48	12	4·03	5·28	−1·25	1·76	
4070·99	11	4·03	6·05	−2·39	0·62	RRT: Cr I
4244·10	9	4·03	5·70	−2·03	0·98	
4362·10	9	4·03	5·18	−1·43	1·58	

9. *Nickel.* The situation here is unfortunately similar to that for Co. Of the ten Ni II lines listed in Table VIII half are at rather short wavelengths. In Fig. 8 the theoretical curve is for 4200 Å and χ = 4·0 V, and the indicated abundance is

$$\log N(\text{Ni}) = 5{\cdot}08.$$

It should be noted that the three lines of longest wavelength give an abundance a factor of two greater than the above.

Using the Ni I f-values of Corliss (1965) (which are on the CB absolute scale) Cowley (1966) found log N(Ni) = 5·69 and Müller & Mutschlecner derived 5·55. The atomic beam measurements of Lawrence *et al.* (1965) on 6 ultra-violet strong lines (3050–3525 Å) indicate that the CB scale is 0·22 dex too high. Again the writer feels that it is premature to claim that all of the Ni I f-values are systematically in error by this amount. It may be noted that in addition to the difficulty of measuring these strong lines in the arc, one would have to assume that the connection between the ultra-violet intensities and those in the visible (i.e. the energy calibration as a function of wavelength) contains no systematic error.

The discrepancy between the Ni abundances derived from neutral and ion lines is not as large as was found for Co. If the three lines of longest wavelength are given high weight, then we are essentially comparing log N(Ni) = 5·38 (from Ni II) with 5·55 (from Ni I). Until further measurements on both Ni I and Ni II are made it is recommended that the latter figure be adopted.

10. *Conclusion.* Apart from Co and Ni the agreement between abundances derived from neutral and ion lines is within the probable errors attached to the scales of *f*-values. This is an indication that iron group abundances are converging onto definitive values. An incidental conclusion concerns the validity of the assumption of local thermodynamic equilibrium in the ionization state of the solar photosphere. The close agreement found in this work for the observed and predicted line strengths of both neutral and ionic lines is perhaps the first comprehensive empirical demonstration of the validity of Saha's equation applied to the photosphere. This should increase confidence in the general methods of analysing stellar atmospheres that have been employed in recent years, at least as far as abundance results are concerned.

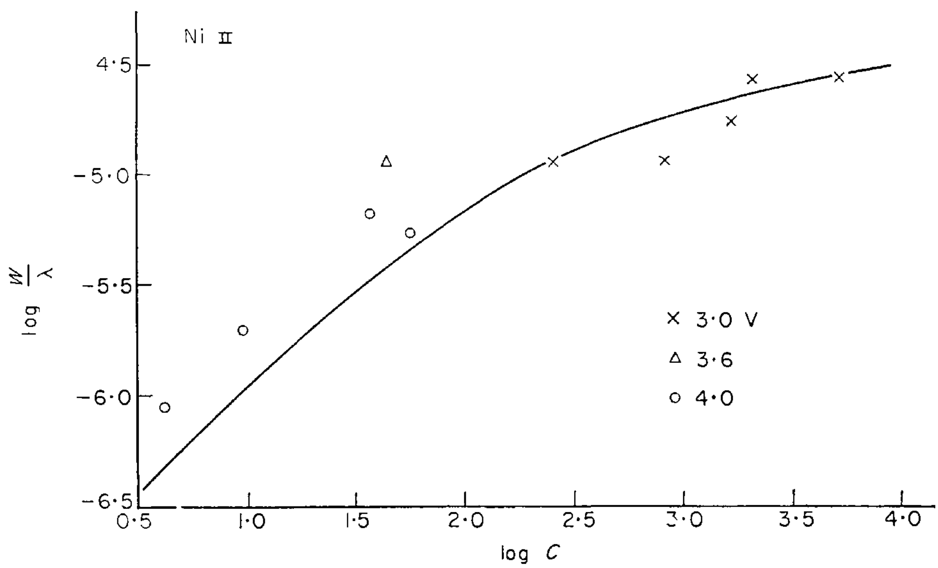

FIG. 8. *Solar curve of growth for Ni* II.

It is worth noting that comparison of the abundances derived in this paper with the predictions of the *e*-process of nucleosynthesis does not alter the conclusions of Fowler (1966) that the best fit is obtained for a density of 10^6 g cm^{-3} and temperature $3{\cdot}6 \times 10^9$ °K.

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Oxford.
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