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Abundances of the elements: Meteoritic and solar

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Abstract—New abundance tables have been compiled for C1 chondrites and the solar photosphere and corona, based on a critical review of the literature to mid-1988. The meteorite data are generally accurate to ±5–10%. Significant discrepancies between Sun and meteorites occur only for Fe, Mn, Ge, Pb, and W; other well-determined elements agree to ±9% on the average. There is no evidence for group fractionations in C1 chondrites of cosmochemically similar elements (refractories, siderophiles, volatiles, etc.), but a selective fractionation of Fe cannot be ruled out. Abundances of odd-A nuclides between A = 65 and 209 show a generally smooth trend, with elemental abundances conforming to the slope defined by isotopic abundances. Significant irregularities occur in the Nd-Sm-Eu region, however, suggesting that the abundance curve is dependably smooth only down to the ~20% level.

1. INTRODUCTION

THIS PAPER IS a new edition of the abundance compilations of ANDERS and EBIHARA (1982; hereafter *AE*) for meteorites and GREVESSE (1984a,b) for the solar photosphere. Although meteoritic values have changed little, many photospheric values, including those for C, N, O, have improved greatly in recent years, mainly due to the use of highly accurate transition probabilities, and thus permit a critical comparison of solar and meteoritic abundances. In addition to better data, our new abundance tables contain many small improvements, such as better coupling of solar and meteoritic scales, better isotopic abundances, etc.

Section 2 of this paper presents the new abundance tables. Sections 3 and 4 review the elements individually for meteorites and the solar photosphere, showing how the values were obtained and discussing uncertainties. Section 5 presents values for the solar corona, from spectroscopy as well as measurements of solar wind and solar energetic particles (SEP). Section 6 reviews data for noble gases. Section 7 compares photospheric, coronal, meteoritic, and cometary abundances, as well as trends in *s*-process and *r*-process nuclides.

2. ABUNDANCE OF THE ELEMENTS AND NUCLIDES

2.1. *Solar-system abundances*[1]*: Elements*

Abundances on the Si = 10^6 scale, based mainly on C1 chondrites, are given in Table 1, along with the values of *AE*. Columns 4 and 5 give the population standard deviation and the number of C1 analyses averaged. Parentheses mean that data for other meteorite classes were included, requiring a more involved procedure (Sec. 3). Columns 7 and 8 give abundances *by weight* and the number of analyses for the Orgueil meteorite. Column 6 gives *weight* abundances for a nominal C1 chondrite of Si ≡ 10.64%, calculated from the *atomic* abundances in column 2. These values, rather than those for Orgueil, should be used whenever abundances by weight are needed (*e.g.*, for normalization to C1 chondrites), as they are fully consistent with the atomic abundances in Column 2 (except for the incompletely condensed elements H, C, N, O and the noble gases).

Comparison with previous data. All together, the values for 61 elements have been reevaluated since 1982 (Fig. 1), but in only one case did the change exceed 20% (Hg) or one standard deviation (Hf). Apparently meteorite analyses have converged to the point where most elements are known to better than 10%. This seems to be true even for elements estimated indirectly from other meteorite classes. These indirect estimates by *AE* were confirmed in all four cases (B, Nb, Ta, W) where they were checked by direct analyses on C1's.

Mass fractions (X, Y, Z). From the abundances in Table 1, we have calculated mass fractions of H, He, and heavier elements (usually referred to as X, Y, Z in the astronomical literature). The values (%) are given below, with an alternative set for the solar Fe value (log Fe = 7.67) in parentheses. The uncertainties are conservative estimates, calculated by varying the individual elements within their error limits.

$$X\,(\mathrm{H}) = 70.683\ (70.643) \pm 2.5\%$$

$$Y\,(\mathrm{He}) = 27.431\ (27.416) \pm 6\%$$

$$Z\,(\mathrm{Li\text{-}U}) = 1.886\ (1.941) \pm 8.5\%$$

The mass fraction of Si (for log Fe = 7.51) is 0.0698891%. With this value, it is easy to calculate from Table 1 mass fractions of various condensates or element groups.

2.2. *Solar abundances*

Table 2 gives solar photospheric abundances on the usual logarithmic ("dex") scale relative to hydrogen [$A_{El} = \log(N_{El}/$

[1] A few definitions. *Solar-system* abundances (formerly known as *cosmic* abundances) are best estimates for the entire solar system. They are based on meteorites except for H, C, N, O and noble gases, where solar and other astronomical data were used. *Solar* abundances are best estimates for the Sun. They are based mainly on photospheric data, augmented as needed by solar wind, SEP, or other astronomical (but not meteoritic) data.

Table 1. Solar-System Abundances of the Elements, Based on Meteorites (Atoms/10^6 Si)

Element	This Work*	Anders & Ebihara (1982)*	σ (%)	N†	Mean CI Chondr.‡	Orgueil§	N
1 H	2.79×10^{10}	2.72×10^{10}		--		2.02 %	2
2 He	2.72×10^{9}	2.18×10^{9}		--		56 nL/g	
3 Li	57.1	59.7	9.2	4	1.50 ppm	1.49 ppm	3
4 Be	0.73	0.78	9.5	(8)	24.9 ppb	24.9 ppb	0
5 B	21.2	24	10	1	870 ppb	870 ppb	1
6 C	1.01×10^{7}	1.21×10^{7}		--		3.45 %	7
7 N	3.13×10^{6}	2.48×10^{6}		--		3180 ppm	4
8 O	2.38×10^{7}	2.01×10^{7}	10	--		46.4 %	4
9 F	843	843	15	7	60.7 ppm	58.2 ppm	5
10 Ne	3.44×10^{6}	3.76×10^{6}	14	--		203 pL/g	
11 Na	5.74×10^{4}	5.70×10^{4}	7.1	20	5000 ppm	4900 ppm	14
12 Mg	1.074×10^{6}	1.075×10^{6}	3.8	15	9.89 %	9.53 %	11
13 Al	8.49×10^{4}	8.49×10^{4}	3.6	19	8680 ppm	8690 ppm	13
14 Si	1.00×10^{6}	1.00×10^{6}	4.4	9	10.64 %	10.67 %	4
15 P	1.04×10^{4}	1.04×10^{4}	10	4	1220 ppm	1180 ppm	3
16 S	5.15×10^{5}	5.15×10^{5}	13	5	6.25 %	5.25 %	2
17 Cl	5240	5240	15	10	704 ppm	698 ppm	8
18 Ar	1.01×10^{5}	1.04×10^{5}	6	--		751 pL/g	7
19 K	3770	3770	7.7	29	558 ppm	566 ppm	20
20 Ca	6.11×10^{4}	6.11×10^{4}	7.1	15	9280 ppm	9020 ppm	12
21 Sc	34.2	33.8	8.6	18	5.82 ppm	5.83 ppm	12
22 Ti	2400	2400	5.0	7	436 ppm	436 ppm	7
23 V	293	295	5.1	9	56.5 ppm	56.2 ppm	7
24 Cr	1.35×10^{4}	1.34×10^{4}	7.6	13	2660 ppm	2660 ppm	9
25 Mn	9550	9510	9.6	20	1990 ppm	1980 ppm	12
26 Fe	9.00×10^{5}	9.00×10^{5}	2.7	19	19.04 %	18.51 %	14
27 Co	2250	2250	6.6	18	502 ppm	507 ppm	12
28 Ni	4.93×10^{4}	4.93×10^{4}	5.1	27	1.10 %	1.10 %	21
29 Cu	522	514	11	8	126 ppm	119 ppm	5
30 Zn	1260	1260	4.4	27	312 ppm	311 ppm	17
31 Ga	37.8	37.8	6.9	14	10.0 ppm	10.1 ppm	10
32 Ge	119	118	9.6	31	32.7 ppm	32.6 ppm	23
33 As	6.56	6.79	12	18	1.86 ppm	1.85 ppm	13
34 Se	62.1	62.1	6.4	18	18.6 ppm	18.2 ppm	11
35 Br	11.8	11.8	19	(18)	3.57 ppm	3.56 ppm	10
36 Kr	45	45.3	18	--		8.7 pL/g	7
37 Rb	7.09	7.09	6.6	19	2.30 ppm	2.30 ppm	13
38 Sr	23.5	23.8	8.1	18	7.80 ppm	7.80 ppm	15
39 Y	4.64	4.64	6.0	5	1.56 ppm	1.53 ppm	4
40 Zr	11.4	10.7	6.4	5	3.94 ppm	3.95 ppm	5
41 Nb	0.698	0.71	1.4	2	246 ppb	246 ppb	2
42 Mo	2.55	2.52	5.5	2	928 ppb	928 ppb	2
44 Ru	1.86	1.86	5.4	9	712 ppb	714 ppb	5
45 Rh	0.344	0.344	8	(7)	134 ppb	134 ppb	0
46 Pd	1.39	1.39	6.6	25	560 ppb	556 ppb	17
47 Ag	0.486	0.529	2.9	6	199 ppb	197 ppb	5
48 Cd	1.61	1.69	6.5	30	686 ppb	680 ppb	21
49 In	0.184	0.184	6.4	24	80 ppb	77.8 ppb	16
50 Sn	3.82	3.82	9.4	11	1720 ppb	1680 ppb	9
51 Sb	0.309	0.352	18	22	142 ppb	133 ppb	15
52 Te	4.81	4.91	10	17	2320 ppb	2270 ppb	12
53 I	0.90	0.90	21	(11)	433 ppb	433 ppb	0
54 Xe	4.7	4.35	20	--		8.6 pL/g	6
55 Cs	0.372	0.372	5.6	20	187 ppb	186 ppb	11
56 Ba	4.49	4.36	6.3	8	2340 ppb	2340 ppb	8
57 La	0.4460	0.448	2.0	4	234.7 ppb	236 ppb	9
58 Ce	1.136	1.16	1.7	4	603.2 ppb	619 ppb	8
59 Pr	0.1669	0.174	2.4	(20)	89.1 ppb	90 ppb	2
60 Nd	0.8279	0.836	1.3	4	452.4 ppb	463 ppb	11
62 Sm	0.2582	0.261	1.3	4	147.1 ppb	144 ppb	10
63 Eu	0.0973	0.0972	1.6	4	56.0 ppb	54.7 ppb	17
64 Gd	0.3300	0.331	1.4	4	196.6 ppb	199 ppb	7
65 Tb	0.0603	0.0589	2.2	(21)	36.3 ppb	35.3 ppb	4
66 Dy	0.3942	0.398	1.4	4	242.7 ppb	246 ppb	6
67 Ho	0.0889	0.0875	2.4	(23)	55.6 ppb	55.2 ppb	3
68 Er	0.2508	0.253	1.3	4	158.9 ppb	162 ppb	6
69 Tm	0.0378	0.0386	2.3	(20)	24.2 ppb	22 ppb	1
70 Yb	0.2479	0.243	1.6	4	162.5 ppb	166 ppb	12
71 Lu	0.0367	0.0369	1.3	4	24.3 ppb	24.5 ppb	12
72 Hf	0.154	0.176	(1.9)	(3)	104 ppb	108 ppb	3
73 Ta	0.0207	0.0226	1.8	2	14.2 ppb	14.0 ppb	1
74 W	0.133	0.137	5.1	3	92.6 ppb	92.3 ppb	3
75 Re	0.0517	0.0507	9.4	21	36.5 ppb	37.1 ppb	15
76 Os	0.675	0.717	6.3	16	486 ppb	483 ppb	12
77 Ir	0.661	0.660	6.1	36	481 ppb	474 ppb	27
78 Pt	1.34	1.37	7.4	10	990 ppb	973 ppb	9
79 Au	0.187	0.186	15	41	140 ppb	145 ppb	27
80 Hg	0.34	0.52	12	--	258 ppb	258 ppb	0
81 Tl	0.184	0.184	9.4	18	142 ppb	143 ppb	12
82 Pb	3.15	3.15	7.8	3	2470 ppb	2430 ppb	1
83 Bi	0.144	0.144	8.2	13	114 ppb	111 ppb	7
90 Th	0.0335	0.0335	5.7	9	29.4 ppb	28.6 ppb	1
92 U	0.0090	0.0090	8.4	16	8.1 ppb	8.1 ppb	7

*Abundances of Mg, S, and Fe are based on average of mean values for individual meteorites. For the remaining elements, a straight average of all acceptable analyses was used.

†Dashes indicate solar or interpolated abundances; parentheses mean that the abundance is based at least in part on meteorites of other classes. See Sec. 3.6 for explanation of the REE values.

‡The CI chondrite mean (for Si = 10.64%) is calculated from the atomic abundances in column 2, using the relation $C = 3.788 \times 10^{-3}$ HA, where C = weight concentration (ppm), H = atomic abundance, and A = atomic weight. However, these values have not been renormalized to 100%.

§Abundances of HCNO in Orgueil are from sources given in Anders & Ebihara (1982). Abundances of noble gases (in nL/g or pL/g at STP) are not for the elements but for the principal isotopes He^4, Ne^{20}, Ar^{36}, Kr^{84}, and Xe^{132} (J2; Mazor et al., 1970). As He and Ne in bulk Orgueil are derived mainly from the solar wind, the indigenous values for these two are based on ratios for NaOH-etched Orgueil silicates: $Ne^{20}/Ar^{36} = 0.27$ and $He^4/Ne^{20} = 277$ (J2).

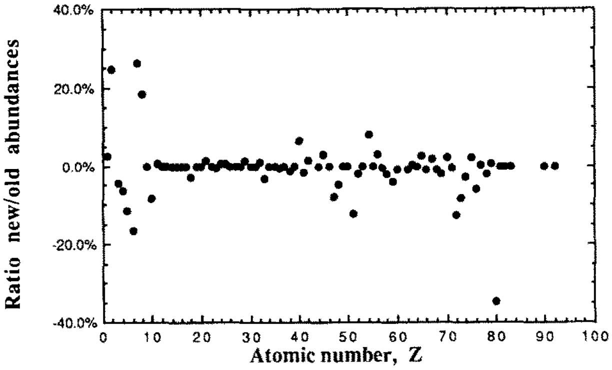

FIG. 1. Comparison of new solar-system abundances with those of ANDERS and EBIHARA (1982).

N_H) + 12.00]. Individual results are discussed in Sec. 4. For comparison, column 3 shows the meteorite-based solar-system abundances from Table 1, converted to the astronomical scale by adding 1.554 to the log of the abundance (see below). Column 4 gives the log of the ratio Sun/meteorites. The ratio itself is plotted in Fig. 2 against atomic number.

The conversion factor from the solar abundance scale (log $N_H = 12.00$) to the meteoritic scale ($N_{Si} = 10^6$) has been derived by comparing the solar-meteoritic ratio, $R \equiv \log$ (sol/met), for all elements. This comparison shows that R for well-determined elements clusters between 1.52 and 1.58, with a maximum around 1.55. We have adopted $R = 1.554 \pm 0.020$, the mean for 12 elements (Na, Mg, Si, Ca, V, Cr, Co, Ni, Y, Zr, Nb, and Mo). This ratio is very close to previous estimates by MEYER (1979), CAMERON (1982), and *AE*: 1.57 ± *0.16*, 1.576, and 1.566 ± *0.023*. The nominal uncertainty in coupling the two scales now is only ±5%.

2.3. Solar-system abundances: Nuclides

Abundances of individual nuclides are given in Table 3. For radioactive and radiogenic nuclides their abundances 4.55 AE ago are given in italics, based on half-lives from HOLDEN (1985a,b,c and priv. commun.), except for K^{40}, where the value recommended in geochronology ($1.2505 \cdot 10^9$ yr, STEIGER and JÄGER, 1977) was used.

For isotopic compositions, we generally used terrestrial rather than solar values, except for H and noble gases. Solar values are hard to measure accurately by spectroscopy, as the isotopic shifts of atomic lines are small compared to the width of photospheric lines. Only for C and O can accurate isotopic ratios be obtained, using the infrared vibration-rotation bands of CO. These values confirm the terrestrial ratios in Table 3.

Isotopic abundances generally are the terrestrial "representative isotopic compositions" recommended by IUPAC (HOLDEN *et al.*, 1984; and HOLDEN, priv. commun.). In cases where the recommended composition gave the abundance of a rare isotope to only one significant figure, we either took that value from the "best measurement from a single natural source" (Se, Os), or used the entire "best" analysis, when it appeared that the recommended composition was merely a rounded-off version of the best analysis (Zn, La, Dy). We also used the latest analyses for Ga (MACHLAN *et al.*, 1986), Sn (ROSMAN *et al.*, 1984), Sb (DELAETER and HOSIE, 1988), Te (SMITH and DELAETER, 1986), and Hg (ZADNIK *et al.*, 1989).

The IUPAC compositions are intended to represent "the chemicals and/or materials most commonly encountered in the laboratory", not necessarily "the most abundant natural material" (HOLDEN *et al.*, 1984). This makes a slight difference for light elements (Li, B, C,

Table 2. Abundances in the Solar Photosphere
(log N_H=12.00)

Element	Photosphere*	Meteorites†	Phot.–Met.*
1 **H**	12.00	[12.00]	–
2 **He**	[10.99 *±0.035*]	[10.99]	–
3 **Li**	1.16 *±0.1*	3.31 *±0.04*	−2.15
4 **Be**	1.15 *±0.10*	1.42 *±0.04*	−0.27
5 **B**	(2.6 *±0.3*)	2.88 *±0.04*	(−0.28)
6 **C**	8.56 *±0.04*	[8.56]	–
7 **N**	8.05 *±0.04*	[8.05]	–
8 **O**	8.93 *±0.035*	[8.93]	–
9 **F**	4.56 *±0.3*	4.48 *±0.06*	+0.08
10 **Ne**	[8.09 *±0.10*]	[8.09 *±0.10*]	–
11 **Na**	6.33 *±0.03*	6.31 *±0.03*	+0.02
12 **Mg**	7.58 *±0.05*	7.58 *±0.02*	0.00
13 **Al**	6.47 *±0.07*	6.48 *±0.02*	−0.01
14 **Si**	7.55 *±0.05*	7.55 *±0.02*	0.00
15 **P**	5.45 *±(0.04)*	5.57 *±0.04*	−0.12
16 **S**	7.21 *±0.06*	7.27 *±0.05*	−0.06
17 **Cl**	5.5 *±0.3*	5.27 *±0.06*	+0.23
18 **Ar**	[6.56 *±0.10*]	[6.56 *±0.10*]	–
19 **K**	5.12 *±0.13*	5.13 *±0.03*	−0.01
20 **Ca**	6.36 *±0.02*	6.34 *±0.03*	+0.02
21 **Sc**	3.10 *±(0.09)*	3.09 *±0.04*	+0.01
22 **Ti**	4.99 *±0.02*	4.93 *±0.02*	+0.06
23 **V**	4.00 *±0.02*	4.02 *±0.02*	−0.02
24 **Cr**	5.67 *±0.03*	5.68 *±0.03*	−0.01
25 **Mn**	5.39 *±0.03*	5.53 *±0.04*	−0.14
26 **Fe**	7.67 *±0.03*‡	7.51 *±0.01*	+0.16‡
27 **Co**	4.92 *±0.04*	4.91 *±0.03*	+0.01
28 **Ni**	6.25 *±0.04*	6.25 *±0.02*	0.00
29 **Cu**	4.21 *±0.04*	4.27 *±0.05*	−0.06
30 **Zn**	4.60 *±0.08*	4.65 *±0.02*	−0.05
31 **Ga**	2.88 *±(0.10)*	3.13 *±0.03*	−0.25
32 **Ge**	3.41 *±0.14*	3.63 *±0.04*	−0.22
33 **As**	–	2.37 *±0.05*	–
34 **Se**	–	3.35 *±0.03*	–
35 **Br**	–	2.63 *±0.08*	–
36 **Kr**	–	3.23 *±0.07*	–
37 **Rb**	2.60 *±(0.15)*	2.40 *±0.03*	+0.20
38 **Sr**	2.90 *±0.06*	2.93 *±0.03*	−0.03
39 **Y**	2.24 *±0.03*	2.22 *±0.02*	+0.02
40 **Zr**	2.60 *±0.03*	2.61 *±0.03*	−0.01
41 **Nb**	1.42 *±0.06*	1.40 *±0.01*	+0.02
42 **Mo**	1.92 *±0.05*	1.96 *±0.02*	−0.04
44 **Ru**	1.84 *±0.07*	1.82 *±0.02*	+0.02
45 **Rh**	1.12 *±0.12*	1.09 *±0.03*	+0.03
46 **Pd**	1.69 *±0.04*	1.70 *±0.03*	−0.01
47 **Ag**	(0.94 *±0.25*)	1.24 *±0.01*	(−0.30)
48 **Cd**	1.86 *±0.15*	1.76 *±0.03*	+0.10
49 **In**	(1.66 *±0.15*)	0.82 *±0.03*	(+0.84)
50 **Sn**	2.0 *±(0.3)*	2.14 *±0.04*	−0.14
51 **Sb**	1.0 *±(0.3)*	1.04 *±0.07*	−0.04
52 **Te**	–	2.24 *±0.04*	–
53 **I**	–	1.51 *±0.08*	–
54 **Xe**	–	2.23 *±0.08*	–
55 **Cs**	–	1.12 *±0.02*	–
56 **Ba**	2.13 *±0.05*	2.21 *±0.03*	−0.08
57 **La**	1.22 *±0.09*	1.20 *±0.01*	+0.02
58 **Ce**	1.55 *±0.20*	1.61 *±0.01*	−0.06
59 **Pr**	0.71 *±0.08*	0.78 *±0.01*	−0.07
60 **Nd**	1.50 *±0.06*	1.47 *±0.01*	+0.03
62 **Sm**	1.00 *±0.08*	0.97 *±0.01*	−0.03
63 **Eu**	0.51 *±0.08*	0.54 *±0.01*	−0.03
64 **Gd**	1.12 *±0.04*	1.07 *±0.01*	+0.05
65 **Tb**	(−0.1 *±0.3*)	0.33 *±0.01*	(−0.43)
66 **Dy**	1.1 *±0.15*	1.15 *±0.01*	−0.05
67 **Ho**	(0.26 *±0.16*)	0.50 *±0.01*	(−0.24)
68 **Er**	0.93 *±0.06*	0.95 *±0.01*	−0.02
69 **Tm**	(0.00 *±0.15*)	0.13 *±0.01*	(−0.13)
70 **Yb**	1.08 *±(0.15)*	0.95 *±0.01*	+0.13
71 **Lu**	(0.76 *±0.30*)	0.12 *±0.01*	(+0.64)
72 **Hf**	0.88 *±(0.08)*	0.73 *±0.01*	+0.15
73 **Ta**	–	0.13 *±0.01*	–
74 **W**	(1.11 *±0.15*)	0.68 *±0.02*	(+0.43)
75 **Re**	–	0.27 *±0.04*	–
76 **Os**	1.45 *±0.10*	1.38 *±0.03*	+0.07
77 **Ir**	1.35 *±(0.10)*	1.37 *±0.03*	−0.02
78 **Pt**	1.8 *±0.3*	1.68 *±0.03*	+0.12
79 **Au**	(1.01 *±0.15*)	0.83 *±0.06*	(+0.18)
80 **Hg**	–	1.09 *±0.05*	–
81 **Tl**	(0.9 *±0.2*)	0.82 *±0.04*	(+0.08)
82 **Pb**	1.85 *±0.05*	2.05 *±0.03*	−0.20
83 **Bi**		0.71 *±0.03*	–
90 **Th**	0.12 *±(0.06)*	0.08 *±0.02*	+0.04
92 **U**	(< −0.47)	−0.49 *±0.04*	–

*Values in parentheses are uncertain.
†Values in brackets are based on solar or other astronomical data.
‡See text (Sec. 4.3).

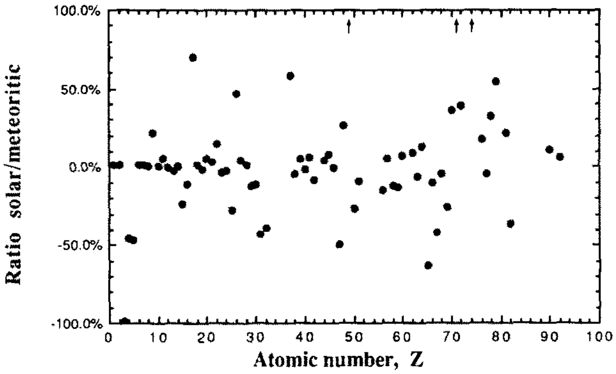

FIG. 2. Comparison of solar-system ("meteoritic") and photospheric abundances.

O) and for elements with small radiogenic components (Sr, Nd, Hf, Os). It makes a much larger difference for elements that are strongly depleted in the Earth (H, N, noble gases) or are largely radiogenic (Pb). For the first group, we have retained the IUPAC compositions, in the expectation that any reader concerned about these small differences will consult the references cited by HOLDEN *et al.* (1984) and papers on isotope geology. Our choices for the second group are discussed below.

For *hydrogen,* we recomputed the protosolar D/H ratio (GEISS and BOCHSLER, 1981) for our He/H ratio, again using the difference between He^3/He^4 in solar wind, (4.9 ± *0.5*)·10^{-4} (COPLAN *et al.*, 1984; BOCHSLER, 1987) and in meteoritic "planetary" He (1.42 ± *0.2*)·10^{-4} (REYNOLDS *et al.*, 1978; JEFFERY and ANDERS, 1970). The resulting protosolar D/H—(3.4 ± *1.0*)·10^{-5}—is somewhat larger than the previous value of 2·10^{-5} (GEISS and BOCHSLER, 1981), but agrees with the results for Jupiter and Saturn (GAUTIER, 1983; OWEN *et al.*, 1986). It is larger, though, than the latest value for the interstellar medium, $0.8 \leq D/H \leq 2 \cdot 10^{-5}$ (BOESGAARD and STEIGMAN, 1985). For an error analysis, see GEISS and BOCHSLER (1981).

For *nitrogen,* it is difficult to find a truly representative value, as trapped (mainly solar-wind) nitrogen in lunar soils shows a ~35% increase in N^{15}/N^{14} during the last 2.5·10^9 yr (KERRIDGE, 1980; CLAYTON and THIEMENS, 1980; GEISS and BOCHSLER, 1982). We have adopted the terrestrial atmospheric ratio, as it falls within the solar-wind range. For *lead,* we have used the most accurate analysis for Orgueil (TATSUMOTO *et al.*, 1976).

For *noble gases,* we used mainly solar-wind values. However, for He^3/He^4, we again used 1.42·10^{-4}, the ratio in "planetary" He, since the solar ratio has been raised by deuterium burning. The situation for Ne^{20}/Ne^{22} is quite complex as this ratio varies widely: *present solar wind* in Al-foils = 13.7 ± *0.3* (GEISS, 1973); *older solar wind* in lunar soils = 13.3 ± *0.1* (WIELER *et al.*, 1986); *low-energy SEP* in lunar soils = 11.3 ± *0.3* (WIELER *et al.*, 1986) and in meteorites = 10.6 ± *0.3* (BLACK, 1972); *high-energy SEP* = 7.7 (*+2.3, −1.5*) or 9.2 (*+1.9, −1.8*) (DIETRICH and SIMPSON, 1979; MEWALDT *et al.*, 1984), which becomes 7.6 (*+1.7, −1.5*) after correction for *Q/M*-dependent fractionation (MEWALDT and STONE, 1987), or various kinds of *"planetary" Ne in meteorites:* Ne-*A*1 or -*A*2 = 8.4–8.9 (TANG and ANDERS, 1988) and *Q*-Ne = 10.1–10.6 (ANDERS, 1988). Much of the planetary Ne is associated with isotopically anomalous Ar, Kr, Xe (ANDERS, 1988) and thus is not a good candidate for primordial solar-system Ne. This leaves SEP-Ne or solar-wind Ne. The latter seems more appropriate, as its lower energy makes isotopic fractionations less likely (GEISS, 1973). Indeed, its isotopic composition is less variable than that of SEP's, as shown by a comparison of *present-day* measurements with

Table 3. Abundance of the Nuclides (Atoms/10^6 Si)

Element	A	Atom Percent	Process*	Abund.†
1 H	1	99.9966		2.79×10^{10}
	2	0.0034	U	9.49×10^{5}
2 He	3	0.0142	U,h?	3.86×10^{5}
	4	99.9858	U,h	2.72×10^{9}
3 Li	6	7.5	X	4.28
	7	92.5	U,x,h	52.82
4 Be	9	100	X	0.73
5 B	10	19.9	X	4.22
	11	80.1	X	16.98
6 C	12	98.90	He	9.99×10^{6}
	13	1.10	H,N	1.11×10^{5}
7 N	14	99.634	H	3.12×10^{6}
	15	0.366	H,N	1.15×10^{4}
8 O	16	99.762	He	2.37×10^{7}
	17	0.038	N,H	9.04×10^{3}
	18	0.200	He,N	4.76×10^{4}
9 F	19	100	N	843
10 Ne	20	92.99	C	3.20×10^{6}
	21	0.226	C,Ex	7.77×10^{3}
	22	6.79	He,N	2.34×10^{5}
11 Na	23	100	CNeEx	5.74×10^{4}
12 Mg	24	78.99	N,Ex	8.48×10^{5}
	25	10.00	NeExC	1.07×10^{5}
	26	11.01	NeExC	1.18×10^{5}
13 Al	27	100	Ne,Ex	8.49×10^{4}
14 Si	28	92.23	O,Ex	9.22×10^{5}
	29	4.67	Ne,Ex	4.67×10^{4}
	30	3.10	Ne,Ex	3.10×10^{4}
15 P	31	100	Ne,Ex	1.04×10^{4}
16 S	32	95.02	O,Ex	4.89×10^{5}
	33	0.75	Ex	3.86×10^{3}
	34	4.21	O,Ex	2.17×10^{4}
	36	0.02	Ex,Ne,S	1.03×10^{2}
17 Cl	35	75.77	Ex	2860
	37	24.23	Ex,C,S	913
18 Ar	36	84.2	Ex	8.50×10^{4}
	38	15.8	O,Ex	1.60×10^{4}
	40		S,Ne	26
	40			*25±14*
19 K	39	93.2581	Ex	3516
	40	0.01167	S,Ex,Ne	0.440
	40			*5.48*
	41	6.7302	Ex	253.7
20 Ca	40	96.941	Ex	5.92×10^{4}
	42	0.647	Ex,O	395
	43	0.135	Ex,C,S	82.5
	44	2.086	Ex,S	1275
	46	0.004	ExCNe	2.4
	48	0.187	E,Ex	114
21 Sc	45	100	ExNeE	34.2
22 Ti	46	8.0	Ex	192
	47	7.3	Ex	175
	48	73.8	Ex	1771
	49	5.5	Ex	132
	50	5.4	E	130
23 V	50	0.250	Ex,E	0.732
	51	99.750	Ex	292
24 Cr	50	4.345	Ex	587
	52	83.789	Ex	1.131×10^{4}
	53	9.501	Ex	1283
	54	2.365	E	319
25 Mn	55	100	Ex,E	9550
26 Fe	54	5.8	Ex	5.22×10^{4}
	56	91.72	Ex,E	8.25×10^{5}
	57	2.2	E,Ex	1.98×10^{4}
	58	0.28	He,E,C	2.52×10^{3}
27 Co	59	100	E,C	2250
28 Ni	58	68.27	E,Ex	3.37×10^{4}
	60	26.10	E	1.29×10^{4}
	61	1.13	E,Ex,C	557
	62	3.59	E,Ex,O	1770
	64	0.91	Ex	449
29 Cu	63	69.17	Ex,C	361
	65	30.83	Ex	161
30 Zn	64	48.63	Ex,E	613
	66	27.90	E	352
	67	4.10	E,S	51.7
	68	18.75	E,S	236
	70	0.62	E,S	7.8
31 Ga	69	60.108	S,e,r	22.7
	71	39.892	S,e,r	15.1
32 Ge	70	20.5	S,e	24.4
	72	27.4	S,e,r	32.6
	73	7.8	e,s,r	9.28
	74	36.5	e,s,r	43.4
	76	7.8	E	9.28
33 As	75	100	R,s	6.56
34 Se	74	0.88	P	0.55
	76	9.0	S,p	5.6
	77	7.6	R,s	4.7
	78	23.6	R,s	14.7
	80	49.7	R,s	30.9
	82	9.2	R	5.7
35 Br	79	50.69	R,s	5.98
	81	49.31	R,s	5.82
36 Kr	78	0.339	P	0.153
	80	2.22	S,p	0.999
	82	11.45	S	5.15
	83	11.47	R,s	5.16
	84	57.11	R,S	25.70
	86	17.42	S,r	7.84
37 Rb	85	72.165	R,s	5.12
	87	27.835	S	1.97
	87			*2.11*
38 Sr	84	0.56	P	0.132
	86	9.86	S	2.32
	87	7.00	S	1.64
	87			*1.51*
	88	82.58	S,r	19.41
39 Y	89	100	S	4.64
40 Zr	90	51.45	S	5.87
	91	11.22	S	1.28
	92	17.15	S	1.96
	94	17.38	S	1.98
	96	2.80	R	0.320
41 Nb	93	100	S	0.698
42 Mo	92	14.84	P	0.378
	94	9.25	P	0.236
	95	15.92	R,s	0.406
	96	16.68	S	0.425
	97	9.55	R,s	0.244
	98	24.13	R,s	0.615
	100	9.63	R	0.246
44 Ru	96	5.52	P	0.103
	98	1.88	P	0.0350
	99	12.7	R,s	0.236
	100	12.6	S	0.234
	101	17.0	R,s	0.316
	102	31.6	R,S	0.588
	104	18.7	R	0.348
45 Rh	103	100	R,s	0.344
46 Pd	102	1.020	P	0.0142
	104	11.14	S	0.155
	105	22.33	R,s	0.310
	106	27.33	R,S	0.380
	108	26.46	R,S	0.368
	110	11.72	R	0.163
47 Ag	107	51.839	R,s	0.252
	109	48.161	R,s	0.234
48 Cd	106	1.25	P	0.0201
	108	0.89	P	0.0143
	110	12.49	S	0.201
	111	12.80	R,S	0.206
	112	24.13	S,R	0.388
	113	12.22	R,S	0.197
	114	28.73	S,R	0.463
	116	7.49	R	0.121
49 In	113	4.3	p,s,r	0.0079
	115	95.7	R,S	0.176
50 Sn	112	0.973	P	0.0372
	114	0.659	P,s	0.0252
	115	0.339	p,s,r	0.0129
	116	14.538	S,r	0.555
	117	7.672	R,S	0.293
	118	24.217	S,r	0.925
	119	8.587	S,R	0.328
	120	32.596	S,R	1.245
	122	4.632	R	0.177
	124	5.787	R	0.221
51 Sb	121	57.362	R,s	0.177
	123	42.638	R	0.132
52 Te	120	0.09	P	0.0043
	122	2.57	S	0.124
	123	0.89	S	0.0428
	124	4.76	S	0.229
	125	7.10	R,s	0.342
	126	18.89	R,S	0.909
	128	31.73	R	1.526
	130	33.97	R	1.634
53 I	127	100	R	0.90
54 Xe	124	0.121	P	0.00571
	126	0.108	P	0.00509
	128	2.19	S	0.103
	129	27.34	R	1.28
	130	4.35	S	0.205
	131	21.69	R	1.02
	132	26.50	R,s	1.24
	134	9.76	R	0.459
	136	7.94	R	0.373
55 Cs	133	100	R,s	0.372
56 Ba	130	0.106	P	0.00476
	132	0.101	P	0.00453
	134	2.417	S	0.109
	135	6.592	R,s	0.296
	136	7.854	S	0.353
	137	11.23	S,r	0.504
	138	71.70	S	3.22
57 La	138	0.089	P	0.000397
	138			*0.000409*
	139	99.911	S,r	0.446
58 Ce	136	0.19	P	0.00216
	138	0.25	P	0.00284
	138			*0.00283*
	140	88.48	S,r	1.005
	142	11.08	R	0.126
59 Pr	141	100	R,S	0.167
60 Nd	142	27.13	S	0.225
	143	12.18	R,S	0.101
	143			*0.100*
	144	23.80	S,R	0.197
	145	8.30	R,s	0.0687
	146	17.19	R,S	0.142
	148	5.76	R	0.0477
	150	5.64	R	0.0467
62 Sm	144	3.1	P	0.00800
	147	15.0	R,s	0.0387
	147			*0.0399*
	148	11.3	S	0.0292
	149	13.8	R,S	0.0356
	150	7.4	S	0.0191
	152	26.7	R,S	0.0689
	154	22.7	R	0.0586
63 Eu	151	47.8	R,s	0.0465
	153	52.2	R,s	0.0508
64 Gd	152	0.20	P,s	0.00066
	154	2.18	S	0.00719
	155	14.80	R,s	0.0488
	156	20.47	R,s	0.0676
	157	15.65	R,s	0.0516
	158	24.84	R,s	0.0820
	160	21.86	R	0.0721
65 Tb	159	100	R	0.0603
66 Dy	156	0.056	P	0.000221
	158	0.096	P	0.000378
	160	2.34	S	0.00922
	161	18.91	R	0.0745
	162	25.51	R,s	0.101
	163	24.90	R	0.0982
	164	28.19	R,S	0.111
67 Ho	165	100	R	0.0889
68 Er	162	0.14	P	0.000351
	164	1.61	P,S	0.00404
	166	33.6	R,s	0.0843
	167	22.95	R	0.0576
	168	26.8	R,S	0.0672
	170	14.9	R	0.0374
69 Tm	169	100	R,s	0.0378
70 Yb	168	0.13	P	0.000322
	170	3.05	S	0.00756
	171	14.3	R,s	0.0354
	172	21.9	R,S	0.0543
	173	16.12	R,s	0.0400
	174	31.8	S,R	0.0788
	176	12.7	R	0.0315
71 Lu	175	97.41	R,s	0.0357
	176	2.59	S	0.000951
	176			*0.001035*
72 Hf	174	0.162	P	0.000249
	176	5.206	S	0.00802
	176			*0.00793*
	177	18.606	R,s	0.0287
	178	27.297	R,S	0.0420
	179	13.629	R,s	0.0210
	180	35.100	S,R	0.0541
73 Ta	180	0.012	p,s,r	2.48×10^{-6}
	181	99.988	R,S	0.0207
74 W	180	0.13	P	0.000173
	182	26.3	R,s	0.0350
	183	14.3	R,s	0.0190
	184	30.67	R,s	0.0408
	186	28.6	R	0.0380
75 Re	185	37.40	R,s	0.0193
	187	62.60	R	0.0324
	187			*0.0351*
76 Os	184	0.018	P	0.000122
	186	1.58	S	0.0107
	187	1.6	S	0.0108
	187			*0.00807*
	188	13.3	R,s	0.0898
	189	16.1	R	0.109
	190	26.4	R	0.178
	192	41.0	R	0.277
77 Ir	191	37.3	R	0.247
	193	62.7	R	0.414
78 Pt	190	0.0127	P	0.000170
	192	0.78	S	0.0105
	194	32.9	R	0.441
	195	33.8	R	0.453
	196	25.2	R	0.338
	198	7.19	R	0.0963
79 Au	197	100	R	0.187
80 Hg	196	0.1534	P	0.00052
	198	9.968	S	0.0339
	199	16.873	R,S	0.0574
	200	23.096	S,r	0.0785
	201	13.181	S,r	0.0448
	202	29.863	S,r	0.1015
	204	6.865	R	0.0233
81 Tl	203	29.524	R,S	0.0543
	205	70.476	S,R	0.1297
82 Pb	204	1.94	S	0.0611
	206	19.12	R,S	0.602
	206			*0.593*
	207	20.62	R,S	0.650
	207			*0.644*
	208	58.31	R,s	1.837
	208			*1.828*
83 Bi	209	100	R,s	0.144
90 Th	232	100	RA	0.0335
	232			*0.0420*
92 U	235	0.7200	RA	6.48×10^{-5}
	235			*0.00573*
	238	99.2745	RA	0.00893
	238			*0.0181*

*Assignments to nucleosynthetic processes are from Cameron (1982), Schramm (private communication, 1982), Walter et al. (1986), Woosley and Hoffman (1986, 1989), and Beer and Penzhorn (1987). Processes are listed in the order of importance, with minor processes (10-30% for r- and s-processes) shown in lower case. See above references for details.

- U = cosmological nucleosynthesis
- H = hydrogen burning
- N = hot or explosive hydrogen burning
- He = helium burning
- C = carbon burning
- O = oxygen burning
- Ne = neon burning
- Ex = explosive nucleosynthesis
- E = nuclear statistical equilibrium
- S = s-process
- R = r-process
- RA = r-process producing actinides
- P = p-process
- X = cosmic-ray spallation

†Italicized values refer to abundances 4.55×10^{9} yr ago.

long-term averages in lunar soils; +3 ± *2*% for solar wind, −33 ± 15% for SEP.

The Ar^{36}/Ar^{38} ratio is virtually the same in solar wind and in the Earth's atmosphere, which makes the choice easy. For Ar^{40}, we have used the lowest Ar^{40}/Ar^{36} ratio observed in meteorites, (2.9 ± *1.7*) · 10^{-4} in an 1850°C fraction from the Dyalpur ureilite (GÖBEL *et al.*, 1978), which leads to Ar^{40} = 25 ± *14*. Part or all of this Ar^{40} could be radiogenic, but since the observed amount is only 5 · 10^{-5} that expected from *in situ* decay of K^{40} in 4.55 AE (recalculated from BEGEMANN and OTT, 1983), it seems that radiogenic Ar^{40} was very efficiently removed in the measurement of GÖBEL *et al.* (1978). Indeed, the observed value is remarkably close to the range predicted by *s*-process calculations, 24 ± *7* to 7 ± *2* for unpulsed or pulsed *s*-processes (BEER and PENZHORN, 1987, MACKLIN *et al.*, 1989). We have therefore assumed that the Dyalpur fraction was nearly pure primordial Ar as of 4.55 AE ago, with only a negligible contribution of Ar^{40} from K^{40} decay.

For Kr and Xe, we used solar-wind compositions selected by GEISS and BOCHSLER (1985).

3. REVIEW OF METEORITIC ABUNDANCES

In this section we discuss the abundances of individual elements in Table 1, using the Si ≡ 10^6 scale. After briefly explaining our methodology, we review the elements by increasing atomic number, omitting those for which no new data have become available since *AE*. *Only new (or previously omitted) references are given, even though the revised abundances generally include all the earlier data from AE.*

Methodology. We closely followed the procedure of *AE*. For each element, we first tabulated all published values for each meteorite, omitting only repeat publications or data obtained by obviously inaccurate methods. We then converted the data to atomic abundances, rejected obvious outliers, and calculated the mean for each meteorite. Replicates were generally counted as separate analyses except when they seemed less accurate than the data by other authors; in such cases only their mean was used. As in *AE*, papers that contained no usable data generally are not cited at all.

For the normalization to Si, we used the author's own Si value if Si was determined on the same sample. In all other cases, we used wet-chemical values: Orgueil 10.64%, Ivuna 10.60%, Alais 9.71% (WIIK, 1969), Tonk 10.47% (CHRISTIE, 1914, cited by MASON, 1963). Generally we averaged all analyses (= "analysis mean"), thus effectively giving greatest weight to the frequently analyzed Orgueil. But for a few elements that showed systematic differences among meteorites (Mg, Si, S, and Fe), we averaged the means for each meteorite, thus giving unit weight to each (= "meteorite mean").

One limit to analytical accuracy that has not been generally recognized is the variable water content of C1 chondrites. These meteorites contain about 8% of loosely bound water, which is lost at low relative humidities due to the transformation of $MgSO_4 \cdot 7\ H_2O$ to the tetra- or (less often) monohydrate. Very few analysts specify their sample drying procedure, and most published data thus have an indeterminate error of 3 to 4% on top of the analytical error.

References. As in *AE*, we use an *abbreviated code for references to analytical data, consisting of the first letter of the senior author's surname and a number.* These references are numbered consecutively with those in *AE*, picking up where *AE* left off.

3.1. Li, Be, B

Lithium (K5). The 7 NAA analyses of *M14* were not used as they showed up to two-fold differences between fragments and bulk samples. If included they would have lowered Li from 57.1 to 53.0.

Beryllium (S1, V2). The atomic absorption values of *V2* are only 15% lower than the (γ, 2αn) data of *Q1*, and 10% lower than the colorimetric values of *S1*, which were previously rejected. Although the data of *Q1* should be superior since they were based on large samples and a highly specific nuclear method, the differences were small, and we have therefore retained all three sets. None of the samples were C1's, and the data were therefore corrected by fractionation factors for refractories (*K1*): 1.11 for C2 and C3O, 1.33 for C3V (see Sec. 7.3, however).

Boron (C11). The latest measurements by Curtis and Gladney (*C11*) give an abundance of 21.1 ± *2* for Orgueil, close to the indirect value of 24 ± *7* of *AE*. The latter value had been derived from the data of *C6* (mainly ordinary chondrites) by applying corrections for chondrule content, on the assumption that boron is moderately volatile and hence depleted in chondrules. The data for C2, 3 chondrites when similarly corrected show even better agreement with the new Orgueil value:

8 C2, 3 chondrites (*C11*):	18.5 ± *3.3*
21 C2, 3 chondrites (*C11*, *C6*):	20.1 ± *3.4*.

There is little to choose among these various estimates, but following *C11*, we adopt the new Orgueil value.

3.2. F, Na, Mg, Al, Si, P, S, Cl

Sodium (G13).
Magnesium (G14).
Aluminum (G14). The scatter of the data of *K1* was reduced by using their Al/Mg ratios rather than Al concentrations and converting them to Al/Si ratios via the Mg/Si ratio from Table 1.

Silicon (M2). The 1912 analysis of Tonk by Christie (*M2*) has been reinstated, as it looks pretty good except for low Mg, Cr and high alkalis. The mean Si content for the 4 C1 chondrites then becomes 10.38 ± *0.45*%. This has no effect on the Si = 10^6 normalization or the Si value (10.64%) for a "nominal" C1 chondrite, which is used to convert atomic abundances back to weight abundances in Table 1.

3.3. K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni

Potassium (B6).
Calcium. The Ca and Al values from Table 1 give a Ca/Al (weight) ratio of 1.07, slightly below the empirical mean of ~1.08 shown by most meteorite classes (AHRENS, 1970). However, we did not adjust our Ca value, as the difference is less than the uncertainty in the empirical mean, especially since the most recent data (*K1*) suggest slight variations in mean Ca/Al among C1–C3 chondrites, in addition to variations within the C1, C2 classes attributable to hydrothermal transport. It is not clear whether the mean C1 chondrite value is preferable to a grand average of all chondrite classes, but for consistency we have chosen the former. The difference is less than 2% in any case.

Scandium (G14, J3). Davis (1988, in preparation) has estimated indirect C1 abundances of Sc and several other refractory elements from their ratios to REE in chondrites, using a very precise set of REE abundances based mainly on isotope dilution analyses (Sec. 3.6). His value for Sc (6.066 ± *0.085* ppm) corresponds to an atomic abundance of 35.6 ± *0.5*, which is 4% higher than the value in Table 1 (but see Sec. 3.6).
Vanadium (G14).
Chromium (G14).
Manganese (G13, G14).
Cobalt (R8).
Nickel (R8, T1).

3.4. Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo

Copper (R8).
Zinc. The revised value uses individual analyses rather than means from *C8* and *K1*.

Germanium. The revised value uses individual analyses rather than means from *K1*.

Arsenic (R8). Two low values from *C7* and *H1* were reinstated, as they were consistent with the new values by *R8*.

Selenium. Data by *K1* are systematically high by ~20% compared to the remaining analyses (which agree within ±3%) and have therefore been omitted.

Rubidium (B6).

Strontium (B6, G2).

Yttrium (J3). The new average of 4.64 ± *0.28* agrees exactly with the old, but the error is smaller. Three indirect estimates give similar values: 4.79 ± *0.33* from Y/Ho of 8 C-chondrites (*J3*), 5.16 ± *0.47* from Zr/Y of C-chondrites (*J3*), or 4.52 ± 0.12 from the Y/REE ratio of 14 chondrites (DAVIS, 1988, in preparation).

Zirconium. Following (*J3*), we deleted the data of *G7*, which gave a low Zr/Hf ratio and were 23% low compared to the mean of the remaining 5 analyses, 11.4 ± *0.7*. This value also gives reasonable Zr/Hf, Zr/Y, and Zr/Ho ratios, agreeing with those for C2 and C3 chondrites (*J3*). It is somewhat disturbing, though, that C2, C3O, and C3V chondrites (*K3, J3*) give a mean Zr abundance virtually identical to the C1 value, 11.7 ± *1.0 vs.* 11.4 ± *0.7*, although *K1* have shown that these three classes are generally enriched in refractories by factors of 1.11, 1.11 and 1.33. Either these fractionations do not apply to Zr or some of the Zr data are wrong. More high-quality analyses are obviously needed for Zr and Hf.

Niobium (J3). The first measurements on a C1 chondrite (*J3*) agree very well with the earlier, indirect estimate of *AE*, 0.698 *vs.* 0.71, and with the mean value from eight C1–C3 analyses: 0.706 ± *0.038* (*J3*). Again, *J3* find no systematic difference between C1's and other C-chondrite classes.

Molybdenum (R8). The new value (*R8*) is based on a slight (~1%) upward revision of the original data of *P3*.

3.5. *Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba*

Palladium (L6). Seven new isotope dilution values by *L6* have left the mean unchanged.

Silver (L6). The six isotope dilution values by *L6* are only slightly lower than the 11 RNAA values used by *AE*, but have better precision: 0.486 ± *0.014 vs.* 0.529 ± *0.050*. We have therefore used only the data of *L6*.

Cadmium (L6).

Tin. BEER *et al.* (1988) have measured the neutron capture cross-section of Sn^{116}, and have argued from *s*-process systematics that the Sn abundance ought to be 2.95 ± *0.23* rather than 3.82 ± *0.36*. It does not seem possible to lower the meteoritic value, which is based on 11 RNAA and ID measurements from four laboratories for three meteorites. The mean of the two isotope dilution values is close to the overall mean: 3.77 ± *0.17 vs.* 3.82 ± *0.36* (as usual, errors are standard deviations of the population, not the mean).

Antimony (R8). The highly accurate metal extraction method of *R8* gave 120 and 123 ppb for Orgueil, which agrees with the 1973–1978 Chicago RNAA values (*K4, T1*) but is markedly lower than many other measurements. We therefore rejected 13 Orgueil and Ivuna values that exceeded 155 ppb (an isotope dilution value by *K3* chosen as a cutoff). For Alais, all four values were systematically high, and we therefore rejected only the highest value (209 ppb).

Tellurium (L6). The mean of nine isotope dilution values is only slightly lower than the mean of all 17 analyses: 4.69 ± *0.16 vs.* 4.81 ± *0.47*.

Iodine. The indirect value for this element, based on ratios to F, Br, In, and Cd, is only negligibly affected by the change in Cd abundance.

Cesium (B6). The new values left the mean unchanged.

Barium (B6). The values of *D2* and *D5* were deleted, as they appeared to be not independent measurements but unreferenced data from the literature.

3.6. *Rare earth elements, Hf, Ta, W, Re, Os, Ir, Pt, Au*

REE (B6, J3). We have used the pattern derived by Davis (1988, in preparation), which was obtained in the following manner:

a. Relative abundances of polyisotopic REE were found by averaging four isotope dilution analyses for C1's (*B6, N2*).

b. For each of 19 C1 chondrite patterns in the literature, the mean REE enrichment factor was calculated relative to the reference pattern from (a), rejecting outlying enrichment factors for individual REE.

c. The grand mean of these mean enrichment factors was then used to normalize the absolute level of the reference pattern. (The 1σ error of the grand mean was ±1.22%, but the individual means ranged from 0.924 to 1.129 the grand mean.)

d. Abundances of monoisotopic REE were found by normalizing literature analyses of C1 and other chondrites to the abundances of polyisotopic REE from (b), rejecting fractionated or irregular patterns. The concentrations of Sc, Y, Pr, Tb, Ho, and Tm in each meteorite were then normalized to a standard C1 by dividing them by the mean enrichment factor for polyisotopic REE in that meteorite. These C1-normalized abundances were then averaged.

The REE data in Table 1 were renormalized to Si = 10.64% from Davis' 10.57%. Errors include both the error in the pattern and that in absolute abundance. Because of this unconventional procedure, the number of analyses used for the *atomic abundances* in Table 1 requires some explanation. For polyisotopic REE, four C1 analyses were used for the relative abundances and ≤19 C1 analyses for absolute abundances. For monoisotopic REE, 20 to 23 analyses—including chondrites of other classes—were used. In contrast, the (*weight*) *abundances for Orgueil* in Table 1 were obtained by straight averaging, as usual.

Hafnium (B6). The analyses of *K3* and *S4* were rejected, as they were some 15% higher than the isotope dilution analyses of *B6* (106.1, 107.1 ppb). Even the latter values gave an atomic Lu/Hf ratio slightly below the value inferred by *B6* from isotope systematics: 0.233 *vs.* 0.243. As we did not feel justified in raising the REE, we lowered Hf from 0.159 to a compromise value of 0.154, which raised the Lu/Hf ratio to 0.238 while giving a Zr/Hf (weight) ratio of 37.9.

Tantalum (J3). The first measurements on a C1 chondrite (*J3*) gave an abundance of 0.0207, only 10% lower than the indirect value of *AE*. (*D5* had previously given a C1 value of 17 ppb, corresponding to an abundance of 0.248, but this seems to be an unreferenced value by *E6* for the Murray C2 chondrite.) Another indirect value can be obtained from the Sc/Ta ratio of 428 ± *3* in Cl and C2 chondrites (w/w; *J3*). With the Sc abundance from Table 1, it yields a Ta abundance of 0.0198, only 4% lower than the direct value.

Tungsten (R8). The mean of *W2* and two new measurements by *R8* agrees well with the indirect value of *AE*, which was based on an average of *W2* and the C2-C3 chondrite mean (corrected for fractionation): 0.133 *vs.* 0.137.

Rhenium (R8).

Osmium (R8). The new values of *R8* are near the low end of the range of previous measurements, and we have therefore rejected the highest four values used by *AE* (from *C9* and *E3*).

The Orgueil value in Table 1 of *AE* should have been given as 504 ppb, not 699 ppb. (The latter number is the abundance on the Si = 10^6 scale, $\cdot 10^3$.)

Iridium (G14).

Platinum (R8). In light of the new data, the Ivuna value of *C9* was rejected (the Alais value had already been rejected by *AE*).

Gold (R8).

3.7. *Hg, Pb, Bi, Th, U*

Mercury (B7). Mercury in C1 chondrites is too variable for a reliable abundance determination, and therefore has been customarily estimated by interpolation. A better approach is to use *s*-process systematics; specifically, the near-constancy of σN. BEER and MACKLIN (1985) have obtained a value of 0.34 ± *0.04* in this manner, using measured cross-sections and the abundances of neighboring elements from *AE*. As these abundances have hardly changed (Table 1), the above value should still be valid.

Lead. The value of *AE* remains unchanged. It agrees within error limits with a theoretical estimate by BEER and MACKLIN (1985): 3.15 ± *0.25 vs.* 2.85 ± *0.19*. However, this estimate assumes no *s*-process branching at Tl^{204}; if such branching occurs, then the lead abundance will be smaller (BEER, 1988). See Sec. 7.2 for further discussion.

4. REVIEW OF SOLAR PHOTOSPHERIC ABUNDANCES

In this section, abundances are expressed on a logarithmic scale relative to log H = 12. Some of the elements in Table 2 have remained unchanged since the last critical compilations by one of us (GREVESSE, 1984a,b). We shall therefore discuss only those elements that have been redetermined since 1984.

4.1. *H, C, N, O*

These major volatiles are incompletely condensed in meteorites, and thus the Sun is the only source of their solar-system abundances (LAMBERT, 1978; SAUVAL *et al.*, 1984). Furthermore, since a fractionation process occurs in the chromosphere that depletes these elements in the corona (Sec. 5 and 7.1), only the photospheric results are reliable. For various reasons summarized by GREVESSE *et al.* (1987), the most accurate values come from a careful analysis of vibration-rotation and pure rotation lines of molecules such as CO, CH, OH, NH that are present in the solar infrared spectrum (SAUVAL *et al.*, 1988, in preparation), as obtained from space by the ATMOS-SL3 experiment (FARMER *et al.*, 1987). These new results (Tables 1 and 2) differ somewhat, for C and N, from those previously adopted by GREVESSE (1984a).

4.2. *Li*

Lithium (STEENBOCK and HOLWEGER, 1984).

4.3. *Sc, Ti, V, Cr, Mn, Fe*

Scandium (GREVESSE, 1988, in preparation).
Titanium (BLACKWELL *et al.*, 1987; GREVESSE *et al.*, 1988).
Vanadium (WHALING *et al.*, 1985; BIÉMONT *et al.*, 1988).
Chromium (BLACKWELL *et al.*, 1987).
Manganese (BOOTH *et al.*, 1984).
Iron. Updating the discussion by GREVESSE (1984a), we note that the earlier results of BLACKWELL *et al.* (1984) have been confirmed by BLACKWELL *et al.* (1986), through study of faint FeI lines of rather low excitation (≤2.6 eV) with accurately known oscillator strengths. This result, based on local thermodynamic equilibrium (LTE), is listed in Table 2. Actually, slight non-LTE effects in excitation have been discovered empirically in FeI (BLACKWELL *et al.*, 1984), TiI, CrI (BLACKWELL *et al.*, 1987), and V I (BIÉMONT *et al.*, 1988), all through the use of very high accuracy transition probabilities. These effects are taken into account in the corresponding abundances in Table 2.

A full non-LTE treatment of FeI-FeII by STEENBOCK (1985; see also HOLWEGER, 1988) shows that LTE-based abundances from FeI lines should be increased slightly (by ~0.05 dex) to allow for deviations from LTE. This would raise the abundance of Fe from 7.67 to 7.72, still farther from the meteoritic value of 7.51. A substantially lower value, 7.56 ± *0.08*, was obtained by O'MARA (priv. commun.), using transition probabilities of high-excitation Fe I lines (MILFORD *et al.*, 1988), which should be less sensitive than low excitation lines to temperature and non-LTE effects.

Similarly, results from lines of FeII (by far the dominant species) should not be affected by slight departures from LTE. Although accurate transition probabilities for good solar FeII lines are very rarely available, promising efforts to measure them have been made by WHALING (1985), MOITY (1988, priv. commun.), and PAULS (1988). The latter author obtained *gf* values for 3 FeII lines in the near infrared, which lead to $A_{Fe} = 7.63$. But a higher value, 7.68 ± *0.05*, was obtained in a reanalysis of ten forbidden Fe II lines (N. GREVESSE, unpublished work). Thus the question of the solar-iron abundance remains in a state of flux, but there is hope that full agreement will soon be reached by joint efforts of atomic physicists and astronomers.

4.4. *Ge, Pb*

Germanium (GREVESSE and MEYER, 1985).
Lead (GREVESSE and MEYER, 1985).

4.5. *Y, Zr, Nb*

Yttrium, Zirconium. The results from GREVESSE (1984a), based on data by HANNAFORD *et al.* (1982) and BIÉMONT *et al.* (1981), have been recalculated on the basis of new ionization potentials (ZrI: HACKETT *et al.*, 1986), with inclusion of a previously overlooked value for Y (GARTON *et al.*, 1973).
Niobium (HANNAFORD *et al.*, 1985).

4.6. *Nd, Sm, Gd, Er, Au, Th*

Neodymium (WARD *et al.*, 1985).
Samarium. A new analysis by BIÉMONT *et al.* (1989, in preparation), based on new, accurate lifetimes of Sm II, has removed the discrepancy between the photospheric and meteoritic values.
Gadolinium (BERGSTRÖM *et al.*, 1988).
Erbium (BIÉMONT and YOUSSEF, 1984).
Hafnium. Because the six Hf II lines used by ANDERSEN *et al.* (1976) are faint and heavily blended, the actual uncertainty of the abundance may be considerably larger than reported by these authors.
Gold. The value in Table 2 is the mean of 0.95 (YOUSSEF, 1986) and 1.08 (N. GREVESSE, unpublished data), both based on the same blended line in the UV.
Thorium. The value in Table 2 is based on a new study of the spectra of the full solar disk and its center (N. GREVESSE, unpublished data). The single Th line at 4019 Å is blended with a CoI line, the transition probability of which was determined only very recently (WHALING and LAWLER, unpublished data). With this correction, the Th value drops from 0.18 to 0.12.

5. SOLAR CORONA, SOLAR WIND, SOLAR ENERGETIC PARTICLES (SEP)

Excellent reviews are available on the problem of deriving abundances in the solar corona, either by spectroscopy or by measurement of particles originating in the solar corona, such as solar wind and SEP (MEYER, 1985a,b; GEISS, 1982; GEISS and BOCHSLER, 1985; BRENEMAN and STONE, 1985; BOCHSLER, 1987). The most recent values are given in Table 4.

Spectroscopic measurements, summarized by MEYER (1985b), are available for H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni. All converge well, but their uncertainties are rather large (~0.20 dex or even up to 0.48 dex for some elements such as He or C).

NOCI *et al.* (1988) reconsidered the abundances of C, N, O, Ne, Mg, Si and S in different regions of the solar transition zone (a coronal hole, a quiet region, and an active region). They concluded that the coronal abundances do not differ from photospheric abundances by

Table 4. Abundances in the Solar Corona[1]

Element	Spectroscopic[2]	Solar Wind[3]	S.E.P.[4]	Corona Adopted	Photosphere[5]	Corona–Phot.
1 H	11.88 ±*0.30*	11.53 ±*0.08*	–	–	≡12.00	–
2 He	(10.88 ±*0.48*)	10.13 ±*0.10*	10.14 ±*0.06*	10.14 ±*0.06*	10.99 ±*0.035*	−0.85
6 C	8.33 ±*0.48*	7.88 ±*0.02*	7.92 ±*0.04*	7.90 ±*0.06*	8.56 ±*0.04*	−0.66
7 N	7.55 ±*0.23*	7.42 ±*0.15*	7.40 ±*0.03*	7.40 ±*0.06*	8.05 ±*0.04*	−0.65
8 O	8.35 ±*0.20*	8.25 ±*0.15*	8.30 ±*0.03*	8.30 ±*0.06*	8.93 ±*0.035*	−0.63
9 F	–	–	(4.00 ±*0.30*)	(4.00 ±*0.30*)	4.56 ±*0.30*	(−0.56)
10 Ne	7.50 ±*0.20*	7.48 ±*0.05*	7.44 ±*0.04*	7.46 ±*0.06*	8.07 ±*0.18*	−0.61
11 Na	6.40 ±*0.23*	–	6.38 ±*0.04*	6.38 ±*0.06*	6.33 ±*0.03*	+0.05
12 Mg	7.53 ±*0.11*	–	7.59 ±*0.03*	7.59 ±*0.06*	7.58 ±*0.05*	+0.01
13 Al	6.40 ±*0.23*	–	6.47 ±*0.03*	6.47 ±*0.06*	6.47 ±*0.07*	0.00
14 Si	≡7.55 ±*0.11*	≡7.55 ±*0.13*	≡7.55 ±*0.03*	≡7.55 ±*0.05*	7.55 ±*0.05*	0.00
15 P	–	–	5.24 ±*0.06*	5.24 ±*0.08*	5.45 ±*0.04*	−0.21
16 S	6.89 ±*0.23*	–	6.93 ±*0.02*	6.93 ±*0.05*	7.21 ±*0.06*	−0.28
17 Cl	–	–	4.93 ±*0.14*	4.93 ±*0.14*	5.5 ±*0.3*	−0.57
18 Ar	6.28 ±*0.26*	5.85 ±*0.10*	5.93 ±*0.06*	5.89 ±*0.10*	6.58 ±*0.18*	−0.69
19 K	–	–	5.14 ±*0.17*	5.14 ±*0.17*	5.12 ±*0.13*	+0.02
20 Ca	6.43 ±*0.20*	–	6.46 ±*0.06*	6.46 ±*0.08*	6.36 ±*0.02*	+0.10
21 Sc	–	–	(4.04 ±*0.40*)	(4.04 ±*0.40*)	3.10 ±*0.09*	(+0.96)
22 Ti	–	–	5.24 ±*0.12*	5.24 ±*0.13*	4.99 ±*0.02*	+0.25
23 V	–	–	(4.23 ±*0.40*)	(4.23 ±*0.40*)	4.00 ±*0.02*	(+0.23)
24 Cr	–	–	5.81 ±*0.08*	5.81 ±*0.09*	5.67 ±*0.03*	+0.14
25 Mn	–	–	5.38 ±*0.17*	5.38 ±*0.18*	5.39 ±*0.03*	−0.01
26 Fe	7.55 ±*0.18*	7.53 ±*0.27*	7.65 ±*0.04*	7.65 ±*0.06*	7.67 ±*0.03*	−0.02
28 Ni	6.29 ±*0.23*	–	6.22 ±*0.06*	6.22 ±*0.08*	6.25 ±*0.04*	−0.03
29 Cu	–	–	(4.31 ±*0.40*)	(4.31 ±*0.40*)	4.21 ±*0.04*	(+0.10)
30 Zn	–	–	4.76 ±*0.18*	4.76 ±*0.19*	4.60 ±*0.08*	+0.16

[1]All logarithmic abundances have been normalized to the photospheric scale, with log A_{Si}≡7.55. Parenthesized values are very uncertain.
[2]Coronal spectroscopic results apply variously to the ordinary quiet corona, active regions, coronal holes, or prominences; they are taken from a review by Meyer (1985b). The hydrogen value has been slightly modified from Meyer's value, on the basis of the Si/H and Ca/H ratios derived by Veck and Parkinson (1981). The helium value is taken from prominence results (see Sec. 6.1).
[3]From a review by Bochsler (1987), except for Fe (Schmid et al., 1988).
[4]From Breneman and Stone (1985), except for He (Cook et al., 1984; McGuire et al., 1986). We quote here the SEP-values corrected for the Q/M-dependent fractionation (SEP-derived corona in Table 1 of Breneman and Stone), which, however, depend on the assumed Fe/Si ratio (Sec. 7.1).
[5]From Table 2 except for Ne and Ar, which are the local galactic values of Meyer (1985a, 1988, 1989).

more than their rather large uncertainties (0.40 dex), except for O, which is underabundant.

Solar-wind (SW) values are available for H, He, C, N, O, Ne, Si, Ar, and Fe; their uncertainties are on the order of 0.05–0.20 dex (BOCHSLER, 1987). Within their error limits, the SW data agree with spectroscopic coronal values, though the match for log He/H is hardly significant in view of the large errors (SW = -1.40 ± 0.10, corona -1.00 ± 0.48).

The data for *SEP*'s in Table 4 (BRENEMAN and STONE, 1985) cover a wider range of elements and are quite accurate (generally ±10%). Following the authors, we list values corrected for a residual charge/mass (Q/M) fractionation; the correction is small for light elements but reaches +0.10 to +0.18 dex in the iron group (Sec. 7.1).

The SEP values—even without this correction—and SW values generally agree within error limits with the spectroscopic values. We therefore took the SEP-SW mean for He, C, Ne and Ar, and SEP alone for the remaining elements as our best estimates for the outer layers of the Sun ("Corona, adopted" in Table 4). Differences between these values and photospheric ones (last column of Table 4) will be discussed in Sec. 7.1.

6. NOBLE GASES

6.1. He

Despite its high abundance and great astrophysical importance, helium is difficult to determine accurately.

In the Sun, He does not appear in the photospheric spectrum, and therefore can be determined only from prominence spectra, solar wind, solar energetic particles, or models of the solar interior. *Prominence spectra* yield very uncertain results, as the relevant physical processes are not well understood. Values of N_{He}/N_H vary from 6.5 to 16% (HIRAYAMA, 1978; MILKEY, 1978; HEASLEY and MILKEY, 1978). In the *solar wind* (BOCHSLER, 1987), helium is extremely variable, but generally N_{He}/N_H is rather low, $\sim 4 \pm 2\%$. A similar value is found for *solar energetic particles* (COOK *et al.*, 1984; MCGUIRE *et al.*, 1986). However, none of these results are reliable enough for our purposes, due to low accuracy (prominences) or possible fractionation (solar wind, SEP).

Giant planets are another source of He/H ratios, but at least Jupiter and Saturn ($5.7 \pm 1.3\%$ and $1.6 \pm 1.3\%$; CONRATH *et al.*, 1984) seem to have been affected by fractionation. Only Uranus ($9.2 \pm 1.7\%$; CONRATH *et al.*, 1987) agrees with the result derived below.

We shall therefore turn to extrasolar sources, such as HII regions or hot stars. Many results are available (SHAVER *et al.*, 1983; WOLF and HEASLEY, 1985; PEIMBERT, 1986; PAGEL, 1987, 1988; MEYER, 1989) and indicate a rather uniform abundance for media with roughly solar metallicity, $N_{He}/N_H \simeq 9$ to 11%. Values in the same range, 9.2 to 10.4%, come from recent standard solar models, which consistently give a He mass fraction, Y, between 0.264 and 0.288 (CAHEN, 1986; TURCK-CHIÈZE *et al.*, 1988; BAHCALL and ULRICH, 1988). We therefore adopt $N_{He}/N_H = 9.75\%$ ($Y = 0.275$), with an uncertainty of ±8% ($9\% \leq N_{He}/N_H \leq 10.5\%$; $0.26 \leq Y \leq 0.29$).

6.2. Ne, Ar

Like He, C, N, O, these elements are fractionated relative to low FIP metals in the solar corona (Sec. 7.1). For this reason we shall again partly rely on local galactic values, *i.e.* for HII regions, HI gas, and stars, as reviewed by MEYER (1985a, 1989). As these data also agree very well with "photospheric" values derived from coronal spectroscopy, solar wind and SEP (corrected by a constant fractionation factor for all elements of $Z > 2$ with FIP > 11 eV), we have adopted the mean values: log Ne = 8.09, log Ar = 6.56 (Sec. 7.1). These values agree with a prominence measurement, which presumably refers to photospheric, not coronal material, as judged from the Mg/O ratio (WIDING *et al.*, 1986). Moreover, the Ar value is only 3% smaller than the value obtained by interpolating Ar^{36} between Si^{28} and Ca^{40} (CAMERON, 1973, 1982; *AE*).

6.3. Kr, Xe

For Kr, the latest value based on *s*-process systematics (45 ± 8; H. BEER, priv. commun., 1987; see also WALTER *et al.*, 1986) agrees well with the earlier estimate of 45.3 (*AE*) obtained by Cameron's method (Kr^{83} was interpolated between Br^{81} and Rb^{85}, and Kr^{84} between Se^{80} and Sr^{88}). The Xe value was obtained by graphically fitting Xe to the Te-I-Cs-Ba peak, using both the even- and odd-*A* nuclides. The result, 4.7, agrees with an estimate of 5.0 ± 1.0 based on *s*-process systematics (BEER *et al.*, 1983).

The corresponding elemental ratios may be compared with those of the solar wind and other estimates (Table 5). He^4/Ne^{20} again is high compared to the solar wind and SEP, apparently due to different depletions of He and Ne in the latter (Fig. 3; Sec. 7.1). The other ratios seem to have stabilized, although the individual abundances of all four noble gases have changed.

7. DISCUSSION

7.1. *Photospheric* vs. *coronal abundances*

It is well known that several different processes affect abundances in the solar corona (MEYER, 1985b; VAUCLAIR and MEYER, 1985; GEISS, 1985; BRENEMAN and STONE, 1985; GEISS and BOCHSLER, 1985; BOCHSLER, 1987 and references therein). There is clear evidence from abundance patterns that separation processes at relatively low temperature fractionate the gas supplied to the corona. Elements with high first ionization potentials (FIP), which are neutral at this temperature, are depleted relative to elements of lower FIP, which are ionized. Figure 3 shows this trend for data from Table 4: a ~4.5-fold drop in abundance occurs between 9.5 and 11 eV.

Thanks to the improvement in the data for CNO, some trends now appear with greater clarity than in previous versions of Fig. 3.

(1) The depletion is constant at -0.65 dex (factor of 4.5) for CNO, and presumably for all heavy elements of FIP ≥ 11 eV. The trend confirms the "two-plateau pattern" for the atom-ion separation process suggested by COOK *et al.* (1979).

(2) H and He part company from the other elements. He lies ~0.20 dex below the high-FIP element plateau at -0.65 dex, in SW as well as SEP. Hydrogen, which cannot be determined in SEP, lies slightly above this plateau in SW, but much higher, right on the *low*-FIP plateau, in the corona itself, according to spectroscopic data (Fig. 3). Similar characteristic deviations have been seen previously in galactic cosmic rays (MEYER, 1985b; GEISS and BOCHSLER, 1985). The reasons for this are not known, but these two elements are much lighter and more abundant than any of the others.

Correction for fractionation. It is not quite clear what correction is most appropriate for Q/M fractionation, as this

Table 5. Noble-Gas Ratios

	$\frac{He^4}{Ne^{20}}$	$\frac{Ne^{20}}{Ar^{36}}$	$\frac{Ar^{36}}{Kr^{84}}$	$\frac{Kr^{84}}{Xe^{132}}$	Ref.
Solar System	850	37	3320	20.6	a
Solar System	670	37	3380	22.5	b
Solar System	780	26	3800	15.5	c
Solar System	400	40	2500	10	d
Solar Wind	570 *±70*	45 *±10*			e
Solar Corona, spectr.	–	17 *+19, −9*			f
SEP, Observed	480 *±90*	43 *±9*			ghi

a. This work
b. Anders & Ebihara (1982)
c. Cameron (1982)
d. Marti et al. (1972)
e. Bochsler (1987)
f. Meyer (1985b)
g. Breneman & Stone (1985)
h. Cook et al. (1984)
i. McGuire et al. (1986)

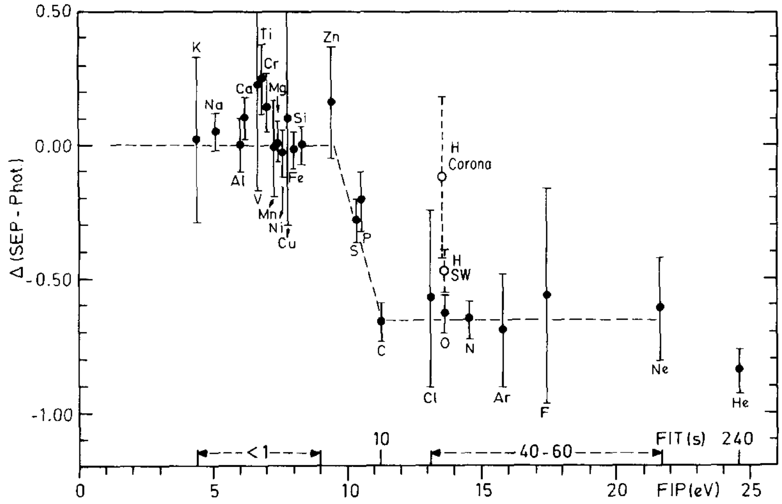

FIG. 3. Abundances of solar energetic particles (SEP) relative to the solar photosphere (Table 4). Elements K to Zn, of first ionization potential (FIP) < 10 eV, are present in normal abundance relative to Si, but elements C to Ne, of higher FIP, are depleted by an approximately constant factor. Apparently these elements are depleted in the corona by a process depending on FIP (or first ionization *time*, FIT). The points for P and S would fall closer to the dashed trend line if they were referenced to meteoritic rather than photospheric abundances. As H cannot be reliably determined in SEP, we plotted representative spectroscopic and solar-wind data from Table 4.

correction depends strongly on the adopted Fe abundance. BRENEMAN and STONE (1985) found that the SEP/photospheric abundance ratio for low-FIP elements—including Fe—fit a power-law in Q/M, and used this power-law as the correction factor, on the tacit assumption that these elements were not fractionated between photosphere and corona. An alternative, if extreme, approach would be to use no correcticn at all. The mean ratio log (SEP/photosphere) then becomes −0.61 dex (instead of −0.65) for high FIP elements and −0.01 ± *0.09* dex (instead of +0.07) for low FIP elements. In particular, the iron abundance then becomes 7.53 (close to the meteoritic value) instead of 7.65. Given these uncertainties in the Q/M fractionation correction, the SEP data cannot be used to resolve the discrepancy between photospheric and meteoritic iron abundance.

Gamma-ray spectroscopy of flares has provided a new technique for determining solar abundances, probably at chromospheric level (MURPHY *et al.*, 1985). Recent results (REAMES *et al.*, 1988) show that if the ratios Mg/O, Si/O, and Fe/O agree with SEP values, then Ne/O is about 3× larger and even C/O may be larger. These results are very puzzling.

Mechanism and site of separation process. If FIP is the relevant physical parameter, then the fractionation must take place in low-T, *i.e.*, chromospheric-type, material ($T \simeq 10^4$ K) consisting of neutral and singly ionized atoms (MEYER, 1985b). Most likely, neutrals somehow diffuse away from the gas and enter the corona, whereas ions are prevented from doing so by the magnetic field. Two mechanisms based on this idea have been investigated thus far. VAUCLAIR and MEYER (1985) proposed gravitational settling of heavy neutrals in the ~6500 K temperature plateau of the middle chromosphere, with FIP as the key parameter. Others (*e.g.* GEISS, 1985) have considered diffusive loss of neutrals during the fast rise of matter from chromosphere to corona in spicule-like features that are rapidly heated; here the relevant parameter is the first ionization time (FIT), which is actually closely related to FIP.

Both mechanisms are very slow (days, for realistic parameters), compared both to turbulent mixing times in the chromosphere and to spicule lifetimes (5 min). A reliable value for the coronal abundance of H would provide strong constraints on these mechanisms.

Neon and Argon. We can derive photospheric abundances of these elements from the rather accurate SEP and solar-wind data, by adding the correction factor of 0.65 dex to the coronal values. We thus find A_{Ne} = 8.11 ± *0.10* and A_{Ar} = 6.54 ± *0.10;* very close to the local galactic values of 8.07 ± *0.18* and 6.58 ± *0.18* derived from HII regions, HI gas, and stars (MEYER, 1985a, 1988). [A new analysis by MEYER (1989) again gives very similar coronal and local galactic values: A_{Ne} = 8.08 ± *0.06* and 8.14 ± *0.10;* A_{Ar} = 6.55 ± *0.08* and 6.63 ± *0.20.*] This agreement is not likely to be fortuitous, and thus seems to support the underlying data: SEP and solar-wind abundances, a constant coronal fractionation factor for all heavy elements with FIP > 11 eV, and the astronomical measurements used for the local galactic estimates. We shall therefore adopt for the solar system the means of the solar and local galactic values, with an estimated uncertainty of ±25%: A_{Ne} = 8.09 ± *0.10* and A_{Ar} = 6.56 ± *0.10.*

7.2. *Meteoritic* vs. *solar abundances*

Gross trends. The log of the abundance ratio Sun/meteorites (Table 2) is plotted in Fig. 4, with the elements grouped according to cosmochemical character. Elements that are poorly determined in the Sun are represented by open symbols.

On the whole, the agreement is remarkably good. Past discrepancies have gone away as the solar values—especially thanks to improved transition probabilities and other atomic data—have become more accurate. Even now, the agreement improves if we delete the less accurate values. The mean Sun-meteorite difference for all elements from Table 2 (except the very uncertain Ag, Tb, Ho, Lu, Tl and the grossly dis-

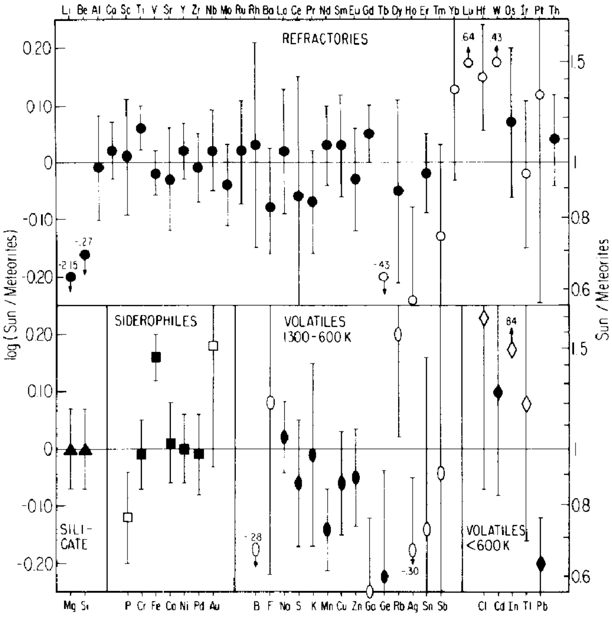

FIG. 4. Solar photospheric and meteoritic abundances (Table 2) agree rather well, except for elements affected by thermonuclear reactions (Li, Be), elements poorly determined in the photosphere (uncertain abundances or errors, or large errors: open symbols), and five problematic cases: W, Fe, Mn, Ge, and Pb (see text). If these elements are omitted, there is no systematic difference between photospheric and C1 chondrite abundances of the five major cosmochemical groups.

cordant In and W) is −0.005 ± *0.10* dex. If we limit ourselves to the 32 elements known to better than 25% (0.10 dex), the mean difference becomes −0.006 ± *0.04* dex. And if we retain only 29 accurately known elements (having a sufficient number of good lines with good transition probabilities) then the data agree within ±0.036 dex, *i.e.,* ±9%. For the last two means, we omitted four well-determined but discordant elements, which are discussed below: Mn, Fe, Ge, and Pb.

Of the elements disagreeing by more than 0.10 to 0.15 dex, Li and Be are depleted by nuclear reactions at the bottom of the convection zone. Twenty others (B, F, P, Cl, Ga, Rb, Ag, In, Sn, Sb, Ce, Tb, Ho, Tm, Yb, Lu, Hf, Pt, Au, Tl) without doubt are poorly determined in the photosphere, due to severe blending of their few available lines, lack of accurate transition probabilities, or both.

However, this leaves five other elements—Ge, Pb, W, Fe, and Mn—that deviate more than expected from the quality of the solar data. In chondrites, elements of similar volatility and cosmochemical properties usually fractionate together, by similar factors (ANDERS, 1971). Thus, if these five elements had been fractionated by *known* cosmochemical processes, other elements of the same cosmochemical group (Fig. 4) should have fractionated by similar factors. We therefore compare mean abundance ratios for each cosmochemical group, omitting the five elements under discussion as well as a few poorly determined elements (Table 6).

All of the deviations are less than 1σ, and except for the <600 K volatiles, all are smaller than in 1982. We must therefore consider the possibility that Ge, Pb, W, Fe, and Mn were fractionated in C1 chondrites by *selective processes* that affected only these elements and no others.

Germanium. GREVESSE and MEYER (1985) have suggested that the discrepancy for this element (and lead, below) could be real, implying chemical enrichment in C1 chondrites. Indeed, Ge is known to be depleted in all other chondrite classes—by factors up to 0.15×—but so are 13 other elements of similar volatility (Fig. 4), apparently reflecting volatile loss during chondrule formation (LARIMER and ANDERS, 1967). Germanium appears to have no unique property that would allow it to go its own ways, unaccompanied by other elements of similar volatility. It is siderophile as well as volatile, but so are, to only slightly lesser degrees, Ag, Cu, Sb, Sn, etc. (WAI and WASSON, 1977).

Lead. At first sight it seems that a suitable enrichment process for Pb is available. The highly volatile (<600 K) elements, to which Pb belongs, show much larger variations in abundance, including—in contrast to the 1300–600 K group—occasional "superenrichments" above C1 chondrite levels, though only in ordinary, not carbonaceous chondrites. Some authors suggest that these volatiles were left behind in the nebula by earlier generations of meteorites and condensed on the last traces of dust after temperatures had dropped (HIGUCHI *et al.,* 1977). Others believe that the volatiles sublimed from the inner parts of the meteorite parent bodies and condensed in the cooler, outer regions (BINZ *et al.,* 1976). In the cases studied, Pb usually is accompanied by other elements of similar volatility (Cd, In, Bi, Tl), but in highly variable proportions (HIGUCHI *et al.,* 1977), with Pb and Bi occasionally predominating (KEAYS *et al.,* 1971; TILTON, 1973).

However, it is very unlikely that such "superenrichment" can explain the high Pb abundance. This process is not specific for Pb, it has never been seen in C-chondrites, and it produces enrichments that are highly variable on a mm or cm scale—in contrast to the observed uniformity of the Pb distribution within meteorites (σ for Orgueil is ±8%, Table 1) or between meteorites (Orgueil and Ivuna agree within ±17%, according to BURNETT *et al.,* 1988). Moreover, 12 C chondrites—including Orgueil—analyzed by spark-source mass spectrometry/isotope dilution (*K3*) show a perfectly normal abundance trend for volatiles: C1/C2/C3 ≃ 1.00/0.50/0.25–0.30. Apparently none of these meteorites, including Orgueil, has been affected by superenrichment.

Tungsten. The discrepancy is large (+0.43 dex), but the fault may well be with the solar data (HOLWEGER and WERNER, 1982). Although the transition probabilities are very accurate, the two ostensible WI lines are very faint and perturbed, and may not even be due to WI. Alternatively, the ionization energy of W may be too low by 0.43 eV.

Iron and Manganese. The discrepancies for these two ele-

Table 6. Mean Abundance Ratios, Photosphere/Meteorites

Elements	N	log Phot./C1	
		This work*	*AE*
Refractories	23	0.002 *±0.04*	−0.029 *±0.15*
Silicate	2	0.000 *±0.00*	−0.007 *±0.013*
Siderophiles	4	−0.003 *±0.01*	−0.054 *±0.081*
Volatiles, 1300-600K	5	−0.022 *±0.04*	−0.099 *±0.15*
Volatiles, <600K	3	(0.13 *±0.08*)	0.059 *±0.14*

*We omitted Li, Be, Mn, Fe, In, W, and Pb (Sec. 7.2) and—except for the <600 K volatiles—the elements poorly determined in the photosphere (open symbols in Fig. 4). However, the means for each group remain close to zero even when the poorly-determined elements are retained.

ments (+0.16 and −0.14 dex, *i.e.* 40–50%) are puzzling, as both elements appear to be well-determined in the solar photosphere. Although the solar data for Fe have not yet fully converged, and need to be confirmed by measurement of the dominant species, Fe II (Sec. 4.3), most results are higher than the meteoritic value. It would be surprising if this discrepancy were resolved merely by improved atomic data or a better understanding of physical processes in the photosphere (HOLWEGER, 1988).

Perhaps the meteoritic abundance of Fe is at fault. The most obvious way to fractionate Fe—as nickel-iron—is not feasible, as it would simultaneously deplete other siderophiles. There are two lines of evidence against such depletion. (1) The most abundant, well-determined siderophiles—Co and Ni—are not depleted in C1 chondrites relative to the Sun (Table 2, Fig. 4). (2) There is no systematic break in the abundances of odd-A nuclei between $A = 99$ and 111 (Fig. 5), where cosmochemical character changes rapidly: Ru, Rh (refractory siderophiles), Pd (normal siderophile), Ag (moderately volatile siderophile) and Cd (highly volatile). Even a 10 to 20% increase, let alone a 50% increase, in the abundances of Ru, Rh, Pd relative to Ag, Cd would cause a marked offset in the curve.

However, a more selective fractionation process of Fe alone is available, at least in principle. Below 400 K in a solar gas, the stable chemical form of Fe is magnetite, Fe_3O_4, which would therefore be the principal condensate of Fe in an interstellar cloud that remained at ≤400 K throughout contraction. On crystal chemical grounds, most other siderophiles should not be enriched in magnetite, and this has actually been confirmed for meteoritic magnetite from C1 chondrites (KRÄHENBÜHL *et al.*, 1973; KERRIDGE *et al.*, 1979). Once formed, magnetite could fractionate from other solids on the basis of its ferromagnetism. Moreover, there is evidence for Fe/Si fractionations in meteorites and planets (LARIMER and ANDERS, 1970; MORGAN and ANDERS, 1980).

It is not certain, however, that the pure Fe_3O_4 grains required by this mechanism were available. Although Fe is strongly depleted in the interstellar gas (SALPETER, 1977; PHILLIPS *et al.*, 1982), so are many other elements (Ni, Mg, Si, etc.), and it is not clear that the major part of Fe is contained in discrete magnetite grains rather than in mixed, perhaps amorphous, grains.

For Mn, no similarly selective chemistry is available. It is one of the least volatile of the 15 moderately volatile (1300–600 K) elements (Fig. 4), and if it is enriched in C1 chondrites, at least some of the other elements should be also. If we take the solar data at face value, then only Ge appears to be so enriched, but since several of these elements are poorly determined in the Sun, it may be possible to devise an *ad hoc* mechanism for enriching Mn, Ge, and a few other elements that is consistent with the data and is cosmochemically tenable.

7.3. C1 chondrites as abundance standards

There are three major reasons why C1 chondrites are used as the abundance standard: 1) they seem to have escaped the fractionation processes (*e.g.* chondrule formation) that affected other meteorite classes (ANDERS, 1971); 2) their volatile element abundances are higher and match solar ratios for Na/Ca, S/Ca, Si/Ca (HOLWEGER, 1977); 3) they give the smoothest nuclidic abundance curve (SUESS, 1947; ANDERS, 1971). Nonetheless, even the best may not be good enough, and one must therefore periodically reexamine C1's for evidence of modification or alteration. We shall summarize and update the discussion in *AE*.

High-temperature minerals. Orgueil contains ~1% of olivine and orthopyroxene, either indigenous or accreted on the regolith of the parent body. This component has only a negligible effect on the overall composition. Some few Orgueil samples are enriched in refractories, suggesting sporadic (regolith?) contamination with Ca, Al-rich inclusions, but since we have rejected all such anomalous analyses, they do not affect the abundance table.

Presolar matter. Several types of interstellar matter have been identified in C-chondrites: diamond, SiC, organic matter, in abundances of a few to a few hundred ppm. As these exotic components account for $<10^{-2}$ of the total C and Si, they have only a negligible effect on overall abundances. The apatite mentioned by *AE* turned out to be local rather than exotic.

Hydrothermal alteration. C1 chondrites have been altered by liquid water in their parent bodies, but for most water-soluble elements there has been no net change, suggesting that the alteration took place in a closed system. The principal exceptions are Br and I, where abundances had to be estimated from other meteorite classes (*AE*). Large variations have been found for C2 chondrites, where in addition Na, K, and Ca have been affected (*K1*).

Interelement ratios: differences between C1's and other meteorite classes. In contrast to volatiles, refractory elements usually have essentially constant ratios in all chondrite (and even some achondrite) classes. Some authors (*e.g.* JOCHUM *et al.*, 1986) have assumed that this constancy is exact for all refractory lithophiles except V (*K1*), so that mean ratios for all C chondrites can be used to refine ratios for C1 chondrites. *AE* pointed out two apparent exceptions to this constancy: the Zr/Hf and Re/Ir ratios of C2 chondrites were ~14% higher than those of C1's. However, these differences have not stood up in the light of new data or reevaluation of older data. The Zr/Hf ratio of C1's now is within the range for other classes (*J3*; Sec. 3.4, 3.6). The variations in Re/Ir and Re/Os ratios seem to reflect mainly differences among laboratories or analysts, not meteorite classes.

Thus at present there is no direct evidence for interelement fractionation of refractories, within the accuracy of the data. However, there are some disturbing inconsistencies. KALLEMEYN and WASSON (1981) have shown that the (Mg-normalized) abundances of eight refractory lithophiles (Al, Sc, Ca, Lu, Yb, Eu, Sm, La) vary systematically among C-chondrite classes: C1/C2,C3O/C3V = 1.00/1.11/1.33. Since the Mg/Si ratios are constant in the first three classes and only 3% higher in C3V's, one would expect element/Si ratios for all refractory lithophiles to vary from class to class by the above factors. But JOCHUM *et al.* (1986) confirmed this trend only for Sc; for Nb, Y, and Ho they found no enrichment in C2's, slight enrichment in C3V's, and large enrichments in a C3O. KNAB (1981) found essentially constant Zr/Si ratios in all C chondrite classes.

Evidently at least some of these data must be wrong. If all refractory lithophiles are fractionated by the Kallemeyn-Wasson factors, then their Si-normalized abundances should vary correspondingly from class to class. Conversely, if these abundances do not vary for some elements (*e.g.* Zr), then the interelement ratios of refractory lithophiles cannot be constant. Obviously, these contradictions will have to be resolved by further measurements; until then, it seems advisable not to use data from other meteorite classes if at all possible.

7.4. *Smoothness of abundance curve*

A major milestone in this field was SUESS' (1947) postulate that the *abundances of nuclides—especially of odd A—are a smooth function of mass number.* The slope of the abundance curve is accurately defined over short segments by isotopic pairs, and on the basis of the above postulate, Suess adjusted elemental abundances as needed to produce a continuous, smooth curve.

Suess' adjustments (by factors of up to 100, *e.g.* Re) were vindicated by subsequent measurements, and in view of this success, his postulate later became one of the main reasons for choosing C1 chondrites as the abundance standard; they gave the smoothest curve.

However, now that most C1 chondrite abundances are known to better than 10%, the smoothness of the abundance curve can be tested to higher accuracy. Deviations may imply either chemical fractionations of C1 chondrites, or failure of Suess' postulate at the ~10% level.

This question was reexamined by *AE,* who claimed smoothness of ≤10% overall, but with irregularities at Pd-Ag-Cd and Nd-Sm-Eu, which they attributed to analytical error or chemical fractionations. BURNETT *et al.* (1988) approached the problem experimentally, analyzing by a single technique the elements Ni through Ru as well as Fe and Pb in six samples of two Cl chondrites. They concluded that the abundance curve is smooth within 4 to 10% between $A = 60$ and $A = 101$, but not necessarily at higher mass numbers. Figures 5 and 6 show our new data for the mass regions 67–139 and 135–209.

The low-mass region (Fig. 5) seems generally smooth, though the steep slopes and varied topography would mask small irregularities. The most sensitive test is provided by the Pd-Ag-Cd region, where the flat trend and contiguity of two isotopic pairs help bring out small irregularities. The Ag-Cd irregularity noted by *AE* has smoothed out somewhat due to the revision in the Ag abundance, and would require only a further 7% drop in Ag/Cd ratio for perfect continuity. Such a change exceeds the combined error of the two means (±1.8%), but since the Ag value is based on only 6 analyses from a single laboratory, a larger systematic error cannot be excluded.

The high-mass region (Fig. 6) is more suitable for a test, as it is flatter, has many more isotopic pairs, and contains mainly refractory elements, which do not readily fractionate from each other in cosmochemical processes. The REE are of particular interest, since they are chemically coherent and analytically very well determined (Sec. 3.6, Table 1).

The most sensitive test is the Nd-Sm-Eu-Gd region, where four isotopic pairs occur in sequence and thus provide four well-defined curve segments. Yet the new data, despite their high accuracy, still fail to give elemental trends agreeing with the isotopic trends: Sm looks too low and Eu looks too high. *AE* ruled out analytical error, and discussed various chemical or nuclear causes for this irregularity. The chemical explanations, involving some special process for Cl chondrites, now look less plausible, as our new REE abundances, based on DAVIS (1988, in preparation), are quite similar to REE patterns in other meteorite classes. Apparently the smoothness postulate breaks down below the 10 to 20% level, due to nuclear causes. This is not quite surprising, since most nuclides in this mass region are made by both the *s*- and *r*-processes, and even if the distributions of pure *s*- or *r*-process nuclei were perfectly smooth, their mixture need not be. The nuclear parameters determining *s*- and *r*-process yields are not perfectly smooth functions of mass number, and thus

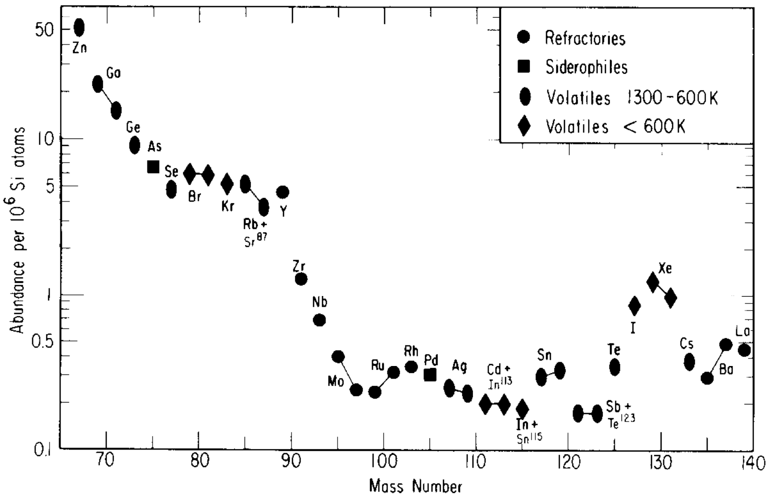

FIG. 5. Abundances of odd-mass nuclides from Zn to La are a smooth function of mass number, with elemental abundances conforming to the trend set by the isotopic ratios (tie lines). Peaks at Y, Sn, and Te-Cs correspond to closed neutron or proton shells of the nuclides themselves or their neutron-rich, shortlived progenitors in the *r*-process. There is no evidence for fractionation of cosmochemical groups from each other, as there are no distinct offsets at junctions where cosmochemical character changes (Ge-As-Se or Rh-Pd-Ag). The only exception is a 7% offset between Ag and Cd.

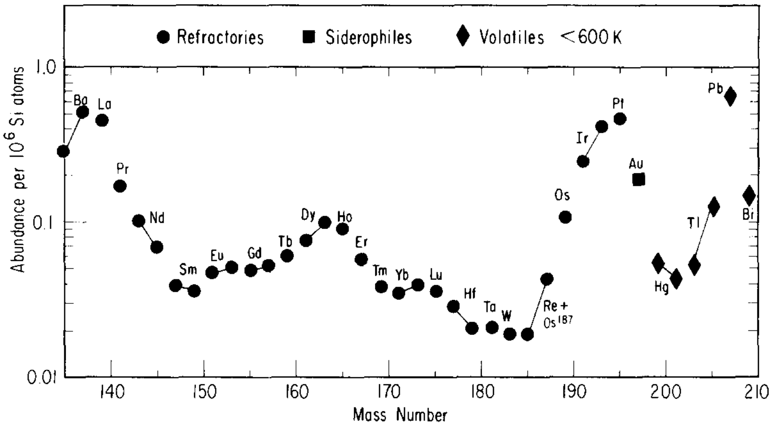

FIG. 6. The trend from Ba to Bi is likewise smooth, except that Sm is too low relative to Nd and Eu. As analytical and cosmochemical causes are ruled out (see text), it appears that the abundance curve is smooth only down to the ~20% level.

the smoothness postulate is bound to fail eventually. Nonetheless, this principle, which has successfully guided the field for 40 years, should be retired with proper honors, now that it has reached its limits of applicability.

7.5. Nucleosynthesis: Contributions of s *and* r*-processes*

Most heavy nuclides are made by both the *s*- and *r*-processes, but the contributions of these processes can be resolved by first assessing the *s*-process component (KÄPPELER *et al.*, 1982 and references therein). The abundance N_s of a pure *s*-process nuclide is inversely proportional to the neutron capture cross section σ and directly proportional to the neutron fluence (CLAYTON *et al.*, 1961). Thus a plot of σN_s vs A indicates the fluence as a function of A, permitting reconstruction of *s*-process conditions in some detail. Progress in this field has required both better abundances and better cross

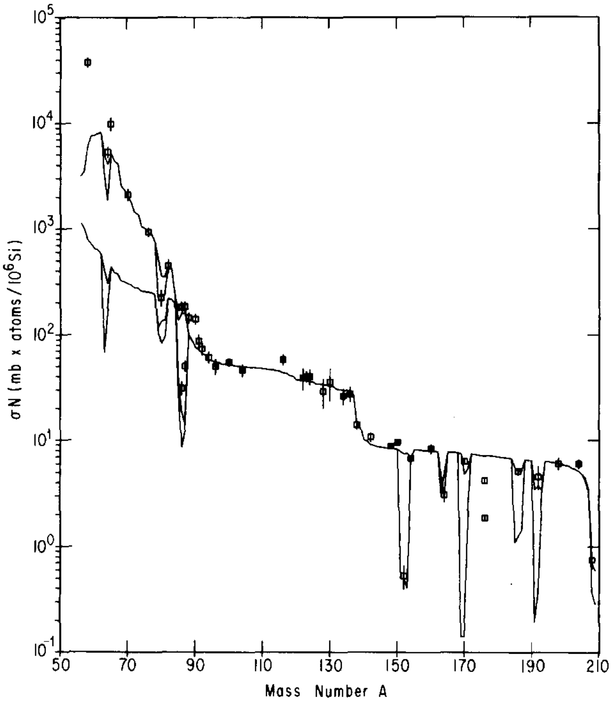

FIG. 7. (BEER, 1988, priv. commun.). In the *s*-process, abundance N and neutron capture cross-section σ are inversely proportional to each other and thus a plot of σN for *s*-process nuclides is a function mainly of neutron exposure (KÄPPELER *et al.*, 1982). A computer fit to the *s*-only points (filled symbols) accounts for the region 90–205, but underproduces Pb^{208} and light nuclides of $A < 90$. Two additional *s*-processes, at higher and lower fluences, are needed to account for these two regions. See text for additional discussion.

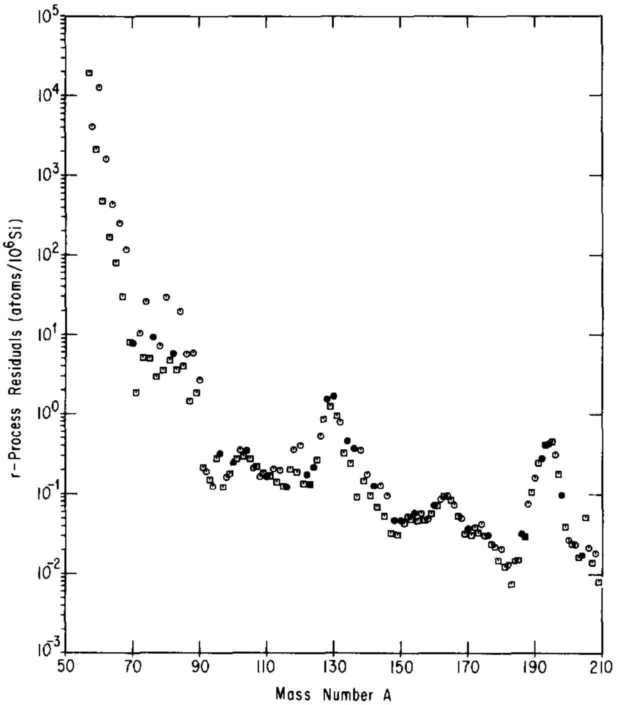

FIG. 8. (BEER, 1988, priv. commun.). To obtain the *r*-process component of nuclides of mixed parentage, the *s*-process component from Fig. 7 is subtracted from the total abundances. These "*r*-process residuals" (open symbols) form a smooth curve passing through the "*r*-only" nuclides (filled symbols), suggesting that the input data (abundances and cross sections) are reasonably accurate. The peaks at $A \simeq 130$ and $\simeq 195$ represent the enhanced abundances of short-lived, neutron-rich progenitors with closed, 82- or 126-neutron shells.

sections, of which the latter were contributed mainly by the Karlsruhe group (BEER, 1986; KÄPPELER, 1986; BAO and KÄPPELER, 1987).

Figure 7 shows a σN_s plot, based on the abundances from Table 3 (BEER, 1988, priv. commun.). The filled symbols are *s*-only nuclides used for normalization of the curve in the mass range $90 < A < 205$. The open symbols represent either "mainly-*s*" nuclides or *s*-only nuclides that are situated in branchings (*e.g.* Gd^{152}), belong to interpolated elements (Kr, Xe, Hg), or were used to normalize the curve below $A = 90$. A computer fit to the *s*-only points accounts for the mass region $90 < A < 205$, but underproduces Pb^{208} and the nuclides of $A < 90$. For these, two additional *s*-processes at high and low fluences ("strong" and "weak" processes) are needed (BEER, 1986). The line splits at branch points where neutron capture competes with β-decay; the top and bottom curves represent the individual branches of the synthesis path.

From the σN curve, the *s*-process components of mixed, $r + s$, nuclides can be calculated, provided their σ's are known. Subtraction of these *s*-components then leaves the *r*-components. These (open symbols) along with pure *r*-nuclides (filled symbols) are plotted in Fig. 8. The curve is rather smooth over most of its range, except below $A = 70$ where the *e*-process begins to contribute. As subtraction of similarly-sized numbers usually inflates errors, the smoothness of the curve suggests that the input data (abundances and cross sections) are reasonably accurate.

A caveat to be noted is that the above conclusions were obtained within the framework of the "classical" *s*- and *r*-processes. The actual processes may be different and more complex (CAMERON, 1988, priv. commun.).

7.6. Comet Halley

Now that the Vega and Giotto missions have obtained data from Comet Halley, it is interesting to compare these data with the new photospheric and meteoritic abundances (Table 7). The most extensive data, from the PUMA-1 mass spectrometer (JESSBERGER *et al.*, 1988), are for the dust component only, and we have therefore added the HCNO abundances for the gas component, using the gas/dust ratios of DELSEMME (1988). These data are compared with photospheric abundances in Fig. 9.

Table 7. Abundances in Comet Halley*

Element	Comet Halley: Geiss (1987)	Comet Halley: Delsemme (1988)	Comet Halley: Jessberger *et al.* (1988)†	Sun	Solar System	Halley−Sun
H	9.41	9.21	9.47 *±0.08*	12.00	12.00	−2.53
C	8.90	8.66	8.64 *±0.08*	8.56	8.56	0.08
N	7.59 *±0.4*	7.88	8.05 *±0.12*	8.05	8.05	0.00
O	9.17	9.00	8.99 *±0.05*	8.93	8.93	0.06
Na		6.58	6.58 *±0.20*	6.33	6.31	0.25
Mg		≡7.58	≡7.58	7.58	7.58	≡0.00
Al			6.41 *±0.10*	6.47	6.48	−0.06
Si	≡7.79	7.73	7.85 *±0.04*	7.55	7.55	0.30
S		7.53	7.44 *±0.12*	7.21	7.27	0.23
K			4.88 *±0.18*	5.12	5.13	−0.24
Ca			6.38 *±0.11*	6.36	6.34	0.02
Ti			5.18 *±0.18*	4.99	4.93	0.19
Cr			5.53 *±0.09*	5.67	5.68	−0.14
Mn			5.28 *±0.15*	5.39	5.53	−0.11
Fe		7.58	7.30 *±0.07*	7.67	7.51	−0.37
Co			5.06 *±0.22*	4.92	4.91	0.14
Ni			6.19 *±0.18*	6.25	6.25	−0.06

*Logarithmic abundances relative to log $N_H \equiv 12.00$ or some other normalization standard, as indicated. Uncertainties in gas/dust ratio introduce an additional error of ±0.3, which is not shown here.

†As the original data were for the dust component only, we have added a gas component by increasing the logarithmic abundances as follows: H (0.58 dex), C (0.15), N (0.85), and O (0.46) (Delsemme, 1988). Jessberger's original values for the dust component only were: H = 8.89 ±0.08, C = 8.49 ±0.08, N = 7.20 ±0.12, O = 8.53 ±0.05.

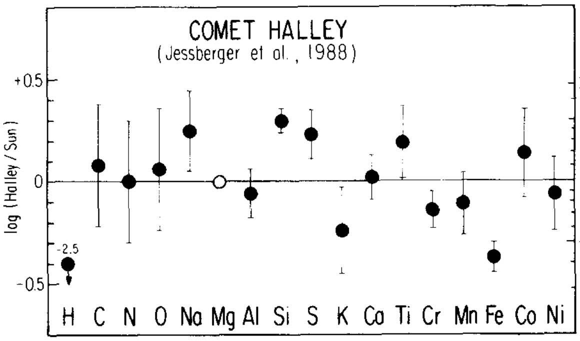

FIG. 9. Mg-normalized abundances in Comet Halley (JESSBERGER *et al.*, 1988) generally match those in the solar photosphere, and—for the gas/dust ratio assumed (DELSEMME, 1988)—show no deficiency for C, N, and O. However, Fe and Si are distinctly anomalous. If these values are correct, then Halley has the lowest Fe/Si ratio of any known solar-system object, except for the Moon, and cannot be pristine interstellar matter.

The depletion of H is very large, and obviously reflects the non-condensation of molecular hydrogen. C, N, and O, on the other hand, agree remarkably well with solar values. Even N no longer shows the depletion reported in earlier studies (GEISS, 1987), but since the N value critically depends on the gas/dust ratio and the composition of the gas, it cannot be regarded as definitive. As N_2 is the most volatile of the principal molecules in comets, it is a potentially valuable indicator of the formation temperature and subsequent thermal history of the comet (YAMAMOTO, 1985).

Of the remaining elements, two disagree by more than 2σ: Si = +0.30 dex, Fe = −0.37 dex. Sulfur is a trifle below 2σ, at +0.23 dex. Relative to meteorites the Si and Fe discrepancies are a little smaller (+0.17 and −0.21 dex), but are still outside the quoted errors. Since these discrepancies have opposite signs, they cannot be eliminated by changing the normalization from Mg to Si or some other element. (Indeed, one argument for the Mg normalization is that it gives a mean residual close to zero, *i.e.* 0.01 ± *0.20* for the 13 elements from Na to Ni.)

To first order, the Halley data suggest that Fe/Mg and Mg/Si both decline with distance from the Sun (HOLWEGER, 1988). However, when additional data for meteorites and the Earth are included, the two sequences are quite different, and thus cannot represent a simple monotonic decline with distance. Note in particular the varying positions of EH and EL chondrites. *Fe/Mg*: Sun > Earth > EH > C ≈ H > EL > L > LL > Halley. *Mg/Si*: Earth > Sun ≈ C > H ≈ L ≈ LL > EL > EH > Halley. At best *one* of these sequences is a simple function of distance, and perhaps neither of them is. We therefore limit ourselves to the following tentative conclusions.

(1) Relative to Mg, Comet Halley seems to possess its cosmic complement of C, O, and perhaps even N, *i.e.* the "ice" component (GEISS, 1987).

(2) Halley has the lowest known Fe/Si and Mg/Si ratios of any object in the solar system (except for the Moon), farthest from the solar ratios (JESSBERGER *et al.*, 1988). If these data are correct, then Halley cannot be pristine interstellar matter. Apparently at least its dust component was affected by the chemical processes that fractionated these elements elsewhere in the solar system (ANDERS, 1986).

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