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SPECIAL COMMUNICATION

Relative Atomic Solar System Abundances, Mass Fractions, and Atomic Masses of the Elements and Their Isotopes, Composition of the Solar Photosphere, and Compositions of the Major Chondritic Meteorite Groups

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Abstract
This brief special communications article gives data for atomic abundances and mass fractions for the elemental and isotopic solar system composition, the atomic masses of the elements and their isotopes, the composition of the solar photosphere, and the compositions of the major chondritic meteorite groups. This additional material is relevant for researchers who are interested in this Topical Collection on planetary evolution.

Keywords Elemental abundances · Isotopic composition · Chondrites · Meteorites · Nuclides · Sun · Solar system

1 Introduction

This special communications article gives the elemental and isotopic composition of solar and meteoritic matter. A large review on the solar system composition is Lodders (2020) from which a portion of the material is drawn. The following briefly describes definitions and some data sources.

The solar system composition is the protosolar composition 4.567 Ga ago. Solar composition describes the current composition of the solar photosphere and the solar wind. The current photospheric composition is not the composition of the sun when it formed. The photospheric composition represents the composition of the underlying outer solar convection zone, which is a small portion of the entire sun. Heavy elements settled from the outer solar convection zone and the overlying photosphere into the sun's interior over the lifetime of the sun. Therefore, the element to hydrogen ratios are about 10-20% lower, which is model dependent, in the photosphere than they were originally. The settling effects on isotopic fractionations are not well known. In addition, the photospheric Li/H ratio is 170 times lower

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than in CI chondrites because of lithium destruction in the interior of the early and current sun; deuterium is essentially absent in the sun. The solar wind, which is derived from photospheric sources, has experienced further isotopic and elemental fractionation during solar wind acceleration.

2 Composition of Chondritic Meteorites

Table 1 gives the elemental composition by mass of the major chondrite groups in parts per million (μg/g). The CI-chondrite data are from Lodders (2020), and data for other chondrite groups are updated from Lodders and Fegley (1998, 2011). Several hundred individual analyses collected from the literature were used to calculate average compositions of observed meteorite falls in each chondrite group, although meteorite finds had to be considered for some elements if no analytical data were available for meteorite falls (particularly for CK and CR chondrites). The weighted chondrite group mean was obtained, if possible, by using the number of analyses for a given meteorite as statistical weight. Some of the data sources used here and other evaluations of the compositions of the chondrite groups can be found in Wasson and Kallemeyn (1988), Friedrich et al. (2003, 2004), Schaefer and Fegley (2007, 2010), Alexander (2019a, 2019b), Brauckmüller et al. (2018) and references therein. The average compositions should be taken as characteristic and could be taken as representative if it is kept in mind that natural concentration variations exist for mobile elements, and that there is variance in concentration determinations caused by differences in analytical methods. For meteorite finds, possible sources of terrestrial contamination or weathering losses of elements were considered. For the CI-chondrites, 2-sigma standard deviations ($\pm 2\sigma$) are listed. For other chondrite groups, typical uncertainties of element concentrations are below ten percent; however, for some elements (e.g., C, N, halogens, Cs, Cd, Hg, Ag, In, Tl, Pb, Bi), uncertainties can be considerably larger because of metamorphic redistribution and/or potential loss of these highly volatile elements as well as loss and redistribution of soluble salts (e.g., for halogens). Therefore, for several of these elements values characteristic for low-petrologic (least metamorphosed) types 3-4 are listed for ordinary (H, L, and LL) chondrites.

3 Solar Abundances: Composition of the Present Day Outer Solar Convection Zone, Mainly from the Photosphere

Table 2 gives the composition of the outer solar convection zone as mainly derived from spectroscopy of the solar photosphere. Many, but not all elements can be determined quantitatively in the solar photosphere. The abundance of He is determined by helioseismology (see Lodders 2020 for details). Currently there are two abundance sets to be considered, depending on which solar model atmospheres were used in the evaluation of spectroscopic observations. One set in Table 2 uses traditional 1D solar atmospheric models, the other set uses 3D atmospheric models, which contain more detailed descriptions of the physic in the solar atmosphere. The abundances are given on the logarithmic astronomical abundance scale:

$$A(X) = 12 + \log_{10}(N(X)/N(\mathrm{H})),$$

where the atomic abundance of hydrogen is set to $N(\mathrm{H}) = 1\mathrm{E}12$. The 3D abundances are generally lower than 1D abundances; in particular, the C, N, and O abundances dropped up to

Table 1 Characteristic elemental compositions of major chondritic meteorite groups (parts per million (ppm) by mass, μg/g)

Z	*E*	CI	±2σ	CM	CV	CO	CK	CR	H	L	LL	EH	EL
1	H	18600	3440	11500	2800	1000	4800	4200	800	1260	1700	630	...
2	He	0.00917	…	…	…	…	…	…	…	…	…	…	...
3	Li	1.51	0.12	1.63	1.8	1.8	1.2	…	1.7	1.9	2	1.7	2
4	Be	0.0220	0.0016	0.032	0.04	…	…	…	0.03	0.03	0.037	0.021	...
5	B	0.744	0.172	0.46	0.4	…	…	…	0.45	0.5	0.56	0.93	0.55
6	C	41300	8400	23200	4900	4900	1000	12600	2350	2500	3920	3800	4900
7	N	2500	660	1120	260	370	60	600	70	34	50	600	800
8	O	453840	20000	424100	367800	364200	382600	392700	337400	368400	383700	308000	332100
9	F	92	40	52	44	30	22	…	52	60	58	250	150
10	Ne	1.80E-4	…	…	…	…	…	…	…	…	…	…	...
11	Na	5100	500	4000	3400	4050	3200	2500	6100	6900	6900	7000	6000
12	Mg	95170	4000	119000	147000	145000	146000	136700	139400	148600	153000	108400	139000
13	Al	8370	600	11400	16900	14000	15300	11900	11100	11700	11800	8100	10200
14	Si	107740	7200	132000	159000	158000	158000	150000	170400	184600	189000	167300	190000
15	P	978	120	980	1100	1150	1100	840	1190	1030	980	2200	1200
16	S	53600	4400	30000	21200	21800	16000	16000	20000	22000	21000	56000	33000
17	Cl	717	270	470	280	290	230	…	87	99	126	670	210
18	Ar	0.00133	…	…	…	…	…	…	…	…	…	…	…
19	K	539	48	410	310	360	350	310	760	880	860	850	705
20	Ca	8840	700	12000	18000	15700	16300	13400	12400	13000	13200	8500	10000
21	Sc	5.83	0.40	8.2	11.1	9.5	11	8.3	8.3	8.4	8.3	5.7	7.5
22	Ti	450	30	610	850	750	770	600	630	690	680	480	510
23	V	53.6	4.0	72	92	90	92	74	72	75	76	54	61
24	Cr	2610	200	3090	3600	3550	3620	3640	3500	3660	3680	3140	3200
25	Mn	1896	160	1700	1470	1640	1440	1730	2340	2580	2600	2130	1600
26	Fe	185620	13000	211000	236000	248000	235000	237700	271500	218450	198000	311000	250000
27	Co	508	30	560	640	680	620	640	805	600	480	880	740
28	Ni	10950	700	12500	14000	14100	13200	13600	17100	12700	10200	18700	15400
29	Cu	130	20	129	109	134	100	86	90	95	83	210	120
30	Zn	311	20	177	113	101	90	65	47	54	55	320	16
31	Ga	9.45	0.70	7.5	6.1	7	5.8	4.2	6	5.4	5.2	17	11
32	Ge	33.4	3.0	24	16.5	20	16	11.6	10	11	11	43	30
33	As	1.77	0.16	1.8	1.57	2	1.6	1.5	2.2	1.4	1.3	3.3	2.3
34	Se	20.4	1.6	13	8.7	8	6.9	4.8	8.2	9.2	9.1	27	15
35	Br	3.77	1.80	2.5	1.5	1.6	1.1	1.1	0.7	0.9	1	3.3	1
36	Kr	5.22E-5	…	…	…	…	…	…	…	…	…	…	…
37	Rb	2.22	0.18	1.6	1.2	1.31	1.2	1.1	2.6	2.8	2.7	3.3	2.3
38	Sr	7.79	0.50	10	14.6	13.2	12.3	10	8.7	11	11	7.1	7.9
39	Y	1.50	0.10	2	2.5	2.4	2.7	…	2	2.1	2	1.43	1.6
40	Zr	3.79	0.28	5.2	6.8	6	6.7	5.2	5.7	5.8	6.8	3.8	4.8
41	Nb	0.279	0.015	0.38	0.51	0.43	0.49	[0.44]	0.38	0.4	0.4	0.3	0.25
42	Mo	0.976	0.050	1.2	1.45	1.6	1.4	1.3	1.4	1.2	1.1	1	0.730

Table 1 (*Continued*)

Z	*E*	CI	±2σ	CM	CV	CO	CK	CR	H	L	LL	EH	EL
43	Tc	...	...	...	...	...	...	...	...	...	...	...	...
44	Ru	0.666	0.04	0.86	1.07	1.03	1	0.91	1.1	0.75	0.55	0.91	0.920
45	Rh	0.133	0.008	0.16	0.183	0.17	0.19	0.18	0.22	0.155	0.11	0.17	0.17
46	Pd	0.558	0.030	0.63	0.664	0.76	0.67	0.73	0.845	0.62	0.51	0.91	0.7
47	Ag	0.204	0.008	0.13	0.097	0.1	0.055	0.076	0.06	0.08	0.065	0.29	0.023
48	Cd	0.679	0.024	0.4	0.245	0.25	0.21	0.16	0.04	0.035	0.02	0.83	0.03
49	In	0.0786	0.0040	0.048	0.0303	0.026	0.022	0.018	0.001	0.0005	0.004	0.11	0.005
50	Sn	1.63	0.16	0.93	0.59	0.69	0.47	0.43	0.39	0.4	0.33	1.6	0.68
51	Sb	0.169	0.018	0.13	0.0886	0.114	0.07	0.06	0.071	0.07	0.07	0.22	0.1
52	Te	2.31	0.18	1.6	1.02	0.94	0.8	0.63	0.35	0.4	0.39	2.5	1.1
53	I	0.77	0.62	0.39	0.23	0.19	0.22	...	0.054	0.07	0.16	0.26	0.1
54	Xe	1.74E-4	...	...	...	...	...	...	...	...	...	...	...
55	Cs	0.188	0.012	0.125	0.09	0.07	0.05	0.07	0.12	0.2	0.17	0.24	0.12
56	Ba	2.39	0.16	3.1	4.3	4.1	4.4	3	3.7	3.8	4	2.5	2.3
57	La	0.244	0.016	0.32	0.48	0.384	0.44	0.32	0.301	0.33	0.33	0.226	0.19
58	Ce	0.627	0.052	0.86	1.18	1.08	1.03	0.79	0.763	0.86	0.88	0.602	0.5
59	Pr	0.0951	0.0066	0.13	0.184	0.156	0.15	0.13	0.121	0.13	0.13	0.083	0.08
60	Nd	0.472	0.036	0.64	0.935	0.805	0.85	0.68	0.581	0.67	0.65	0.441	0.39
61	Pm	...	...	...	...	...	...	...	...	...	...	...	...
62	Sm	0.153	0.012	0.207	0.307	0.245	0.27	0.23	0.194	0.203	0.21	0.135	0.14
63	Eu	0.0577	0.0050	0.078	0.111	0.097	0.1	0.085	0.074	0.079	0.08	0.0535	0.051
64	Gd	0.208	0.018	0.287	0.384	0.372	0.36	0.32	0.27	0.3	0.29	0.198	0.185
65	Tb	0.0380	0.0030	0.052	0.069	0.064	0.064	0.057	0.049	0.054	0.055	0.0342	0.034
66	Dy	0.252	0.020	0.345	0.445	0.439	0.43	0.38	0.32	0.36	0.35	0.239	0.24
67	Ho	0.0563	0.0044	0.077	0.095	0.098	...	...	0.074	0.077	0.079	0.0513	0.053
68	Er	0.164	0.012	0.221	0.277	0.285	0.27	0.25	0.213	0.23	0.23	0.161	0.16
69	Tm	0.0259	0.0024	0.035	0.049	0.042	0.045	0.039	0.033	0.033	0.035	0.0245	0.027
70	Yb	0.167	0.014	0.225	0.313	0.272	0.3	0.25	0.203	0.226	0.23	0.162	0.18
71	Lu	0.0249	0.0020	0.035	0.045	0.042	0.044	0.036	0.033	0.034	0.034	0.0230	0.028
72	Hf	0.106	0.008	0.15	0.181	0.187	0.18	0.15	0.15	0.17	0.17	0.102	0.15
73	Ta	0.0148	0.0014	0.02	0.029	...	0.027	...	0.021	0.021	...	0.013	...
74	W	0.102	0.014	0.13	0.17	0.15	0.14	0.14	0.17	0.15	0.1	0.13	0.16
75	Re	0.0369	0.0028	0.049	0.065	0.056	0.054	0.048	0.074	0.055	0.032	0.052	0.06
76	Os	0.475	0.020	0.65	0.819	0.773	0.81	0.65	0.83	0.56	0.39	0.61	0.72
77	Ir	0.474	0.020	0.59	0.76	0.739	0.72	0.63	0.76	0.52	0.36	0.57	0.6
78	Pt	0.931	0.072	1.1	1.36	1.27	1.3	1.2	1.58	1.08	0.88	1.19	1.35
79	Au	0.147	0.024	0.152	0.146	0.186	0.12	0.15	0.22	0.16	0.14	0.34	0.26
80	Hg	0.288	0.140	...	0.035	0.05	0.007	...	...	0.002	0.022	0.06	...
81	Tl	0.141	0.014	0.088	0.061	0.04	...	0.042	0.004	0.002	0.002	0.095	0.007
82	Pb	2.64	0.16	1.76	1.08	0.84	0.75	0.47	0.14	0.06	0.06	2.24	0.24
83	Bi	0.113	0.016	0.07	0.05	0.041	0.031	0.044	0.009	0.004	0.012	0.084	0.012
90	Th	0.0298	0.0030	0.042	0.059	0.046	0.059	0.041	0.040	0.04	0.046	0.029	0.031
92	U	0.00816	0.00106	0.011	0.016	0.014	0.014	0.012	0.013	0.013	0.013	0.0095	0.008

30% from values considered 30-40 years ago. These lower abundances caused concerns for solar models, and this issue is currently still under investigation – see, e.g., Asplund et al. (2009), Grevesse et al. (2015), Scott et al. (2015a, 2015b), Lodders (2020). The (earlier) good agreement of 1D photospheric abundances with the meteoritic abundances of several non-volatile elements was no longer present with the early 3D abundances (Asplund et al. 2009), and disagreements persist for several elements in subsequent updates (Grevesse et al. 2015; Scott et al. 2015a, 2015b). There were also differences in some 3D results by different groups which were mainly due to different line selections (e.g., Asplund et al. 2009, Caffau et al. 2011). The latest 3D analyses employing important corrections for non-local thermodynamic equilibrium (NLTE) are moving closer to meteoritic values again (see references to individual elements in the following). The recommended 1D photospheric abundances are from Alexeeva and Mashonkina 2015; Holweger 2001; Grevesse et al. 2015, Lawler et al. 2014, 2017, 2018, 2019; Scott et al. 2015a, 2015b, Sneden et al. 2009, 2016, and Zhao et al. 2016. The recommended 3D abundances are largely from Caffau et al. 2011; Grevesse et al. 2015, and Scott et al. 2015a, 2015b, plus Amarsi et al. 2018 (O), Caffau et al. 2015 (O), Amarsi and Asplund 2017 (Si), Amarsi et al. 2019 (C), Caffau et al. 2011 (C), Bergemann et al. 2017 (Mg), Bergemann et al. 2019 (Mn), Lind et al. 2017 (Fe), Nordlander and Lind 2017 (Al). Sunspot data are from Maas et al. 2016 (Cl), Maiorca et al. 2014 (F), Vitas et al. 2008 (In). For more information, see Lodders (2020).

Indirect determinations provide data for the noble gases. The helium abundance is estimated from helioseismology (see Lodders 2020 and references therein). Related to the He abundance are the mass fractions of H, He, and the combined mass fraction of all other elements, called X, Y, and Z in the astronomical literature (see also Table 4 below). Mass fractions for the recommended 3D composition are: $X = 0.7389$ (Basu and Antia 2004), $Y = 0.2462$ for $Z = 0.0149$ and $Z/X = 0.0201$. Mass fractions for the recommended 1D composition are: $X = 0.7389$ (Basu and Antia 2004), $Y = 0.2458$ for $Z = 0.0153$ and $Z/X = 0.0207$. The neon abundance is estimated using solar wind and coronal Ne/O ratios from Young (2018) using oxygen abundances recommended here. The Ne abundance is still uncertain and debatable. The Ar abundance is from solar wind, B-stars and other considerations, see Lodders (2008). Krypton and xenon abundances are estimated from nuclear systematics, see Lodders (2003, 2020). Photospheric abundances of A(Ne) $= 8.060 \pm 0.033$ and A(Ar) $= 6.38 \pm 0.12$ from solar wind Genesis data (Huss et al. 2020) were not included when Table 2 was assembled.

4 Protosolar or Solar System Abundances from Solar and Meteoritic Data

Table 3 gives the atomic abundances of the solar photosphere, CI-chondrites, and the protosolar solar system composition. The Table is organized as follows. Columns (1) and (2) give atomic numbers and the element symbols. Columns (3)-(10) contain the atomic abundances of the elements on the cosmochemical abundance scale $N(X)$ where the amount of silicon is set to one million: $N(\text{Si}) = 1\text{E}+6$. Uncertainties are 1-sigma. The data for CI chondrites (columns (3) and (4)) are from Table 1 and are converted using the atomic weights listed in Table 4. The solar data in columns (5) and (6) are mainly from spectroscopic values of the photosphere, and are representative for the outer solar convection zone. Here the 3D photospheric results are adopted.

The present and protosolar compositions are in columns (7)-(8) and (9)-(10), respectively. Column (11) indicates how the values were selected: No entry means the values are based on

Table 2 Abundances in the Sun's outer convection zone mainly from photospheric and sunspot abundances, and solar wind and indirect data

Z	E	Recommended 3D		Recommended 1D	
		$A(E)$	$\pm a$	$A(E)$	$\pm a$
1	H	12		12	
2	He	[10.924]in	0.02	[10.923]in	0.02
3	Li	1.04	0.10	1.04	0.10
4	Be	1.38	0.09	1.38	0.09
5	B	2.70	0.20	2.70	0.20
6	C	8.47	0.06	8.58	0.11
7	N	7.85	0.12	8.00	0.11
8	O	8.71	0.04	8.76	0.06
9	F	[4.40]sp	0.25	[4.40]sp	0.25
10	Ne	[8.15]in	0.10	[8.10]in	0.10
11	Na	6.21	0.04	6.28	0.04
12	Mg	7.56	0.05	7.50	0.05
13	Al	6.43	0.04	6.41	0.03
14	Si	7.51	0.03	7.52	0.06
15	P	5.41	0.03	5.42	0.03
16	S	7.15	0.05	7.12	0.05
17	Cl	[5.25]sp	0.12	[5.25]sp	0.12
18	Ar	[6.50]in	0.10	[6.50]in	0.10
19	K	5.04	0.05	5.10	0.07
20	Ca	6.32	0.03	6.34	0.06
21	Sc	3.16	0.04	3.15	0.06
22	Ti	4.93	0.04	4.97	0.04
23	V	3.89	0.08	3.96	0.04
24	Cr	5.62	0.04	5.62	0.07
25	Mn	5.52	0.03	5.45	0.05
26	Fe	7.48	0.04	7.52	0.05
27	Co	4.93	0.05	4.96	0.06
28	Ni	6.20	0.04	6.28	0.06
29	Cu	4.18	0.05	4.21	0.03
30	Zn	4.56	0.05	4.61	0.09
31	Ga	3.02	0.05	3.09	0.05
32	Ge	3.63	0.07	3.62	0.07
33	As	...		...	
34	Se	...		...	
35	Br	...		...	
36	Kr	[3.25]in	0.08	[3.25]in	0.08
37	Rb	2.47	0.07	2.57	0.07
38	Sr	2.83	0.06	2.92	0.05
39	Y	2.21	0.05	2.20	0.05
40	Zr	2.59	0.04	2.59	0.06
41	Nb	1.47	0.06	1.49	0.06
42	Mo	1.88	0.09	2.04	0.05
43	Tc	...		...	

Table 2 (*Continued*)

Z	E	Recommended 3D		Recommended 1D	
		$A(E)$	$\pm a$	$A(E)$	$\pm a$
44	Ru	1.75	0.08	1.91	0.10
45	Rh	0.89	0.08	1.07	0.08
46	Pd	1.55	0.06	1.61	0.06
47	Ag	0.96	0.1	1.04	0.10
48	Cd	1.77	0.15	1.79	0.15
49	In	...		[0.8]sp	0.20
50	Sn	2.02	0.1	2.04	0.10
51	Sb	...		...	
52	Te	...		...	
53	I	...		...	
54	Xe	[2.25]in	0.08	[2.25]in	0.08
55	Cs	...		...	
56	Ba	2.25	0.07	2.19	0.07
57	La	1.11	0.04	1.14	0.03
58	Ce	1.58	0.04	1.61	0.06
59	Pr	0.72	0.04	0.76	0.04
60	Nd	1.42	0.04	1.45	0.05
61	Pm	...	...	...	...
62	Sm	0.95	0.04	1.00	0.05
63	Eu	0.52	0.04	0.52	0.04
64	Gd	1.08	0.04	1.11	0.05
65	Tb	0.31	0.1	0.28	0.10
66	Dy	1.1	0.04	1.13	0.06
67	Ho	0.48	0.11	0.51	0.10
68	Er	0.93	0.05	0.96	0.06
69	Tm	0.11	0.04	0.14	0.04
70	Yb	0.85	0.11	0.86	0.10
71	Lu	0.1	0.09	0.12	0.08
72	Hf	0.85	0.05	0.88	0.03
73	Ta	...		...	
74	W	0.83	0.11	1.03	0.11
75	Re	...		...	
76	Os	1.4	0.05	1.5	0.05
77	Ir	1.42	0.07	1.46	0.07
78	Pt	...		...	
79	Au	0.91	0.08	0.93	0.08
80	Hg	...		...	
81	Tl	...		[0.95]sp	[0.2]
82	Pb	1.92	0.08	2.05	0.08
83	Bi	...		...	
90	Th	$\leq$0.03	uncert.	$\leq$0.07	uncert.
92	U	...		...	

Abundances from photospheric data unless indicated by "in" for indirect determinations or by "sp" for sunspot data

Table 3 Recommended atomic solar system abundances: present and proto-solar 4.567 Ga ago (see text for data sources)

		CI-Chondrites		Sun, Outer Convection Zone, mainly photosphere, 3D		Solar system* (present)		Solar system* (proto-solar)†, ‡			Solar system* (present)		Solar system (proto-solar)†, ‡	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Z	E	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	Note	$A(E)$	$\pm a$	$A(E)$	$\pm a$
1	H	4.83E+6	4.5E+5	3.09E+10		3.09E+10		2.52E+10		s	12		12	
2	He	0.599		2.59E+9	1.2E+8	2.59E+9	1.2E+8	2.51E+9	1.2E+8	s	10.924	0.02	10.994	0.02
3	Li	56.9	3.4	0.339	0.088	0.339	0.088	56.9	3.4		3.27	0.03	3.35	0.03
4	Be	0.637	0.044	0.741	0.171	0.637	0.044	0.637	0.044		1.31	0.04	1.40	0.04
5	B	18	1.3	15.5	9.1	18	1.3	18	1.3		2.77	0.03	2.85	0.03
6	C	9.44E+5	1.79E+5	9.12E+6	1.35E+6	9.12E+6	1.8E+5	9.12E+6	1.8E+5	s	8.47	0.06	8.56	0.06
7	N	44830	9700	2.19E+6	7.0E+5	2.19E+6	9700	2.19E+6	9700	s	7.85	0.12	7.94	0.12
8	O	7.38E+6	1.3E+5	1.66E+7	2.9E+6	1.66E+7	1.3E+5	1.66E+7	1.3E+5	s	8.73	0.07	8.82	0.07
9	F	1270	275	780	600	1270	275	1270	275		4.61	0.09	4.79	0.09
10	Ne	0.00234		4.37E+6	1.13E+6	4.37E+6	1.13E+6	4.37E+6	1.13E+6	s,o	8.15	0.10	8.24	0.10
11	Na	57800	4700	50120	4840	57800	4700	57800	4700		6.27	0.03	6.36	0.03
12	Mg	1.03E+6	4.4E+4	1.12E+6	1.4E+5	1.03E+6	4.4E+4	1.03E+6	4.4E+4		7.52	0.02	7.61	0.02
13	Al	81820	6110	83180	8030	81820	6110	81820	6110		6.42	0.03	6.51	0.03
14	Si	1.00E+6	3.4E+4	1.00E+6	7E+4	1.00E+6	3.4E+4	1.00E+6	3.4E+4		7.51	0.01	7.60	0.01
15	P	8260	530	8430	810	8260	530	8260	530		5.43	0.03	5.52	0.03
16	S	4.37E+5	2.6E+4	4.37E+5	5.3E+4	4.37E+5	2.6E+4	4.37E+5	2.6E+4		7.15	0.03	7.24	0.03
17	Cl	5290	810	5495	1750	5290	810	5290	810		5.23	0.06	5.32	0.06
18	Ar	0.00959		...		97700	25300	97700	25300	s,o	6.50	0.10	6.59	0.10
19	K	3610	190	3685	850	3606	190	3611	190		5.07	0.02	5.16	0.02
20	Ca	57239	4500	64565	4620	57239	4500	57234	4500		6.27	0.03	6.36	0.03
21	Sc	33.7	2.2	44.7	4.3	33.7	2.2	33.7	2.2		3.04	0.03	3.13	0.03
22	Ti	2460	150	2630	254	2459	150	2459	150		4.90	0.03	4.99	0.03

Table 3 (*Continued*)

		CI-Chondrites		Sun, Outer Convection Zone, mainly photosphere, 3D		Solar system* (present)		Solar system* (proto-solar)†, ‡			Solar system* (present)		Solar system (proto-solar)†, ‡	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Z	E	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	Note	$A(E)$	$\pm a$	$A(E)$	$\pm a$
23	V	275	18	240	49	275	18	275	18		3.95	0.03	4.04	0.03
24	Cr	13130	460	12880	1240	13130	460	13130	460		5.63	0.02	5.72	0.02
25	Mn	9090	620	10230	730	9090	620	9090	620		5.47	0.03	5.56	0.03
26	Fe	8.72E+5	3.8E+4	9.33E+5	9.0E+4	8.72E+5	3.8E+4	8.72E+5	3.8E+4		7.45	0.02	7.54	0.02
27	Co	2260	100	2630	320	2260	100	2260	100		4.86	0.02	4.95	0.02
28	Ni	48670	2940	48980	4730	48670	2940	48670	2940		6.20	0.03	6.29	0.03
29	Cu	535	50	468	57	535	50	535	50		4.24	0.04	4.33	0.04
30	Zn	1260	180	1120	140	1260	180	1260	180		4.61	0.60	4.70	0.60
31	Ga	36.2	1.8	32.4	3.9	36.2	1.8	36.2	1.8		3.07	0.02	3.16	0.02
32	Ge	120	7	132	23	120	7	120	7		3.59	0.03	3.68	0.03
33	As	6.07	0.50	…		6.07	0.50	6.07	0.50		2.29	0.03	2.38	0.03
34	Se	67.6	5.0	…		67.6	5.0	67.6	5.0		3.34	0.03	3.43	0.03
35	Br	12.3	2.9	…		12.3	2.9	12.3	2.9		2.60	0.09	2.69	0.09
36	Kr	1.63E-04		…		51.3	10.4	51.3	10.4	o	3.22	0.08	3.31	0.08
37	Rb	7.04	0.46	9.12	1.60	7.04	0.46	7.17	0.47		2.36	0.03	2.45	0.03
38	Sr	23.4	1.3	20.9	3.1	23.4	1.3	23.3	1.3		2.88	0.02	2.97	0.02
39	Y	4.35	0.24	5.01	0.61	4.35	0.24	4.35	0.24		2.15	0.02	2.24	0.02
40	Zr	10.9	1.0	12.5	1.84	10.9	1.0	10.9	1.0		2.55	0.04	2.64	0.04
41	Nb	0.780	0.070	0.912	0.135	0.78	0.070	0.78	0.070		1.4	0.04	1.49	0.04
42	Mo	2.6	0.26	2.34	0.54	2.6	0.26	2.6	0.26		1.92	0.04	2.01	0.04
43	Tc	…		…		…		…				…		…
44	Ru	1.81	0.02	1.74	0.35	1.81	0.02	1.81	0.02		1.77	0.01	1.86	0.01

Table 3 (*Continued*)

		CI-Chondrites		Sun, Outer Convection Zone, mainly photosphere, 3D		Solar system* (present)		Solar system* (proto-solar)†, ‡			Solar system* (present)		Solar system (proto-solar)†, ‡	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Z	E	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	Note	$A(E)$	$\pm a$	$A(E)$	$\pm a$
45	Rh	0.338	0.015	0.240	0.049	0.338	0.015	0.338	0.015		1.04	0.02	1.13	0.02
46	Pd	1.38	0.07	1.10	0.16	1.38	0.07	1.38	0.07		1.65	0.02	1.74	0.02
47	Ag	0.497	0.022	0.282	0.073	0.497	0.022	0.497	0.022		1.21	0.02	1.29	0.02
48	Cd	1.58	0.06	1.82	0.75	1.58	0.06	1.58	0.06		1.71	0.02	1.80	0.02
49	In	0.179	0.008	0.195	0.114	0.179	0.008	0.179	0.008		0.76	0.02	0.85	0.02
50	Sn	3.59	0.22	3.24	0.84	3.59	0.22	3.59	0.22		2.07	0.03	2.15	0.03
51	Sb	0.359	0.045	...		0.359	0.045	0.359	0.045		1.06	0.05	1.15	0.05
52	Te	4.72	0.23	...		4.72	0.23	4.72	0.23		2.18	0.02	2.27	0.02
53	I	1.59	0.64	...		1.59	0.64	1.59	0.64		1.71	0.15	1.80	0.15
54	Xe	3.47E-04		...		5.50	1.11	5.50	1.11	o	2.25	0.08	2.34	0.08
55	Cs	0.368	0.043	...		0.368	0.043	0.368	0.043		1.08	0.02	1.16	0.02
56	Ba	4.55	0.27	5.5	0.92	4.55	0.27	4.55	0.27		2.17	0.02	2.26	0.02
57	La	0.459	0.024	0.398	0.038	0.459	0.024	0.459	0.024		1.17	0.02	1.26	0.02
58	Ce	1.16	0.05	1.17	0.11	1.16	0.05	1.16	0.05		1.58	0.02	1.66	0.02
59	Pr	0.175	0.012	0.162	0.016	0.175	0.012	0.175	0.012		0.75	0.01	0.84	0.01
60	Nd	0.865	0.022	0.813	0.078	0.865	0.022	0.864	0.022		1.45	0.01	1.53	0.01
61	Pm	...		...		...		...				...		...
62	Sm	0.271	0.012	0.275	0.027	0.271	0.012	0.273	0.012		0.94	0.02	1.03	0.02
63	Eu	0.100	0.005	0.102	0.010	0.1	0.005	0.1	0.005		0.51	0.02	0.60	0.02
64	Gd	0.346	0.013	0.372	0.036	0.346	0.013	0.346	0.013		1.05	0.02	1.14	0.02
65	Tb	0.0625	0.0025	0.0631	0.0163	0.0625	0.0025	0.0625	0.0025		0.31	0.02	0.39	0.02
66	Dy	0.407	0.016	0.389	0.038	0.407	0.016	0.407	0.016		1.12	0.02	1.21	0.02

Table 3 (*Continued*)

		CI-Chondrites		Sun, Outer Convection Zone, mainly photosphere, 3D		Solar system* (present)		Solar system* (proto-solar)†, ‡			Solar system* (present)		Solar system (proto-solar)†, ‡	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Z	E	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	$N(E)$	$\pm\sigma$	Note	$A(E)$	$\pm a$	$A(E)$	$\pm a$
67	Ho	0.0891	0.0035	0.0933	0.0269	0.0891	0.0035	0.0891	0.0035		0.46	0.02	0.55	0.02
68	Er	0.256	0.009	0.263	0.032	0.256	0.009	0.256	0.009		0.92	0.02	1.01	0.02
69	Tm	0.0403	0.0014	0.0398	0.0038	0.0403	0.0014	0.0403	0.0014		0.11	0.02	0.20	0.02
70	Yb	0.252	0.009	0.219	0.063	0.252	0.009	0.252	0.009		0.91	0.02	1.00	0.02
71	Lu	0.038	0.0018	0.0389	0.0090	0.038	0.0018	0.0381	0.0018		0.09	0.02	0.18	0.02
72	Hf	0.155	0.011	0.219	0.027	0.155	0.011	0.155	0.011		0.70	0.03	0.79	0.03
73	Ta	0.0215	0.0010	...		0.0215	0.0010	0.0215	0.0010		-0.16	0.02	-0.07	0.02
74	W	0.144	0.013	0.209	0.060	0.144	0.013	0.144	0.013		0.67	0.04	0.76	0.04
75	Re	0.0521	0.0042	...		0.0521	0.0042	0.0547	0.0042		0.23	0.03	0.34	0.03
76	Os	0.655	0.040	0.776	0.095	0.655	0.040	0.652	0.040		1.33	0.03	1.41	0.03
77	Ir	0.633	0.029	0.813	0.142	0.633	0.029	0.633	0.029		1.31	0.02	1.40	0.02
78	Pt	1.24	0.10	...		1.24	0.10	1.24	0.10		1.60	0.03	1.69	0.03
79	Au	0.195	0.016	0.251	0.051	0.195	0.016	0.195	0.016		0.80	0.03	0.89	0.03
80	Hg	0.376	0.156	...		0.376	0.156	0.376	0.156		1.08	0.15	1.17	0.15
81	Tl	0.179	0.015	0.275	0.161	0.179	0.015	0.179	0.015		0.76	0.04	0.85	0.04
82	Pb	3.33	0.20	2.57	0.52	3.33	0.20	3.31	0.20		2.03	0.03	2.12	0.03
83	Bi	0.141	0.010	...		0.141	0.010	0.141	0.010		0.66	0.03	0.75	0.03
90	Th	0.0336	0.0017	> 0.033		0.0336	0.0017	0.0421	0.0021		0.04	0.02	0.22	0.02
92	U	0.00897	0.00064	...		0.00897	0.00064	0.02389	0.00170		-0.54	0.03	-0.02	0.03

Note. *based on CI-chondrites except as indicated: s = from sun, o = by other means

†corrected for radioactive decay. ‡present day photospheric values corrected for element settling from the outer convection zone to obtain protosolar values

CI-chondrites, "*s*" means data are from the Sun, and "*o*" indicates the data were derived by other means such as nucleosynthesis theory (see Lodders 2020 for details). The protosolar abundances (subscript "*o*" contain corrections for gain or loss of isotopes due to radioactive decay, and corrections to the present day photospheric values to take losses from continuous element settling from the outer convection zone into the solar interior into account (see also notes for Table 4). For convenience, the solar system data are also given on the astronomical abundance scale in columns (12)-(15). For practical purposes, the abundance scales are linked through the abundance of Si as:

$$A(E) = 1.510 + \log_{10} N(E) \text{ for the present-day abundances, and}$$

$$A(E)o = 1.598 + \log_{10} N(E) = 0.088 + A(E) \text{ for the proto-solar abundances except for H and He.}$$

For a detailed explanation and issues with the scaling see Lodders (2003, 2020), Lodders et al. (2009). The conversion of the uncertainties (U, in percent) from the linear cosmochemical scale to the logarithmic astronomical abundance scale (where the uncertainty corresponds to an uncertainty factor "a") can be done using:

$$U(\%) = \pm 100(10^{\pm a} - 1)$$

The percent uncertainty is smaller for $-a$ than for $+a$; or vice versa, a given percent uncertainty on the linear scale results in two different uncertainty factors on the logarithmic scale. Here the larger percentage U from a given uncertainty of "a" or the larger uncertainty "a" from a given U is taken (see Lodders 2003).

5 Atomic Abundances and Mass Fractions of the Isotopes in the Solar System and Atomic Weights of the Elements

Table 4 gives the proto-solar (solar system) isotopic composition of the elements, isotopic and elemental abundances relative to 1E6 silicon atoms, mass fractions of the isotopes in the overall proto-solar composition, atomic masses of the isotopes, and resulting protosolar and current mean atomic weights of the elements.

The first three columns of Table 2 list the element symbol, atomic number or charge number (Z), and mass number (A). Entries in column (1) marked with $*$ are long-lived radioactive nuclides with half-lives up to 10^{12} years and abundances are for 4.567 Ga ago. Isotopes with half-lives above 10^{12} years (marked with ˆ) can be regarded as stable compared to the age of the solar system and are of interest in studies of double-beta decay.

Column (4) gives the isotopic composition (in atom %) of each element for the protosolar composition 4.567 Ga ago. The isotopic compositions are mainly adopted from Meija et al. (2016). The sources for the isotopic compositions of H, C, N, O, and the noble gases are described below. Several elements (e.g., C, N, O, Ar) have different isotopic compositions in the Sun (taken as representative for the solar system composition) than on Earth. For radioactive isotopes and their stable decay products, the protosolar isotopic compositions differ from present-day values and the listed composition considers decay of radioactive isotopes and gain in stable isotopes over the past 4.567 Ga.

Column (5) gives the relative atomic *elemental* abundances on the cosmochemical abundance scale where the silicon abundance is fixed at $N(\text{Si}) = 1\text{E6}$ atoms. These are the same data as in Table 1 for the proto-solar abundances.

Table 4 Proto-Solar Isotopic Composition of the Elements, Isotopic and Elemental Abundances Relative to 1E6 Silicon Atoms, Mass Fractions of the Isotopes in the Overall Proto-Solar Composition, Atomic Masses of the Isotopes, and Resulting Protosolar and Current Mean Atomic Weights of the Elements (see text for data sources)

E (1)	*Z* (2)	*A* (3)	Isotopic composition atom % (4)	*N* (Elemental) Si = 1E+6 (5)	*N* (Isotopic) ΣSi = 1E+6 (6)	Elemental mass fractions (7)	Isotope mass fractions (8)	Atomic mass (Daltons, Da) (9)	Protosolar mean atomic mass (Da) (10)	Current mean atomic mass (Da) (11)
H	1	1	99.9980		2.52E+10		7.057E-01	1.007825032		
H	1	2	0.00197		4.97E+5		2.781E-05	2.014101778		
			100	2.52E+10		7.057E-01			1.007844856	1.007825032
He	2	3	0.0166		4.13E+5		3.461E-05	3.01602932		
He	2	4	99.9834		2.49E+9		2.769E-01	4.002603254		
			100	2.49E+9		2.770E-01			4.002439456	4.002198759
Li	3	6	7.589		4.3		7.187E-10	6.015122885		
Li	3	7	92.411		52.6		1.025E-08	7.016003428		
			100	56.9		1.097E-08			6.940046604	6.940046604
Be	4	9	100	0.637	0.637	1.595E-10	1.595E-10	9.01218291	9.01218291	9.01218291
B	5	10	19.827		3.6		1.002E-09	10.01293696		
B	5	11	80.173		14.4		4.405E-09	11.00930537		
			100	18.0		5.406E-09			10.81175541	10.81175541
C	6	12	98.965		9.03E+6		3.011E-03	12.00000000		
C	6	13	1.035		9.44E+4		3.411E-05	13.00335484		
			100	9.12E+6		3.045E-03			12.01038885	12.01038885
N	7	14	99.774		2.18E+6		8.482E-04	14.003074		
N	7	15	0.226		4.94E+3		2.059E-06	15.0001089		
			100	2.19E+6		8.502E-04			14.00532465	14.00532465
O	8	16	99.777		1.66E+7		7.377E-03	15.99491462		
O	8	17	0.035		5.80E+3		2.739E-06	16.99913176		
O	8	18	0.188		3.13E+4		1.565E-05	17.99915961		
			100	1.66E+7		7.396E-03			15.99904151	15.99904151

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
F	9	19	100	1267	1267	6.688E-07	6.688E-07	18.99840317	18.99840317	18.99840317
Ne	10	20	93.1251		4.07E+6		2.261E-03	19.99244018		
Ne	10	21	0.2236		9.76E+3		5.693E-06	20.99384668		
Ne	10	22	6.6513		2.90E+5		1.772E-04	21.99138512		
			100	4.37E+6		2.444E-03			20.12763505	20.12763505
Na	11	23	100	57800	57800	3.692E-05	3.692E-05	22.98976928	22.98976928	22.98976928
Mg	12	24	78.992		8.10E+5		5.398E-04	23.9850417		
Mg	12	25	10.003		1.03E+5		7.151E-05	24.98583691		
Mg	12	26	11.005		1.13E+5		8.158E-05	25.98259295		
			100	1.03E+6		6.929E-04			24.30498176	24.30498176
Al	13	27	100	8.18E+4	8.18E+04	6.132E-05	6.132E-05	26.98153859		
Si	14	28	92.230		9.223E+5		7.167E-04	27.97692653		
Si	14	29	4.683		4.683E+4		3.768E-05	28.97649467		
Si	14	30	3.087		3.087E+4		2.573E-05	29.97377017		
			100	1.000E+6		7.801E-04			28.08538367	28.08538367
P	15	31	100		8260	7.109E-06	7.109E-06	30.973762	30.973762	30.973762
S	16	32	95.04074		415600		3.692E-04	31.97207117		
S	16	33	0.74869		3270		2.996E-06	32.97145569		
S	16	34	4.19599		18300		1.727E-05	33.9678669		
S	16	36	0.01458		64		6.396E-08	35.96708076		
			100	437300		3.895E-04			32.06387933	32.06387933
Cl	17	35	75.7647		4010		3.896E-06	34.96885268		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Cl	17	37	24.2353		1280		1.315E-06	36.96590259		
			100	5290		5.211E-06			35.45284372	35.45284372
Ar	18	36	84.596		82670		8.265E-05	35.96754511		
Ar	18	38	15.830		15030		1.582E-05	37.96273234		
Ar	18	40	0.025		23.5		2.609E-08	39.96238312		
			100	97724		9.850E-05			36.27537813	36.27535886
K	19	39	93.132		3363		3.638E-06	38.96370649		
K*	19	40	0.147		5		5.552E-09	39.96399848		
K	19	41	6.721		243		2.766E-07	40.96182526		
			100	3611		3.920E-06			39.09946879	39.09830181
Ca	20	40	96.941		55500		6.163E-05	39.96259086		
Ca	20	42	0.647		370		4.314E-07	41.95861801		
Ca	20	43	0.135		77		9.191E-08	42.95876667		
Ca	20	44	2.086		1194		1.458E-06	43.95548173		
Ca	20	46	0.004		2		2.554E-09	45.9536926		
Ca	20	48	0.187		107		1.426E-07	47.9525343		
			100	57200		6.375E-05			40.07802253	40.07802253
Sc	21	45	100	33.7	3.370E+01	4.209E-08	4.209E-08	44.9559119	44.9559119	44.9559119
Ti	22	46	8.249		203		2.592E-07	45.95262889		
Ti	22	47	7.437		183		2.387E-07	46.95176293		
Ti	22	48	73.72		1810		2.411E-06	47.94794631		
Ti	22	49	5.409		133		1.809E-07	48.94786998		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ti	22	50	5.185		128		1.776E-07	49.94479117		
			100	2460		3.268E-06			47.8668887	47.8668887
V	23	50	0.2497		0.7		9.715E-10	49.9471585		
V	23	51	99.7503		274.5		3.886E-07	50.9439595		
			100	275.2		3.895E-07			50.94147049	50.94147049
Cr	24	50	4.3452		571		7.924E-07	49.9460442		
Cr	24	52	83.7895		11000		1.587E-05	51.94050751		
Cr	24	53	9.5006		1250		1.839E-06	52.94064943		
Cr	24	54	2.3647		310		4.646E-07	53.93888045		
			100	13100		1.897E-05			51.9961191	51.9961191
Mn	25	55	100	9090	9090	1.388E-05	1.388E-05	54.93804512	54.93804512	54.93804512
Fe	26	54	5.845		51000		7.643E-05	53.93961046		
Fe	26	56	91.754		8.01E+5		1.245E-03	55.93493745		
Fe	26	57	2.1191		18500		2.927E-05	56.93539427		
Fe	26	58	0.2819		2460		3.960E-06	57.93327558		
			100	8.73E+5		1.355E-03			55.84514458	55.84514458
Co	27	59	100	2260	2260	3.701E-06	3.701E-06	58.93319506	58.93319506	58.93319506
Ni	28	58	68.0769		33100		5.328E-05	57.9353435		
Ni	28	60	26.2231		12800		2.131E-05	59.93078635		
Ni	28	61	1.1399		555		9.396E-07	60.93105603		
Ni	28	62	3.6345		1770		3.046E-06	61.92834511		
Ni	28	64	0.9256		450		7.993E-07	63.92796594		
			100	48700		7.938E-05			58.69335196	58.69335196

Table 4 (*Continued*)

E (1)	*Z* (2)	*A* (3)	Isotopic composition atom % (4)	*N* (Elemental) Si = 1E+6 (5)	*N* (Isotopic) ΣSi = 1E+6 (6)	Elemental mass fractions (7)	Isotope mass fractions (8)	Atomic mass (Daltons, Da) (9)	Protosolar mean atomic mass (Da) (10)	Current mean atomic mass (Da) (11)
Cu	29	63	69.174		370		6.469E-07	62.92959751		
Cu	29	65	30.826		165		2.977E-07	64.92778945		
			100	535		9.446E-07			63.54556016	63.54556016
Zn	30	64	49.1704		620		1.101E-06	63.92914224		
Zn	30	66	27.7306		349		6.393E-07	65.92603345		
Zn	30	67	4.0401		51		9.484E-08	66.92712739		
Zn	30	68	18.4483		233		4.397E-07	67.9248442		
Zn	30	70	0.6106		8		1.554E-08	69.9253193		
			100	1260		2.291E-06			65.37776549	65.37776549
Ga	31	69	60.108		21.7		4.156E-08	68.9255735		
Ga	31	71	39.892		14.4		2.838E-08	70.9247026		
			100	36.2		6.994E-08			69.72306808	69.72306808
Ge	32	70	20.526		24.7		4.799E-08	69.9242474		
Ge	32	72	27.446		33.0		6.595E-08	71.9220758		
Ge	32	73	7.76		9.3		1.884E-08	72.9234589		
Ge	32	74	36.523		43.9		9.017E-08	73.92117777		
Ge	32	76	7.745		9.3		1.962E-08	75.92140273		
			100	120		2.426E-07			72.62958875	72.62958875
As	33	75	100	6.07	6.07	1.264E-08	1.264E-08	74.9215965	74.9215965	74.9215965
Se	34	74	0.86		0.58		1.191E-09	73.92247594		
Se	34	76	9.22		6.23		1.314E-08	75.91921372		
Se	34	77	7.59		5.13		1.096E-08	76.919914		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Se	34	78	23.69		16.00		3.464E-08	77.9173091		
Se	34	80	49.81		33.66		7.474E-08	79.9165213		
Se	34	82	8.83		5.96		1.357E-08	81.9166994		
			100	67.6		1.482E-07			78.97168088	78.97168088
Br	35	79	50.686		6.26		1.373E-08	78.9183371		
Br	35	81	49.314		6.09		1.369E-08	80.9162906		
			100	12.3		2.742E-08			79.90360789	79.90360789
Kr	36	78	0.362		0.19		4.114E-10	77.92036486		
Kr	36	80	2.326		1.20		2.665E-09	79.91637915		
Kr	36	82	11.655		5.99		1.363E-08	81.91348282		
Kr	36	83	11.546		5.94		1.368E-08	82.9141271		
Kr	36	84	56.903		29.18		6.803E-08	83.91149717		
Kr	36	86	17.208		8.79		2.098E-08	85.91061067		
			100	51.3		1.194E-07			83.79283539	83.7896357
Rb	37	85	70.844		5.080		1.199E-08	84.91178974		
Rb*	37	87	29.156		2.091		5.049E-09	86.90918054		
			100	7.17		1.703E-08			85.4941539	85.46775548
Sr	38	84	0.5584		0.13		3.031E-10	83.9134203		
Sr	38	86	9.8708		2.30		5.490E-09	85.9092602		
Sr	38	87	6.8982		1.61		3.888E-09	86.9088771		
Sr	38	88	82.6725		19.2		4.690E-08	87.9056122		
			100	23.3		5.658E-08			87.61750433	87.61352847

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Y	39	89	100	4.35	4.35	1.075E-08	1.075E-08	88.9058483		
Zr	40	90	51.452		5.621		1.404E-08	89.9047044		
Zr	40	91	11.223		1.226		3.097E-09	90.9056458		
Zr	40	92	17.146		1.873		4.783E-09	91.9050408		
Zr	40	94	17.38		1.899		4.955E-09	93.9063152		
Zr^	40	96	2.799		0.306		8.154E-10	95.9082734		
			100	10.92		2.769E-08			91.22353759	91.22353759
Nb	41	93	100	0.780	0.780	2.014E-09	2.014E-09	92.9063781	92.9063781	92.9063781
Mo	42	92	14.525		0.380		9.704E-10	91.90680811		
Mo	42	94	9.151		0.238		6.210E-10	93.9050856		
Mo	42	95	15.838		0.412		1.086E-09	94.9058394		
Mo	42	96	16.672		0.433		1.154E-09	95.90467712		
Mo	42	97	9.599		0.249		6.704E-10	96.9060196		
Mo	42	98	24.391		0.630		1.714E-09	97.9054058		
Mo^	42	100	9.824		0.253		7.023E-10	99.9074724		
			100	2.60		6.918E-09			95.95978968	95.94866441
Ru	44	96	5.542		0.100		2.665E-10	95.9075939		
Ru	44	98	1.869		0.034		9.249E-11	97.9052876		
Ru	44	99	12.758		0.230		6.321E-10	98.9059393		
Ru	44	100	12.599		0.228		6.329E-10	99.9042195		
Ru	44	101	17.060		0.308		8.635E-10	100.9055821		
Ru	44	102	31.552		0.570		1.614E-09	101.9043493		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ru	44	104	18.621		0.336		9.700E-10	103.9054326		
			100	1.81		5.071E-09			101.0650881	101.0650881
Rh	45	103	100	0.338	0.338	9.664E-10	9.664E-10	102.9055043	102.9055043	102.9055043
Pd	46	102	1.02		0.0141		3.992E-11	101.9056286		
Pd	46	104	11.14		0.1536		4.434E-10	103.9040359		
Pd	46	105	22.33		0.3079		8.975E-10	104.9050847		
Pd	46	106	27.33		0.377		1.109E-09	105.9034808		
Pd	46	108	26.46		0.365		1.094E-09	107.9038907		
Pd	46	110	11.72		0.162		4.947E-10	109.9051703		
			100	1.38		4.079E-09			106.4153292	106.4153292
Ag	47	107	51.839		0.258		7.664E-10	106.9050965		
Ag	47	109	48.161		0.239		7.232E-10	108.9047523		
			100	0.497		1.490E-09			107.8681467	107.8681467
Cd	48	106	1.249		0.020		5.885E-11	105.9064602		
Cd	48	108	0.89		0.014		4.197E-11	107.9041824		
Cd	48	110	12.485		0.197		6.016E-10	109.9030035		
Cd	48	111	12.804		0.202		6.225E-10	110.9041781		
Cd	48	112	24.117		0.381		1.185E-09	111.9027578		
Cdˆ	48	113	12.225		0.193		6.055E-10	112.9044026		
Cd	48	114	28.729		0.454		1.437E-09	113.9033595		
Cdˆ	48	116	7.501		0.119		3.832E-10	115.9047632		
			100	1.58		4.935E-09			112.4121436	112.4121436

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
In	49	113	4.281		0.008		2.510E-11	112.9040574		
In^	49	115	95.719		0.171		5.459E-10	114.9038788		
			100	0.179		5.710E-10			114.8182664	114.8182664
Sn	50	112	0.971		0.035		1.088E-10	111.9048218		
Sn	50	114	0.659		0.024		7.596E-11	113.9027788		
Sn	50	115	0.339		0.012		3.831E-11	114.9033424		
Sn	50	116	14.536		0.522		1.681E-09	115.9017405		
Sn	50	117	7.676		0.276		8.965E-10	116.9029516		
Sn	50	118	24.223		0.870		2.850E-09	117.9016031		
Sn	50	119	8.585		0.308		1.018E-09	118.9033076		
Sn	50	120	32.593		1.171		3.901E-09	119.9022002		
Sn	50	122	4.629		0.166		5.623E-10	121.9034391		
Sn	50	124	5.789		0.208		7.161E-10	123.9052761		
			100	3.59		1.185E-08			118.71035	118.71035
Sb	51	121	57.213		0.205		6.887E-10	120.9038157		
Sb	51	123	42.787		0.154		5.259E-10	122.904214		
			100	0.359		1.215E-09			121.7597261	121.7597261
Te	52	120	0.096		0.005		1.666E-11	119.9040452		
Te	52	122	2.603		0.123		4.166E-10	121.9030439		
Te^	52	123	0.908		0.043		1.468E-10	122.9042701		
Te	52	124	4.816		0.227		7.815E-10	123.9028176		
Te	52	125	7.139		0.337		1.170E-09	124.9044307		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Te	52	126	18.952		0.894		3.127E-09	125.9033117		
Te^	52	128	31.687		1.494		5.309E-09	127.9044621		
Te^	52	130	33.799		1.594		5.753E-09	129.9062228		
			100	4.72		1.672E-08			127.5855887	127.5855887
I	53	127	100	1.59	1.59	5.606E-09	5.606E-09	126.9044728	126.9044728	126.9044728
Xe^	54	124	0.129		0.007		2.410E-11	123.905893		
Xe	54	126	0.110		0.006		2.099E-11	125.9042912		
Xe	54	128	2.220		0.122		4.336E-10	127.9035313		
Xe	54	129	27.428		1.507		5.398E-09	128.9047809		
Xe	54	130	4.349		0.239		8.626E-10	129.9035094		
Xe	54	131	21.763		1.196		4.350E-09	130.9050524		
Xe	54	132	26.360		1.449		5.311E-09	131.9041551		
Xe	54	134	9.730		0.535		1.991E-09	133.9053945		
Xe^	54	136	7.911		0.435		1.643E-09	135.9072145		
			100	5.495		2.003E-08			131.1826916	131.1826916
Cs	55	133	100	0.368	0.368	1.359E-09	1.359E-09	132.905452	132.905452	132.905452
Ba^	56	130	0.106		0.005		1.805E-11	129.9063215		
Ba	56	132	0.101		0.005		1.833E-11	131.9050613		
Ba	56	134	2.417		0.110		4.093E-10	133.9045084		
Ba	56	135	6.592		0.300		1.125E-09	134.9056886		
Ba	56	136	7.853		0.357		1.348E-09	135.904576		
Ba	56	137	11.232		0.511		1.944E-09	136.9058274		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ba	56	138	71.699		3.264		1.251E-08	137.9052473		
			100	4.552		1.737E-08			137.3269159	137.3269159
La*	57	138	0.092		4.000E-04		1.533E-12	137.907112		
La	57	139	99.908		0.459		1.772E-09	138.9063533		
			100	0.459		1.773E-09			138.905438	138.905466
Ce	58	136	0.186		0.002		7.552E-12	135.9071295		
Ceˆ	58	138	0.250		0.003		1.150E-11	137.905991		
Ce	58	140	88.450		1.030		4.004E-09	139.9054387		
Ceˆ	58	142	11.114		0.129		5.086E-10	141.9092442		
			100	1.165		4.532E-09			140.1157106	140.1156862
Pr	59	141	100	0.175	0.175	6.851E-10	6.851E-10	140.9076525	140.9076525	140.9076525
Nd	60	142	27.045		0.234		9.226E-10	141.9077233		
Nd	60	143	12.021		0.104		4.130E-10	142.9098143		
Ndˆ	60	144	23.729		0.205		8.197E-10	143.9100873		
Nd	60	145	8.763		0.076		3.060E-10	144.9125736		
Nd	60	146	17.130		0.148		6.000E-10	145.9131169		
Nd	60	148	5.716		0.049		2.014E-10	147.9168933		
Ndˆ	60	150	5.596		0.048		1.999E-10	149.9208949		
			100	0.864		3.463E-09			144.2446602	144.2427553
Sm	62	144	3.083		0.008		3.199E-11	143.9120046		
Sm*	62	147	15.017		0.042		1.714E-10	146.9148979		
Smˆ	62	148	11.254		0.031		1.274E-10	147.9148227		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Sm	62	149	13.830		0.038		1.572E-10	148.9171847		
Sm	62	150	7.351		0.020		8.331E-11	149.9172755		
Sm	62	152	26.735		0.073		3.081E-10	151.9197324		
Sm	62	154	22.730		0.062		2.652E-10	153.9222093		
			100	0.273		1.145E-09			150.3632757	150.3649949
Eu^	63	151	47.81		0.0479		2.009E-10	150.9198502		
Eu	63	153	52.19		0.0523		2.222E-10	152.9212303		
			100	0.1002		4.231E-10			151.9643705	151.9643705
Gd^	64	152	0.2029		0.00013		5.357E-13	151.9197922		
Gd	64	154	2.1809		0.00755		3.227E-11	153.9208693		
Gd	64	155	14.7998		0.0512		2.204E-10	154.9226276		
Gd	64	156	20.4664		0.0708		3.068E-10	155.9221287		
Gd	64	157	15.6518		0.0542		2.361E-10	156.9239647		
Gd	64	158	24.8347		0.0859		3.770E-10	157.9241101		
Gd	64	160	21.8635		0.0756		3.361E-10	159.9270585		
			100	0.3454		1.509E-09			157.2520476	157.2520476
Tb	65	159	100	0.0625	6.250E-02	2.760E-10	2.760E-10	158.9253468	158.9253468	158.9253468
Dy	66	156	0.054		0.00005		2.166E-13	155.9242829		
Dy	66	158	0.095		0.0004		1.755E-12	157.9244096		
Dy	66	160	2.329		0.0095		4.221E-11	159.9251975		
Dy	66	161	18.889		0.0769		3.438E-10	160.9269334		
Dy	66	162	25.479		0.1038		4.670E-10	161.9267984		

Table 4 (*Continued*)

E (1)	*Z* (2)	*A* (3)	Isotopic composition atom % (4)	*N* (Elemental) Si = 1E+6 (5)	*N* (Isotopic) ΣSi = 1E+6 (6)	Elemental mass fractions (7)	Isotope mass fractions (8)	Atomic mass (Daltons, Da) (9)	Protosolar mean atomic mass (Da) (10)	Current mean atomic mass (Da) (11)
Dy	66	163	24.895		0.1014		4.590E-10	162.9287312		
Dy	66	164	28.260		0.1151		5.243E-10	163.9291748		
			100	0.407		1.838E-09			162.4997627	162.4997627
Ho	67	165	100	0.0891	8.910E-02	4.083E-10	4.083E-10	164.9303221	164.9303221	164.9303221
Er	68	162	0.139	0.0004			1.800E-12	161.9287799		
Er	68	164	1.601	0.0041			1.867E-11	163.9292065		
Er	68	166	33.503	0.0859			3.965E-10	165.9302931		
Er	68	167	22.869	0.0587			2.737E-10	166.9320482		
Er	68	168	26.978	0.0692			3.220E-10	167.9323702		
Er	68	170	14.910	0.0382			1.794E-10	169.9354643		
			100	0.256		1.192E-09			167.2590764	167.2590764
Tm	69	169	100	0.0403	4.030E-02	1.892E-10	1.892E-10	168.9342133		
Yb	70	168	0.12		0.0003		1.400E-12	167.9338869		
Yb	70	170	2.98		0.0075		3.541E-11	169.9347618		
Yb	70	171	14.09		0.0356		1.691E-10	170.9363258		
Yb	70	172	21.69		0.0547		2.613E-10	171.9363815		
Yb	70	173	16.10		0.0406		1.951E-10	172.9382108		
Yb	70	174	32.03		0.0808		3.905E-10	173.9388621		
Yb	70	176	13.00		0.0328		1.603E-10	175.9425717		
			100	0.252		1.213E-09			173.0544616	173.0544616
Lu	71	175	97.1795		0.0370		1.798E-10	174.9407712		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Lu*	71	176	2.8205		0.0011		5.377E-12	175.9426867		
			100	0.0381		1.852E-10			174.9690303	174.9668077
Hf^	72	174	0.161		0.0003		1.450E-12	173.9400462		
Hf	72	176	5.205		0.0081		3.960E-11	175.9414091		
Hf	72	177	18.604		0.0289		1.421E-10	176.9432224		
Hf	72	178	27.297		0.0424		2.096E-10	177.9437004		
Hf	72	179	13.627		0.0212		1.054E-10	178.945817		
Hf	72	180	35.105		0.0545		2.725E-10	179.9465512		
			100	0.155		7.707E-10			178.4865658	178.4851456
Ta*	73	180	0.0120		2.600E-06		1.300E-14	179.9474648		
Ta	73	181	99.9880		0.0215		1.081E-10	180.9479958		
			100	0.0215		1.081E-10			180.9478756	180.9478756
W^	74	180	0.120		0.0002		1.000E-12	179.9467091		
W	74	182	26.499		0.0381		1.926E-10	181.9482042		
W	74	183	14.314		0.0206		1.047E-10	182.9502223		
W	74	184	30.642		0.0440		2.249E-10	183.9509312		
W	74	186	28.426		0.0408		2.108E-10	185.9543641		
			100	0.144		7.340E-10			183.8416979	183.8416979
Re	75	185	35.662		0.0195		1.002E-10	184.9529549		
Re*	75	187	64.338		0.0352		1.828E-10	186.9557531		
			100	0.0547		2.831E-10			186.2415239	186.2067466
Os^	76	184	0.020		0.0001		5.111E-13	183.9524891		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Os^	76	186	1.597		0.0104		5.373E-11	185.9538382		
Os	76	187	1.298		0.0085		4.415E-11	186.9557505		
Os	76	188	13.325		0.0869		4.538E-10	187.9558382		
Os	76	189	16.252		0.106		5.565E-10	188.9581475		
Os	76	190	26.433		0.172		9.078E-10	189.9584471		
Os	76	192	41.076		0.268		1.429E-09	191.9614807		
			100	0.652		3.446E-09			190.2476945	190.2349378
Ir	77	191	37.272		0.236		1.252E-09	190.9605941		
Ir	77	193	62.728		0.397		2.129E-09	192.9629264		
			100	0.633		3.381E-09			192.2166171	192.2166171
Pt*	78	190	0.013		0.0004		1.056E-12	189.9599321		
Pt	78	192	0.794		0.01		5.334E-11	191.961038		
Pt	78	194	32.808		0.407		2.193E-09	193.962679		
Pt	78	195	33.787		0.419		2.270E-09	194.9647901		
Pt	78	196	25.290		0.314		1.710E-09	195.9649515		
Pt	78	198	7.308		0.091		5.006E-10	197.967891		
			100	1.24		6.728E-09			195.0839451	195.0839494
Au	79	197	100	0.195	0.195	1.067E-09	1.067E-09	196.9665687	196.9665687	196.9665687
Hg	80	196	0.16		0.001		5.445E-12	195.9658326		
Hg	80	198	10.04		0.038		2.090E-10	197.9667689		
Hg	80	199	16.94		0.064		3.538E-10	198.9682804		
Hg	80	200	23.14		0.087		4.834E-10	199.968326		

Table 4 (*Continued*)

E	*Z*	*A*	Isotopic composition atom %	*N* (Elemental) Si = 1E+6	*N* (Isotopic) ΣSi = 1E+6	Elemental mass fractions	Isotope mass fractions	Atomic mass (Daltons, Da)	Protosolar mean atomic mass (Da)	Current mean atomic mass (Da)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Hg	80	201	13.17		0.049		2.736E-10	200.9703022		
Hg	80	202	29.74		0.112		6.285E-10	201.970643		
Hg	80	204	6.82		0.026		1.474E-10	203.9734941		
			100	0.376		2.101E-09			200.5923999	200.5923999
Tl	81	203	29.524		0.053		2.989E-10	202.9723442		
Tl	81	205	70.476		0.126		7.176E-10	204.9744275		
			100	0.179		1.017E-09			204.3833324	204.3833324
Pb^	82	204	1.997		0.066		3.740E-10	203.9730436		
Pb	82	206	18.582		0.615		3.520E-09	205.9744653		
Pb	82	207	20.563		0.680		3.911E-09	206.9758969		
Pb	82	208	58.858		1.947		1.125E-08	207.976652		
			100	3.308		1.906E-08			207.3188698	207.3162565
Bi^	83	209	100	0.1414	1.414E-01	8.210E-10	8.210E-10	208.9803987	208.9803987	208.9803987
Th*	90	232	100	0.0421	4.210E-02	2.714E-10	2.714E-10	232.0380553	232.0380553	232.0380553
U*	92	234	0.004		9.90E-07		6.438E-15	234.0409521		
U*	92	235	24.302		0.0058		3.788E-11	235.0439299		
U*	92	238	75.694		0.0181		1.197E-10	238.0507882		
			100	0.0239		1.576E-10			237.3199066	238.0289064

Column (6) gives the relative atomic *isotopic* composition on the same abundance scale as in column (5), hence the sum of all silicon atoms ("ΣSi" in header of column 6) must sum up to 1E6 atoms. These values are easily calculated from the abundance of an element (col5) times the isotopic composition of the respective element (col. 4).

Column (7) gives the mass fraction of each element in the overall protosolar composition, and column (8) the mass fraction of each isotope. Thus the sum of all elemental mass fractions = sum of all isotope mass fractions = 1.

Column (9) lists the atomic masses in atomic mass units (AMU) or Daltons (Da, which is 1/12 mass of a single ^{12}C atom) for each isotope, the data are from Audi et al. (2003), Wang et al. (2012, 2017), and Pfeiffer et al. (2014).

Column (10) lists the mean atomic masses (or mean atomic weights) for the elements with the given protosolar isotopic composition. For reference, column (11) present-day gives the atomic weights if the present-day isotopic compositions (not listed here) are used. The atomic weight or atomic mass of an element is generally calculated as the weighted mean of the individual atomic masses of the isotopes an element (column 9 in Table 4), where the statistical weight is the fractional isotopic atomic composition (column 4 in Table 4):

$$\text{Mean Atomic Mass Element [AMU]} = \frac{\sum \text{Isotopic Composition (atom\% of element)}}{100\text{Isotope Atomic Mass [AMU]}}$$

The atomic weights derived from the adopted isotopic compositions of the elements must be used to be self-consistent. (The difference to the usual atomic weight tables is particularly noteworthy for Ar, which is mainly ^{40}Ar in the terrestrial atmosphere and thus dominates the atomic weight of Ar on Earth). Differences between the protosolar and present-day atomic weights are noticeable for elements with larger losses of radioactive isotopes over the past 4.567 Ga and for elements with larger gain of stable isotopes from decay of radioactive isotopes of other elements.

5.1 Calculation of the Overall Mass-Fractions of the Elements for the Solar-System Composition

The calculation of mass fractions requires knowledge of the abundances of all (major) elements and their isotopic composition. The calculation of the isotopic mass fractions from the abundances on the atomic scale are done by multiplying the abundances of the isotopes by their respective atomic masses and renormalizing the mass abundances to unity (or 100%). The mass fractions of an element (column 7) are just the sum of the mass fraction of its isotopes (col. 8). Another way to get the elemental mass fractions of the protosolar composition is multiplying the abundances of the elements (col. 5) by their respective mean atomic masses (col.10) and renormalizing the mass abundances to unity (or 100%). If the elemental mass fractions for the present-day composition is desired, the mean atomic weights in column (11) need to be used. In astronomy, often the mass fractions are designated as X for H, Y for He, and Z for heavy elements from Li to U (the Z for mass fraction of heavy elements should not be confused with Z for atomic number or charge).

5.2 Isotopic Composition of H, C, N, O, and the Noble Gases He, Ne, Ar, Kr, and Xe

The H isotopic composition (i.e., D/H ratio) of the Earth is not representative for the solar system as a whole because of secondary fractionations of the D/H ratio in the Earth's hydrological cycle. The D/H ratio cannot be derived from the solar photosphere or the solar wind because D was destroyed in the proto-Sun when it was fully convective. The proto-solar D/H ratio ($1.97[\pm 0.35] \times 10^{-5}$; Geiss and Gloeckler 2003) is thus derived from comparing the helium isotopic measurements of Jupiter's atmosphere with that of the solar wind and mass-balance calculations accounting for ^{3}He produced by deuterium burning. Direct measurements of the D/H ratio from Jupiter may not be representative according to Geiss and Gloeckler. However, Jupiter is the most massive planet in the solar system and has the largest proportion of captured solar gas, so it is the best proxy for the proto-solar D/H. But it should be kept in mind that the increase of D/H ratios in the giant planets' atmospheres with increasing distance from the Sun makes the assignment of the "correct" D/H ratio for the solar system more problematic.

The helium isotopic composition of ^{3}He/^{4}He of $1.66(\pm 0.05) \times 10^{-4}$ of Jupiter's atmosphere is adopted as proto-solar value (Geiss and Gloeckler 2003; Mahaffy et al. 1998). The current outer atmosphere of the sun has a higher ^{3}He/^{4}He because D-burning produced ^{3}He, therefore the ratio is above the respective proto-solar ratio. In addition, the solar wind ^{3}He/^{4}He from in-situ measurements shows that the various solar wind regimes are isotopically fractionated, and is seen with much higher precision in Genesis regime targets (Heber et al. 2012). Very ^{3}He-enriched solar energetic particles from solar flares have been observed (e.g., Mason et al. 2004), complicating the interpretation of the current "solar" ^{3}He/^{4}He ratio because the derivation of the proto-solar D/H ratio depends on the ^{3}He/^{4}He ratio of the present-day Sun. Hence differences in reported proto-solar D/H values exist (see Geiss and Gloeckler 2003; Trieloff 2018; Wieler 2016 for alternate choices).

The isotopic compositions of the other noble gases, C, N, and O are from solar wind measurements; a preferred choice for the solar system isotopic composition by several authors. One caveat is that the solar wind isotopic compositions may not be representative for the solar system as a whole because the solar wind is fractionated in elemental composition relative to the photosphere and meteorites, and corresponding mass-dependent isotopic fractionations are observed in the solar wind. Fractionation effects from the settling of elements during the sun's lifetime need to be considered in addition to the model-dependent corrections that are applied to account for fractionations effect during solar wind acceleration. Therefore the adopted values remain subject to change, however, the solar wind values appear more realistic choices for representative solar system values than terrestrial values that have been used in the past (see below).

The C, N, and O isotopic compositions in solar system materials are more variable and can reach 10 to 100 per-mil levels. The choices for representative solar system values are not necessarily straight-forward. Ideally, the solar isotopic composition should be the most representative choice, as it should be for the elemental composition. Spectroscopic measurements of the photospheric C and O isotopic compositions have large uncertainties. The recent solar wind measurements from Genesis samples give a light isotopic composition (i.e., the lower-mass isotope of an element is more abundant than heavier isotopes of the element relative to terrestrial standard materials). The C-isotopic composition is still relatively close to the terrestrial and meteoritic values.

The solar wind nitrogen is poor in ^{15}N when compared to Earth and most meteorites, and the adopted ratio of $^{14}\text{N}/^{15}\text{N} = 440$ is similar to that found for Jupiter). which seems to vindicates the adoption of the solar wind as isotopic standard (e.g., see Füri and Marty 2015; Marty et al. 2010; Avice and Marty 2020). The oxygen isotopic composition of the solar wind is depleted in ^{17}O and ^{18}O by about 7% relative to Earth and most meteoritic materials (Laming 2017; McKeegan et al. 2011).

The Ne, Ar, Kr, and Xe data are from soar wind measurements from the Genesis mission Crowther and Gilmour (2013), Heber et al. (2009), Heber et al. (2012), Pepin et al. (2012), Vogel et al. (2011), and Meshik et al. (2014). Isotopic fractionations are less for the heavier Ne and Ar than for He. However, theoretical corrections to mass-dependent fractionations of the adopted solar wind isotopic compositions were not applied here because they are not yet well understood and vary with different authors (e.g., Heber et al. 2012; Ott 2015, see also Huss et al. 2020).

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References

C.M.O'D.Alexander, Quantitative models for the elemental and isotopic fractionations in chondrites: the non-carbonaceous chondrites. Geochim. Cosmochim. Acta **254**, 246–276 (2019a)

C.M.O'D.Alexander, Quantitative models for the elemental and isotopic fractionations in chondrites: the carbonaceous chondrites. Geochim. Cosmochim. Acta **254**, 277–309 (2019b)

S.A. Alexeeva, L.I. Mashonkina, Carbon abundances of reference late-type stars from 1D analysis of atomic C I and molecular CH lines. Mon. Not. R. Astron. Soc. **453**, 1619–1631 (2015)

A.M. Amarsi, M. Asplund, The solar silicon abundance based on 3D non-LTE calculations. Mon. Not. R. Astron. Soc. **464**, 264–273 (2017)

A.M. Amarsi, P.S. Barklem, M. Asplund, R. Collet, O. Zatarinny, Inelastic O+H collisions and the O I 777 nm solar centre-to-limb variation. Astron. Astrophys. **616**, A89 (2018)

A.M. Amarsi, P.S. Barklem, R. Collet, N. Grevesse, M. Asplund, 3D non-LTE line formation of neutral carbon in the Sun. Astron. Astrophys. **624**, A111 (2019)

M. Asplund, N. Grevesse, A.J. Sauval, P. Scott, The chemical composition of the Sun. Annu. Rev. Astron. Astrophys. **47**, 481–522 (2009)

G. Avice, B. Marty, Perspectives on atmospheric evolution from noble gas and nitrogen isotopes on Earth, Mars & Venus. Space Sci. Rev. **216**, 36 (2020). https://doi.org/10.1007/s11214-020-00655-0

S. Basu, H.M. Antia, Constraining solar abundances using helioseismology. Astrophys. J. **606**, L85–L88 (2004)

M. Bergemann, R. Collet, A.M. Amarsi, M. Kovalev, G. Ruchti, Z. Magic, Non-local thermodynamic equilibrium stellar spectroscopy with 1D and <3D> models. I. Methods and application to magnesium abundances in standard stars. Astrophys. J. **847**, 15 (2017)

M. Bergemann, A.J. Gallagher, P. Eitner, M. Bautista, R. Collet, S.A. Yakovleva, A. Mayriedl, B. Plez, M. Carlsson, J. Leenaarts, A.K. Belyaev, C. Hansen, On the origin of the elements, I. 3D NLTE formation of Mn lines in late-type stars. Astron. Astrophys. **631**, A80 (2019)

N. Brauckmüller, F. Wombacher, D.C. Hezel, R. Escoube, C. Münker, The chemical composition of carbonaceous chondrites: implications for volatile element depletion, complementarity and alteration. Geochim. Cosmochim. Acta **239**, 17–48 (2018)

E. Caffau, H.G. Ludwig, M. Steffen, B. Freytag, P. Bonifacio, Solar chemical abundances determined with a CO5BOLD 3D model atmosphere. Sol. Phys. **268**, 255–269 (2011)

E. Caffau, H.-G. Ludwig, M. Steffen, W. Livingston, P. Bonifacio, J.-M. Malherbe, H.-P. Doerr, W. Schmidt, The photospheric solar oxygen project. III. Investigation of the centre-to-limb variation of the 630 nm [OI]-NiI blend. Astron. Astrophys. **579**, A88 (2015)

S.A. Crowther, J.D. Gilmour, The Genesis solar wind composition and its relationship to planetary xenon signatures. Geochim. Cosmochim. Acta **123**, 17–34 (2013)

J.M. Friedrich, M.S. Wang, M.E. Lipschutz, Chemical studies of L chondrites. V: compositional patterns for 49 trace elements in 14 L4–6 and 7 LL4–6 falls. Geochim. Cosmochim. Acta **67**, 2467–2479 (2003)

J.M. Friedrich, J.C. Bridges, M.S. Wang, M.E. Lipschutz, Chemical studies of L chondrites. VI: variations with petrographic type and shock-loading among equilibrated falls. Geochim. Cosmochim. Acta **68**, 2889–2904 (2004)

E. Füri, B. Marty, Nitrogen isotope variations in the solar system. Nat. Geosci. **8**, 515–522 (2015)

J. Geiss, G. Gloeckler, Isotopic composition of H, He and Ne in the protosolar cloud. Space Sci. Rev. **106**, 3–18 (2003)

N. Grevesse, P. Scott, M. Asplund, A.J. Sauval, The elemental composition of the Sun. III. The heavy elements Cu to Th. Astron. Astrophys. **573**, A27 (2015)

V.S. Heber, R. Wieler, H. Baur, C. Olinger, T.A. Friedmann, D.S. Burnett, Noble gas composition of the solar wind as collected by the Genesis mission. Geochim. Cosmochim. Acta **73**, 7414–7432 (2009)

V.S. Heber, H. Baur, P. Bochsler, K.D. McKeegan, M. Neugebauer, D.B. Reisenfeld, R. Wieler, R.C. Wiens, Isotopic mass fractionation of solar wind: evidence from fast and slow solar wind collected by the Genesis mission. Astrophys. J. **759**, 121 (2012)

H. Holweger, Photospheric abundances, problems, updates, implications. AIP Conf. Proc. **598**, 23–30 (2001)

G.R. Huss, E. Koeman-Shields, A.J. Jurewicz, D.S. Burnett, K. Nagashima, R. Ogliore, C.T. Olinger, Hydrogen fluence in Genesis collectors: implications for acceleration of solar wind and for solar metallicity. Meteorit. Planet. Sci. **55**, 326–351 (2020)

J.M. Laming, The first ionization potential effect from the ponderomotive force: on the polarization and coronal origin of Alfvén waves. Astrophys. J. **844**, 153 (2017)

J.E. Lawler, M.P. Wood, E.A. Den Hartog, T. Feigenson, C. Sneden, J.J. Cowan, Improved V I log(gf) values and abundance determinations in the photospheres of the Sun and metal-poor Star HD 84937. Astrophys. J. Suppl. Ser. **215**, 20 (2014)

J.E. Lawler, C. Sneden, G. Nave, E.A. Den Hartog, N. Emrahoğlu, J.J. Cowan, Improved Cr II log(gf) values and abundance determinations in the photospheres of the Sun and metal-poor Star HD 84937. Astrophys. J. Suppl. Ser. **228**, 10 (2017)

J.E. Lawler, T. Feigenson, C. Sneden, J.J. Cowan, G. Nave, Transition probabilities of Co II weak lines to the ground and low metastable levels. Astrophys. J. Suppl. Ser. **238**, 7 (2018)

J.E. Lawler, F.N. Hala, C. Sneden, G. Nave, M.P. Wood, J.J. Cowan, Transition probabilities of Sc I and Sc II and Scandium abundances in the Sun, Arcturus, and HD 84937. Astrophys. J. Suppl. Ser. **241**, 21 (2019)

K. Lind, A.M. Amarsi, M. Asplund, P.S. Barklem, M. Bautista, M. Bergemann, R. Collet, D. Kiselman, J. Leenaarts, T.M.D. Pereira, Non-LTE line formation of Fe in late-type stars—IV. Modelling of the solar centre-to-limb variation in 3D. Mon. Not. R. Astron. Soc. **468**, 4311–4322 (2017)

K. Lodders, Solar System abundances and condensation temperatures of the elements. Astrophys. J. **591**, 1220–1247 (2003)

K. Lodders, The solar argon abundance. Astrophys. J. **674**, 607–611 (2008)

K. Lodders, Solar elemental abundances, in *Online Oxford Research Encyclopedia of Planetary Science* (2020). https://doi.org/10.1093/acrefore/9780190647926.013.145. arXiv:1912.00844

K. Lodders, B. Fegley Jr., *The Planetary Scientist's Companion* (Oxford University Press, Oxford, 1998), 384 pp.

K. Lodders, B. Fegley Jr., *Chemistry of the Solar System* (Roy. Soc. Chemistry Publishing, Cambridge, 2011), 476 pp.

K. Lodders, H. Palme, H.P. Gail, Abundances of the elements in the solar system, in *Landolt-Börnstein*, ed. by J.E. Trümper. New Series, vol. VI/4B (Springer, Berlin, 2009), pp. 560–630. Chap. 4.4

Z.G. Maas, C.A. Pilachowski, K. Hinkle, Chlorine abundances in cool stars. Astrophys. J. **152**, id196 (2016)

P.R. Mahaffy, T.M. Donahue, S.K. Atreya, T.C. Owen, H.B. Niemann, Galileo probe measurements of D/H and He/ He in Jupiter's atmosphere. Space Sci. Rev. **84**, 251–263 (1998)

E. Maiorca, H. Uitenbroek, S. Uttenthaler, S. Randich, M. Busso, L. Magrini, A new solar fluorine abundance and a fluorine determination in the two open clusters M67 and NGC 6404. Astrophys. J. **788**, id149 (2014)

B. Marty, L. Zimmermann, P.G. Burnard, R. Wieler, V.S. Heber, D.S. Burnett, R.C. Wiens, P. Bochsler, Nitrogen isotopes in the recent solar wind from the analysis of Genesis targets: evidence for large scale isotope heterogeneity in the early solar system. Geochim. Cosmochim. Acta **74**, 340–355 (2010)

G.M. Mason, J.E. Mazur, J.R. Dwyer, J.R. Jokipii, R.E. Gold, S.M. Krimigis, Abundances of heavy and ultraheavy ions in 3He-rich solar flares. Astrophys. J. **606**, 555–564 (2004)

K.D. McKeegan, A.P.A. Kallio, V.S. Heber, G. Jarzebinski, P.H. Mao, C.D. Coath, T. Kunihiro, R.C. Wiens, J.E. Nordholt, R.W. Moses, D.B. Reisenfeld, A.J.G. Jurewicz, D.S. Burnett, The oxygen isotopic composition of the Sun inferred from captured solar wind. Science **332**, 1528–2011 (2011)

J. Meija, T.B. Coplen, M. Berglund, W.A. Brand, P. de Bievre, M. Groning, N.E. Holden, J. Irrgher, R.D. Loss, T. Walczyk, T. Prohaska, Isotopic compositions of the elements 2013 (IUPAC technical report). Pure Appl. Chem. **88**, 293–306 (2016)

A. Meshik, C. Hohenberg, O. Pravdivtseva, D. Burnett, Heavy noble gases in solar wind delivered by Genesis mission. Geochim. Cosmochim. Acta **127**, 326–347 (2014)

T. Nordlander, K. Lind, Non-LTE aluminium abundances in late-type stars. Astron. Astrophys. **607**, A75 (2017)

U. Ott, Planetary and pre-solar noble gases in meteorites. Chem. Erde **74**, 519–544 (2015)

R.O. Pepin, D.J. Schlutter, R.H. Becker, D.B. Reisenfeld, Helium, neon, and argon composition of the solar wind as recorded in gold and other Genesis collector materials. Geochim. Cosmochim. Acta **89**, 62–80 (2012)

B. Pfeiffer, K. Venkataramaniahc, U. Czoka, C. Scheidenberger, Atomic mass compilation 2012. At. Data Nucl. Data Tables **100**, 403–535 (2014)

L. Schaefer, B. Fegley, Outgassing of ordinary chondritic material and some of its implications for the chemistry of asteroids, planets, and satellites. Icarus **186**, 462–483 (2007)
L. Schaefer, B. Fegley, Volatile element chemistry during metamorphism of ordinary chondritic material. Icarus **205**, 483–496 (2010)
P. Scott, N. Asplund, N. Grevesse, M. Bergemann, A.J. Sauval, The elemental composition of the Sun. II. The iron group elements Sc to Ni. Astron. Astrophys. **573**, A26 (2015a)
P. Scott, N. Grevesse, M. Asplund, A.J. Sauval, K. Lind, Y. Takeda, R. Collet, R. Trampedach, W. Hayek, The elemental composition of the Sun. I. The intermediate mass elements Na to Ca. Astron. Astrophys. **573**, A25 (2015b)
C. Sneden, J.E. Lawler, J.J. Cowan, I.I. Ivans, E.A. Den Hartog, New rare Earth element abundance distributions for the Sun and five r-process-rich very metal-poor stars. Astrophys. J. Suppl. Ser. **182**, 80–96 (2009)
C. Sneden, J.J. Cowan, C. Kobayashi, M. Pignatari, J.E. Lawler, E.A. Den Hartog, M.P. Wood, Iron-group abundances in the metal-poor main-sequence turnoff star HD84937. Astrophys. J. **817**, 53 (2016)
M. Trieloff, Noble gases, in *Oxford Research Encyclopedia of Planetary Science*, vol. 30, ed. by P. Read et al. (Oxford University Press, London, 2018). 978-0-190-64792-6. https://doi.org/10.1093/acrefore/9780190647926.013.33
N. Vitas, I. Vince, M. Lugaro, O. Andriyenko, M. Gosic, R.J. Rutten, On the solar abundance of indium. Mon. Not. R. Astron. Soc. **384**, 370–375 (2008)
N. Vogel, V.S. Heber Veronika, H. Baur, D.S. Burnett, R. Wieler, Argon, krypton, and xenon in the bulk solar wind as collected by the Genesis mission. Geochim. Cosmochim. Acta **75**, 3057–3071 (2011)
M. Wang et al., The Ame2012 atomic mass evaluation. Chin. Phys. C **36**, 1603–2014 (2012)
M. Wang et al., The Ame2016 atomic mass evaluation. Chin. Phys. C **41**, 030003 (2017)
J.T. Wasson, G.W. Kallemeyn, Compositions of chondrites. Philos. Trans. R. Soc. Lond. A **325**, 535–544 (1988)
R. Wieler, Do lunar and meteoritic archives record temporal variations in the composition of solar wind noble gases and nitrogen? A reassessment in the light of Genesis data. Chem. Erde **76**, 463–480 (2016)
P.R. Young, Element abundance ratios in the quiet sun transition region. Astrophys. J. **855**, 15 (2018)
G. Zhao, L. Mashonkina, H.L. Yan, S. Alexeeva et al., Systematic non-LTE study of the −2.6 <=[Fe/H]<=0.2 F and G dwarfs in the solar neighborhood. II. Abundance patterns from Li- to Eu. Astrophys. J. **833**, 225 (2016)

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