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The abundances of the elements in the solar photospheres – IX: Na to Ca

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Summary. Revised photospheric abundances are presented for the elements sodium to calcium. A thorough assessment of current information on the f values is given. Abundance calculations are reported for a selection of recent model solar atmospheres. On the usual scale $\log \epsilon(\mathrm{H}) = 12.0$, the recommended abundances are:

Na	6.32	Mg	7.62	Al	6.49
Si	7.63	P	5.45	S	7.23
K	5.12	Ca	6.34		

A comparison of the photospheric and meteoritic abundances shows that the relative abundances are in good agreement.

1 Introduction

When the chemical composition of a star, gaseous nebula or a galaxy is discussed, the astrophysicist's reference frame is frequently the solar photosphere. Piece-meal revisions of the photospheric abundances may have left the non-participants bewildered. This paper attempts to assuage the bewilderment by offering a critical rediscussion of photospheric abundances for elements in the periodic table between sodium and calcium.

For each element, the photospheric evidence is reviewed briefly; Cl and Ar are not considered. Line lists were examined and weak to medium-strong lines were selected. When possible, equivalent widths were remeasured off the best of the available atlases; e.g. Delbouille, Neven & Roland (1973) and Hall (1972). A critical assessment is presented of theoretical and experimental information on the f values for each spectrum. Results of an abundance analysis are discussed for a reference model atmosphere obtained by combining the Holweger & Müller (1974) model with a constant, isotropic microturbulent velocity $\xi = 1.0$ km/s. The choice of this model is discussed in Section 3.1 where sample abundances yielded by other recent model atmospheres are compared. The concluding section compares the solar abundances with a recent critical evaluation of the meteoritic abundances.

Table 1. The Na I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log *gf*	W_λ (mÅ)	log ε
$3p\ ^2P^0-5s\ ^2S$	$\frac{3}{2}-\frac{1}{2}$	6160.8	2.10	−1.27	53.7	6.34
	$\frac{1}{2}-\frac{1}{2}$	6154.2	2.10	−1.57	35.0	6.34
$3p\ ^2P^0-6s\ ^2S$	$\frac{1}{2}-\frac{1}{2}$	5148.8	2.10	−2.06	11.6	6.29
$3p\ ^2P^0-7s\ ^2S$	$\frac{3}{2}-\frac{1}{2}$	4751.8	2.10	−2.11	11.8	6.35
$3p\ ^2P^0-7d\ ^2D$	$\frac{3}{2}-$	4497.7	2.10	−1.53	31.2	6.33
$4s\ ^2S-5p\ ^2P^0$	$\frac{1}{2}-\frac{3}{2}$	10746.4	3.19	−1.29	13.8	6.29
$3d\ ^2D-6f\ ^2F^0$		10834.9	3.62	−0.25	40.5	6.19
$3d\ ^2D-7f\ ^2F^0$		9961.4	3.62	−0.58	19.2	6.19

2 The abundance analyses

2.1 SODIUM

2.1.1 Solar data

The strong Na D lines must be separated from the weaker excited lines because the derivation of the Na abundance from the NaD lines is inextricably linked with the collisional-broadening parameters. The list of excited Na I lines (see Table 1) is culled from earlier analyses (Lambert & Warner 1968a [LWa]; Holweger 1971). Stronger lines are available but the derived abundance is sensitive to the unknown line-broadening parameters.

2.1.2 Na I f values

The *f* values for the Na D lines are known with good accuracy. A well known compilation (Wiese, Smith & Miles 1969) gives *f* values which are equivalent to a radiative lifetime $\tau(3p\ ^2P) = 15.9 \pm 0.5$ ns. Recent measurements are consistent with this value; $\tau = 16.4 \pm 0.6$ (Erdmann, Figger & Walther 1972), 16.2 ± 0.5 (Andersen, Madsen & Sørensen 1972), 15.9 ± 0.4 (Baumann 1969) and 16.12 ± 0.22 (Mashinskii & Chaika 1970) are a sample of new results. The simple Coulomb approximation predicts $\tau = 16.7$ ns but more refined calculations, which allow for the polarization of core electrons by a single valence electron, give shorter lifetimes; e.g. $\tau = 15.9$ ns (Norcross 1971) and 16.1 ns (Weisheit 1972). Although the 'best' lifetime might be a few per cent larger than the Wiese *et al.* recommendation, the *f*-value uncertainty is trivial beside the uncertainty surrounding the line-broadening coefficient. Unless the radial integral is subject to severe cancellation, the Coulomb approximation (ca) should provide reliable *f* values. Various theoretical refinements have been discussed; e.g. Warner (1968a) included the spin–orbit interaction, Norcross (1971) used scaled Thomas–Fermi wave functions and a valence electron-core polarization term, Ellis & Goscinski (1974) reported a transition-state calculation and Anderson & Zailitis (1964) developed a semi-empirical method similar to the ca. The published *f* values are very similar to ca results; typical differences do not exceed a few per cent.

Throughout atomic and molecular physics, the laser, especially the tunable dye laser, is opening up frontiers. An example is provided by the radiative lifetime measurements for Na I. Dye laser double-pumping experiments (Kaiser 1975; Gallagher, Edelstein & Hill 1975, 1976) have provided accurate lifetimes for $ns\ ^2S$, $np\ ^2P^0$ and $nd\ ^2D$ levels. In Fig. 1, these lifetimes are compared with the Coulomb approximation predictions. Agreement is excellent even for the low levels providing the majority of the solar lines.

A few measurements by other techniques confirm the applicability of the Coulomb approximation. For the $4p\ ^2P^0$ levels, a level-crossing experiment (Schmieder *et al.* 1970) gave $\tau = 95 \pm 4$ ns and electron-beam excitation as developed by Erman (1975) gave $\tau = 96 \pm$

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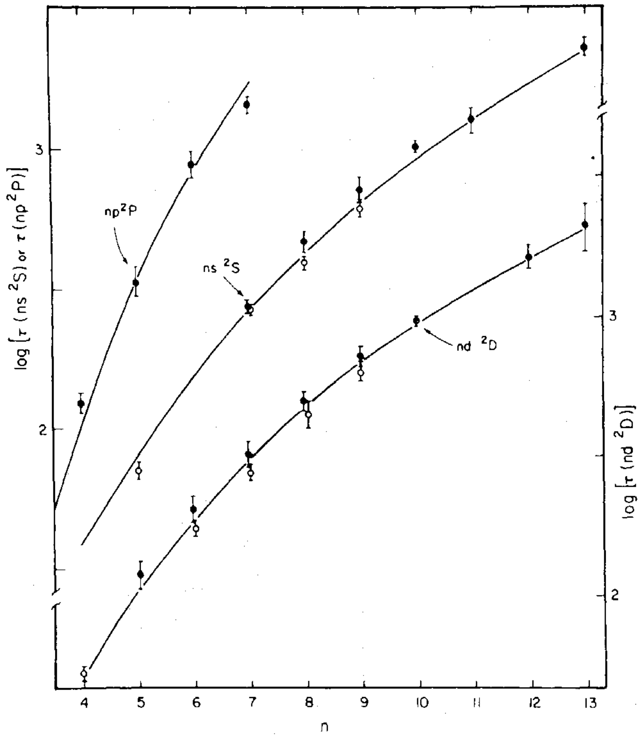

Figure 1. Radiative lifetimes for Na I. Coulomb approximation predictions (solid lines) are compared with the results from two dye-laser experiments: Kaiser (1975, open circles) and Gallagher *et al.* (1975, 1976, filled circles) for *ns* ^2S, *np* $^2P^0$ and *nd* ^2D states.

20 ns (Erman, Brzozowski & Smith 1974). The ca prediction is $\tau = 103$ ns. However, Erman *et al.* measurement $\tau(5p) = 635 \pm 30$ ns disagrees with Gallagher *et al.* (1976) measurement, $\tau(5p) = 345 \pm 43$ ns, and the ca prediction $\tau(5p) = 349$ ns. A Stark-effect measurement (Harvey *et al.* 1975) using the new technique of two-photon spectroscopy made possible with high-intensity lasers led to the f values; $f = 0.274 \pm 0.029$ (0.229) for the $4d$–$5p$ transition and $f = 0.01885 \pm 0.00024$ (0.0181) for the $4d$–$5f$ transition where ca predictions appear in parentheses.

This survey of recent experiments and earlier work considered by Wiese *et al.* (1969) confirms the accuracy of the ca; these theoretical f values appear to be accurate to ±10 per cent or better except in cases of severe cancellation.

2.1.3 The Na abundance

The Na D line wings may be used to obtain an abundance estimate; the line cores are insensitive to the abundance and affected by non-LTE effects. A prerequisite to the use of the wings is an accurate theory of the line broadening under photospheric conditions. The most complete theory is that described by Lewis, McNamara & Michels (1971, 1972). Direct experimental checks of their molecular-orbital treatment of the Na and H collisions are unavailable. An oblique check is offered through the comparison (Lwin, McCartan & Lewis 1976) of related calculations with measurements of the broadening and shift of the D lines by the noble gases (He, Ne, Ar, Xe).

Two recent studies of the Na D wings are based on the same solar observations (Waddell 1962) but spring from slightly different views of the line-broadening calculation. Blackwell, Kirby & Smith (1972) prefer to use the solar spectrum as a test of these calculations. Worrall (1973) accepts the broadening calculations and proceeds to derive an abundance from the line wings. Their analyses are in good agreement. The abundances derived from the Harvard–

Smithsonian reference atmosphere (Gingerich *et al.* 1971) are $\log \epsilon = 6.33$ (Worrall) and 6.37 (Blackwell). The reference model requires an abundance increase of about 0.1 dex or $\log \epsilon(\mathrm{Na}) = 6.46$ from the D line wings.

With the reference model, six weak Na I lines give a mean abundance $\log \epsilon = 6.32 \pm 0.07$ (rms error) dex in agreement with results by Holweger (1971) and Blackwell *et al.* (1972). The rms error is calculated from the abundances provided by the individual lines and does not include model atmosphere and *f*-value uncertainties. The two *d–f* transitions give a lower abundance and are excluded from the sample.

These abundances are based on the assumption of local thermodynamic equilibrium (LTE). Gehren's (1975) NLTE calculations for a nine-level model Na atom and three model solar atmospheres show that the NLTE and LTE predictions for the equivalent widths of the excited Na I lines differ by only a few per cent; i.e. the above abundance might be reduced by 0.02 dex to account for the departures from LTE.

2.2 MAGNESIUM

2.2.1 *Solar data*

The abundance may be derived from Mg I and Mg II lines. At present, the MgH $A-X$ transition near 5160 Å cannot be included as an abundance indicator. Although recent determinations of the dissociation energy (Balfour & Cartwright 1975, 1976) assure reasonable accuracy, the lack of an accurate *f*-value measurement precludes the use of these weak molecular lines. Since an accurate measurement of the radiative lifetime of the $A^2\Pi$ state appears possible using a laser-fluorescence technique, this omission should soon be remedied.

The selected Mg I and Mg II lines are listed in Tables 2 and 3. The Mg I lines are a sample of the rich representation of Mg I lines in the photospheric spectrum. The selection (see Section 2.2.2) is based upon arguments concerned with the reliability of the theoretical *f*

Table 2. The Mg I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log *gf*	W_λ (mÅ)	log ϵ
$3p\,^1P^0-6s\,^1S$	1–0	4730.0	4.35	−2.39	67	7.79
$4s\,^3S-5p\,^3P^0$	1–2	7657.6	5.11	−1.28	114	7.79
$4s\,^3S-6p\,^3P^0$	1–2	6318.7	5.11	−1.97	42	7.63
	1–1	6319.2	5.11	−2.20	26	7.57
$3d\,^1D-7p\,^1P^0$	2–1	8209.9	5.75	−2.07	8.7	7.38
$4p\,^3P^0-5d\,^3D$	0–	10953.3	5.93	−0.86	96	7.55
$4p\,^3P^0-6d\,^3D$	1–	9432.7	5.93	−0.79	100	7.64
$4p\,^3P^0-7d\,^3D$	2–	8717.8	5.93	−0.86	104	7.78
	1–	8712.7	5.93	−1.09	59	7.55
$4p\,^3P^0-8d\,^3D$	2–	8310.3	5.93	−1.09	68	7.66
	1–	8305.6	5.93	−1.32	39	7.54
$4p\,^3P^0-6s\,^3S$	2–1	12433.4	5.93	−0.94	109	7.58
	1–1	12423.0	5.93	−1.16	88	7.62
	0–1	12417.9	5.93	−1.63	37	7.53
$4s\,^1S-4p\,^1P^0$	0–1	8923.6	5.94	−1.65	54	8.06
$3d\,^3D-5p\,^3P^0$	–2	15879.5	5.95	−1.17	104	7.38
	–1	15886.3	5.95	−1.39	68	7.32
$3d\,^3D-6p\,^3P^0$	–1	11033.6	5.95	−2.10	10	7.45
$4p\,^1P^0-6d\,^1D$	1–2	11522.3	6.12	−1.61	31	7.65
$4p\,^1P^0-7d\,^1D$	1–2	10312.5	6.12	−1.52	15	7.29
$5s\,^1S-6p\,^1P^0$	0–1	21458.9	6.52	−1.30	56	7.59

Table 3. The Mg II line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log gf	W_λ (mÅ)	log ϵ
$3d\,^2D-4p\,^2P^0$	$5/2-3/2$	10914.3	8.86	0.011	55	7.70
	$3/2-1/2$	10951.8	8.86	−0.245	32	7.51
$4p\,^2P^0-4d\,^2D$	$3/2-5/2$	7896.4	10.00	0.648	27	7.71
	$1/2-3/2$	7877.1	10.00	0.390	17	7.64

values. Unfortunately, the Mg I intercombination line at 4571 Å ($3s^2\,^1S_0$–$3s\,3p\,^3P^0_1$) is too strong for a reliable abundance analysis.

2.2.2. *Mg* II *f values*

Since Mg II and Na I are adjacent members of an isoelectronic sequence, the ca f values should be reliable. Improved theoretical treatments (Warner 1968a; Black, Weisheit & Laviana 1972) lead to small revisions of ca values. This abundance analysis is based upon Black *et al.* calculated f values which include the core–valence electron polarization effect and differ by not more than 10 per cent from the simple ca predictions.

Available measurements provide a useful check on the adopted f values. Measured and predicted radiative lifetimes are compared in Table 4. With the exception of the $3p\,^2P^0$ level (the upper level for the resonance lines at 2795 and 2802 Å), all measurements are provided

Table 4. Measured and calculated radiative lifetimes for Mg II.

Level	Theory		Experiment	
	τ (ns)	Reference★	τ (ns)	Reference
$4s\,^2S$	3.11	ca	2.8 ± 0.4	Andersen *et al.* (1970
	2.98	BWL	3.8 ± 0.5	Berry, Bromander & Buchta (1970)
			2.6 ± 0.3	Lundin *et al.* (1973)
$3p\,^2P^0$	3.92	ca, BWL	4.2 ± 0.4	Andersen *et al.* (1970)
			4.5 ± 0.8	Berry *et al.* (1970)
			4.0 ± 0.3	Lundin *et al.* (1973)
			3.67 ± 0.18†	Smith & Gallagher (1966)
			3.65 ± 0.12†	Rambow & Schearer (1976)
$4p\,^2P^0$	19.0	ca	21 ± 2	Lundin *et al.* (1973)
	19.8	BWL		
$3d\,^2D$	2.08	ca	1.9 ± 0.2	Andersen *et al.* (1970)
	2.13	BWL	2.3 ± 0.4	Berry *et al.* (1970)
			2.2 ± 0.2	Lundin *et al.* (1973)
$4d\,^2D$	7.68	ca	12.2 ± 0.7	Andersen *et al.* (1972)
	8.23	BWL		
$5d\,^2D$	19.2	ca	17 ± 2	Berry *et al.* (1970)
$4f\,^2F^0$	4.28	ca	5.0 ± 0.4	Andersen *et al.* (1970)
	4.48	BWL	3.7 ± 0.4	Berry *et al.* (1970)
			4.6 ± 0.3	Lundin *et al.* (1973)
$5f\,^2F^0$	8.12	ca	9.1 ± 0.6	Andersen *et al.* (1970)
	8.31	BWL	5.8 ± 0.4	Berry *et al.* (1970)
$6f\,^2F^0$	13.7	ca	11.7 ± 0.8	Andersen *et al.* (1972)
$7f\,^2F^0$	21.5	ca	21 ± 3	Andersen *et al.* (1972)

★ ca = Coulomb approximation.
BWL = Black, Weisheit & Laviana (1972).

† All measurements except these are from beam-foil experiments.

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by beam-foil experiments. The agreement between theory and experiment is satisfactory except for the $4d\ ^2D$ level for which a single experimental result is avilable. The two upper levels of the four solar lines (Table 3) appear in Table 4.

2.2.3 *The Mg* I *f values*

Unfortunately, *f* values and relevant radiative lifetime measurements are unavailable for the weak Mg I photospheric lines. A theoretical approach must recognize the considerable configuration interaction. Lambert & Warner (1968b [LWb]) sifted the Mg I line list for lines showing minimal effects of configuration interaction. Their 15 Mg I lines showed a disappointingly large spread in the Mg abundances which was attributed to subtle effects not revealed by Warner's configuration-interaction calculation.

Froese-Fischer (1975) published *f* values for *nS–mP* and *nP–mD* transitions based on a multi-configuration Hartree–Fock (MCHF) approximation. Two comparisons show these new values to be a substantial improvement. Froese–Fischer compared her results with relative *f*-value measurements (Lincke & Ziegenbein 1971) obtained with a novel type of confined arc. Very good agreement was found (see Table 5). The second comparison with the 'astrophysical' *gf* values (LWb) also shows the MCHF results to be superior to Warner's results. In these comparisons, her dipole length calculations are adopted.

Another configuration-interaction calculation uses a semi-empirical model potential (Victor, Stewart & Laughlin 1976). As the authors note, these calculations compare favourably with the MCHF results. Table 5 compares theoretical results with the relative *f* values provided by Lincke & Ziegenbein. Since the $3p$–$4d$ transition is affected by radial integral cancellation, the theoretical *f* values are normalized to the $3p$–$5d$ transition. The large difference between the ca *f* value for the $3p$–$5d$ transition and the other theoretical results is a reflection of the severe configuration interaction in the p–d transitions.

Unfortunately, the theoretical *f* values for solar lines comprising the abundance line list cannot be given a direct check against accurate experimental values. Radiative lifetime measurements are available for several levels but these are responsible for lines in the ultraviolet or strong visible lines. The accurate relative *f* values for the ultraviolet series $3s^2\ ^1S_0$–$3snp\ ^1P_1^0$ ($n = 3$–8) obtained by Mitchell (1975) are also not of direct use in an abundance determination. Furthermore, these measurements fit equally well with the configuration interactions of Froese-Fischer (1975), Warner (1968b) and Victor *et al.* (1976).

Table 5. Relative *f* values for Mg I.

Transition	Experiment* (LZ)	Theory† FF	VSL	W	ca
$3p$–$4d\ ^1P^0$–^1D	1.0	0.967	7.4	2.05	0.004
–$5d$	0.90 ± 0.04	0.900	0.900	0.900	0.900
–$6d$	0.61 ± 0.03	0.592	0.579	2.61	0.983
–$7d$	0.41 ± 0.02	0.414		0.519	0.778
–$8d$	0.26 ± 0.01	0.276			0.577
–$9d$	0.15 ± 0.01				0.426
$3p$–$5s\ ^1P^0$–^1S	0.061 ± 0.002	0.039	0.056	0.135	1.226
–$6s$	0.013 ± 0.007	0.009	0.016	0.033	0.369

* Relative *f* values from Lincke & Ziegenbein (1971).

† Theoretical *f* values normalized to $f(3p$–$5d) = 0.9$ from the following references: FF = Froese-Fischer (1975); VSL = Victor, Stewart & Laughlin (1976); W = Warner (1968b) and ca = Coulomb approximation. These calculations give absorption *f* values for the $3p$–$5d$ transition as $f = 0.141$ (FF), 0.110 (VSL), 0.083 (W), 0.007 (ca).

Table 6. The Al I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log gf	W_λ (mÅ)	log ε
$4s\,^2S-5p\,^2P^0$	$\frac{1}{2}-\frac{3}{2}$	6696.0	3.14	−1.32	36	6.29★
		6698.7	3.14	−1.62	20	6.26★
$4s\,^2S-6p\,^2P^0$	$\frac{1}{2}-\frac{3}{2}$	5557.1	3.14	−1.95	5.3	5.99★
$3d\,^2D-5p\,^2P^0$	$\frac{5}{2}-\frac{3}{2}$	12749.8	4.02	−1.82	16	6.85★
$3d\,^2D-5f\,^2F$	$\frac{5}{2}-$	8773.9	4.02	0.04	108	6.60†
	$\frac{3}{2}-$	8772.9	4.02	−0.13	77	6.45†
$3d\,^2D-6f\,^2F$	$\frac{5}{2}-$	7836.1	4.02	−0.29	65	6.52†
	$\frac{3}{2}-$	7835.3	4.02	−0.47	43	6.40†
$3d\,^2D-7f\,^2F$	$\frac{5}{2}-$	7361.3	4.02	−0.55	43	6.49†
	$\frac{3}{2}-$	7361.6	4.02	−0.72	31	6.48†
$3d\,^2D-8f\,^2F$	$\frac{5}{2}-$	7084.7	4.02	−0.75	17	6.20†
$4p\,^2P^0-6s\,^2S$	$\frac{3}{2}-\frac{1}{2}$	10891.7	4.09	−1.09	30	6.55§
	$\frac{1}{2}-\frac{1}{2}$	10873.0	4.09	−1.39	14	6.46§
$4p\,^2P^0-7s\,^2S$	$\frac{3}{2}-\frac{1}{2}$	8841.2	4.09	−1.58	6.4	6.42§
	$\frac{1}{2}-\frac{1}{2}$	8828.9	4.09	−1.88	3.2	6.40§
$4p\,^2P^0-4d\,^2D$	$\frac{3}{2}-\frac{5}{2}$	16750.6	4.09	0.58	430	6.56‡§
	$\frac{1}{2}-\frac{3}{2}$	16719.0	4.09	0.32	337	6.56‡§
	$\frac{3}{2}-\frac{3}{2}$	16763.4	4.09	−0.38	171	6.49‡§
$4p\,^2P^0-5d\,^2D$	$\frac{3}{2}-\frac{5}{2}$	10782.0	4.09	−1.26	9.6	6.15★
	$\frac{1}{2}-\frac{3}{2}$	10768.4	4.09	−1.51	4.9	6.10★
$4p\,^2P^0-6d\,^2D$	$\frac{1}{2}-\frac{3}{2}$	8913.0	4.09	−2.36	2.3	6.72★
$4p\,^2P^0-7d\,^2D$	$\frac{1}{2}-\frac{3}{2}$	8066.0	4.09	−1.94	6.8	6.85★

★ Coulomb approximation radial integral affected by severe cancellation.

† The $3d-nf$ series and the $3d-5p$ abundances include a + 0.12 increase to allow for configuration interaction (see LWa). The $d-f$ lines are strongly broadened.

‡ The abundance was decreased by 0.04 dex to allow for the configuration interaction affecting the $4d$ level (see LWa).

§ These lines were retained in the abundance analysis.

2.2.4 The Mg abundance

The Mg I line-list with the reference atmosphere and the Froese-Fischer f values provides an abundance log ε(Mg) = 7.59 ± 0.13 dex. A major contributor to the mean error must be the theoretical f values; i.e. the lines λ11522 ($4p-6d$) and λ10313 ($4p-7d$) suggest this. Adoption of the f values calculated by Victor *et al.* for common lines leads to smaller abundance by 0.05 dex; this smaller samples gives log ε = 7.61 (FF) and 7.56 (VSL).

The four Mg II lines provide a mean abundance log ε(Mg) = 7.64 for the reference atmosphere and the Black *et al.* (1972) f values.

In this analysis, the Mg I and II lines yield concordant abundances. Earlier, LWb found a smaller abundance from Mg I than from Mg II. the difference of 0.23 dex was disturbing. Revision of the model atmosphere and the use of improved theoretical f values for the Mg I lines are responsible for the elimination of the discrepancy.

A final abundance log ε(Mg) = 7.62 is adopted in which the Mg II lines are given greater weight on account of the larger uncertainty afflicting the Mg I f values.

2.3 ALUMINIUM

2.3.1 Solar data

The Al I line list (LWa) was scrutinized and updated (see Table 6).

2.3.2 *Al* I *f values*

Ca *f* values are the basis for the abundance analysis. This choice is a forced one because extensive experimental results and refined theoretical calculations are unavailable.

Radiative lifetimes of the $4s\,^2S$ and $4d\,^2D$ levels have been measured. The former is the upper state for the strong resonance lines which are not considered in this abundance analysis. The $4d\,^2D$ level is the upper state for the strong infrared multiplet $4p\,^2P^0-4d\,^2D$ in Table 6. The measurements of the lifetime are $\tau = 21 \pm 2$ (Stuck & Zimmerman 1970) and 16.1 ± 0.3 ns (Andersen, Jessen & Sørensen 1969). The ca prediction is $\tau = 25$ ns with the $4p-4d$ transition contributing a major share. However, the $4d\,^2D$ levels are affected by configuration interaction and, therefore, the apparent discrepancy between predicted and measured lifetimes may not be representative of the Coulomb approximation.

Two important factors demand that the line list in Table 6 be pared before calculating a mean abundance. The radial integrals for several transitions exhibit substantial cancellation. The eight affected lines give abundances ranging over 0.9 dex with a mean which is fortuitously within 0.09 dex of the recommended abundance. Lines from the $3d-nf$ series are ejected from the sample because the $3d$ level is affected by configuration interactions and the higher members of the series are desaturated sufficiently by collision broadening that the adoption of the standard van der Waals' broadening coefficients is likely to be a critical source of uncertainty. However, the mean abundance from seven lines of this series is also within 0.05 dex of the recommended value when the *f*-value correction estimated by LWa is adopted.

2.4.3 *The Al abundance*

Seven Al I lines remain from Table 6. The mean abundance is $\log \epsilon(\mathrm{Al}) = 6.49 \pm 0.07$.

2.5 SILICON

2.5.1 *Solar data*

Silicon is represented by a variety of lines: a single forbidden line and many permitted lines of Si I, two Si II lines and the molecular SiH and SiH$^+$ lines. Obvious considerations suggest that these various abundance indicators cannot be assigned an equal weight.

Identification of SiH$^+$ (Grevesse & Sauval 1970) cannot be translated to an abundance because the *f* value for the transition is unknown. Although both the dissociation energy and the appropriate *f* value are available for the SiH lines, the photospheric lines are weak with uncertain equivalent widths. Independent searches by Sauval (1969) and Lambert & Mallia (1970) of photoelectric spectra of similar quality led to SiH equivalent widths differing by almost 0.2 dex. The SiH lines are consistent with the Si abundance obtained from the Si I and II lines (see Grevesse & Sauval 1971) but the precision of the SiH abundance is low.

The electric quadrupole transition at 10991.414 Å (Moore 1967) is the only observable forbidden line from the $3p^2$ ground configuration. The [Si I] line is blended with water-vapour lines. Doppler-shifted limb spectra enabled Grevesse & Swings (1972) partially to resolve the lines. Unpublished limb observations by Mallia (1974, private communication) show weaker H_2O lines and a slightly larger [Si I] equivalent width, $W_\lambda \sim 4.8$ mÅ. Adoption of the transition probability, $A = 0.854/\mathrm{s}$ (Warner 1968c) provides an abundance, $\log \epsilon(\mathrm{Si}) = 7.8$, which is slightly larger than the value suggested by the Si I and II lines. However, before the [Si I] line can be ranked with these latter lines an improved equivalent width is needed and the transition probability calculation should be extended to include configuration interaction effects.

2.5.2 The Si I f values

A theoretical approach to the Si I *f*-value question faces two major problems: an accounting for the pronounced effects of configuration interaction and severe cancellation affecting certain radial integrals. Lambert & Warner (1968c [LWc]) selected transition arrays for which marked configuration interaction and severe cancellation did not occur. Their *f* values and a refinement of their line list are re-examined here.

A useful set of *f*-value measurements was obtained by Garz (1973). Relative *f* values were derived from emission lines produced by a wall-stabilized arc. Their conversion to an absolute scale used a radiative lifetime measurement (Marek & Richter 1973). Garz claims an accuracy of 20–25 per cent for her absolute *f* values. Her line list was adopted by Holweger (1973) for a solar Si abundance determination. Comparison of the line lists shows that the LW and Holweger abundance analyses do not share a single common line. A majority (11 of 19 lines) of Holweger's lines belong to the $4s$–$5p$ array which was disregarded by LWc because the radial integral was affected by cancellation.

The abundance spread obtained from the refined LW line list is suggestive of an inadequate treatment of the configuration interaction. However, the mean value should have an accuracy that is competitive with the accuracy (20–25 per cent) claimed by Garz.

The majority of the available measurements of radiative lifetimes are not of direct interest to a solar abundance determination. However, Warner's predictions are in reasonable agreement with these measurements.

2.5.3 The Si II f values

Si II is represented in the photospheric spectrum by lines at 6347 and 6371 Å from the multiplet $4s\,{}^2S$–$4p\,{}^2P^0$. Recent theoretical *f* values are in reasonable agreement; Migdalek (1976) employed semi-empirical wave functions to obtain $gf(6347) = 1.776$ and $gf(6371) = 0.886$. He shows that the predicted lifetimes for the $4s\,{}^2S$ and $3d\,{}^2D$ levels are in agreement with measured radiative lifetimes. Froese-Fischer's (1968) superposition of configuration calculations gave $gf = 2.71$ for the multiplet. Two measurements are of interest. Berry *et al.* (1971) measured the radiative lifetime $\tau(4p\,{}^2P^0) = 8.3 \pm 0.8$ ns. After allowing for the competing transitions out of the $4p\,{}^2P^0$ level, their results translate to $gf = 3.0 \pm 0.4$ for the multiplet. Schulz-Gulde (1968) obtained relative *gf* values from emission lines produced in an arc which, after normalization to the 5041 Å ($4p$–$4d$) line, gave $gf = 2.37$. The value $gf = 2.7$ for the multiplet will be adopted. The uncertainty is of the order of ± 10 per cent.

2.5.4 The Si abundance

The revised line list for transition arrays selected by LWc are the least sensitive to effects of configuration interaction is given in Table 7. The mean abundance from 29 lines is $\log \epsilon(\mathrm{Si}) = 7.64 \pm 0.13$. If three apparently discrepant lines are rejected, the abundance decreases to $\log \epsilon(\mathrm{Si}) = 7.61 \pm 0.09$.

Table 8 shows the alternative Si I line list considered by Holweger (1973). When possible, the equivalent widths were remeasured off the new Liège Atlas (Delbouille *et al.* 1973). The mean abundance is $\log \epsilon(\mathrm{Si}) = 7.70 \pm 0.06$ from 18 lines. This is within 0.09 dex of the abundance obtained from Table 7. Since the error in the absolute scale for the *f* values is 0.08–0.13 dex, the difference is hardly significant. A mean abundance $\log \epsilon(\mathrm{Si}) = 7.66 \pm 0.05$ is taken as representative of the Si I spectrum.

The two Si II lines were remeasured on the new Liège Atlas (see Table 9). An abundance $\log \epsilon(\mathrm{Si}) = 7.60$ is obtained with the two lines yielding essentially identical results. This abundance is consistent with the mean value derived from the richer Si I spectrum.

Table 7. The revised Lambert & Warner (1968c) Si I line list.

Transition	J''–J'	λ (Å)	χ (eV)	log $gf^\star$	W_λ (mÅ)	log ϵ
$4s\,^3P^0$–$4p\,^3D$	2–1	12395.9	4.95	−1.66	97	7.52
$4s\,^3P^0$–$4p\,^1D$	2–2	9768.4	4.95	−2.40	31	7.64
$4s\,^1P^0$–$4p\,^3P$	1–1	12390.2	5.08	−1.81	79	7.58
$4s\,^1P^0$–$4p\,^3S$	1–1	11890.5	5.08	−2.19	73	7.96
$4p\,^3D$–$5s\,^3P^0$	2–2	15558.0	5.96	−0.72	194	7.72
	1–2	15361.2	5.95	−1.95	29	7.56
	1–1	15884.5	5.95	−0.73	132	7.49
$4p\,^3P$–$5s\,^1P^0$	1–1	17205.8	6.08	−1.55	87	7.85
$4p\,^3S$–$5s\,^3P^0$	1–1	20343.9	6.13	−0.91	132	7.58
$4p\,^3D$–$6s\,^3P^0$	3–2	8892.7	5.98	−0.83	77	7.73
	2–2	8766.4	5.96	−1.68	16	7.56
	2–1	8949.1	5.96	−1.12	48	7.62
	1–1	8883.7	5.95	−1.78	15	7.60
	1–0	8925.3	5.95	−1.42	32	7.65
$4p\,^3P$–$6s\,^3P^0$	2–2	9689.4	6.10	−1.09	49	7.69
	1–0	9839.4	6.08	−1.66	17	7.60
$4p\,^3S$–$6s\,^3P^0$	1–2	9891.6	6.13	−1.33	27	7.57
	1–1	10124.6	6.13	−2.10	6	7.57
$4p\,^3D^0$–$6s\,^1P^0$	1–1	8606.0	5.95	−2.14	7.8	7.65
$4p\,^1D^0$–$6s\,^1P^0$	2–1	10582.2	6.22	−1.01	38	7.46
$4p\,^1S$–$6s\,^1P^0$	0–1	12458.5	6.40	−1.87	11	7.67
$4p\,^1P$–$6s\,^3P^0$	1–1	8338.3	5.86	−1.90	17	7.72
$4p\,^3D$–$7s\,^3P^0$	3–2	7393.0	5.98	−1.30	42	7.81
	2–2	7286.0	5.96	−2.15	5	7.54
	1–0	7395.5	5.95	−1.89	11	7.63
$4p\,^3P$–$7s\,^3P^0$	2–2	7912.4	6.10	−1.56	13	7.51
	1–1	7975.6	6.08	−2.17	5.9	7.71
$4p\,^3S$–$7s\,^3P^0$	1–2	8046.8	6.13	−1.80	6.5	7.44
$4p\,^1P$–$7s\,^1P^0$	1–1	6848.6	5.86	−2.09	16	7.94

**gf* values from Warner (1968c).

The recommended abundance, log ϵ(Si) = 7.63, is a simple mean of the Si I and II results. A simple mean appears appropriate. Although the Si I line list is extensive, the mean abundance depends on an absolute *f*-value scale that is not better established than the Si II scale.

2.6 PHOSPHORUS

2.6.1 *Solar data*

A handful of weak infrared lines from the $4s$–$4p$ transition array represent phosphorus in the photospheric spectrum. The present line list (Table 10) is a reconsideration of the longer list given by LWa.

2.6.2 *P I f values*

The *f* values for the $4s$–$4p$ array are provided by ca radial integrals and LS-coupling line strengths. The $4p\,^4P^0$ and $4p\,^2D^0$ terms are affected by configuration interaction and lines ending on these terms are rejected. No *f*-value measurements are known for the $4s$–$4p$ array.

Table 8. The revised Holweger (1973) Si I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log gf	W_λ (mÅ)	log ϵ
$4s\,^3P^0-5p\,^3P$	1–2	5645.6	4.93	−2.14	35.4	7.68
	0–1	5665.6	4.92	−2.04	40.7	7.66
	1–1	5690.4	4.93	−1.87	49.1	7.64
	1–0	5701.1	4.93	−2.05	36.6	7.61
	2–2	5708.4	4.95	−1.47	79.3	7.71
$4s\,^3P^0-5p\,^3S$	2–1	5684.5	4.95	−1.65	60.7	7.61
$4s\,^3P^0-5p\,^3D$	0–1	5780.4	4.92	−2.35	26.0	7.68
	1–2	5793.1	4.93	−2.06	43.9	7.73
	2–3	5797.9	4.95	−2.05	43.6	7.73
$4s\,^3P^0-5p\,^3S$	1–0	5772.1	5.08	−1.75	54.0	7.71
$4s\,^1P^0-5p\,^1D$	1–2	5948.5	5.08	−1.23	90.7	7.73
$3d\,^1D^0-5f\,^1F$	2–3	7034.9	5.87	−0.88	67.0	7.66
$3p^3\,^3D^0-4f\,^1D$	1–2	7226.2	5.61	−1.51	36.0	7.62
$4p\,^1P-5d\,^1D^0$	1–2	7680.3	5.86	−0.69	98.0	7.82
$4p\,^3D-5d\,^3F^0$	1–2	7918.4	5.95	−0.61	95.0	7.76
	2–3	7932.4	5.96	−0.47	97.0	7.65
	2–2	7970.3	5.96	−1.47	32.0	7.77
$4p\,^3D-6d\,^3F^0$	1–2	6976.5	5.95	−1.17	43.0	7.68
$4p\,^3D-8s\,^3P^0$	3–2	6714.6	5.96	−1.75	16.1	7.73

Table 9. The Si II line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log gf	W_λ (mÅ)	log ϵ
$4s\,^2S-4p\,^2P^0$	$^1/_2-^3/_2$	6347.1	8.12	0.26	49	7.61
	$^1/_2-^1/_2$	6371.4	8.12	−0.05	35	7.59

Table 10. The P I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	log gf	W_λ (mÅ)	log ϵ
$4s\,^4P-4p\,^4D^0$	$^5/_2-^7/_2$	10581.6	6.98	0.45	23	5.46
	$^3/_2-^5/_2$	10529.6	6.95	0.17	15	5.46
	$^1/_2-^3/_2$	10511.6	6.93	−0.23	6.6	5.44
$4s\,^4P-4p\,^4P^0$	$^5/_2-^5/_2$	9796.8	6.98	0.19	14	5.50
	$^3/_2-^1/_2$	9750.8	6.95	−0.21	5.5	5.41

Measurements for the $4s-5p$ array are available but they cannot test the applicability of the ca to P I because the ca radial integral for the $4s-5p$ transitions is affected by severe cancellation.

2.6.3 *The P abundance*

The six P I lines provide an abundance log ϵ(P) = 5.45 ± 0.03.

2.7 SULPHUR

2.7.1 *Solar data*

Sulphur is represented in the solar spectrum by forbidden lines from the ground $3p^4$ configuration and permitted lines from excited configurations. A preliminary catalogue (LWa) of permitted lines should be updated when the definitive term analysis is available.

Table 11. Experimental and theoretical *gf* values for S I transitions.

				gf			
Multiplet	λ (Å)	Theory*		Experiment†			
		(ca)	(ic)	Miller *et al.* (1974)	Bridges & Wiese (1967)	Foster (1967)	Schulze-Gulde (1971)
$4s$–$4p$ $^5S^0$–^5P	9222	5.18	7.24		7.7 (2.7)		
$^3S^0$–^3P	10456	3.24	3.82		4.4 (1.1)		
$4s$–$5p$ $^5S^0$–^5P	4695	0.088‡		0.033 (7)	0.051 (15)	0.029 (5)	0.033
$^3S^0$–$^3P^0$	5279	0.036		0.017 (4)	0.020 (6)	0.013 (2)	
$4p$–$6s$ ^5P–$^5S^0$	7690	0.26		0.35 (9)			
$4p$–$4d$ ^5P–$^5D^0$	8685	2.97			4.5 (1.4)		
$4p$–$5d$ ^5P–$^5D^0$	6752	1.09		1.6 (0.4)	1.9 (0.7)		

* ca = Coulomb approximation.
ic = Intermediate coupling calculations (Aymar 1973).
† Errors are in parenthesis: e.g. 7.7 (2.7) ≡ 7.7 ± 2.7 or 0.051 (15) ≡ 0.051 ± 0.015.
‡ Radial integrals affected by severe cancellation.

2.7.2 *The S I and [S I] f values*

The combination of ca radial integrals and LS coupling line strengths cannot be applied to all S I lines. Configuration interaction and cancellation within the radial integral affect certain transitions. An intermediate-coupling calculation (Aymar 1973) demonstrates that LWa correctly identified transitions insensitive to configuration interaction. Aymar's calculations are based on a parameterized potential which is not obviously superior to the ca.

A comparison of theoretical and experimental results is given in Table 11. The latter appear to confirm the ca predictions. Comparison of results for three common multiplets suggest that the Bridges & Wiese (1967) *gf* values may be too large by a factor of 1.2–1.6 relative to the shock tube measurements reported by Miller *et al.* (1974). If the former were adjusted on to the latter scale, the measured (Bridges & Wiese) *gf* values for the three infrared multiplets, which contribute several solar lines, would be consistent with the ca values.

The ca results are adopted for all lines except those from the $4s$–$5p$ array for which the measurements by Miller *et al.* are taken.

The ground $3p^4$ configuration provides two weak forbidden lines in the solar spectrum. A recent experiment provides a useful check on the calculated transition probabilities. Kernahan & Pang (1975) obtain $A = 0.34 \pm 0.10$ and 1.64 ± 0.48/s for the [S I] lines at 4589 and 7725 Å respectively. The best theoretical calculation (Czyzak & Krueger 1963) gives $A = 0.35$ and 1.78/s for these lines. The 7725 Å is blended but observable in the Sun. A second [S I] line at 10821 Å is a magnetic-dipole transition for which $A = 0.0275$/s was calculated. The calculated values for the 7725 and 10821 Å lines are adopted.

2.7.3 *The S abundance*

Selection of S I lines (see Table 12) follows the guidelines described by LWa. The four lines from the $4s$–$5p$ array provide a mean abundance $\log \epsilon(\mathrm{S}) = 7.41$ which is significantly larger than the overall mean. This difference must reflect a scale difference between the shock tube and ca f values. The strong lines, $W_\lambda > 60$ mÅ, also provide a systematically larger abundance; $\log \epsilon(\mathrm{S}) = 7.36$ from six lines. This could be reduced to the mean abundance by an increase in the microturbulent velocity from 1.0 to 2.0 km/s. Other contributing

Table 12. The S I line list.

Transition	$J''-J'$	λ (Å)	χ (eV)	$\log gf$	W_λ (mÅ)	$\log \epsilon$
$4s\ ^5S^0-4p\ ^5P$	2–3	9212.9	6.52	0.38	166	7.44
	2–2	9228.1	6.52	0.24	135	7.33
	2–1	9237.5	6.52	0.01	116	7.37
$4s\ ^3S^0-4p\ ^3P$	1–2	10455.5	6.86	0.26	130	7.37
	1–1	10459.4	6.86	0.03	106	7.29
	1–0	10456.8	6.86	−0.44	65	7.36
$4p\ ^5P-4d\ ^5D^0$	3–4	8694.7	7.87	0.03	31	7.21
	3–3	8694.0	7.87	−0.56	12	7.21
	1–1	8670.7	7.87	−0.57	11.6	7.21
	1–0	8670.2	7.87	−0.92	5.7	7.19
	1–2	8671.4	7.87	−0.69	10	7.24
$4p\ ^3P^0-4d\ ^3D$	1–2	9036.3	8.05	−0.93	2.9	7.02
$4s\ ^5S^0-5p\ ^5P$	2–3	4694.1	6.52	−1.82	15.0	7.45
	2–2	4695.4	6.52	−1.96	8.5	7.31
$4s\ ^3S^0-5p\ ^3P$	1–2	5278.9	6.86	−2.02	6.6	7.56
	1–1	5278.6	6.86	−2.24	2.5	7.32
$4p\ ^5P-5d\ ^5D^0$	3–	6757.1	7.87	−0.29	22.5	7.37
	2–	6748.6	7.87	−0.44	17.8	7.37
	1–	6743.6	7.87	−0.70	10.5	7.30
$4p\ ^5P-6s\ ^5S^0$	2–2	7686.1	7.87	−1.06	4.3	7.25
	1–2	7679.6	7.87	−1.28	2.0	7.13

factors could be an error in the *gf* value (adoption of Aymar's *gf* values would reduce the abundance from $\log \epsilon(\mathrm{S}) = 7.36$ to 7.26) and an underestimate of the collision broadening of these lines. The remaining 11 weak lines give a mean abundance of $\log \epsilon(\mathrm{S}) = 7.23 \pm 0.14$. Although the rms error is small, a larger uncertainty may result from the use of the ca *f* values.

The [S I] lines were reviewed by Swings, Lambert & Grevesse (1969). Spectrum synthesis of the 7725 Å, which is blended with CN and Si I lines, gave $\log \epsilon(\mathrm{S}) = 7.1$. This would be increased slightly (~ 0.05 dex) for the Holweger–Müller atmosphere. The [S I] 10821 Å line was identified with a solar line for which independent photoelectric spectra gave

$\lambda = 10821.23 \pm 0.03$ Å and $W_\lambda = 3.2 \pm 0.2$ mÅ

$\lambda = 10821.28 \pm 0.03$ Å and $W_\lambda = 3.6 \pm 0.3$ mÅ.

Recently improved term values (Eriksson 1973) for the $3p^4$ configuration predict $\lambda = 10821.14 \pm 0.03$ Å and suggest that the solar line may be blended. Careful scrutiny of the highest resolution photoelectric spectra including a centre-limb study may clarify this question. The predicted intensity, $W_\lambda = 2.5$ mÅ, for $\log \epsilon(\mathrm{S}) = 7.23$ appears to be consistent with the observed solar line. However, if a blend is confirmed, the [S I] line should not be accepted as a primary abundance indicator. In summary, the two [S I] lines confirm but do not improve upon the abundance provided by the S I lines.

2.8 POTASSIUM

2.8.1 Solar data

Potassium is represented by the strong resonance lines at 7664 and 7699 Å and a few excited lines of K I. de la Reza & Müller (1975) show that a NLTE analysis is required for the resonance lines. Table 13 lists the selected excited lines.

Table 13. The K I line list.

Transition	J''–J'	λ (Å)	χ (eV)	log *gf*	W_λ (mÅ)	log ε
$4s\ ^2S$–$4p\ ^2P^0$	½–³⁄₂	4044.2	0.0	−1.93	14.0	4.97
$4p\ ^2P^0$–$5s\ ^2S$	³⁄₂–½	12522.1	1.62	−0.18	85.0	5.29
	½–½	12439.3	1.62	−0.48	53.0	5.25
$4p\ ^2P^0$–$7s\ ^2S$	³⁄₂–½	5801.8	1.62	−1.69	1.6	5.10
$4p\ ^2P^0$–$3d\ ^2D$	³⁄₂–³⁄₂	11769.7	1.62	−0.45	42.0	5.11

Table 14. Radiative lifetimes for K I.

	Theory		Experiment	
Level	τ (ns)	Reference	τ (ns)	Reference
$4p\ ^2P^0$	26.8	ca	27.1 ± 0.9	Stephenson (1951)
	27.4	W*	27.8 ± 0.5	Link (1966)
			26.0 ± 0.5	Schmeider, Lurio & Happer (1968)
			28 ± 2	Ney (1969)
			27.8 ± 0.8	Copley & Krause (1969)
			27.3 ± 0.3	Zimmerman (1975)
$5p\ ^2P^0$	119	ca	141 ± 1	Schmeider *et al.* (1968)
	135	ca†	120 ± 4	Ney (1968)
			133 ± 3	Svanberg (1971)
$6p\ ^2P^0$	293	ca	310 ± 15	Svanberg (1971)

*W = Weisheit (1972).

† The $4s$–$5p$ contribution is calculated from the measured ratio $gf(4s–4p)/gf(4s–5p)$.

2.8.2 K I f values

Warner's (1968a) calculated *f* values are adopted. He used the ca radial integrals and introduced a small correction to the line strengths to allow for the spin–orbit interaction. The $4s$–$5p$ and $4p$–$5d$ integrals are affected by severe cancellation.

Radiative lifetime measurements and calculations for the $4p$, $5p$ and $6p$ levels are compared in Table 14. The ca predictions appear to be confirmed. Dye-laser fluorescence experiments should soon provide an enlarged experimental basis for such a comparison.

The *f* value for the $4s$–$5p$ line at 4044 Å is derived from the ca prediction for the $4s$–$4p$ transition and the ratio $gf(4s–4p)/gf(4s–5p) = 111.5$ (Fillipov 1933) measured by the hook method.

2.8.3 The K abundance

The five lines in Table 13 provide a mean abundance $\log \epsilon(\mathrm{K}) = 5.14 \pm 0.13$. Two points might be noted. The 4044 Å line gives an abundance 0.17 dex below the mean. A possible interpretation is that the *f* value is in error; the required correction increases the lifetime of the $5p$ level to 142 ns which is not excluded by the lifetime measurements. The two strongest lines in Table 13 give an abundance above the mean value; this might suggest that the microturbulence should be increased to near 2 km/s, the line broadening is larger than the assumed van der Waal's broadening, or NLTE effects vitiate a LTE analysis. If the line list is reduced to the remaining two lines, the abundance is $\log \epsilon(\mathrm{K}) = 5.11$.

A NLTE line profile centre-limb analysis (de la Reza & Müller 1975) for the Holweger–Müller atmosphere gave $\log \epsilon(\mathrm{K}) = 5.12$ for the 7699 Å resonance line. This is in excellent agreement with the weak-line abundance.

The recommended abundance is $\log \epsilon(\mathrm{K}) = 5.12$.

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Table 15. Weak Ca I lines.

Transition	J''–J'	λ (Å)	χ (eV)	log *gf*	W_λ (mÅ)	log ε
$3d\,^3D$–$4p\,^3P^0$	1–2	5260.4	2.52	−1.70	30.5	6.33
$3d\,^3D$–$5p\,^3P^0$	2–2	6161.3	2.52	−1.31	67.0	6.53
	1–1	6163.8	2.52	−1.46	63.0	6.62
	1–0	6166.4	2.52	−1.30	72.0	6.62
$3d\,^3D$–$4p\,^1D^0$	2–2	6455.6	2.52	−1.54	56.1	6.59
$4s^2\,^1S$–$4p\,^3P^0$	0–1	6572.0	0.00	−4.31	25.0	6.32

Table 16. The Ca II line list.

Transition	J''–J'	λ (Å)	χ (eV)	log *gf*	W_λ (mÅ)	log ε
$5p\,^2P^0$–$6s\,^2S$	$^3/_2$–$^1/_2$	9931.5	7.51	0.08	48	6.48
	$^1/_2$–$^1/_2$	9854.7	7.50	−0.22	27	6.37
$5p\,^2P^0$–$5d\,^2D$	$^3/_2$–$^5/_2$	8248.8	7.51	0.57	70	6.48
	$^3/_2$–$^3/_2$	8254.7	7.51	−0.38	17	6.36
	$^1/_2$–$^3/_2$	8201.7	7.50	0.32	51	6.43
$5p\,^2P^0$–$6d\,^2D$	$^3/_2$–$^3/_2$	5021.2	7.51	−1.21	3.7	6.38
	$^1/_2$–$^3/_2$	5001.5	7.50	−0.51	11.5	6.25
$4f\,^2F^0$–$5d\,^2D$	–$^5/_2$	21388.9	8.44	0.19	40	6.38
	$^5/_2$–$^3/_2$	21428.9	8.44	0.11	35	6.38
$4f\,^2F^0$–$5g\,^2G$		9890.7	8.44	1.27	70	6.43
$4f\,^2F^0$–$6g\,^2G$		6456.9	8.44	0.43	19.3	6.42
$4f\,^2F^0$–$7g\,^2G$		5339.2	8.44	−0.05	6.0	6.20

2.9 CALCIUM

2.9.1 *Solar data*

Calcium signatures comprise Ca I and II lines (See Tables 15 and 16). The latter includes a useful forbidden line as well as excited permitted lines. Many of the Ca I lines are strong and ill-suited to an abundance analysis. Moreover, their *f* values may be uncertain. Fortunately, the intercombination line at 6572 Å is an excellent abundance indicator; the line is quite weak and the *f* value is well determined. The rediscussion updates the abundance analysis by Holweger (1972).

2.9.2 *Ca II f values*

Predicted and measured radiative lifetimes are compared in Table 17. Unfortunately, the experimental results lack the precision to discriminate between the two theoretical calculations. When available, the Black *et al.* (1972) calculations are adopted. Otherwise, Warner's values are taken. The measured lifetimes indicate that the calculations cannot be in error by more than 20 per cent.

The [Ca II] at 7323 Å is an electric-quadrupole transition ($4s^2 S_{1/2}$–$3d\,^2D_{3/2}$). Warner (1968a) calculated a transition probability $A = 1.28$/s. Black, Weisheit & Laviana (1972) include the valence-core electron polarization and calculate $A = 1.011$/s. The value $A = 1.1$/s is adopted or $\log gf = -7.45$.

2.9.3 *Ca I f values*

The intercombination resonance line at 6572 Å may be isolated in the *f*-value discussion. Recent results are summarized in Table 18. The lifetime measurement by Giusfredi *et al.*

Table 17. Measured and calculated radiative lifetimes for Ca II.

	Theory		Experiment	
Level	τ (ns)	Reference*	τ (ns)	Reference
$5s\ ^2S$	4.51	ca (W)	4.3 ± 0.4	Andersen *et al.* (1970)
	3.85	BWL	3.4 ± 0.3	Emmoth *et al.* (1975)
$4p\ ^2P$	6.63	ca (W)	6.7 ± 0.2†	Gallagher (1967)
	6.38	BWL	7.5 ± 0.5	Andersen *et al.* (1970)
			6.4 ± 0.5	Emmoth *et al.* (1975)
$5p\ ^2P$	37.8	ca (W)	29 ± 5	Emmoth *et al.* (1975)
	36.0	BWL		
$4d\ ^2D$	2.94	ca (W)	3.2 ± 0.3	Andersen *et al.* (1975)
	2.79	BWL	2.9 ± 0.3	Emmoth *et al.* (1975)
$5d\ ^2D$	6.09	ca (W)	4.3 ± 0.2	Andersen *et al.* (1970)
	6.10	BWL‡		

* ca (W) = Coulomb approximation including spin–orbit interaction, see Warner (1968a).
BWL = Black, Weisheit & Laviana (1972).

† = All measurements except these are from beam-foil experiments.

‡ = The $5d$–$4f$ contribution was taken from Warner (1968a).

Table 18. The Ca I intercombination line at 6572 Å: oscillator strength and transition probability.

Authors	Method	A (10^3 s^{-1})	log gf
Giusfredi *et al.* (1975)	Lifetime: atomic beam and electron excitation	1.8 ± 0.2	–4.46
Furcinetti, Baling & Wright (1975)	Lifetime: dye-laser fluorescence	2.6 ± 0.3	–4.30
Parkinson, Reeves & Tomkins (1976)	Hook method: relative to 4226 Å	2.46	–4.32
Ostrovskii & Penkin (1961)	Hook method: relative to 4226 Å [τ(4226) = 4.60 ns assumed here]	2.51	–4.31
	Adopted	2.55	–4.31

(1975) appears to be discrepant and is excluded. The adopted gf value, log $gf = -4.31$, would appear to be accurate to about 0.02 dex.

Excited lines of Ca I are plentiful in the solar spectrum. The key problem is the lack of reliable f values for weak lines. LWb adjusted the relative f values of Olsen, Routly & King (1959) to an absolute scale through theoretical f values for selected transitions. Holweger (1972) proposed a normalization of these relative f values using the measured radiative lifetime of the $4f\ ^1F$ level (Brinkmann *et al.* 1969). The two normalizations are equivalent. Havey, Balling & Wright (1977) obtained radiative lifetimes for eight excited singlet states via one- and two-step dye-laser excitation. Their results for the $4p^2\ ^1D$ and $5d\ ^1D$ states give a mean normalization factor within 2 per cent of the Holweger value. However, this analysis assumes that the states are de-excited by one dominant transition ($4p^2\ ^1D \rightarrow 4p\ ^1P^0$ and $5d\ ^1D \rightarrow 4p\ ^1P^0$). Recently, Smith & O'Neill (1975) made accurate relative f-value measurements for two low-lying multiplets for which an absolute f value was obtainable from lifetime measurements (Gornik *et al.* 1973). Their results suggest a 30 per cent correction to the Holweger f-value scale. However, this may not apply to the entire Olsen *et al.* line list; the lines measured by Smith & O'Neill are too strong to be included in Table 15. Hopefully, the f-value question will be resolved in the near future when dye lasers are used to obtain additional precision lifetimes which are analysed using carefully measured branching ratios.

Five weak Ca I lines ($W_\lambda < 75$ mÅ) are listed in Table 15 with the *gf* values taken from Holweger (1972).

2.9.4 *The Ca abundance*

The 12 Ca II lines give a mean abundance log ϵ(Ca) = 6.38 ± 0.08. Equivalent widths for the [Ca II] line at 7327 Å are adopted as follows: $W_\lambda = 9.9$ mÅ for integrated light (Day 1972), = 8.2 mÅ for the centre of the disk (Ayres 1977) and = 12.9 for the limb (Lambert & Mallia 1969). The three measurements yield consistent (to ±0.05 dex) abundances: log ϵ(Ca) = 6.33 is adopted. Schorn, Young & Barker (1975) reported $W_\lambda = 7.4 \pm 0.4$ mÅ for integrated sunlight. This value is primarily a photographic measurement using the Venus spectrum. Since this low equivalent width is in conflict with the above three independent photoelectric measurements, it is presumed to be affected by a systematic error.

The Ca I intercombination resonance line (Table 15) gives an abundance log ϵ(Ca) = 6.32. The five excited Ca I lines provide a mean abundance which is markedly larger than that provided by the other indicators. Several reasons can be suggested. As Smith & O'Neill suggest the adopted *f* values may be too small. These lines are also quite sensitive to the adopted microturbulence; if the standard value of 1.0 km/s is increased by 0.5 km/s, the mean abundance from the four strongest lines in Table 15 drops by 0.09 dex.

A recommended abundance for Ca is log ϵ(Ca) = 6.34. The Ca II, [Ca II] and the Ca I 6572 Å lines are considered in reaching this recommendation. The excited Ca I lines are excluded because the *f* values may be unreliable.

3 Discussion

3.1 ABUNDANCE UNCERTAINTIES AND THE MODEL ATMOSPHERE

Effects of model atmosphere uncertainties on the abundances were assessed through sample calculations with six model atmospheres. Five of the atmospheres were taken from the recent literature. They incude the Holweger–Müller atmosphere adopted for this analysis, the Harvard–Smithsonian reference (HSRA) atmosphere (Gingerich *et al.* 1971) and models detailed by Vernazza, Avrett & Loeser (1976, VAL), Ayres & Linsky (1976, AL) and Allen (1976, A, in preparation). Within the framework imposed by the common assumptions, these five models appear to cover the span of acceptable models; Lambert (1978) compared the observed and predicted continuous spectra to show that neither the AL or HSRA models is satisfactory and model VAL is marginally acceptable. A sixth model comprising two streams or columns was also tested. This is a first approximation to a modelling of the granulation.

Sample abundance calculations to show the effects of the different models are summarized in Table 19. The two-stream model result is referred to the abundance obtained from a mean temperature distribution. The abundance decrease resulting from an increase in the microturbulence from 1.0 to 1.5 km/s is given under Δ(mic).

Examination of results for the standard models shows that ± 0.05 dex should cover this source of uncertainty; larger differences are apparent in Table 19 but these refer to models that do not give wholly acceptable fits to the observed continuous spectrum.

The crude granulation modelling suggests that that standard models *may* introduce systematic errors in the relative abundances of the elements; e.g. the abundances of Na and K may be offset relative to those of P and S. Ca offers a test of this idea because the abundance may be obtained from both Ca I and II. If the permitted, excited Ca I lines are omitted on the reasonable grounds that their *f* values are uncertain, the abundances from the permitted and forbidden Ca II lines and the resonance intercombination line of Ca I do not

Table 19. Model atmospheres and abundances.

Line sample	HM	A	log ϵ VAL	AL	HSRA	Δ log $\epsilon^\star$ (2 stream)	Δ(mic)†
Na I	6.32	6.31	6.26	6.32	6.26	−0.09	−0.02
Mg I	7.59	7.58	7.57	7.61	7.53	−0.02	−0.02
Mg II	7.64	7.64	7.69	7.74	7.61	+ 0.08	−0.03
Mg H‡	7.62	7.56	7.45	7.56	7.42	−0.67	0.00
Al I	6.49	6.49	6.47	6.49	6.44	−0.01	−0.01
Si I	7.66	7.66	7.66	7.68	7.62	+ 0.07	−0.03
[Si I]‡	7.63	7.60	7.49	7.59	7.49	−0.12	0.00
Si II	7.60	7.56	7.65	7.68	7.58	+ 0.06	−0.09
P I	5.45	5.45	5.48	5.48	5.40	+ 0.06	0.00
S I	7.22	7.20	7.27	7.27	7.18	+ 0.09	−0.05
K I (weak lines)	5.12	5.13	5.10	5.12	5.07	−0.11	0.00
Ca I 6572 Å	6.32	6.29	6.14	6.28	6.19	−0.35	−0.02
Ca I (excited weak lines)	6.54	6.50	6.42	6.55	6.44	−0.05	−0.09
[Ca II] 7323 Å	6.33	6.29	6.29	6.29	6.25	0.00	−0.01
Ca II	6.38	6.38	6.42	6.44	6.34	+ 0.07	−0.02

[★] The abundance difference $\Delta \log \epsilon = (\log \epsilon)_{2\ \mathrm{stream}} - (\log \epsilon)_{\mathrm{mean}}$.

[†] The abundance correction (in dex) resulting from an increase in the microturbulence from 1.0 to 1.5 km/s.

[‡] Sample lines were selected for these calculations in which the abundance was adjusted to the value given under HM. The calculations show the sensitivity of the abundance to the adopted model.

Table 20. Meteoritic and photospheric abundances.

Element	Meteorites★	This paper	GMA†	log ϵ LW‡	H§	Others¶
Na	6.33	6.32	6.30	6.18	6.32	6.31 (BKS)
Mg	7.58	7.62	7.40	7.48		
Al	6.48	6.49	6.20	6.40		
Si	7.55	7.63	7.50	7.55	7.65	
P	5.55	5.45	5.34	5.43		
S	7.25	7.23	7.30	7.21	7.19	
K	5.03	5.12	4.70	5.05		
Ca	6.41	6.34	6.15	6.33	6.36	6.38 (A)

[★] Abundances relative to silicon are taken from Mason (1971) and normalized to the solar abundances by putting log ϵ(Si) = 7.55.

[†] Goldberg, Müller & Aller (1960).

[‡] Lambert & Warner (1968a, b c).

[§] Holweger (1971, 1972, 1973, 1977).

[¶] BKS = Blackwell, Kirby & Smith (1974); A = Ayres (1977).

differ by more than 0.05 dex. This compares with the two-stream suggestion of a spread of 0.3 dex. A conclusion is that either the present crude two-stream model exaggerates the granulation effects or the two-stream prediction is masked by other effects (departures from LTE, inapplicability of the Holweger–Müller model etc.).

3.2 SOLAR AND METEORITIC ABUNDANCES

A comparison of the solar and meteoritic abundances (Table 20) is instructive. The latter are taken for the carbonaceous chondrites (type C-1) from Mason (1971). The logarithmic

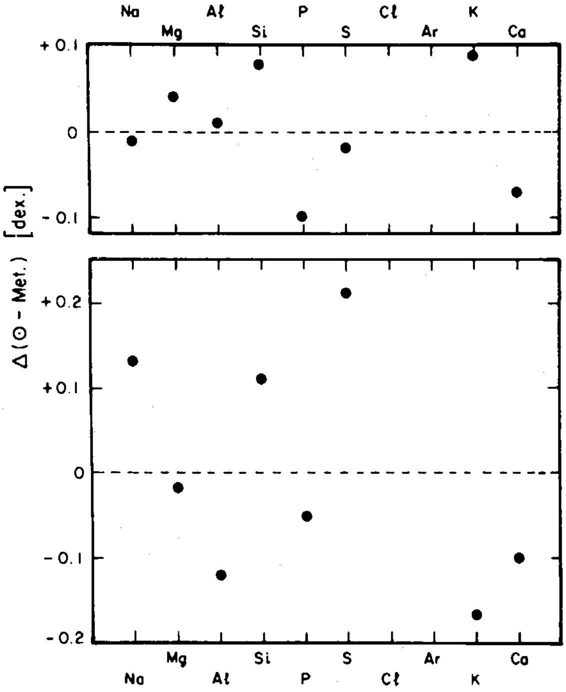

Figure 2. Solar and meteoritic (carbonaceous chondrites type C-1) abundances. In the upper panel, the solar abundances are taken from this paper. In the lower panel, the solar abundances of Goldberg, Müller & Aller (1960) are used.

difference, $\Delta = \log \epsilon(\text{Sun}) - \log \epsilon(\text{meteorite})$, is shown in Fig. 2. Clearly, there are no significant differences between the Sun and the meteorities in this mass range. A similar plot using the solar abundances of Goldberg, Müller & Aller (1960) is shown in the lower half of Fig. 2. The differences, Δ, are approximately doubled in this plot. This reflects the improvement in the solar abundances. The 1968 abundances provided by LW also show excellent agreement with the meteoritic abundances. The primary difference between current and 1968 abundances is a small net increase in the abundances; the largest increase of 0.14 dex occurs for Mg. Table 20 also includes abundances taken from recent papers. The single selection criterion was an adequate discussion of the *f* values.

Another indicator of the converging trend of solar abundance determinations emerges from a comparison of the new results and the Ross & Aller (1976) survey of the chemical composition of the Sun. Their recommended abundances are the result of a review of photospheric (including an unpublished re-analysis for four of the eight in the current group), coronal and solar wind (for four of the eight) abundance determinations. The new results and the Ross & Aller recommendations differ in the mean by less than 0.01 dex with a maximum difference of only 0.05 dex for P. Coronal and photospheric abundance determinations would appear to be in agreement.

An interesting question remains for future investigations: 'will the photospheric and meteoritic abundances be identical when the uncertainties are reduced to below 0.05 dex'? Surely, the discovery of small abundance differences across the periodic table will reveal clues to the early history of the solar system. Holweger (1977) has pointed out that the photospheric Na/Ca and S/Ca ratios are in excellent agreement with abundances for carbonaceous chondrites of Type 1 but are inconsistent with the results for Types 2 and 3. The former agreement leads him to the important deduction that 'C-1 matter is a well-preserved condensate from parts of the solar nebula whose composition was very close to solar and which constitutes a chemically closed system during condensation with no supply or loss of volatites such as Na or S'. He notes that this excludes the possibility that C-1 meteorites consist of interstellar grains for which a lower S/Ca ratio is highly probable. One point deserves some emphasis. The source of uncertainty in the photospheric abundance analyses are numerous and obvious; a precision of ±0.10 dex has probably been achieved in this group. Perhaps, the uncertainties in the meteoric abundances are unappreciated by astrophysicists. Two comments from recent discussions must suffice (see Mason 1971).

(i) The author of the section on the phosphorus abundance in meteorites remarks 'phosphorus determinations have not shown a great degree of precision';

(ii) A more dramatic comment is found in the section on potassium which concludes that there is 'little justification for choosing a value from the observed range to represent the cosmic abundance of K. For those who enjoy playing that game, the average is . . .'.

4 Conclusions

Although elements should be individually assessed, the accuracy of the solar abundances within the Na–Ca range is surely now at the ±0.1 dex level. This is suggested by the improved solar spectra, the critical *f*-value reviews, the model atmosphere calculations and the external comparison with other recent abundance studies.

Solar spectra are now of such a high quality that detailed line profile analysis is an appropriate analytical tool. Centre-limb variations should be utilized. To break the ±0.1 dex barrier, spectra with high spatial resolution should be obtained and analysed with the appropriate inhomogeneous models and a relaxation of the LTE assumption.

Throughout this paper, an attempt has been made to draw attention to areas of uncertainty in the required *f* values. Extension of dye laser one- and two-step excitation for the measurement of radiative lifetimes coupled with accurate branching ratio determinations will surely resolve the *f*-value problems for the Al I, K I and Ca I spectra. Development of suitable lasers for the ultraviolet will enable the same techniques to be applied to the other spectra; Mg I, Si I and S I stand out as prime targets for attention.

Also, the identification of several lines should be examined; in particular, the infrared [Si I] and [S I] lines deserve further attention.

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References

Andersen, E. M. & Zailitis, V. A., 1964. *Opt. Spectr.*, **16**, 99.
Andersen, T., Desesquelles, J., Jessen, K. A. & Sørensen, G., 1970. *J. quant. Spectr. rad. Trans.*, **10**, 1143.
Andersen, T., Jessen, K. A. & Sørensen, G., 1969. *J. opt. Soc. Am.*, **59**, 1197.
Andersen, T., Madsen, O. H. & Sørensen, G., 1972. *Phys. Scripta*, **6**, 125.
Aymar, M., 1973. *Physica*, **66**, 364.
Ayres, T. R., 1977. *Astrophys. J.*, **213**, 296.
Ayres, T. R. & Linsky, J. L., 1976. *Astrophys. J.*, **205**, 874.

Balfour, W. H. & Cartwright, H. M., 1975. *Can. J. Phys.*, **53,** 1477.

Balfour, W. H. & Cartwright, H. M., 1976. *Astr. Astrophys. Suppl.*, **26,** 389.

Baumann, M., 1969. *Z. Natür. A*, **24,** 1049.

Berry, H. G., Bromander, J. & Buchta, R., 1970. *Phys. Scripta*, **1,** 181.

Berry, H. G., Bromander, J., Curtis, L. J. & Buchta, R., 1971. *Phys. Scripta*, **3,** 125.

Black, J. H., Weisheit, J. C. & Laviana, E., 1972. *Astrophys. J.*, 177, 567.

Blackwell, D. E., Kirby, J. H. & Smith, G., 1972. *Mon. Not. R. astr. Soc.*, **160,** 189.

Bridges, J. M. & Wiese, W. L., 1967. *Phys. Rev. A*, **159,** 31.

Brinkmann, U., Goschler, J., Steudel, A. & Walther, H., 1969. *Z. Phys. A*, **228,** 427.

Copley, G. & Krause, L., 1969. *Can. J. Phys.*, **47,** 533.

Czyzak, S. J. & Krueger, T. K., 1963. *Mon. Not. R. astr. Soc.*, **126,** 177.

Day, R. W., 1972. *Sol. Phys.*, **36,** 25.

de la Reza, R. & Müller, E. A., 1975. *Sol. Phys.*, **43,** 15.

Delbouille, L., Neven, L. & Roland, D., 1973. *Photometric atlas of the solar spectrum from λ3000 to λ10 000*, Université de Liège.

Ellis, P. G. & Goscinski, D., 1974. *Phys. Scripta*, 9, 104.

Emmoth, B., Braun, M., Bromander, J. & Martinson, I., 1975. *Phys. Scripta*, **12,** 75.

Erdmann, T. A., Figger, H. & Walther, H., 1972. *Opt. Comm.*, **6,** 166.

Eriksson, K. B. S., 1973. *J. opt. Soc. Am.*, **63,** 631L.

Erman, P., 1975. *Phys. Scripta*, **11,** 65.

Erman, P., Brzozowski, J. & Smith, W. H., 1974. *Astrophys. J.*, **192,** 59.

Fillipov, A. N., 1933. *Z. eksper. teor. Fiz.*, **3,** 520.

Foster, E. W., 1967. *Proc. phys. Soc.*, A90, 275.

Froese-Fischer, C., 1968. *Astrophys. J.*, 151, 759.

Froese-Fischer, C., 1975. *Can. J. Phys.*, **53,** 184 and 338.

Furcinitti, P. S., Baling, L. C. & Wright, J. J., 1975. *Phys. Lett. A*, **53,** 75.

Gallagher, A., 1967. *Phys. Rev.*, 157, 24.

Gallagher, T. F., Edelstein, S. A.. & Hill, R. M., 1975. *Phys. Rev. A*, 11, 1504.

Gallagher, T. F., Edelstein, S. A. & Hill, R. M., 1976. *Phys. Rev.*, **157,** 24.

Garz, T., 1973. *Astr. Astrophys.*, **26,** 471.

Gehren, T., 1975. *Astr. Astrophys.*, **38,** 289.

Gingerich, O., Noyes, R. W., Kalkofen, W. & Cuny, Y., 1971. *Sol. Phys.*, **18,** 347.

Giusfredi, G., Minguzzi, P., Strumia, F. & Tonelli, M., 1975. *Z. Phys. A*, **274,** 279.

Goldberg, L., Müller, E. A. & Aller, L. H., 1960. *Astrophys. J. Suppl.*, **5,** 1.

Gornik, W., Kaiser, D., Lange, W., Luther, J., Meier, K., Radloff, H.-H. & Schulz, H.-H., 1973. *Phys. Lett. A*, **45,** 219.

Grevesse, N. & Sauval, J., 1970. *Astr. Astrophys.*, **9,** 232.

Grevesse, N. & Sauval, J., 1971. *J. quant. Spectr. rad. Trans.*, **11,** 65.

Grevesse, N. & Swings, J. P., 1972. *Astrophys. J.*, 171, 179.

Hall, D. N. B., 1972. *An atlas of infrared spectra of the solar photosphere and of sunspot umbrae*, Kitt Peak National Observatory.

Harvey, K. C., Hawkins, R. T., Meisel, G. & Schaulow, A. L., 1975. *Phys. Rev. Lett.*, 34, 1073.

Havey, M. D., Balling, L. C. & Wright, J. J., 1977. *J. opt. Soc. Am.*, 67, 488.

Holweger, H., 1971. *Astr. Astrophys.*, **10,** 128.

Holweger, H., 1972. *Sol. Phys.*, **25,** 14.

Holweger, H., 1973. *Astr. Astrophys.*, **26,** 275.

Holweger, H., 1977. *Earth planet. Sci. Lett.*, in press.

Holweger, H. & Müller, E. A., 1974. *Sol. Phys.*, **39,** 19.

Kaiser, D., 1975. *Phys. Lett. A*, **51,** 375.

Kernahan, J. A. & Pang, P. H.-L., 1975. *Can. J. Phys.*, **53,** 1114.

Lambert, D. L., 1978. *Mon. Not. R. astr. Soc.*, **182,** 294.

Lambert, D. L. & Mallia, E. A., 1969. *Sol. Phys.*, **10,** 311.

Lambert, D. L. & Mallia, E. A., 1970. *Mon. Not. R. astr. Soc.*, **148,** 313.

Lambert, D. L. & Warner, B., 1968a. *Mon. Not. R. astr. Soc.*, **138,** 181.

Lambert, D. L. & Warner, B., 1968b. *Mon. Not. R. astr. Soc.*, **140,** 197.

Lambert, D. L. & Warner, B., 1968c. *Mon. Not. R. astr. Soc.*, **138,** 213.

Lewis, E. L., McNamara, L. F. & Michels, H. H., 1971. *Phys. Rev. A*, **3,** 1939.

Lewis, E. L., McNamara, L. F. & Michels, H. H., 1972. *Sol. Phys.*, **23,** 287.

Lincke, R. & Ziegenbein, B., 1971. *Z. Phys.*, **241,** 369.

Link, J. K., 1966. *J. opt. Soc. Am.*, **56,** 1195.

Lundin, L., Engman, B., Hilke, J. & Martinson, I., 1973. *Phys. Scripta,* **8,** 274.
Lwin, N., McCartan, D. G. & Lewis, E. L., 1976. *J. Phys. B,* **9,** L161.
Marek, J. & Richter, J., 1973. *Astr. Astrophys.,* **26,** 155.
Mashinskii, A. L. & Chaika, M. P., 1970. *Opt. Spectr.,* **28,** 589.
Mason, B., 1971. *Handbook of elemental abundances in meteorites,* Gordon and Breach, New York.
Migdalek, J., 1976. *J. quant. Spectr. rad. Trans.,* **16,** 265.
Miller, M. H., Wilkerson, T. D., Roig, R. A. & Bengston, R. D., 1974. *Phys. Rev. A,* **9,** 2312.
Mitchell, C. J., 1975. *J. Phys. B,* **8,** 25.
Moore, C. E., 1967. *Selected tables of atomic spectra: Si I,* NSRDS-NBSB, Section 2.
Ney, J., 1969. *Z. Phys.,* **223,** 126.
Norcross, D. W., 1971. *J. Phys. B,* **4,** 1458.
Olsen, K. H., Routly, P. M. & King, R. B., 1959. *Astrophys. J.,* **130,** 688.
Ostrovskii, Y. I. & Penkin, N. P., 1961. *Opt. Spectr.,* **10,** 219.
Parkinson, W. H., Reeves, E. M. & Tomkins, F. W., 1976. *J. Phys. B,* **9,** 157.
Rambow, F. H. K. & Schearer, L. D., 1976. *Phys. Rev. A,* **14,** 1735.
Ross, J. E. & Aller, L. H., 1976. *Science,* **191,** 1223.
Sauval, J., 1969. *Sol. Phys.,* **10,** 319.
Schmeider, R. W., Lurio, A. & Happer, W., 1968. *Phys. Rev.,* **173,** 76.
Schmeider, R. W., Lurio, A., Happer, W. & Khadjavi, A., 1970. *Phys. Rev. A,* **2,** 1216.
Schorn, R. A., Young, A. T. & Barker, E. S., 1975. *Sol. Phys.,* **43,** 9.
Schulz-Gulde, E., 1968. *J. quant. Spectr. rad. Trans.,* **9,** 13.
Schulz-Gulde, E., 1971. *Z. Phys.,* **245,** 308.
Smith, W. W. & Gallagher, A., 1966. *Phys. Rev. D,* **145,** 26.
Smith, G. & O'Neill, J., 1975. *Astr. Astrophys.,* **38,** 1.
Stephenson, G., 1951. *Proc. phys. Soc. A,* **64,** 458.
Stuck, H. L. & Zimmerman, P., 1970. *Z. Phys.,* **239,** 345.
Svanberg, S., 1971. *Phys. Scr.,* **4,** 275.
Swings, J. P., Lambert, D. L. & Grevesse, N., 1969. *Sol. Phys.,* **6,** 3.
Vernazza, J. E., Avrett, E. H. & Loeser, R., 1976. *Astrophys. J. Suppl.,* **30,** 1.
Victor, G. A., Stewart, R. F. & Laughlin, C., 1976. *Astrophys. J. Suppl.,* **31,** 237.
Waddell, J. H., 1962. *Astrophys. J.,* **136,** 223.
Warner, B., 1968a. *Mon. Not. R. astr. Soc.,* **139,** 217.
Warner, B., 1968b. *Mon. Not. R. astr Soc.,* **139,** 103.
Warner, B., 1968c. *Mon. Not. R. astr. Soc.,* **139,** 1.
Weisheit, J. C., 1972. *Phys. Rev. A,* **5,** 1621.
Wiese, W. L., Smith, M. W. & Miles, B. M., 1969. *Atomic transition probabilities,* vol. 2, NSRDS-NBS 22, Government Printing Office, Washington DC.
Worrall, G., 1973. *Astr. Astrophys.,* **29,** 37.
Zimmermann, D., 1975. *Z. Phys. A,* **275,** 5.