Mon. Not. R. astr. Soc. (1969) **142**, 71–95.

THE ABUNDANCES OF THE ELEMENTS IN THE SOLAR PHOTOSPHERE—VII

Zn, Ga, Ge, Cd, In, Sn, Hg, Tl and Pb

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(Received 1968 May 20)

Summary

A detailed account is presented of the limited number of Fraunhofer lines which are attributable to the heavier elements with ground state configurations of s^2, s^2p or s^2p^2. The Oxford photoelectric spectrometer was used to obtain new measurements of the equivalent width for selected lines of Zn I, Ge I, Cd I, In I and Tl I. A thorough discussion is given of the available experimental and theoretical oscillator strengths. The following abundances are obtained on the standard scale where $\log N(\mathrm{H}) = 12{\cdot}00$:

$\log N(\mathrm{Zn}) = 4{\cdot}42$	$\log N(\mathrm{Ga}) = 2{\cdot}94$	$\log N(\mathrm{Ge}) = 3{\cdot}32$
$\log N(\mathrm{Cd}) = 2{\cdot}07$	$\log N(\mathrm{In}) = 1{\cdot}71$	$\log N(\mathrm{Sn}) = 1{\cdot}71$
$\log N(\mathrm{Hg}) < 3{\cdot}0$	$\log N(\mathrm{Tl}) \lesssim 0{\cdot}2$	$\log N(\mathrm{Pb}) = 1{\cdot}90$

1. *Introduction.* The present paper gives a discussion of the photospheric abundance for the heavier elements with ground state configurations of s^2, s^2p or s^2p^2:

s^2: Zn, Cd, Hg

s^2p: Ga, In, Tl

s^2p^2: Ge, Sn, Pb.

These elements are represented in the Fraunhofer spectrum by a handful of lines; the best represented element is zinc with six lines of the neutral spectrum included in the abundance determination. It is, therefore, imperative that the identifications and intensities of the Fraunhofer lines, which are attributed to these elements, be derived from solar spectra of the highest possible quality. The Oxford photoelectric spectrometer (Blackwell, Petford & Mallia 1967) was used to observe lines attributed to eight of the nine elements; the paper also includes a new discussion of the Pb I line at 7229 Å, which was observed and discussed by Peach (1968).

The techniques of abundance analysis were outlined in earlier papers of this series. The adopted model atmosphere was that given in Paper I (Lambert 1968) and modified in Paper III (Lambert & Warner 1968). The elements are discussed in ascending order of atomic weight from Zn to Pb.

2. *Zinc*

2.1 *Introduction.* The zinc abundance determination is based on a selection from the ten lines which are free from serious blending and for which details are given in Table I. Two new identifications (λλ11054 and 13053) are given; laboratory

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wavelengths for these and other infrared transitions, which are masked by atmospheric H_2O absorption, were given by Fisher, Knopf & Kinney (1959). It is shown in Section 2.3 that the Fraunhofer lines λλ4292 and 4629 are not attributable to Zn I.

2.2 *Oscillator Strengths.* There are no reliable experimental determinations of absolute oscillator strengths for the Zn I lines listed in Table I. The measurements by Corliss & Bozman (1962), which were used by Aller (1965) for a redetermination of the solar Zn abundance, are liable to be in error by a factor in excess of two. Schuttevaer & Smit (1943) published results of an extensive program of relative oscillator strength measurements, which were derived from emission line intensities. They normalized their relative measurements to an absolute measurement of the oscillator strength of the Zn I resonance line λ3075. Goldberg, Müller & Aller* (1960) based their Zn abundance analysis on this normalization of the relative measurements. The normalization procedure is discussed in a later paragraph.

Theoretical calculations of the Zn I oscillator strengths may be reliably undertaken for certain selected transitions. Warner (1968a) has given results for the $4s^2$, $4sns$–$4snp$ transitions. The radial integrals were computed from scaled Thomas–Fermi–Dirac (STFD) wave functions. Spin–orbit coupling within the np configurations results in a slight mixing of $^1P^0$ into $^3P^0$, which is responsible for the intercombination lines such as $4p\ ^3P_1{}^0$–$5s\ ^1S_0$. The slight departures from LS coupling were taken into account.

The spectrum of Zn I is very similar to that of Mg I, which was studied by Warner (1968b). Therefore, by analogy, it is assumed that the $nd\ ^3D$ levels in Zn I will be fairly pure in LS coupling but the $nd\ ^1D$ levels will be considerably mixed both together and with $4p^2\ ^1D$. This latter interaction is responsible for the depression of the $nd\ ^1D$ levels to a position in the term diagram below the $nd\ ^3D$ levels. The oscillator strength for the $4p\ ^3P^0$–$4d\ ^3D$ multiplet was derived using the STFD wave functions and the LS coupling line strengths. Accurate oscillator strengths for the transitions involving the $nd\ ^1D$ levels cannot be calculated without performing a detailed investigation of configuration interaction in Zn I. However, it is reasonable to suppose that the use of LS coupling line strengths will provide an upper limit to the oscillator strengths; an exception may be the transition λ6362 $4p\ ^1P^0$–$4d\ ^1D^0$ for which contributions from both $4s4p\ ^1P^0$–$4s4d\ ^1D$ and $4s4p\ ^1P^0$–$4p^2\ ^1D$ are possible.

The oscillator strengths for the transitions $4p\ ^1P^0$–$4d$, $5d\ ^1D$ were measured by Schuttevaer & Smit (1943) relative to the $4p$–ns series. Since the equivalent width for the unblended line λ6362 has been measured on tracings obtained with the Oxford spectrometer, it is of interest to examine whether the relative oscillator strengths may be placed onto an absolute scale. Schuttevaer & Smit achieved a normalization by adopting the mean of eight independent measurements of the absolute oscillator strength for the resonance line λ3075 $4s^2\ ^1S_0$–$4p\ ^3P_1{}^0$. The lifetime of the $4p\ ^3P_1{}^0$ level was measured by Byron, McDermott, Novick, Perry & Saloman (1964); the corresponding oscillator strength for λ3075 is

$$gf = (2{\cdot}13 \pm 0{\cdot}21) \times 10^{-4}.$$

This is the most accurate experimental determination and is approximately a factor of four greater than that adopted by Schuttevaer & Smit. The revised normalization

* Subsequently referred to as GMA.

TABLE I

Zn I lines in the solar spectrum

Transition array	J''–J'	λ_{air}(Å)*	χ(eV)	log gf	W_λ(mÅ)	log $\frac{W_\lambda}{\lambda}+7$	[Zn]	Remarks†
$4p\ ^3P^0$–$5s\ ^3S$	2–1	4810·534	4·08	−0·24	80	2·22	−0·04	84RRT, 76HOL
	1–1	4722·159	4·03	−0·45	66	2·15	−0·08	63RRT, 68HOL
	0–1	4680·138	4·01	−0·92	42	1·95	−0·01	42RRT
$4p\ ^3P^0$–$5s\ ^1S$	1–0	4292·885	4·03	−3·53	1·0	0·37		1RRT, 1·0OX
$4p\ ^3P^0$–$4d\ ^3D$	2–3	3345·020	4·08	+0·24	62	2·27	−0·61	62RRT
	2–2	3345·572	4·08	−0·51	50	2·17	−0·05	50RRT
	1–2	3302·588	4·03	−0·03	55	2·22	−0·45	55RRT
$4p\ ^1P^0$–$5s\ ^1S$	1–0	11054·21	5·08	−0·30	15	1·13	+0·06	15DR
$4p\ ^1P^0$–$4d\ ^1D$	1–2	6362·347	5·80	+0·15	24	1·58	+0·10	23RRT, 19GMA, 24OX
$4p\ ^1P^0$–$5d\ ^1D$	1–2	4629·814	5·80	−1·62	2·6	0·75		4RRT, 1·86MA, 2·6OX
$5s\ ^3S$–$5p\ ^3P^0$	1–2	13053·65	6·65	+0·34	20	1·22	+0·13	12MO, 20CC

* Wavelengths from Hetzler, Boreman & Burns (1935); for λλ11054, 13053 from Fisher, Knopf & Kinney (1959).

† The W_λs from various sources are listed: CC = Connes & Connes (1968), DR = Delbouille & Roland (1963), GMA = Goldberg, Müller & Aller (1960), HOL = Holweger (1967), MO = Mohler (1955), OX = observations with the Oxford photo-electric spectrometer, RRT = Moore, Minnaert & Houtgast (1966).

provides the following results for λλ6362 and 4629:

$$\lambda 6362 \quad \log gf = +0{\cdot}18$$
$$\lambda 4629 \quad = -1{\cdot}25.$$

This simple and direct procedure assumes that the set of relative oscillator strengths is unaffected by systematic errors. Since the results of the theoretical calculations are applicable to several of the multiplets measured by Schuttevaer & Smit, it is possible to test their results for certain systematic errors. The most likely source of error is in the adopted temperature for the arc and, if present, this error will produce a correlation between the theoretical oscillator strengths ($gf_{\rm abs}$) and the relative measurements ($gf_{\rm rel}$) such that

$$\log \frac{gf_{\rm abs}}{gf_{\rm rel}} = \text{constant} - \chi_u \theta$$

where χ_u is the excitation potential (in eV) of the upper level for the transition and $\theta = 5040/T$ is the reciprocal temperature. The data for $4p\ ^3P^0$–$4d\ ^3D$, $ns\ ^3S$ ($5 \leqslant n \leqslant 9$) is plotted in Fig. 1. The resonance line λ3075 is also included; a point is plotted for both the theoretical value (Warner 1968a) and the absolute oscillator strength obtained from the lifetime measurement. The straight line drawn through the points is a best fit as judged by eye. It corresponds to an underestimate of 450 °K in the arc temperature. Penkin & Red'ko (1960) used the hook method to obtain relative oscillator strengths for three multiplets in Zn I ($4p\ ^3P^0$–$5s\ ^3S$, $4d\ ^3D$, $5d\ ^3D$). Their results are in approximate agreement with the deduced temperature error of 450 °K.

A second possible source of systematic error is the wavelength dependence of the

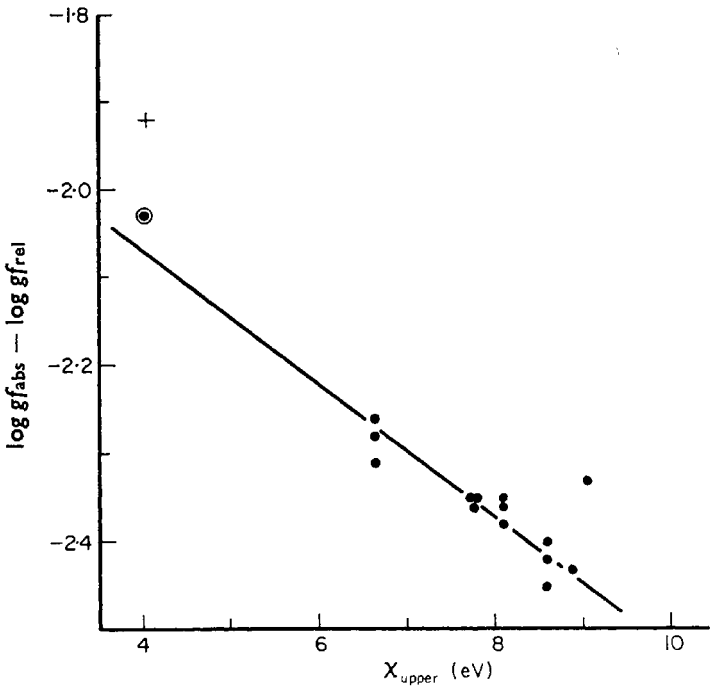

FIG. 1. *Comparison of the measured oscillator strengths for Zn I (Schuttevaer & Smit 1943) and the absolute oscillator strengths calculated by Warner (1968). The larger symbols at $\chi_{upper} = 4$ eV refer to resonance line λ3075; the absolute oscillator strength was calculated by Warner (cross) and determined from a measurement of the radiative lifetime (semi-filled circle).*

calibration of the apparatus (source, spectrograph, plates, etc.). The lines, which are plotted in Fig. 1, are spread across the interval $2000 \leqslant \lambda \leqslant 4800$ Å and there is no evidence for a wavelength dependence in the (gf_{abs}, gf_{rel}) plot. However, the theoretical calculations for $\lambda 5182$ $4p\ ^1P^0$–$6s\ ^1S$ place the point for this line about 0·28 dex* above the straight line in Fig. 1. This might suggest a wavelength error for $\lambda \gtrsim 5000$ Å. Since $\lambda\lambda 5182$ and 6362 are the only lines in the list longward of 5000 Å, a detailed examination is impossible. The following absolute oscillator strengths are obtained by correction for the temperature error and the assumption that the wavelength dependent error is identical for $\lambda\lambda 5182$ and 6362:

$$\lambda 6362 \quad \log gf = +0{\cdot}15$$
$$\lambda 4629 \quad = -1{\cdot}62.$$

These results are adopted for the ensuing abundance analysis. The theoretical oscillator strengths are $\log gf = +0{\cdot}48$, $-0{\cdot}52$ for $\lambda\lambda 6362$ and 4629 respectively. The normalized experimental results confirm the above claim that the assumption of LS coupling provides an upper limit to the oscillator strength.

2.3 *The Zn abundance.* The present determination of the Zn abundance is based on a selection from the line list of Table I. The multiplet $4p\ ^3P^0$–$4d\ ^3D$ must be excluded because unidentified sources contribute appreciably to the continuous opacity at 3300 Å. The adopted oscillator strength for $\lambda 4629$ corresponds to a predicted equivalent width $W_\lambda = 0{\cdot}1$ mÅ; the observed equivalent width is $W_\lambda = 2{\cdot}6 \pm 0{\cdot}3$ mÅ according to scans obtained with the Oxford spectrometer. Moore, Minnaert & Houtgast (1966) also list the intercombination line $4p\ ^3P_1{}^0$–$5s\ ^1S_1$ as present at 4292·885 Å in the Fraunhofer spectrum. The predicted intensity is $W_\lambda = 0{\cdot}15$ mÅ but scans obtained with the Oxford spectrometer give

$$W_\lambda = 1{\cdot}0 \pm 0{\cdot}3 \text{ mÅ}.$$

The conclusion is drawn that the Zn I transition is not the major contributor to the Fraunhofer lines at $\lambda\lambda 4629$ and 4292. Clearly, an identification, which is based on a wavelength coincidence, should be confirmed by a calculation of the predicted intensity.

The remaining six lines show a small spread in the abundance; [Zn]† ranges from $-0{\cdot}08$ to $+0{\cdot}13$. The mean abundance is

$$[\text{Zn}] = +0{\cdot}02 \quad \text{or} \quad \log N(\text{Zn}) = 4{\cdot}42$$

when equal weight is assigned to all lines.

The mean result for the multiplet $4p\ ^3P^0$–$4d\ ^3D$ is [Zn] $= -0{\cdot}37$. The apparent discrepancy with the above result would diminish if additional continuous opacity were introduced. A quantitative examination of this effect would be of interest.

The present revision of the Zn abundance is within 5 per cent of the GMA result. This coincidence is fortuitous. GMA adopted the absolute oscillator strengths, which are derived from the relative measurements with the normalization proposed by Schuttevaer & Smit (1943). The differences between these and the present values should result in an increase in the abundance but a compensating decrease is obtained by the removal of their assumption that the damping constants could be

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

† $[X] = \log N(X) - \log N_{\text{GMA}}(X)$; the abundance $\log N(X)$ is given on the usual scale where $\log N(H) = 12{\cdot}00$.

put equal to zero. Aller (1965) obtained a zinc abundance log $N(\mathrm{Zn}) = 3{\cdot}52$. This result is a consequence of his use of the Corliss & Bozman (1962) oscillator strengths. The absolute oscillator strengths adopted for this investigation must be considered superior to the latter values.

The isotopic composition of terrestrial zinc is 0·489 Zn^{64}, 0·276 Zn^{66}, 0·187 Zn^{68} with smaller fractions of Zn^{67} and Zn^{70}. If the isotopic shifts were appreciable, accurate line profile observations might lead to a measurement of the isotopic composition of solar zinc. Unfortunately, measurements by Hately & Littlefield (1958) show that the isotope shifts are very small; for example, the wavelength shift Zn^{68}–Zn^{64} is less than 1 mÅ for the multiplet $4p\ ^3P^0$–$5s\ ^3S$. Although some of the lines in Table I are not included in the reported measurements, no measurable isotope shift is to be expected.

3. *Gallium*

3.1 *Introduction.* The resonance lines (λλ4172 and 4032) of Ga I are present in the Fraunhofer spectrum. Unfortunately, both are severely blended. The stronger line λ4172 is the least blended and, owing to the complete lack of other identified lines, was employed by Goldberg, Müller & Aller (1960) for their abundance analysis. New observations of this blend were secured with the Oxford spectrometer.

The serious blending affecting both resonance lines prompted a search for weak lines from the first excited level. The strongest lines must come from the multiplet $5s\ ^2S$–$5p\ ^2P^0$. The Ga I spectrum was measured recently by Johansson & Litzen (1967), who give accurate wavelengths ($\Delta\lambda \simeq \pm 0{\cdot}01$ Å) for the $5s$–$5p$ transitions. The stronger transition ($J''-J' \equiv 1/2$–$3/2$) appears to be present in the solar spectrum. The Delbouille & Roland Atlas (1963) shows that a weak line ($W_\lambda = 2$ mÅ) is present in the far wing of a Ca II line. The measured wavelength is $\lambda_\odot = 11949{\cdot}15 \pm 0{\cdot}05$ Å, which is consistent with the laboratory measurement $\lambda_{air} = 11949{\cdot}12$ Å. The weaker line at $\lambda_{air} = 12109{\cdot}78$ is masked by atmospheric H_2O absorption. The multiplet $5s\ ^2S$–$6p\ ^2P^0$ will be too weak to be observed.

3.2 *Oscillator strengths.* The oscillator strengths for the Ga I resonance lines have been measured by various methods. The results for λ4172 are summarized in Table II.

TABLE II

The oscillator strength for the Ga I resonance line:

λ4172·042, $4p\ ^2P_{3/2}{}^0$–$5s\ ^2S_{1/2}$

f	Method	Reference
0·115 ± 0·006*	Lifetime	Cunningham & Link (1967)
0·125 ± 0·009	Hook	Penkin & Shabanova (1967)
0·076 ± 0·011	Atomic beam	Lawrence, Link & King (1965)
0·085 ± 0·017	Lifetime	Demtroder (1962)
0·133	Emission lines	Corliss & Bozman (1962)

* The theoretical branching ratio was adopted in the conversion of the measured lifetime to the oscillator strength for λ4172.

The most recent measurement (Cunningham & Link 1967) of the lifetime of the $5s\ ^2S_{1/2}$ level undoubtedly provides the most accurate oscillator strength. Thi

result is adopted for the present investigation. Cunningham & Link suggest possible reasons to account for the poor agreement with the independent lifetime determination (Demtroder 1962) and an atomic beam measurement (Lawrence, Link & King 1965). The agreement is surprisingly good with the most recent results from the hook method (Penkin & Shabanova 1967).

Finally, it is of interest to record that a theoretical computation using STFD wave functions gave $f = 0{\cdot}115$, which is in excellent accord with the recent lifetime result. This agreement suggests that confidence may be placed in the theoretical results for the $5s$–$5p$ multiplet. The STFD wave functions give $gf = 1{\cdot}71$ for $\lambda 11949{\cdot}12$.

3.3 *The Ga abundance.* The Oxford scan of the $\lambda 4172$ blend was made at a higher resolution and with a superior signal–noise ratio to the scans available to GMA. An attempt was made to analyse the blend in detail. According to Moore, Minnaert & Houtgast (1966), the composite feature comprises of

λ	W_λ	
4171·908	90	Fe I, Ti II
4172·053	42	Ga I
4172·131	99	Fe I

A completely satisfactory fit to the observed profile was not achieved. Approximate fits to the observations could be obtained for an increase of the abundance by a factor of $3{\cdot}0 \pm 1$ (or 0·48 dex) over the GMA result; the revised abundance is

$$\log N(\mathrm{Ga}) = 2{\cdot}84$$

and only 0·16 of the 0·48 dex increase is attributable to a reduction in the adopted oscillator strength.

The newly identified line at 11949 Å leads to the abundance $\log N(\mathrm{Ga}) = 2{\cdot}88$, which is in satisfactory agreement with the revised figure from the resonance line.

The uncertainty in the gallium abundance should not be under-estimated; the close agreement between the results from $\lambda 4172$ and 11949 may be largely fortuitous. Improved observations of the newly identified line would be welcomed. It is reasonable to expect the line to show a detectable hyperfine structure, which would provide positive confirmation of the proposed identification. The possibility of determining the isotopic composition is remote; natural gallium is composed of 60 per cent Ga^{69} and 40 per cent Ga^{71}.

4. *Germanium*

4.1 *Introduction.* Five Fraunhofer lines attributable to Ge I are listed in the recent revision of Rowland's *Preliminary Table of Solar Wavelengths* (Moore, Minnaert & Houtgast 1966). Three lines ($\lambda\lambda 3039{\cdot}06$, 3124·82 and 3269·49) are in the ultraviolet where accurate measurements of equivalent widths cannot be obtained and, furthermore, the presence of unidentified sources of continuous opacity renders uncertain the interpretation of the equivalent widths. The two remaining lines are at 4226·568 and 4685·854 Å. The former was used by GMA for their abundance determination. Unfortunately, this line is close to the strong Ca I line at 4226·740 Å. Although an analysis of the blend could be attempted, the result for the germanium abundance would be uncertain because of the fact that the Ca I–Ge I blend is formed

in the low chromosphere and the model atmosphere is ill defined for such layers. The present discussion is based on the weak intercombination line λ4685 arising from the transition $4p^2\ {}^1S_0$–$5s\ {}^3P_1{}^0$. A theoretical calculation of its oscillator strength is discussed in the following section. The wavelength interval 4684–4687 Å was scanned with the Oxford spectrometer. The interpretation of the spectrum is discussed in Section 4.3.

4.2 *Oscillator strength of Ge I 4685·85 Å.* The oscillator strength for $4p^2\ {}^1S_0$–$5s\ {}^3P_1{}^0$ was calculated from intermediate coupling theory; configuration interaction is expected to be unimportant and was neglected. STFD wave functions were used for the computation of the radial integrals.

Lawrence (1967) has given oscillator strengths for the Ge I $4p^2$–$4p5s$ transition array, which were based upon an experimentally determined value of the dipole radial integral. The value adopted in the present investigation differs slightly from his for two reasons. In the first place, the present result relies upon theoretical wave functions, which should be quite reliable for atoms of intermediate atomic weight. Secondly, Lawrence adopted one value of the radial integral for the entire transition array while the present calculations employed radial integrals computed for the individual multiplets. In addition, the theory of intermediate coupling, which is adopted for the calculations, is more complete than that employed by Lawrence.

The calculated oscillator strength is $\log gf_{4686} = -1{\cdot}70$, as opposed to $\log gf_{4686} = -2{\cdot}07$ as obtained by Lawrence. In a paper in preparation by one of us (B.W.), it is made evident that the former value should be the more reliable.

4.3 *The Ge abundance.* The location of the Fraunhofer line λ4685·85 is shown in the lower part of Fig. 2. A smaller portion of the scan is illustrated in greater detail in the upper part. The noise level of the scan is about 0·1 per cent. The scan was obtained with the entrance slit of the spectrometer position at the centre of the solar disk.

Moore, Minnaert & Houtgast (1966) indicate that a Co I line is a contributor to λ4685. An analysis of the new scans confirms their suggestion. The wavelength for the peak of the probable blend was derived by interpolation from the stronger lines present on the scan. The accurate absolute wavelengths given by Moore, Minnaert & Houtgast were adopted for the stronger lines. The measured wavelength for the Ge I–Co I blend is 4685·856 ± 0·005 Å, which is in good agreement with the wavelength 4685·854 Å given by Moore, Minnaert & Houtgast. The wavelength after subtraction of the gravitational redshift is 4685·846 Å*. The measured wavelength for the Ge I transition is 4685·8286 ± 0·0004 Å according to an interferometric determination by Van Veld & Meissner (1956). The *M.I.T. Wavelength Tables* (1939) give the wavelengths of the Ge I and Co I transition as 4685·837 and 4685·856 Å respectively. The observed wavelength indicates that the Co I transition is the stronger component. The observed total half width is 123 mÅ which must be contrasted with a predicted half width of only 65 to 75 mÅ for the Ge I–Co I blend. The discrepancy probably results from an additional broadening of the Co I transition by hyperfine splitting. Unfortunately, measurements of the splitting are not available for λ4685

* Lambert & Mallia (1968) have shown that the wavelength of a Fraunhofer line (for example, the Ge I–Co I blend), which is formed in the outer layers of the photosphere ($\tau_0 \lesssim 0{\cdot}1$) is displaced to the red in quantitative agreement with the prediction of the general theory of relativity.

but measurements for several similar lines (More 1934; Rasmussen 1936) show that splittings of up to 235 mÅ were recorded.

The isotopic composition of natural germanium is 0·205 Ge^{70}, 0·274 Ge^{72}, 0·078 Ge^{73}, 0·366 Ge^{74}, 0·078 Ge^{76}. The isotope shift measurements by Heilig, Riesner & Steudel (1966) did not include λ4685 but the shift can be deduced from their results; the shift for Ge^{70}–Ge^{76} does not exceed 2 mÅ. The isotope shift and the hyperfine structure for the least abundant isotope Ge^{73} will have a negligible influence on the profile.

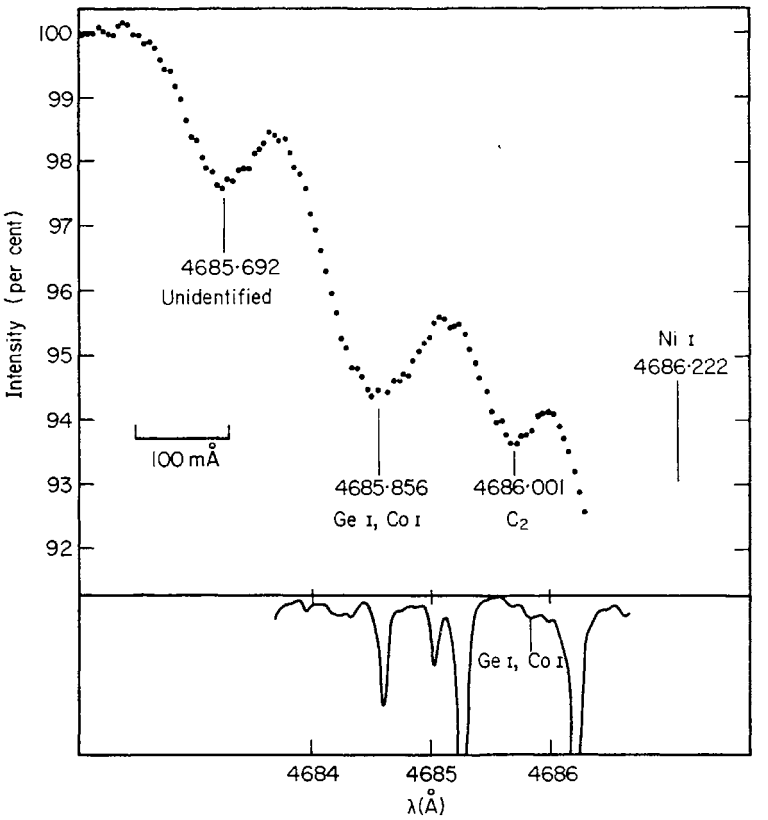

FIG. 2. *The Ge I intercombination line at 4685 Å. The location of the Ge I–Co I blend is shown in the lower part of the figure. The blend is shown in greater detail in the upper plot of the Oxford scan.*

The equivalent width for the entire Co I–Ge I blend is estimated to be 5·9 ± 0·2 mÅ. The uncertainty was estimated from the difficulties which were experienced in the location of the continuum. An analysis of the combined profile indicates that the Ge I and Co I transitions contribute to the blend in the proportions Co I : Ge I = 1·6 : 1·0. This ratio corresponds to $W_\lambda = 2{\cdot}3 \pm 0{\cdot}3$ mÅ for the Ge I line. This equivalent width with the above oscillator strength and the adopted atmosphere give the germanium abundance as

$$\log N(\mathrm{Ge}) = 3{\cdot}32$$

with an uncertainty of 0·1 to 0·2 dex.

5. *Cadmium*

5.1 *Introduction.* GMA based their abundance determination on observations of the intercombination line $5s\ ^1S_0$–$5p\ ^3P_1^0$ at $\lambda_\odot = 3261{\cdot}065$ Å. They considered

Cd I to be a minor contributor to the Fraunhofer line at this wavelength. Their adopted equivalent width of $W_\lambda = 1{\cdot}5$ mÅ gave an abundance $\log N(\mathrm{Cd}) = 1{\cdot}46$. A recalculation of the abundance which was based upon a more accurate oscillator strength and the revised model atmosphere, would differ only slightly. However, Moore, Minnaert & Houtgast (1966) suggest that Cd I is the major contributor to the Fraunhofer line and that $W_\lambda = 23$ mÅ is the appropriate intensity. If this is correct, a substantial increase in the Cd abundance occurs: $\log N(\mathrm{Cd}) = 2{\cdot}7$ (Müller 1967). Miss Müller has pointed out that the increased abundance is not substantiated by observations of the $5p\ ^3P^0$–$6s\ ^3S$ multiplet which should be present in the visible region of the spectrum. Two of the three lines from this multiplet are severely blended; she tentatively identified the third and strongest line at $\lambda_{\mathrm{air}} = 5085{\cdot}823$ Å with a faint absorption feature with $W_\lambda \leqslant 0{\cdot}8$ mÅ. The corresponding abundance was given as $\log N(\mathrm{Cd}) \leqslant 1{\cdot}6$.

The present discussion is based on improved observations of the faint absorption feature at 5085 Å. The oscillator strength is discussed in the following section. The interpretation of the scans, which were obtained with the Oxford spectrometer, is given in Section 5.3.

5.2 *Oscillator strengths.* Oscillator strengths for s–p transitions have been calculated by Warner (1968a). The radial integrals were computed from STFD wave functions. The line strengths were obtained from intermediate coupling calculations. The result for $\lambda 5085\ 5p\ ^3P_2{}^0$–$6s\ ^3S_1$ is $gf = 0{\cdot}602$.

Experimental determinations of absolute oscillator strengths in Cd I are limited to the resonance line and to the intercombination line $\lambda 3261\ 5s\ ^1S_0$–$5p\ ^3P_1{}^0$. Van Hengstum & Smit (1956) obtained measurements of relative oscillator strengths for 31 lines in the Cd I spectrum. Their list includes both $\lambda 3261$ and $\lambda 5085$ and, therefore, the possibility of a satisfactory normalization to an absolute scale was examined. The experimental techniques including the method of temperature measurement and the reduction procedures were modeled closely upon those developed for the earlier measurements of the Zn I spectrum (Schuttevaer & Smit 1943).

It is an apparently simple process to normalize their relative measurements to the oscillator strength ($gf = 2{\cdot}00 \pm 0{\cdot}03 \times 10^{-3}$) for $\lambda 3261$, which is now available following the accurate measurement of the lifetime of the $5p\ ^3P_1{}^0$ level (Byron, McDermott & Novick 1964). This normalization results in a value $gf = 2{\cdot}5$ for $\lambda 5085$, which is a factor of four greater than the above theoretical estimate. This discrepancy must be attributed to systematic errors in the relative measurements; in particular, it is noted that van Hengstum & Smit emphasize that the ratio f_λ/f_{3261} is the least reliable result.

The series $5p\ ^3P^0$–$ns\ ^3S$ ($n = 6, 7, 8$) was observed by van Hengstum & Smit. A comparison of the theoretical and relative experimental results suggests that the arc temperatures were over-estimated by about 250°K (see Section 2.2). Furthermore, Penkin & Red'ko (1960) used the hook method to measure relative oscillator strengths for the multiplets $5p\ ^3P^0$–$6s\ ^3S$, $5d$, $6d\ ^3D$ and a comparison of their results with those by van Hengstum & Smit indicates a systematic trend which can be also interpreted as a result of a 250°K over-estimate by the latter authors of their arc temperature. The satisfactory agreement of the two estimates for the temperature error indicates that the corrected relative measurements would be in close agreement with the theoretical results.

If an error of 250°K is assumed for the arc temperature, the corrected ratio of f_λ/f_{3261} obtained from the measurements is a factor of five greater than the ratio deduced by combining the theoretical estimates for the $5p$–ns series with the accurate absolute oscillator strength measurement for λ3261*. This large discrepancy is unexplained.

This discussion provides a further illustration of the dangers inherent in an over-enthusiastic acceptance of measurements of relative oscillator strengths and their normalization to an absolute scale based upon an absolute oscillator strength measurement for a single and atypical line.

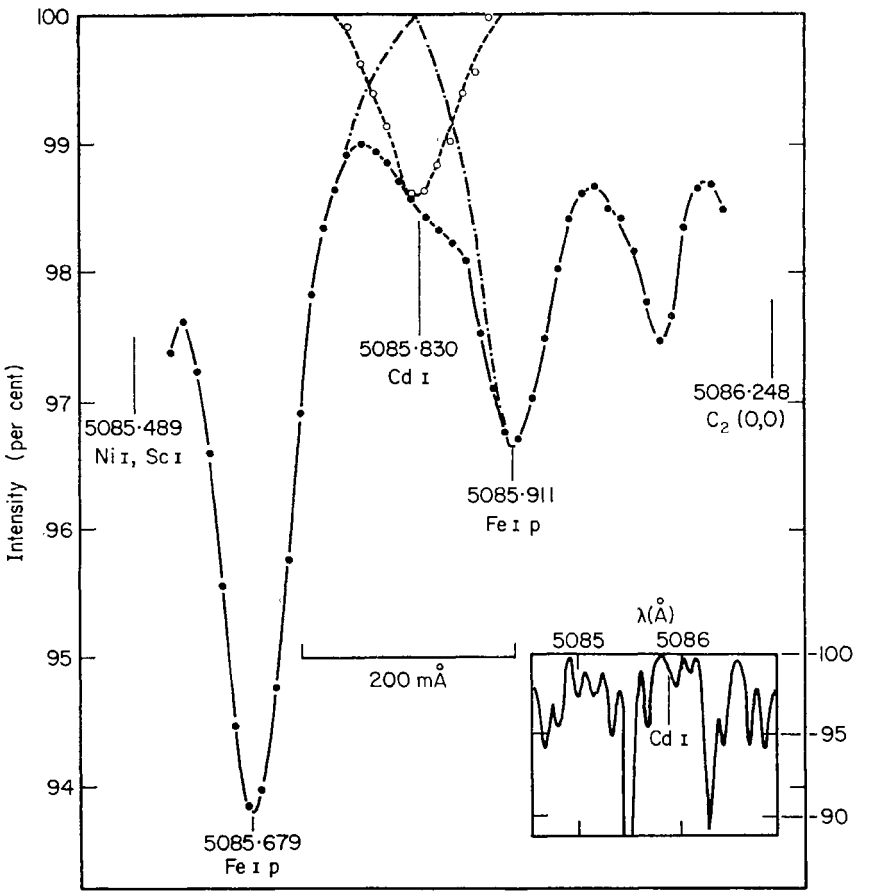

FIG. 3. *The Cd I line at 5085·830 Å. The inset illustrates the location of the line. The wings of the Fe I lines at 5085·679 and 5085·911 Å were extrapolated (dash–dot line) on the assumption that these line profiles are gaussian with a half-width of 72 mÅ (see text). The subtraction of these wings from the observed (filled circles) spectrum gives the profile (open circles) for the Cd I line. The theoretical profile for the Cd I line is shown by the dashed line and is placed at the predicted wavelength for the transition.*

5.3 *The Cd abundance.* The interval 5084–5087 Å was scanned with the Oxford spectrometer (see Fig. 3). The noise level of the scan is about 0·05 per cent of the continuum intensity.

The predicted wavelength for the Cd I line is indicated on Fig. 3. This prediction is derived from the accurate laboratory wavelength, λ_{air} = 5085·8230 (Allen 1963), on addition of the gravitational redshift of 11 mÅ but less a small blue shift (4 mÅ)

* The ratio obtained from the measurements by Corliss & Bozman (1962) is a factor of fifteen greater than this latter ratio.

which results from convective motions in the photosphere (Lambert & Mallia 1968). An inspection of Fig. 3 indicates that a weak Fraunhofer line is present close to the predicted Cd I wavelength. A thorough reduction confirms the identification.

The method of reduction will be outlined. The mean observed half width of the Fe I lines at 5085·679 and 5086·772 Å is 72 mÅ. A gaussian profile with this half-width is fitted to the Fe I line λ5085·911, which is blended with the proposed Cd I line. The extrapolated gaussian wing is subtracted from the observed spectrum. A similar process is adopted for λ5085·679, which lies to the blue of the proposed Cd I line. The resultant observed profile is in excellent agreement with the predicted Cd I profile.

The measured peak wavelength for the Fraunhofer line is equal to the predicted wavelength to within an uncertainty of 5 mÅ. The observed halfwidth is 77 ± 5 mÅ, which is consistent with the model prediction of 80 mÅ. The equivalent width of the observed profile is $W_\lambda = 1{\cdot}2 \pm 0{\cdot}2$ mÅ. The excellent fit with the predicted profile and, in particular, the close coincidence of the predicted and observed peak wavelengths, is convincing evidence that the line may be identified with the Cd I transition.

The theoretical oscillator strength ($gf = 0{\cdot}602$) together with the above equivalent width results in an abundance

$$\log N(\mathrm{Cd}) = 2{\cdot}07$$

with an uncertainty of between 0·1 and 0·2 dex.

Natural cadmium is composed of five even isotopes (108, 110, 112, 114, 116) and two odd isotopes (111, 113), in the ratio even : odd = 3 : 1. The isotope shifts for λ5085 are too small to affect the line profile: $\Delta\lambda$ for Cd^{111}–Cd^{113} is less than 1·5 mÅ (Hull & Stroke 1963). The principal hyperfine component ($F'' = 5/2 \rightarrow F' = 3/2$) is within 5 mÅ of the single line given by the even isotopes (Hull & Stroke 1963). The weaker components cannot produce a measurable asymmetry.

6. *Indium*

6.1 *Introduction.* Indium is represented in the solar spectrum by a single resonance line of the neutral spectrum: $5p\ ^2P_{3/2}{}^0$–$6s\ ^2S_{1/2}$ at $\lambda_\odot = 4511{\cdot}31$ Å. The weaker resonance line is masked by the Balmer line Hδ. An accurate oscillator strength is available for λ4511. The predicted equivalent width is insensitive to the adopted model atmosphere. These two considerations indicate that the precision of an abundance determination is directly linked to uncertainties in the equivalent width measurements of this weak line: $W_\lambda = 2$ mÅ according to Moore, Minnaert & Houtgast (1966). The line λ4511 was observed with the Oxford spectrometer.

6.2 *Oscillator strength.* The oscillator strengths of the In I resonance lines have been determined in several independent experiments and by a variety of techniques. These results are summarized in Table III.

The most reliable results are those based upon a measurement of the lifetime of the $6s\ ^2S_{1/2}$ level. The most recent lifetime measurement (Cunningham & Link 1967) was converted to an oscillator strength via the branching ratio measurement obtained by Hulpke, Paul & Paul (1964). Although the two lifetime measurements differ by an amount exceeding the quoted uncertainties, the mean results are probably subject to an uncertainty of less than ten per cent.

TABLE III

Oscillator strengths for the In I resonance lines $5p\ ^2P^0$–$6s\ ^2S$

f_{4102}	f_{4511}	Method	Reference
$0{\cdot}105 \pm 0{\cdot}006$	$0{\cdot}115 \pm 0{\cdot}006$	Lifetime	Hulpke, Paul & Paul (1964)
$0{\cdot}119 \pm 0{\cdot}008$	$0{\cdot}131 \pm 0{\cdot}010$	Lifetime	Cunningham & Link (1967)
$0{\cdot}120 \pm 0{\cdot}012$	$0{\cdot}111 \pm 0{\cdot}022$	Atomic beam	Lawrence, Link & King (1965)
$0{\cdot}141 \pm 0{\cdot}007$	$0{\cdot}153 \pm 0{\cdot}008$	Hook	Penkin & Shabanova (1963a, 1967)
$0{\cdot}172$		Absorption line	Moise (1963)
$0{\cdot}096$	$0{\cdot}100$	Absorption line	Ch'en & Smith (1959)
$0{\cdot}24$	$0{\cdot}17$	Emission lines	Corliss & Bozman (1962)

The methods involving the measurement of absorption lines may be divided into two groups. The distinguishing feature is the method employed to calculate the number density of absorbing atoms. The density of atoms in the atomic beam is measured directly and calculations based upon the vapour pressure data are not required. Therefore, it is pleasing to note that the result of the atomic beam experiment (Lawrence, Link & King 1965) is in good agreement with the lifetime results. The second group of absorption experiments comprises those in which the number density of absorbing atoms is calculated from a knowledge of the vapour pressure. The results of three separate experiments are in poor agreement. Lawrence, Link & King (1965) point out that the results published by Ch'en & Smith (1959) and by Moise (1963) are decreased where they are recalculated using the vapour pressure data adopted by Penkin & Shabanova (1963a, 1967). The overall agreement is not improved by this decrease of the published values.

Since there can be little doubt that the lifetime experiments give satisfactory results, the mean of the two experiments is adopted as the basis for the present analysis; the mean oscillator strength for $\lambda 4511$ is $f = 0{\cdot}123 \pm 0{\cdot}010$.

Finally, it is of interest to note that this mean value is in excellent agreement with theoretical estimates based on the STFD wave functions, which give

$$\lambda 4511 \quad f = 0{\cdot}124$$
$$\lambda 4102 \quad f = 0{\cdot}135.$$

6.3 *The In abundance.* The interval 4509–4512 Å was scanned with the Oxford spectrometer. The noise level of the scan is about 0·1 per cent. The entrance slit was positioned at the centre of the disk. The location of the In I resonance line is shown in Fig. 4. The line is not seriously blended and its profile can be determined.

The identification of the Fraunhofer line $\lambda 4511{\cdot}31$ has been questioned in some earlier discussions. The present scans remove the existing doubts on this point. On the assumption that the isotopic composition of the solar and terrestrial indium are identical, the predominant isotope is In^{115} with a small mixture (about 4 per cent) of In^{113}. Hyperfine splitting of the energy levels occurs for both isotopes. A predicted profile for $\lambda 4511$ has been computed from the hyperfine splittings measured by Jackson (1957, 1958). The total halfwidth is predicted to be 98 mÅ with a halfwidth of 60 mÅ for a single component. The measured halfwidth is 107 ± 10 mÅ. The measured wavelength for the centre of gravity of the Fraunhofer line is $\lambda_\odot = 4511{\cdot}316 \pm 0{\cdot}010$ Å according to an interpolation from the Oxford scan. The standard air wavelength from interferometric measurements by Deverall, Meissner & Zissis (1953) is $\lambda_{air} = 4511{\cdot}2972$ Å. The corresponding wavelength for

the Fraunhofer spectrum is obtained by addition of gravitational redshift: $\lambda_{\odot} = 4511{\cdot}307$ Å. The close correspondence between the predicted and observed wavelength and profile for the suspected In I resonance line should dispel all doubts as to the correct identification for the Fraunhofer line $\lambda 4511{\cdot}316$.

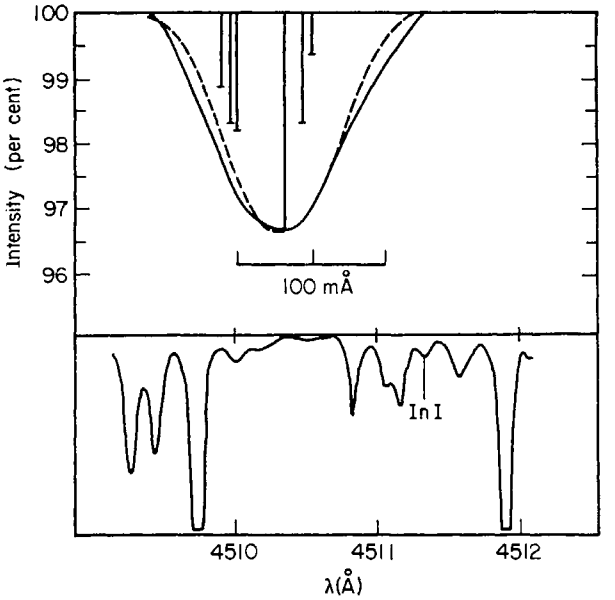

FIG. 4. *The In I resonance line at* 4511·316 *Å. The small scale reproduction of the scan in the lower half of the figure shows that the resonance line is relatively free from blending. The positions and relative intensities of the hyperfine components are indicated by the vertical lines in the upper part of the figure; the composite predicted profile is shown by the solid line. The observed profile (broken line) closely resembles the predicted profile.*

The observed profile corresponds to an equivalent width $W_{\lambda} = 3{\cdot}7 \pm 0{\cdot}5$ mÅ. The uncertainty is principally attributable to slight ambiguities in the location of the continuum level. The abundance for $f = 0{\cdot}123$ is

$$\log N(\mathrm{In}) = 1{\cdot}71$$

with an uncertainty of about 0·1 dex. This abundance is a factor of 3·5 (0·55 dex) greater than the GMA result. An increase in the measured equivalent width and a decrease in the adopted oscillator strength are about equally responsible for the abundance increase.

7. *Tin.* The solar abundance of tin was given by GMA as $\log N(\mathrm{Sn}) = 1{\cdot}54$. Their result was based on two weak intercombination lines in the ultra-violet region of the spectrum: $5p\ ^{2}{}^{1}D_{2}$–$5p6s\ ^{1}D_{2,1}$ at 3330·62 and 3801·03 Å respectively. The equivalent widths were subject to considerable uncertainty. The oscillator strengths were taken from measurements by Allen & Asaad (1957).

Grevesse, Blanquet & Boury (1967) have reported a new determination of the Sn abundance, which is based upon one of the inter-combination lines with an equivalent width obtained from the superior Jungfraujoch tracings. The line is not identified nor is the equivalent width measurement stated. Since $\lambda 3330{\cdot}62$ is severely blended with a molecular (NH) line, it may be presumed that $\lambda 3801{\cdot}03$ is the re-measured line. The abundance $\log N(\mathrm{Sn}) = 1{\cdot}32$ was obtained using the oscillator strength given by Corliss & Bozman (1962). The analysis was performed for three

very similar model atmospheres; the sample included the model which has been adopted for the present series of papers. The Sn abundance will be rediscussed because the Corliss & Bozman oscillator strengths are in general unsatisfactory. No additional observations of the solar spectrum are reported.

Penkin & Slavenas (1963b) employed the hook method to measure absolute oscillator strengths for 29 lines in the Sn I spectrum. Their selection includes the intercombination line(s) observed in the solar spectrum. Their technique yields accurate relative oscillator strengths but the absolute scale may be in doubt because of uncertainties in the adopted vapour pressure data. An atomic beam experiment has given absolute oscillator strengths for six low-level lines (Lawrence, Link & King 1965); however, the intercombination lines were not included.

More recently lifetime measurements have become available and these provide a valuable check on the absolute scale of the hook and atomic beam experiments. The three independent measurements of the radiative lifetime of the $5p6s\ ^3P_1^0$ level are

$$\begin{aligned} \tau &= (6{\cdot}0 \pm 0{\cdot}9) \times 10^{-9}\ \text{s} && \text{(Lawrence 1967)} \\ &= (4{\cdot}5 \pm 0{\cdot}7) \times 10^{-9}\ \text{s} && \text{(Brieger \& Zimmerman 1967)} \\ &= (4{\cdot}84 \pm 0{\cdot}26) \times 10^{-9}\ \text{s} && \text{(de Zafra \& Marshall 1968).} \end{aligned}$$

The latter value is the most accurate and will be adopted. The radiative lifetime is related to the sum of the transition probabilities for all downward transitions

$$\tau = \frac{1}{\sum A_\lambda}.$$

Penkin & Slavenas (1963) measured the absorption oscillator strengths for all the downward transitions from $5p6s\ ^3P_1^0$ with the exception of the transition to $5p^2\ ^1S_0$ at 5633 Å. The intermediate coupling calculations by Lawrence show that $\lambda 5633$ contributes less than one per cent to the total sum. The above lifetime measurement shows that the oscillator strengths published by Penkin & Slavenas should be reduced by a factor of 0·81. Lawrence measured the radiative lifetime of the $5p6s\ ^3P_2^0$ and $^3P_1^0$ levels in addition to that for $5p6s\ ^3P_1^0$ which was quoted above. His results are in good agreement with the lifetimes which may be calculated from the adjusted hook method results:

$$\begin{aligned} 5p6s\ ^3P_0^0 \quad \tau &= (6{\cdot}0 \pm 0{\cdot}9) \times 10^{-9}\ \text{s} && \text{(Lawrence 1967)} \\ &= (5{\cdot}5 \pm 0{\cdot}4) \times 10^{-9}\ \text{s} && \text{(corrected hook method)} \\ 5p6s\ ^3P_2^0 \quad \tau &= (4{\cdot}7 \pm 0{\cdot}7) \times 10^{-9}\ \text{s} && \text{(Lawrence 1967)} \\ &= (3{\cdot}8 \pm 0{\cdot}5) \times 10^{-9}\ \text{s} && \text{(corrected hook method).} \end{aligned}$$

The lifetime measurements provide convincing evidence that the absolute scale of the oscillator strengths obtained by the hook method should be reduced by a factor of 0·81*. This reduction provides the following oscillator strength for the intercombination line $\lambda 3801$

$$f_{3801} = 0{\cdot}035 \pm 0{\cdot}007.$$

Lawrence employed intermediate coupling calculations in order to determine the relative line strength within the $5p^2$–$5p6s$ transition array. For $\lambda 3801$, he

* A similar study shows that the atomic beam measurements (Lawrence, Link & King 1965) should be increased by a factor of 1·24.

obtained $f = 0{\cdot}020$. This is in approximate agreement with the above measurement. Other measurements of f_{3801} have been made by Corliss & Bozman (1962) and by Allen & Asaad (1957) who obtained $f = 0{\cdot}086$ and $f = 0{\cdot}28$ respectively. The accuracy of these results is low and no weight is attached to them.

It is instructive to compare the results obtained from the hook method with those given by Corliss & Bozman (1962). There is a systematic difference: $f_{CB} = 2{\cdot}5 f_{PS}$. The scatter about the mean result is especially striking; the result for a single line may vary by as much as a factor of four from the mean value. Since the internal precision of the hook method is high, this large scatter is attributed to a random error affecting the Corliss & Bozman oscillator strengths.

If the above revision of the hook method result is adopted, the abundance quoted by Grevesse, Blanquet & Boury must be increased to

$$\log N(\mathrm{Sn}) = 1{\cdot}71.$$

The uncertainty in this result is probably quite considerable; the combined influence of errors in the equivalent width and the oscillator strength might amount to $\pm 0{\cdot}3$ dex, in addition, the analysis under-estimated the continuous opacity at 3800 Å.

8. *Mercury.* Moore, Minnaert & Houtgast (1966) state that further study is required to confirm the presence of mercury in the Fraunhofer spectrum. Grevesse, Blanquet & Boury (1967) have proposed tentative identifications for the two strongest lines of Hg I: $\lambda\lambda 5460{\cdot}742$ and $4358{\cdot}343$ or $6p\ ^3P_{2,1}{}^0$–$7s\ ^3S_1$. Moore, Minnaert & Houtgast list weak unidentified lines close to these wavelengths: $W_\lambda = 2$ mÅ at 5460·701 Å and $W_\lambda = 4$ mÅ at 4358·361 Å. Improved spectra were obtained at the Jungfraujoch Station and the equivalent widths were remeasured. The oscillator strengths given by Corliss & Bozman (1962) were adopted to obtain an abundance $\log N(\mathrm{Hg}) = 1{\cdot}13$.

The oscillator strengths measured by Corliss & Bozman must be in error by a large factor: their oscillator strengths for the multiplet $6p\ ^3P^0$–$7s\ ^3S$ ($\lambda\lambda 5460$, 4358 and 4046) are 7·6, 8·0 and 8·8 and, therefore, their sum violates the well established f-sum rule. The oscillator strengths have been computed (Warner 1968a) in the same manner as those for Zn I and Cd I. The results for the two lines, which may be present in the solar spectrum, are

$$\lambda 5460 \quad gf = 0{\cdot}539$$

$$\lambda 4358 \quad gf = 0{\cdot}394.$$

It is a simple matter to adjust the abundance estimate, the result is

$$\log N(\mathrm{Hg}) = 2{\cdot}95.$$

The cosmic abundance of mercury is approximately two orders of magnitude smaller; $\log N(\mathrm{Hg}) = 0{\cdot}9$ (Allen 1963) or $= 0{\cdot}75$ (Aller 1961). Since the suggested identifications are uncertain, it is unreasonable to suppose that mercury is over-abundant by this large factor.

The region 4356–4360 Å was scanned with the Oxford spectrometer. There is a broad depression ($\Delta\lambda \simeq 0{\cdot}15$ Å) which encompasses the predicted position of the Hg I line: $\lambda_{air} = 4358{\cdot}3376$ Å for Hg^{198} (Allen 1963). The Fraunhofer line at 4358·361 Å, which is listed by Moore, Minnaert & Houtgast (1966), is not distin-

guishable from the broad absorption feature. There is a weak ($W_\lambda \simeq 3$ mÅ) line at 4358·317 Å but this cannot be assigned to Hg I because of the poor wavelength agreement. Clearly, the tentative identifications should be withdrawn and the abundance of mercury in the Sun must be considered an unknown quantity. The Hg I resonance line λ1849·57 is present as a weak absorption line (McAllister 1960) but a corresponding estimate of the abundance is not available.

9. *Thallium*

9.1 *Introduction.* The recent revision of Rowland's *Preliminary Table of Solar Wavelengths* (Moore, Minnaert & Houtgast 1966) lists thallium as absent from the solar spectrum. In an attempt to provide a useful upper limit to the abundance of thallium in the Sun, a small region of the disk spectrum around the predicted position of the Tl I λ5350 line was scanned with the Oxford spectrometer.

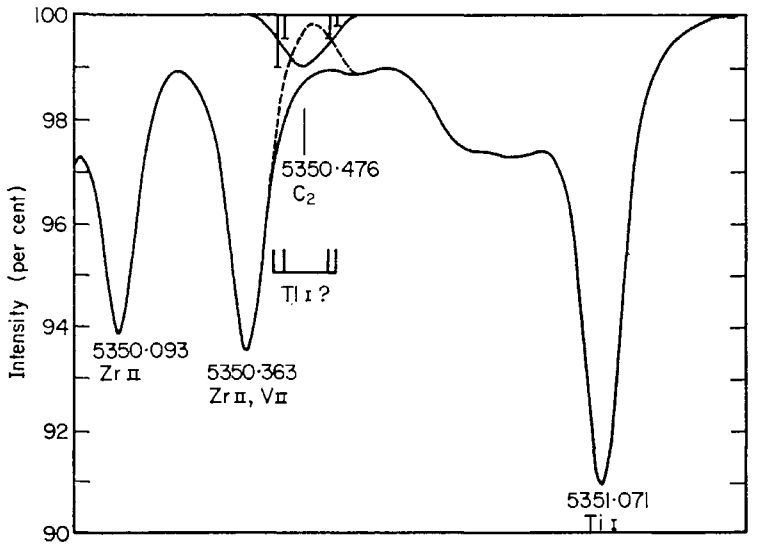

FIG. 5. *A portion of the scan showing the predicted positions of the Tl I λ5350 components. The positions and relative intensities of the isotopic and hyperfine components (Table IV) are indicated by the vertical lines. The predicted profile for a 1 mÅ C_2 line is shown. The observed spectrum minus the C_2 line is given by the broken line.*

9.2 *Oscillator strength.* An accurate oscillator strength for λ5350 $6p\ ^2P_{3/2}{}^0$–$7s\ ^2S_{1/2}$ is available as a result of measurements of the radiative lifetime of the $7s\ ^2S_{1/2}$ level. Gallagher & Lurio (1964) give $f = 0{\cdot}133 \pm 0{\cdot}007$. A more recent experiment (Cunningham & Link 1967) has confirmed this result. It is of interest to note that Penkin & Shabanova (1963b) obtained $f = 0{\cdot}135$ from the hook method. Corliss & Bozman (1962) obtained $f = 0{\cdot}23$.

9.3 *The Tl abundance.* The wavelength interval 5350–5352 Å was scanned with the Oxford photoelectric spectrometer. A portion of the scan is illustrated in Fig. 5. The r.m.s. noise level is approximately 0·05 per cent but difficulties associated with the location of the continuum level contribute about a 0·25 per cent uncertainty in the intensity at the predicted position of the Tl I lines.

In order to state an upper limit to the equivalent width contributed by the Tl I lines, it is essential that the wavelengths and relative intensities of the hyperfine components be known. Two isotopes—Tl^{203} and Tl^{205}—occur in natural thallium with an abundance ratio $Tl^{203} : Tl^{205} = 3 : 7$. The isotope shifts and hyperfine

splittings for λ5350 were measured by Hull & Stroke (1961) and Schuler, Ciftan, Bradley & Stroke (1962) respectively. Accurate absolute wavelengths for the λ5350 complex are not available in the literature. Wavelengths with an uncertainty of ± 5 mÅ were kindly provided by S. P. Davis and D. Goorvitch (private communication, 1967). The adopted wavelengths are given in Table IV. The relative intensities of the four components were computed from the standard formulae for hypermultiplets (Condon & Shortley 1951) and on the assumption that the terrestrial and solar ratios for the isotopic abundances are equal. The relative intensities and the wavelengths are indicated in Fig. 5 where the strongest component is arbitrarily given an intensity of one per cent. The predicted total half-width for a Tl I component is 60 mÅ.

TABLE IV

The Tl I $6s\ ^2P_{3/2}$–$7s\ ^2S_{1/2}$ transition at 5350 Å

Isotope	Transition*	λ_{air}† (Å)		Relative intensity
Tl^{203}			0·532	0·16
	$6s\ ^2P_{3/2}[F = 1]$–$7s\ ^2S_{1/2}[F = 0]$	5350		
Tl^{205}			0·515	0·37
Tl^{203}			0·421	0·43
	$6s\ ^2P_{3/2}[F=2, 1]$–$7s\ ^2S_{1/2}[F=1]$	5350		
Tl^{205}			0·404	1·00

* The hyperfine splitting in $6s\ ^2P_{3/2}$ is small: 0·0175 and 0·0177 cm^{-1} for Tl^{203} and Tl^{205} respectively (Hull & Stroke 1961). The transition $F'' = 1 \rightarrow F' = 1$ contributes less than 6 per cent of the total strength and it is, therefore, not considered as a separate transition.

† $\lambda_0 = \lambda_{air} + 0{\cdot}011$ where λ is in Å.

Unfortunately, the Fraunhofer spectrum is complex at the predicted positions of the Tl I components. The stronger pair of lines at 5350·404 and 5350·416 Å falls in the wing of the weak line at 5350·363 Å*. According to Moore, Minnaert & Houtgast (1966), this line is a blend of Zr II and V II lines. The lines responsible for the broad depression of the continuum between 5350·4 and 5350·7 Å have not been identified.

The oscillator strengths measured by Corliss & Bozman (1962) should provide a reasonable guide to the relative intensities within a multiplet. Estimates of the equivalent width for the Zr II and V II components of λ5350·363 were derived from the oscillator strengths and the observed equivalent widths for Fraunhofer lines ascribed to the same multiplet. It would appear that Zr II is the dominant contributor. In addition, the measured laboratory wavelengths (*M.I.T. Wavelength Tables*, 1939) are 5350·353 Å for the Zr II and 5350·380 Å for the V II lines. The former is in excellent agreement with the observed solar wavelength; the difference of 10 mÅ is to be compared with the predicted gravitational red shift of 11 mÅ.

A thorough search for possible line identifications in the interval 5350·4–5350·6 Å was undertaken. Recent measurements of the C_2 Swan band system (J. G. Phillips, private communication, 1966) give a line at $\lambda_{air} = 5350{\cdot}465$ Å. The predicted intensity was estimated from the measured intensities for some unblended lines belonging to the same vibrational band. The equivalent width measurements listed by Moore, Minnaert & Houtgast (1966) give $W_\lambda \simeq 1$ mÅ and the line should have a total half-width of about 100 mÅ. The predicted line profile is shown in Fig. 5.

* The wavelength scale was derived using the published wavelengths for the stronger lines (Moore, Minnaert & Houtgast 1966).

The blended red wing of the line λ5350·363 appears to be satisfactorily explained in terms of a Zr II and C_2 blend. It is estimated that the Tl I contribution is such that the central intensity of the strongest component at 5350·404 Å cannot exceed 0·5 per cent of the continuum intensity and may be less than 0·25 per cent. The corresponding upper limit to the Tl abundance is

$$\log N(\mathrm{Tl}) < 1{\cdot}3$$

for a maximum contribution of 0·5 per cent.

In the photosphere, thallium is predominantly once-ionized; the ionization potential of neutral thallium is only 6·11 eV. In a sunspot, the degree of ionization must be markedly reduced and the Tl I λ5350 lines may be enhanced above the limit for detection. It is of interest to note that Rowland's early identification of the Tl I line was shown by Moore (1956) to be incorrect because the proposed line showed no marked strengthening in the spot spectrum. An examination of the Mount Wilson *Sunspot Spectrum Atlas* revealed a broad and shallow absorption feature, which is not present in the accompanying photospheric spectrum. The wavelength coincidence indicates that this line may be tentatively assigned to Tl I. A visual estimate of the equivalent width, which was based upon a comparison with phosphoric lines of known equivalent width, gave for the Tl I line

$$W_\lambda \lesssim 20 \text{ mÅ}.$$

In order to convert this approximate estimate into an abundance, a sunspot model is required. The Zwaan (1965) spot model was selected. The above upper limit for the equivalent width of the entire Tl I λ5350 complex yields

$$\log N(\mathrm{Tl}) < 0{\cdot}2.$$

The uncertainty of this upper limit is difficult to estimate but it is unlikely to exceed ±0·3 to 0·4 dex. The higher upper limit, which was derived from the absence of the line from the Fraunhofer spectrum, corresponds to a predicted equivalent width of 200–300 mÅ for the sunspot spectrum.

Clearly, it would be extremely valuable to obtain accurate sunspot spectra of this region. Such observations promise to yield the first positive evidence for the presence of thallium in the solar photosphere. A careful analysis and a comparison of the spot model predictions against the observed spectrum should provide an accurate value for the thallium abundance.

10. *Lead*

10.1 *Introduction.* The solar lead abundance is discussed in three recent papers (Grevesse 1967; Ross, Aller & Mohler 1968; Peach 1968). New measurements and an interpretation of the ultraviolet lines of Pb I are reported in the first two of these papers. Peach used the Oxford photoelectric spectrometer to obtain an accurate measurement of the equivalent width of the very weak Pb I line at 7229 Å. No new observations of the solar spectrum are reported here. The present opportunity is taken to give a unified discussion of these recent remeasurements of Pb I lines on the basis of the best available oscillator strengths.

10.2 *Oscillator strengths.* The Pb I lines present in the solar spectrum belong to the transition array $6p^2$–$6p7s$ and involve only the $^3P_1$ and $^3P_0$ levels in the upper ($6p7s$) configuration.

Three measurements of the radiative lifetime of the $6p7s\ ^3P_1$ level have been made

$$\tau = (5{\cdot}75 \pm 0{\cdot}20) \times 10^{-9}\ \text{s} \quad \text{(Saloman \& Happer 1966)}$$
$$= (6{\cdot}05 \pm 0{\cdot}3) \times 10^{-9}\ \text{s} \quad \text{(Cunningham \& Link 1967)}$$
$$= (5{\cdot}58 \pm 0{\cdot}72) \times 10^{-9}\ \text{s} \quad \text{(de Zafra \& Marshall 1968).}$$

These independent measurements are in agreement to within the quoted experimental uncertainties. A straight mean of the first two results is adopted for the present study. This result provides the basis for the present derivation of absolute oscillator strengths for Pb I.

The lifetime is determined by the sum of the transition probabilities for all downward transitions from the $6p7s\ ^3P_1$ level (see Table V)

$$\tau = \frac{1}{\sum A_\lambda} = \frac{1}{A_{2833} + A_{3639} + A_{4057}}$$

where the weak transitions to $6p^2\ ^1D$ (λ7229) and to $6p^2\ ^1S_0$ (λ17180) are neglected.

TABLE V

The oscillator strengths for selected Pb I transitions

Transition	λ(Å)	SH*	PS* a	PS* b	B*	K* a	K* b	Adopted
$6p7s\ ^3P_1^0$–$6p^2\ ^3P_0$	2833	0·169	0·212	0·194		0·6	0·11	0·165
$^3P_1$	3639	0·040	0·063	0·058	0·039	0·28	0·052	0·058
$^3P_2$	4057	0·155	0·153	0·140	0·139	0·85	0·157	0·140
$^1D_2$	7229					0·19	0·035	0·035
$6p7s\ ^3P_0$–$6p^2\ ^3P_1$	3683		0·117	0·106	0·070	0·49	0·091	0·094
$^1D_2$	3740					1·08	0·200	0·200

* SH = Saloman & Happer (1966); PS = Penkin & Slavenas (1963); B = Brown (1966) K = Khoklov (1959, 1960). The published and normalized oscillator strengths are given in columns a and b respectively.

Saloman & Happer (1966) measured the branching ratio to ground state

$$\frac{A_{2833}}{A_{2833} + A_{3639} + A_{4057}} = 0{\cdot}27 \pm 0{\cdot}03.$$

The measured lifetime together with the observed branching ratio provides an accurate oscillator strength for the resonance line at 2833 Å: $f_{2833} = 0{\cdot}165$.

Saloman & Happer (1966) derived absolute oscillator strengths for λ4057 and λ3639 by combining their measurements with the ratio f_{4057}/f_{3639} obtained from measurements by Khokhlov (1959, 1960). An alternative reduction is adopted for the present study. Penkin & Slaveras (1963) obtained accurate oscillator strengths from an application of the hook method. The authors give their results on an absolute scale but the conversion requires that the vapour pressure of lead be known without systematic error. In the present discussion, their results are considered as a source of reliable relative oscillator strength measurements; their results give

$$f_{3639}/f_{4057} = 0{\cdot}412.$$

This ratio can be combined with the measured lifetime and branching ratio to give (see Table V)

$$f_{3635} = 0{\cdot}058 \quad \text{and} \quad f_{4057} = 0{\cdot}140.$$

The absolute scale for the hook method results is now derived from a normalization to the accurate results for λλ2833, 3639, and 4057. The scaling factor of 0·915 leads to an absolute oscillator strength for λ3683: $f_{3683} = 0{\cdot}106$.

Brown (1966) performed a shock tube experiment and derived the oscillator strengths for λλ3639, 3683 and 4057. His results are given in Table V. The agreement with the adjusted hook method results is reasonable; Brown states that his absolute scale is uncertain to about 30 per cent.

Khoklov (1959, 1960) made relative measurements using a hollow cathode source and employed both emission and absorption measurements. His result for the resonance line λ2833 is almost certainly in error owing to self-absorption in the source (this criticism is advanced by Penkin & Slavenas (1963) and by Saloman & Happer (1966)). Khoklov's published results were normalized to fit the above results for λλ3639 and 4057 (see Table V). This normalization yields absolute oscillator strengths for λλ7229 and 3740.

The adopted oscillator strengths are given in the final column of Table V. The result for λ3683 is a weighted mean of the three entries with double weight given to the hook method. This survey of Pb I oscillator strengths omits references to the older experimental papers; full references and results are summarized by Peach (1968, Table I).

Corliss & Bozman (1962) obtained oscillator strengths for all the Pb I lines which appear in Table V. Unfortunately, their results are subject to a large random error (see Section 7) and systematic errors cannot be excluded.

Lawrence (1967) derived the dipole radial integral for the $6p^2$–$6p7s$ transition array from the lifetime measurement by Saloman & Happer (1966). He performed intermediate coupling calculations and calculated the line strengths. The standard combination of line strength and radial integral provides a set of absolute oscillator strengths. Considerable configuration mixing is to be expected in Pb I because of the nearness (in energy) of $6p^2\ {}^3P$ and $6p7p\ {}^3P$ and of $6p7s\ {}^3P^0$ and $6p8s\ {}^3P^0$. Intermediate coupling calculations in $6p^2$–$6p7s$ which neglect configuration interaction (e.g. Lawrence 1967) will be very unreliable. For example, the calculated oscillator strengths for λλ2883, 3639 and 4057 correspond to a branching ratio of 49 per cent which should be compared with the measured value of 27 ± 3 per cent.

10.3 *The Pb abundance.* Ross, Aller & Mohler (1968) performed a detailed analysis of the four ultraviolet lines λλ3638, 3683, 3740 and 4057. It is a simple matter to adjust their results to take account of improved oscillator strengths obtained in Section 10.2. The weighted mean result is $\log N(\mathrm{Pb}) = 1{\cdot}92$ when the weights are proportional to the inverse square of their quoted errors. A similar weighting of their published abundances gave $\log N(\mathrm{Pb}) = 1{\cdot}68$. The revised oscillator strengths result in a slight increase in the Pb abundance. Grevesse (1967) remeasured the equivalent widths of the ultraviolet Pb I lines from tracings obtained with the Jungfraujoch installation. His published weighted mean was

$$\log N(\mathrm{Pb}) = 2{\cdot}00$$

when the oscillator strengths calculated by Lawrence (1967) were adopted. The adopted oscillator strengths lead to a weighted mean of $\log N(\mathrm{Pb}) = 1{\cdot}85$ (N. Grevesse, private communication, 1967). These independent investigations provide very similar results for the abundance. These studies used model solar atmospheres which are very similar to that adopted for the present series of papers. The average

of the two results

$$\log N(\mathrm{Pb}) = 1{\cdot}89$$

is adopted to represent the abundance obtained from the ultraviolet lines.

The equivalent width of the weak Pb I line at 7229 Å was measured by Peach (1968). He obtained $W_\lambda = 0{\cdot}29 \pm 0{\cdot}04$ mÅ. A review of the published oscillator strengths led Peach to adopt $f_{7229} = 0{\cdot}034$ and use of the Müller–Mutschlechner model atmosphere gave $\log N(\mathrm{Pb}) = 1{\cdot}93$. The revised oscillator strength gives $\log N(\mathrm{Pb}) = 1{\cdot}92$. Grevesse (1967) has suggested that the Fraunhofer line at 7229 Å corresponds to an abundance about 80 times greater than that obtained from the ultraviolet lines. The greater part of this discrepancy results from his adoption of the oscillator strength computed by Lawrence which is $f_{7229} = 0{\cdot}0019$.

The mean result from the ultra-violet lines and $\lambda 7229$ is

$$\log N(\mathrm{Pb}) = 1{\cdot}90$$

with an uncertainty of about $\pm 0{\cdot}10$ dex.

11. *Concluding remarks.* It is the aim of this series of papers to provide comprehensive data on the abundances of the elements in the solar atmosphere. The preceding analyses for nine elements have high-lighted a broad range of problems. There can be no general recipe for a successful abundance determination but, in this concluding section, some of the principal problems and their solutions will be surveyed with particular reference to the nine elements discussed in this paper.

The earlier abundance analyses of the least abundant or trace elements were based upon photographic measurements of the equivalent widths of weak lines. The identifications for weak Fraunhofer lines may be questioned and the equivalent width determinations may be in error. The low noise scans provided by the Oxford spectrometer eliminate basic uncertainties inherent in earlier recordings of the Fraunhofer spectrum. However, the new scans do not remove the uncertainties arising from line blending and ambiguities associated with the positioning of the continuum level. The successful identification and measurement of the Cd I $\lambda 5085$ and Ge I $\lambda 4685$ lines illustrate the application of the Oxford spectrometer. A further decisive test of the value of the spectrometer is shown by the In I analysis; the Oxford scans provide the essential confirmatory evidence that the weak Fraunhofer line at 4511·316 Å is the In I resonance line in absorption; in particular, the half-width of the line is in excellent agreement with the predicted hyperfine broadened profile.

The uncertainties in the oscillator strength measurements and calculations have attracted much critical comment by earlier analysts of the solar composition. The discussion presented in this paper high-lights the continuing advances in the measurement and calculation of oscillator strengths. Results with a precision of about ± 10 per cent are now available for many resonance lines; for example, the Ga I, In I, Tl I and Pb I resonance lines discussed in this paper. These results were obtained in recent years from the measurements of the radiative lifetime for a level within the first excited term. The necessary conditions for an accurate result are now fully recognized. Unfortunately, the resonance lines are often inaccessible or unsuitable (e.g. Zn I, Sn I) for an abundance analysis. Nonetheless, an accurate determination of the oscillator strength may be of value. The measurement provides a challenge for the theoretician. Accurate measurements of oscillator strengths on a relative scale exist for many elements. If these relative measurements include the

resonance line, they may be normalized by reference to the accurate lifetime measurement for the resonance line. In particular, attention should be drawn to the measurements reported by Penkin and his collaborators. They employ the method of hooks (or anomalous dispersion) to obtain accurate relative oscillator strengths. Certain results are referred to an absolute scale which is derived from vapour pressure calculations. However, the vapour pressure data is often subject to considerable uncertainty. If the hook method results include the dominant transitions from the level with the measured radiative lifetime, the published results may be recalibrated, the discussions on the Sn I (Section 7) and Pb I (Section 10.2) oscillator strengths illustrate application of this calibration. The method must be applied with due caution as the discussion of the Cd I oscillator strengths (Section 5.2) illustrated.

The analyses in this and earlier papers of the series were based upon a consideration of absorption lines in the visible or infrared region of the photospheric spectrum; the approximate limiting wavelengths were 3700–26000 Å. Some elements and, in particular, the trace elements may not leave an imprint upon the photospheric spectrum within this wavelength interval. A variety of approaches are possible by reference to the following additional sources of information: sunspot spectra, the absorption line spectrum shortward of 3700 Å, the ultra-violet and X-ray (XUV) emission line spectrum of the corona and coronal-chromospheric transition region, the coronal forbidden lines in the visible region of the spectrum, solar cosmic rays and the solar wind.

The sunspot and ultraviolet absorption spectra will prove useful sources for the trace elements. The discussion on the Tl I λ5350 transition demonstrated the essential relevance of sunspot observations for trace elements with a low first ionization potential. In Section 8, it was shown that no satisfactory identification may be made for Hg I lines in the visible spectrum but the resonance line of Hg I at 1849·57 Å is apparently present in absorption. This line is probably the only evidence for Hg in the solar atmosphere. Resonance lines of several interesting elements occur in this wavelength interval.

The XUV emission line spectrum and the coronal forbidden lines are promising sources of abundance estimates for several of the more abundant elements which are absent from the photospheric spectrum; neon and helium are observable in the ultra-violet and argon has been identified with a coronal forbidden line. Solar cosmic rays provide valuable estimates for the most abundant elements including helium and neon. The controversial question concerning possible composition differences between the photosphere and the corona and chromosphere must be resolved before a combination of data can be presumed to reflect the composition of the surface layers.

Acknowledgments. We wish to thank Professor S. P. Davis and Dr D. Goorvitch for providing us with the accurate measurement of the wavelength of the Tl I λ5350 transition, Professor J. G. Phillips for sending us the Berkeley wavelength measurements of the C_2 Swan band, and Dr N. Grevesse for helpful correspondence. One of us (D.L.L.) has been supported in part by the U.S. National Aeronautics and Space Administration.

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1968 *May.*

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