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A Table of Relative Abundances of Nuclear Species

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A new table of relative abundances of nuclear species existing in nature has been prepared based upon the best available data on the compositions of the sun, stars, and meteorites. The general methods utilized in compiling the table are explained.

I. INTRODUCTION

As long ago as 1917 it became apparent that relationships exist between nuclear properties and relative abundances.[1] In recent years increasing thought has been given by physicists to such relationships, and in particular to the question of the origin of the elements.[2–19] To date, the only reasonably adequate table of relative abundances of nuclear species available for comparing theory with experiment has been that of V. M. Goldschmidt, compiled in 1937.[20] Goldschmidt utilized primarily chemical data obtained on meteorites, coupled with data derived from stellar spectra. Since that time new developments have warranted re-evaluation of existing information. Significant changes from Goldschmidt's original table result from the following developments:

1. More extensive and accurate stellar data
2. More precise linking of stellar abundances to meteoritic abundances
3. More accurate evaluation of the ratio of metal to silicate phase in meteorites and in the inner planets
4. Statistical evaluation of standard deviations of elemental abundances in meteorites
5. Development of a general background guiding the use of meteoritical data in the compilation of such a table
6. The existence of more precisely determined isotope ratios

Ideally, values for the relative abundances of elements in the visible universe would be derived entirely from stellar spectra. However, two main difficulties stand in the way of such an achievement:

1. The difficulty of converting spectral intensities to atomic abundances
2. The uncertainty as to whether or not elements are distributed homogeneously through stellar interiors

The first difficulty requires no comment here. The reader is referred to various papers on the derivation of abundances from stellar data.[21–31] The second difficulty is nearly as serious as the first. Arguments have been presented supporting both the concept of mixing, and of non-mixing, in stellar interiors. If it is correct that lithium and boron exist in the sun's atmosphere[22–24] then, in view of the short half-lives of these elements at

TABLE I. Stellar abundances of the lighter elements (atoms per atom of oxygen).

Element	Sun (Menzel and Goldberg)[a]	Sun (Unsöld)[b]	Planetary nebulae (Aller and Menzel)[c]	τ-Scorpii (Unsöld)[d]	γ-Pegasi (Aller)[e]
H	2,700	560	1,400*	1,000	10,000
He	595		400	182	2,000
C	0.10	0.37	2.4	0.17	0.05
N	0.32	0.76	0.25*	0.39	0.23
O	1.00	1.00	1.00	1.00	1.00
F			0.0004		
Ne			0.04	1.1	
Na	0.010	0.0035			
Mg	0.65	0.062		0.058	0.31
Al	0.0065	0.0040		0.0037	0.011
Si	0.20	0.037		0.064	0.09
S	0.10	0.016	0.14		0.04
Cl			0.008		0.02?
A			0.0060		0.10
K	0.0032	0.00029			
Ca	0.010	0.0031			
Ti	0.00010	0.00017			
V	0.000032	0.000021			

* L. H. Aller, private communication.

[a] D. H. Menzel: See Goldberg and Aller, "Atoms, Stars and Nebulae" (The Blakiston Company, Philadelphia, 1943), p. 114.

[b] A. Unsöld, Zeits. f. Astrophys. 24, 323 (1948).

[c] L. H. Aller and D. H. Menzel, Astrophys. J. 102, 239 (1945).

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TABLE II. Abundances of elements in meteoritic phases (percent by weight).

		Silicate		Metal		Sulfide		
Z	Element	Value	Ref.	Value	Ref.	Value	Ref.	Gross
1	H	0.063 ± 0.015	f	—		—		3.8×10^{-2}
2	He	—		—		—		—
3	Li	3×10^{-4}	g–i	—		—		2×10^{-4}
4	Be	1×10^{-4}	g,j	—		—		6×10^{-5}
5	B	3×10^{-4}	g,k	—		—		2×10^{-4}
6	C	0.04	g,l	0.11	l,m	—		7×10^{-2}
7	N	9×10^{-5}	g	—		—		5×10^{-5}
8	O	41.02 ± 0.95	f	—		—		24.61
9	F	4×10^{-3}	g	—		—		2×10^{-3}
10	Ne	—		—		—		—
11	Na	0.779 ± 0.053	f	—		—		0.47
12	Mg	15.82 ± 0.30	f	3.2×10^{-2}	l	—		9.5
13	Al	1.74 ± 0.14	f	4×10^{-3}	l	—		1.0
14	Si	20.57 ± 0.18	f	4×10^{-3}	h	—		12.3
15	P	0.158 ± 0.013	f	0.22	m,n	0.31		0.18
16	S	1.79 ± 0.08	o	3.6×10^{-2}	l	34.3		1.08
17	Cl	9×10^{-2}	l	—		—		5×10^{-2}
18	A	—		—		—		—
19	K	0.199 ± 0.020	f	—		—		0.12
20	Ca	1.97 ± 0.20	f	5.0×10^{-2}		—		1.2
21	Sc	5.8×10^{-4}	p,q	—		—		3.5×10^{-4}
22	Ti	0.093 ± 0.030	f	1×10^{-2}	r,s	—		6.0×10^{-2}
23	V	9×10^{-3}	g	6×10^{-4}	l	—	t,u	5.6×10^{-3}
24	Cr	0.345 ± 0.059	f	0.024	l	0.12	l	0.22
25	Mn	0.296 ± 0.067	f	0.03	l	0.046	l	0.19
26	Fe	15.64 ± 0.54	f	90.78 ± 0.26	v	61.1	l	45.7
27	Co	0.0206 ± 0.0086	f	0.63 ± 0.02	v	0.01	h	0.26
28	Ni	0.138 ± 0.024	f	8.59 ± 0.24	v	0.1	h	3.51
29	Cu	1.6×10^{-4}	l	0.031	l	0.420	l	1.3×10^{-2}
30	Zn	3.4×10^{-4}	l	1.15×10^{-2}	l	0.152	l	4.8×10^{-2}
31	Ga	5×10^{-5}	l,w	5.0×10^{-3}	l,w	5×10^{-5}	w	2.0×10^{-3}
32	Ge	1.0×10^{-3}	l,x	1.9×10^{-2}	l,x	6.0×10^{-2}	l,x	8.2×10^{-3}
33	As	2.0×10^{-3}	l	3.6×10^{-2}	l	0.10	l	1.6×10^{-2}
34	Se	1.3×10^{-3}	y	3×10^{-4}	z	1×10^{-2}	z	9.0×10^{-4}
35	Br	2.5×10^{-3}	g,aa	1×10^{-4}	aa	—		1.5×10^{-4}
36	Kr	—		—		—		—
37	Rb	4.5×10^{-4}	l	—		—		2.7×10^{-4}
38	Sr	2.6×10^{-3}	g,bb	—		—		1.6×10^{-3}
39	Y	6.6×10^{-4}	p	—		—		4.0×10^{-4}
40	Zr	1×10^{-2}	l	8×10^{-4}		—		6.0×10^{-3}
41	Cb	5.0×10^{-5}	cc	2.0×10^{-5}		—		3.8×10^{-5}
42	Mo	2.5×10^{-4}	l	1.66×10^{-3}	l	1.1×10^{-3}		8.1×10^{-4}
43	Tc	—		—		—		—
44	Ru	0	l	1.06×10^{-3}	g	4.2×10^{-4}	l	4.2×10^{-4}
45	Rh	0	l	4.1×10^{-4}	g	1.0×10^{-4}	l	1.6×10^{-4}
46	Pd	0	l	3.7×10^{-4}	dd,ee	4.5×10^{-4}	l	1.5×10^{-4}
47	Ag	0	l	3.3×10^{-4}	g	2.1×10^{-3}	l	1.3×10^{-4}
48	Cd	1.6×10^{-4}	g	8×10^{-4}	l	3.0×10^{-3}	l	1.3×10^{-4}
49	In	2.4×10^{-5}	g	1×10^{-4}	h	8×10^{-5}	l	5×10^{-5}
50	Sn	3×10^{-4}	x	7.7×10^{-3}	x	0.16(?)	l	3.3×10^{-3}
51	Sb	1×10^{-5}	l	2×10^{-4}	l	7.8×10^{-4}	l	9×10^{-5}
52	Te	—		—		1.7×10^{-3}	l	?
53	I	1.26×10^{-4}	aa	6×10^{-5}	aa	—		1.0×10^{-4}
54	Xe	—		—		—		—
55	Cs	1×10^{-5}	l	—		—		6×10^{-6}
56	Ba	9.0×10^{-4}	g,bb	—		—		5.4×10^{-4}
57	La	2.2×10^{-4}	p	—		—		1.3×10^{-4}
58	Ce	2.5×10^{-4}	p	—		—		1.5×10^{-4}
59	Pr	1.0×10^{-4}	p	—		—		6.0×10^{-5}
60	Nd	3.7×10^{-4}	p	—		—		2.2×10^{-4}
61	Cp	—		—		—		—
62	Sm	1.3×10^{-4}	p	—		—		7.8×10^{-5}
63	Ev	3.3×10^{-5}	p	—		—		2.0×10^{-5}
64	Gd	2.0×10^{-4}	p	—		—		1.2×10^{-4}
65	Tb	6.4×10^{-5}	p	—		—		3.8×10^{-5}
66	Dy	2.5×10^{-4}	p	—		—		1.5×10^{-4}
67	Ho	7.2×10^{-5}	p	—		—		4.3×10^{-5}
68	Er	2.1×10^{-4}	p	—		—		1.3×10^{-4}
69	Tu	3.8×10^{-5}	p	—		—		2.2×10^{-5}
70	Yb	2.0×10^{-4}	p	—		—		1.2×10^{-4}
71	Lu	6.5×10^{-5}	p	—		—		3.9×10^{-5}
72	Hf	1×10^{-4}	l	—		—		6×10^{-5}
73	Ta	3.8×10^{-5}	ff	6×10^{-6}	l	—		2.5×10^{-5}
74	W	1.8×10^{-3}	l	8.1×10^{-4}	l	—		1.4×10^{-3}
75	Re	—		8.5×10^{-5}	gg	—	x	3.4×10^{-5}
76	Os	—		7.6×10^{-4}	g,hh	1.0×10^{-3}	l	3.0×10^{-4}
77	Ir	0	l	3.0×10^{-4}	g	5×10^{-5}	l	1.2×10^{-4}
78	Pt	8.3×10^{-6}	l	1.9×10^{-3}	g	3×10^{-4}	l	7.6×10^{-4}
79	Au	0	l	1.8×10^{-4}	ee	4.5×10^{-5}	l	7.2×10^{-5}
80	Hg	1×10^{-6}	g	—		2×10^{-5}	x	?
81	Tl	1.5×10^{-5}	g	—		3×10^{-5}	l	?
82	Pb	2×10^{-4}	x	6.0×10^{-3}	x	2.0×10^{-3}	h	2.5×10^{-3}
83	Bi	—		5×10^{-5}	l	2×10^{-4}	l	2.0×10^{-5}
90	Th	2×10^{-4}	l	4×10^{-6}	jj	—		1.2×10^{-4}
92	U	4×10^{-5}	ii,kk	7×10^{-7}	jj	—		2.8×10^{-4}

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the central temperature of the sun, it is possible that concentration gradients exist which cannot be neglected. If this is true, measurements of abundances of elements on stellar atmospheres would not be representative of the interior abundances.

Goldschmidt and others circumvented these difficulties by utilizing, wherever possible, data derived from the composition of meteoritic matter. The use of such data requires assumptions which are reasonable, but as yet not entirely proved. The primary assumption necessary is that the sum total of meteoritic matter is representative of the composition of stellar matter, with the exception of those elements which are extremely volatile (such as the rare gases) and those elements which probably existed in the form of volatile compounds at the time of planet condensation (such as CH_4 and H_2O).

Recent developments in the theory of planet formation make it appear reasonable that the planets are representative of the sun in composition, excepting the volatile constituents, which are probably responsible for the marked differences in physical characteristics that exist between the outer and inner planets. Lately the trend of thought has been directed more and more in the direction of planet condensation at relatively low temperatures.[32, 33] If this concept is correct, the line of demarcation between "volatile" and "non-volatile" constituents can be clearly drawn.

It is possible that meteorites had their origin in a planet very similar to the earth in general physicochemical characteristics, and a gross composition very

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[32] C. von Weizsächer: see S. Chandrasekhar; Rev. Mod. Phys. **18**, 94 (1946).

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similar to that of the earth.[34,35] It further appears reasonable that the inner planets have similar compositions, the marked differences in density among them arising almost entirely from their differing masses, and, as a result, their differing internal compressions.[36]

If the inner planets in reality have nearly identical compositions, and gross meteoritic matter corresponds to the composition of the inner planets, then the composition of meteoritic matter should correspond to the gross composition of the sun with respect to nonvolatile constituents. How closely this might represent the relative abundances of the same constituents in gross cosmic matter is not clear. Data derived from stellar spectra do not permit many precise comparisons between the sun and other stars. Greenstein,[30] who studied the abundances of the elements in a group of *F* stars of a wide range of luminosity found that no well-established abundance differences by a factor of 2 exist, except in the peculiar star τ-Ursae Majoris. In the mean, the stellar and solar abundances appear to be identical.

Most available data are consistent with the picture of stellar bodies being similar in composition to one another in all respects except for those elements which can be consumed or formed by thermonuclear reactions at stellar temperatures (primarily hydrogen, helium, lithium, beryllium, boron, carbon, and nitrogen). However, Unsöld's analysis of the spectrum of τ-Scorpii[26] indicates that major differences might exist between some stellar bodies insofar as the abundances of some elements of intermediate mass are concerned.*

II. METHOD OF COMPILING TABLE

Wherever possible, elemental abundance data have been derived from meteoritic sources. Solar and stellar data have been used for all elements where the use of meteoritic data is not warranted (H, He, C, N, O, Ne, A) and in borderline cases where the use of meteoritic data might be dubious or where the meteoritic data are not sufficiently precise (F, S, Cl). Data for lithium, beryllium, and boron are not given in the final abundance table because of the short half-lives of those elements at stellar interior temperatures. Data for five elements (Kr, Te, Xe, Hg, Tl) are either nonexistent or of such poor quality as to justify their exclusion.

Among those elements for which solar and stellar values must be used, Unsöld's solar values have been used wherever possible. In the cases of carbon, nitrogen, oxygen, and neon, where substantial differences exist in the sources of data, the most reliable values have been chosen. The planetary nebulae data of Aller and Menzel have been used for deriving the abundances of fluorine and chlorine. The argon value was derived from Aller's results on γ-Pegasi. Table I gives the stellar abundances of the lighter elements as determined by various observers. The table has been calculated on the basis of the number of atoms of a given element present per atom of oxygen. As the hydrogen and helium contents of stars are in general determined by means other than spectroscopic,[37–39] considerable divergence exists as to the best ratios of "Russell mixture" to hydrogen and helium. The results of Greenstein and Harrison were adopted in final compilation.

Meteorites in general are classified into two main categories: irons and stones. Iron meteorites consist of approximately ninety percent metallic iron, eight percent nickel and two percent minor constituents. Stony meteorites are composed primarily of magnesium and iron silicates. Most stony meteorites possess finely divided metal distributed throughout their masses. The average metal-phase content of stony meteorites is approximately eleven percent, but the quantity of metal may vary from nearly zero to well over fifty percent. A third and less abundant meteoritic phase, known as troilite and composed primarily of FeS, exists in both stony and iron meteorites, usually distributed throughout the mass, but frequently collected into pockets of substantial size. Table II gives the relative abundances of elements in the three main meteoritic phases as experimentally determined in various laboratories.

In order to calculate the composition of gross meteoritic matter it is necessary to determine the proportion of iron meteorites which fall relative to stony meteorites. This ratio cannot be readily determined experimentally

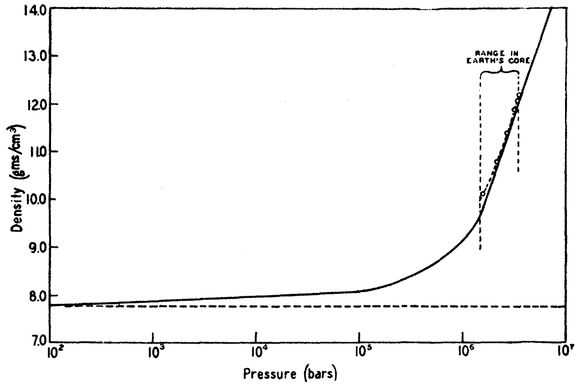

FIG. 1. The density of iron as a function of pressure as calculated by Jensen compared with the pressure-density relationship within the earth's core as determined by Bullen.

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[34] C. Bauer, paper presented at the Chicago meeting of the AAAS Dec. 26, 1947.

[35] H. Brown and C. Patterson, J. Geol. **56**, 85 (1948).

[36] H. Brown, paper presented at the Chicago meeting of the AAAS, Dec. 27, 1947.

* The expression "neon star" which is frequently applied to τ-Scorpii appears to be something of a misnomer. The neon content of τ-Scorpii as determined by Unsöld differs from the "interpolated" abundance of neon (see Table V) by an amount which does not appear to be very much greater than the experimental error involved in the determination.

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TABLE III. Elemental abundances (atoms per 10,000 atoms of Si).

Z	Element	Abundance	Source
1	H	3.5×10^{8}	*S**
2	He	3.5×10^{7}	*S**
3	Li	—	
4	Be	—	
5	B	—	
6	C	80,000	*S*
7	N	160,000	*S*
8	O	220,000	*S*
9	F	90	*P*
10	Ne	9,000–240,000	*P*, *Sc*†
11	Na	462±36	*M*
12	Mg	8,870±250	*M*
13	Al	882±81	*M*
14	Si	10,000	*M*
15	P	130	*M*
16	S	3500	*S*
17	Cl	170	*P*
18	A	130–2,200	*P*, *Pe*†
19	K	69.3±7.5	*M*
20	Ca	670±74	*M*, *S***
21	Sc	0.18	*M*
22	Ti	26.0±9.0	*M*
23	V	2.5	*M*
24	Cr	95	*M*
25	Mn	77	*M*
26	Fe	18,300	*M*
27	Co	99	*M*
28	Ni	1,340	*M*
29	Cu	4.6	*M*
30	Zn	1.6	*M*
31	Ga	0.65	*M*
32	Ge	2.5	*M*
33	As	4.8	*M*
34	Se	0.25	*M*
35	Br	0.42	*M*
36	Kr	—	†
37	Rb	0.071	*M*
38	Sr	0.41	*M*
39	Y	0.10	*M*
40	Zr	1.5	*M*
41	Cb	0.009	*M*
42	Mo	0.19	*M*
43	Tc	—	
44	Ru	0.093	*M*
45	Rh	0.035	*M*
46	Pd	0.032	*M*
47	Ag	0.027	*M*
48	Cd	0.026	*M*
49	In	0.01	*M*
50	Sn	0.62	*M*
51	Sb	0.017	*M*
52	Te	?	
53	I	0.018	*M*
54	Xe	—	†
55	Cs	0.001	*M*
56	Ba	0.039	*M*
57	La	0.021	*M*
58	Ce	0.023	*M*
59	Pr	0.0096	*M*
60	Nd	0.033	*M*
61	Pm	—	
62	Sm	0.012	*M*
63	Eu	0.0028	*M*
64	Gd	0.017	*M*
65	Tb	0.0052	*M*
66	Dy	0.020	*M*
67	Ho	0.0057	*M*
68	Er	0.016	*M*
69	Tm	0.0029	*M*
70	Yb	0.015	*M*
71	Lu	0.0048	*M*
72	Hf	0.007	*M*
73	Ta	0.0031	*M*
74	W	0.17	*M*
75	Re	0.0041	*M*
76	Os	0.035	*M*
77	Ir	0.014	*M*
78	Pt	0.087	*M*
79	Au	0.0082	*M*
80	Hg	?	*M*
81	Tl	?	*M*
82	Pb	0.27	*M*
83	Bi	0.0021	*M*
90	Th	0.012	*M*
92	U	0.0026	*M*

* The hydrogen-helium ratio and the ratio of hydrogen and helium to the "oxygen group" elements (C, N, O, Ne, Fe) are those computed by J. Greenstein and reported by M. Harrison, Astrophys. J. **108**, 310 (1948).

† See Table V.

** Stellar and meteoritic values have been combined by equalizing the calcium abundances.

because of the following differences in behavior of the two species.[40]

1. Stony meteorites tend to break into fragments while passing through the atmosphere, thus producing more spectacular displays than do iron meteorites. This creates a situation whereby more stony than iron meteorites are seen to fall.
2. Many meteorites are found on the ground without actually having been observed to fall. As stony meteorites appear to the untrained eye to be "rocks," many of them are never collected. Iron meteorites, being more unusual, are picked up more frequently.
3. Many meteorites corrode quite rapidly, and as a result may frequently disappear forever shortly after landing.

In order to circumvent these difficulties, an indirect method must be used for determining the ratio of metal phase to silicate phase. Observations on the earth are used for this purpose. It is assumed that the gross composition of the earth is in the main identical with the gross composition of meteoritic matter, and that the major constituents are distributed as follows:

1. An iron-nickel core with boundary defined by the well-known seismic discontinuity of first order.[41] The discontinuity occurs at approximately half the earth's radius.
2. A silicate mantle identical in composition with stony meteorites.

In order to determine the relative weights of metal phase to silicate phase it is necessary to determine the mean density of the core. Bullen[42,43] has calculated the densities and pressures within the earth using seismic data. His results for the volume corresponding to the core can be compared with the *a priori* calculation

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[40] F. G. Watson, J. Geol. **47**, 426 (1939).

[41] J. B. Macelwane, *Internal Constitution of the Earth* (B. Gutenberg, editor, McGraw-Hill Book Company, Inc., New York, 1939), p. 219.

[42] K. E. Bullen, Month. Not. Roy. Ast. Soc., Geophys. Sup. **3**, 395 (1936).

[43] K. E. Bullen, Roy. Soc. New Zealand Trans. **67**, 122 (1937).

and interpolation made by Jensen[44] of the density of iron as a function of pressure, based on the Fermi-Thomas model. The two calculations are plotted in Fig. 1, and it can be seen that the interpolation is sufficiently smooth to warrant integration of Bullen's curve of density *vs.* radius in order to determine the weight of the core. When this is done, one finds that the weight ratio of core to mantle is approximately

$$\frac{\text{weight of core}}{\text{weight of mantle}} \cong 0.50.$$

If we assume that the mantle contains approximately 10 percent by weight metal phase (the meteoritic value); then we have for the ratio of metal phase to silicate phase:

$$\frac{\text{weight metal phase}}{\text{weight silicate phase}} \cong 0.67.$$

This figure has been used in compiling the last column of Table II.

Use of the above metal-to-silicate ratio gives for the atomic ratio of iron to silicon:

$$(N_{\mathrm{Fe}}/N_{\mathrm{Si}})_{\mathrm{meteorites}} = 1.7.$$

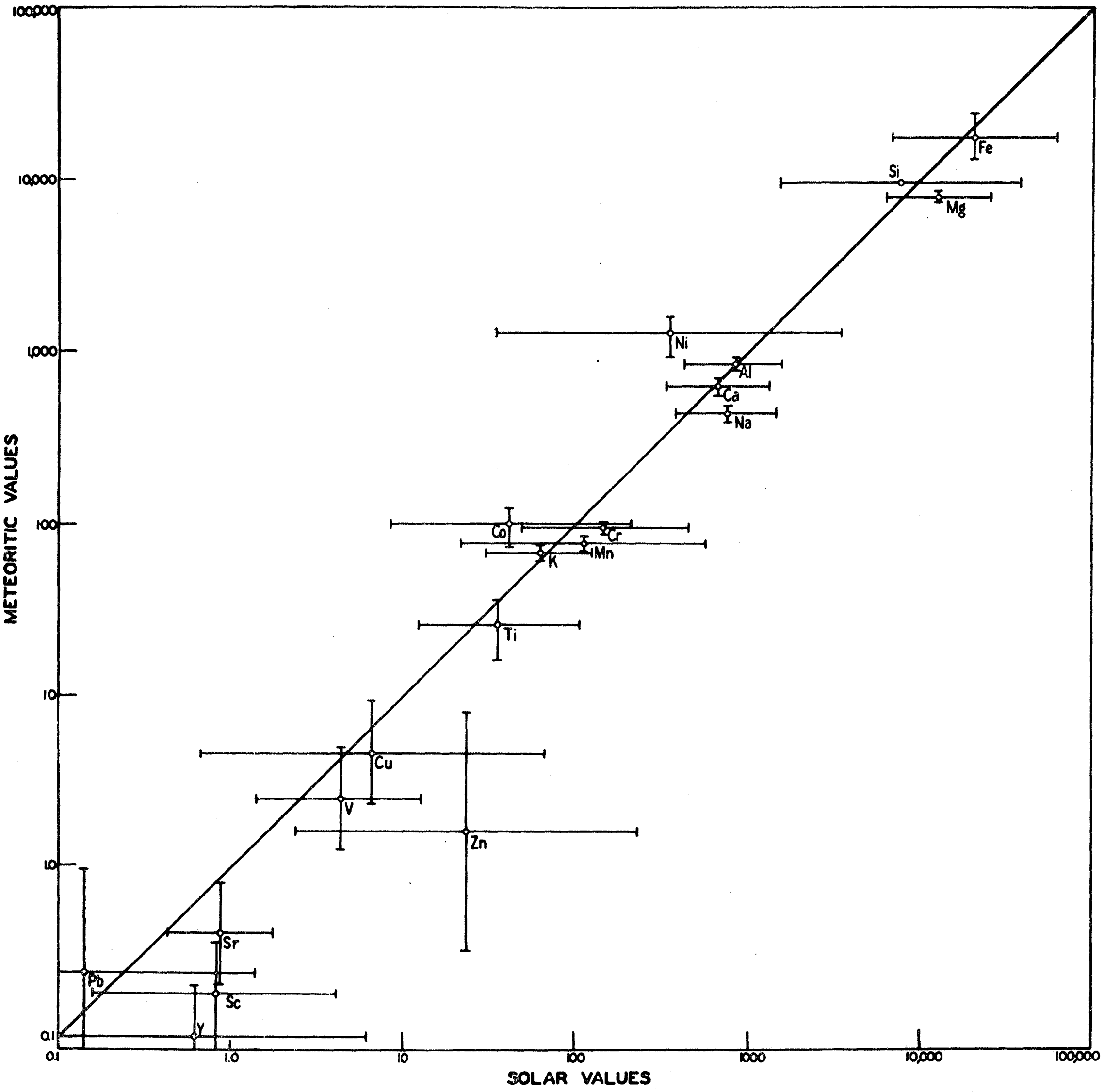

FIG. 2. The concentrations of various elements in meteorites compared with concentrations in the solar atmosphere. The values have been normalized by setting solar calcium equal to meteoritic calcium. The lengths of the lines designate the estimates of the limits of error.

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[44] H. Jensen, Zeits. f. Physik **111**, 373 (1938).

TABLE IV. Relative abundance of nuclear species (atoms per 10,000 atoms of silicon)

Z	Element	Species	Odd abundance	Even abundance
8	O	16		220,000
		17	86	
		18		450
9	F	19	90	
10	Ne	20		42,000*
		21	130*	
		22		4,300*
11	Na	23	462±36	
12	Mg	24		6,970±240
		25	897±97	
		26		1,000±100
13	Al	27	882±81	
14	Si	28		9,228±3
		29	467±1	
		30		305±3
15	P	31	130	
16	S	32		3,300
		33	26	
		34		150
		36		0.56
17	Cl	35	130	
		37	42	
18	A	36		450†
		38		87†
		40		?
19	K	39	64.7±7.0	
		(40)		0.0076±0.0008
		41	4.64±0.50	
20	Ca	40		650±72
		42		4.29±0.49
		43	1.01±0.12	
		44		13.8±1.6
		46		0.022±0.004
		48		1.27±0.15
21	Sc	45	0.18	
22	Ti	46		2.07±0.72
		47	2.02±0.70	
		48		19.1±6.6
		49	1.43±0.50	
		50		1.39±0.48
23	V	51	2.5	
24	Cr	50		4.3
		52		80
		53	9.0	
		54		2.2
25	Mn	55	77	
26	Fe	54		1100
		56		17,000
		57	400	
		58		60
27	Co	59	99	
28	Ni	58		910
		60		350
		61	17	
		62		49
		64		16
29	Cu	63	3.2	
		65	1.4	
30	Zn	64		0.78
		66		0.44
		67	0.065	
		68		0.30
		70		0.0099
31	Ga	69	0.39	
		71	0.26	
32	Ge	70		0.51
		72		0.68
		73	0.19	
		74		0.92
		76		0.19
33	As	75	4.8	
34	Se	74		0.0022
		76		0.023
		77	0.019	
		78		0.059
		80		0.12
		82		0.023
35	Br	79	0.21	
		81	0.21	
36	Kr	78		
		80		
		82		
		83		
		84		
		86		
37	Rb	85	0.052	
		(87)	0.019	
38	Sr	84		0.0023
		86		0.040
		87	0.029	
		88		0.34
39	Y	89	0.10	
40	Zr	90		0.77
		91	0.17	
		92		0.26
		94		0.26
		96		0.042
41	Cb	93	0.009	
42	Mo	92		0.030
		94		0.017
		95	0.030	
		96		0.031
		97	0.018	
		98		0.045
		100		0.018
44	Ru	96		0.0053
		98		0.0021
		99	0.012	
		100		0.012
		101	0.016	
		102		0.029
		104		0.017
45	Rh	103	0.035	
46	Pd	102		0.00026
		104		0.0030
		105	0.0072	
		106		0.0087
		108		0.0086
		110		0.0043

TABLE IV. (*Continued*).

Z	Element	Species	Odd abundance	Even abundance
47	Ag	107	0.014	
		109	0.013	
48	Cd	106		0.00032
		108		0.00023
		110		0.0032
		111	0.0033	
		112		0.0063
		113	0.0032	
		114		0.0075
		116		0.0020
49	In	113	0.00042	
		115	0.0096	
50	Sn	112		0.0056
		114		0.0038
		115	0.0022	
		116		0.087
		117	0.047	
		118		1.149
		119	0.053	
		120		0.19
		122		0.030
		124		0.038
51	Sb	121	0.0097	
		133	0.0073	
52	Te	122		
		123		
		124		
		125		
		126		
		128		
		130		
53	I	127	0.018	
54	Xe	124		
		126		
		128		
		129		
		130		
		131		
		132		
		134		
		136		
55	Cs	133	0.001	
56	Ba	130		0.000039
		132		0.000038
		134		0.00094
		135	0.0026	
		136		0.0030
		137	0.0044	
		138		0.028
57	La	138		0.000019
		139	0.021	
58	Ce	136		0.000044
		138		0.000058
		140		0.020
		142		0.0025
59	Pr	141	0.0096	
60	Nd	142		0.0090
		143	0.0040	
		144		0.0079
		145	0.0027	
		146		0.0057
		148		0.0019
		150		0.0018

TABLE IV. (*Continued*).

Z	Element	Species	Odd abundance	Even abundance
62	Sm	144		0.00038
		147	0.0018	
		148		0.0014
		149	0.0017	
		150		0.00090
		152		0.0032
		154		0.0027
63	Eu	151	0.0013	
		153	0.0015	
64	Gd	152		0.000034
		154		0.00037
		155	0.0025	
		156		0.0035
		157	0.0027	
		158		0.0042
		160		0.0037
65	Tb	159	0.0052	
66	Dy	156		0.00001
		158		0.00002
		160		0.00046
		161	0.0038	
		162		0.0051
		163	0.0050	
		164		0.0056
67	Ho	165	0.0057	
68	Er	162		0.000016
		164		0.00024
		166		0.0053
		167	0.0039	
		168		0.0043
		170		0.0023
69	Tm	169	0.0029	
70	Yb	168		0.000009
		170		0.00063
		171	0.0021	
		172		0.0032
		173	0.0026	
		174		0.0044
		176		0.0020
71	Lu	175	0.0047	
		(176)		0.00012
72	Hf	174		0.000013
		176		0.00037
		177	0.0013	
		178		0.0019
		179	0.00097	
		180		0.0025
73	Ta	181	0.0031	
74	W	180		0.00021
		182		0.044
		183	0.024	
		184		0.052
		186		0.050
75	Re	185	0.0015	
		187	0.0026	
76	Os	184		0.0000063
		186		0.00056
		187	0.00057	
		188		0.0047
		189	0.0056	
		190		0.0092
		192		0.014

TABLE IV. (*Continued*).

Z	Element	Species	Odd abundance	Even abundance
77	Ir	191	0.0054	
		193	0.0086	
78	Pt	192		0.00068
		194		0.029
		195	0.029	
		196		0.022
		198		0.0063
79	Au	197	0.0082	
80	Hg	196		
		198		
		199		
		200		
		201		
		202		
		204		
81	Tl	203		
		205		
82	Pb	204		0.0041
		206		0.064
		207	0.061	
		208		0.14
83	Bi	209	0.0021	
90	Th	(232)		0.012
92	U	(235)	0.000018	
		(238)		0.0026

* The logarithmic mean of the neon extremes has been utilized in compiling these values.

† The logarithmic mean of the argon extremes has been utilized in compiling these values. It is assumed that A^{36} is the major constituent of cosmic argon.

( ) indicates a naturally-occurring radioactive species.

The value for this ratio as determined from Unsöld's data for the sun is:

$$(N_{\mathrm{Fe}}/N_{\mathrm{Si}})_{\mathrm{sun}}=2.7.$$

When one considers that stellar abundances can seldom be determined with a higher precision than a factor of two, the agreement appears to be reasonably satisfactory.

Superficially it would appear that the lack of precision in the metal-to-silicate ratio constitutes an insurmountable limitation to the use of meteoritic data in the determination of cosmic abundances. Actually the difficulty is not in the long run too serious, for the reason that most elements tend to concentrate markedly in one of the two phases. Few elements exist which are more or less evenly distributed between the two phases. This makes possible the comparison of the abundances of rather large numbers of elements, one against the other, without the necessity of introducing the errors involved in the metal-to-silicate ratio determination. A notable example in this case is the sequence of oxide forming elements Na, Mg, Al, Si, K and Ca.[45] Another example of importance is the long sequence of precious metals which concentrate almost entirely in the metal phase. As a result, it is possible to determine the abundances of these elements relative to one another with a high degree of precision.

TABLE V. Cosmic abundances of the rare gases as estimated by interpolation of the abundance curves (abundances in atoms per 10,000 atoms of silicon).[kk]

Gas	Isotope used for interpolation	Estimated abundance of isotope	Estimated abundance of element
Ne	Ne^{21}	100	37,000
A	A^{36}	1,000	1,000
Kr	Kr^{83}	0.1	0.87
Xe	Xe^{131}	0.004	0.015

[kk] H. Brown, *The Atmospheres of the Earth and Planets* (G. Kuiper, ed., University of Chicago Press, Chicago, 1949), p. 260.

In the compilation of the table of elemental abundances from meteoritic data, the sulfide phase is not taken into consideration for two reasons:

1. The portion of the sulfide phase which is fairly uniformly distributed throughout stony and iron meteorites is automatically determined in the analysis of an individual meteorite.
2. The portion of the sulfide phase which exists in the form of large globules in meteorites is probably not large compared with that amount which is uniformly dispersed. Nevertheless, it must be kept in mind that the abundances given for those elements which exist in the sulfide phase in considerable concentration may well be somewhat too low.

Table III is a compilation of elemental abundances derived by combining the last column of Table II with selected values for various elements from Table I. The letters *S*, *P*, *Sc*, *Pe* and *M* designate the sources chosen (solar, planetary nebulae, τ-Scorpii, γ-Pegasi or meteoritic).

It is of interest to compare the abundances as determined from solar data with the abundances as determined from meteoritic data wherever this is possible. Figure 2 shows a comparison of Unsöld's solar data, for a series of elements, with the corresponding values as determined from meteorites. The general agreement is gratifying and indicates that the general procedure utilized in compiling the abundance table is justified.**

The elemental abundance data of Table III has been

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[45] H. Brown and C. Patterson, Phys. Rev. **72**, 456 (1947).

** Unsöld estimates that in good cases his solar abundances should be correct to within a factor of two. J. L. Greenstein says (private communication): "The elements Na, Mg, Al, K, Ca, Sr, Ba should be quite good, since for these, transition-probabilities can be accurately estimated; for Na, Mg, K, and Ca they are computed quantum-mechanically. The other elements have transition probabilities based upon the 'sum-rules;' for Ti, Cr, Fe, and V certain laboratory data have roughly corroborated the sum-rule intensities. However, these, plus Si, Sc, Mn, Co, and Zr, should eventually become accurately determinable cases. The elements Ni and Y will be difficult, since only high-excitation or ionized lines are available. Others like Cu, Mo, and Pb are poor cases in every way."

The following errors were assigned to the solar values shown in Fig. 2:

Na, Mg, K and Ca—a factor of two
Ti, Cr, Fe and V —a factor of three
Si, Sc, Mn, Co, Zr —a factor of five
all others —a factor of ten.

compounded with terrestrial isotope abundances,[46] thus obtaining the table of nuclear abundances shown in Table IV. In order to minimize the confusion occasioned by the "even-odd" abundance oscillations, the table has been divided into two columns, one for species of odd mass number, the other for species of even mass number. Figure 3 shows the abundance curve for nuclear species of odd mass number in order that the reader may see the general abundance trend free of the confusion associated with the large number of isobars present among the even species. In preparing Fig. 3 the assumption is made that terrestrial isotope abundances are identical with meteoritic isotope abundances, an assumption which has thus far been tested in the cases of seven elements, utilizing the mass spectrometer (iron,[47] nickel,[48] copper,[49] chromium,[50]

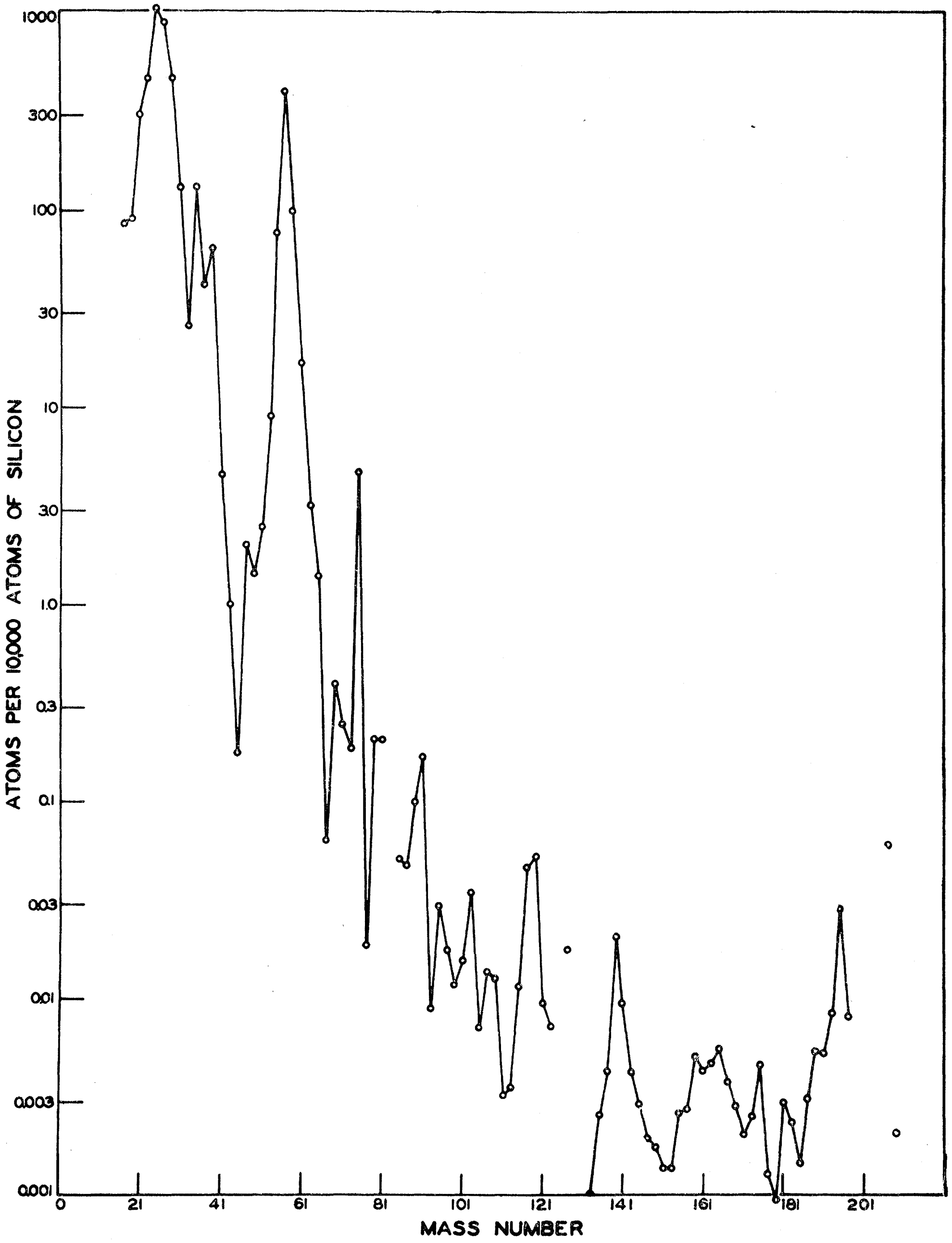

FIG. 3. The relative abundance of nuclear species of odd mass number as a function of mass number.

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[46] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).
[47] G. E. Valley and H. H. Anderson, J. Am. Chem. Soc. **69**, 1871 (1947).
[48] M. Inghram and H. Brown, unpublished.
[49] H. Brown and M. Inghram, Phys. Rev. **72**, 347 (1947).
[50] M. Inghram and H. Brown, unpublished.

TABLE VI. Abundances of elements in interstellar material according to Struve and Dunham.[l,m,*]

Element	Abundance atoms per atom of calcium Struve	 Dunham
H	2×10^7	2.5×10^6
O	10,000	
Na	10	25
K		2.5
Ca	1	1
Ti		0.005
CH	10	
CN	10	

[*] B. Strömgren (Astrophys. J. **108**, 242 (1948)) gives the following ratios:

$$H/Na \quad 5\times10^6-2.5\times10^7$$
$$Ca/Na>1$$
$$Ti/Na\cong3\times10^{-2}.$$

[l] O. Struve, J. Wash. Acad. Science **31**, 217 (1941).

[m] T. Dunham, Jr., Proc. Am. Phil. Soc. **81**, 277 (1939).

gallium,[51] carbon,[52] and oxygen[53]) and in the cases of silicon,[54] chlorine,[55] potassium,[56] uranium,[57] and cobalt,[58] utilizing other techniques. Only in the case of carbon has any difference in abundance ratio been detected, and that difference, though probably significant, is exceedingly small. It should be noted, however, that there are apparently stars in which the isotopic ratio in carbon may be markedly different from that existing on our earth and in the sun.[59]

Unfortunately the rare gases, being volatile substances, do not exist in meteorites, and as only neon has been determined precisely in stars, their abundances are practically unknown. Figure 3 indicates, however, that the general abundance curve is sufficiently smooth to permit interpolation for specific rare gas isotopes. This permits in turn the evaluation of approximate gross rare gas abundances.[60] Table V shows the abundances of the various rare gases relative to silicon when determined in this manner. In the case of argon, A^{36} has been considered to be the most abundant argon isotope occurring in the universe, the bulk of the A^{40} on earth probably having been produced by decay of K^{40}.[61]

In general the values given in the abundance table should be accurate to within a factor of four, with a factor of two being the more usual error. There are several cases where the relative values are considerably more precise than this however, notably the lighter elements Na, Mg, Al, Si, K, and Ca relative to one another. In addition there are isolated cases where the ratios of two individual elements can be expressed with considerable precision, as for example, the weight ratio of palladium to gold.[62]

With the development of new techniques of quantitative analysis[63, 64] it seems likely that such precisions in abundance ratios may be extended to cover substantial numbers of elements.

No discussion of abundances would be complete without mentioning the interesting considerations of Professor Hans Suess[65] who has, on the basis of reasonableness and continuity, estimated "correction factors" which would be necessary in order to smooth out the experimental abundance curve. The correction factors proposed by Suess are quite within the bounds of reasonableness, indicating that further work must be done before a really precise table of abundances can be compiled.

It is well recognized that in certain regions of our own and other galaxies as much as fifty percent of the mass exists in the form of finely divided matter distributed throughout interstellar space. Any table of relative abundances should, of course, be compiled in such a way as to take this into consideration. However, the data as yet (see Table VI) are not sufficiently precise to warrant its incorporation into the abundance table.† The significance and extent of interstellar material has been discussed by several investigators.[66–68]

ACKNOWLEDGMENTS

The author is grateful for the help and suggestions of his colleagues and students Edward Goldberg and Claire Patterson, and for the advice and criticism of numerous of his colleagues, notably Drs. Maria and Joseph Mayer, and Edward Teller. The advice and information given by Drs. L. H. Aller, J. L. Greenstein, Gerard Kuiper, Thornton Page, and Otto Struve have been particularly helpful.

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[51] Inghram, Hess, Brown, and Goldberg, Phys. Rev. **74**, 343 (1948).

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[60] H. Brown, The Atmospheres of the Earth and Planets (G. Kuiper, ed., University of Chicago Press, Chicago, 1949), p. 260.

[61] L. Aldrich and A. O. Nier, Phys. Rev. **74**, 870 (1948).

[62] H. Brown and E. Goldberg (unpublished).

[63] C. Tobias and R. Dunn, Science **109**, 109 (1949).

[64] H. Brown and E. Goldberg, Science **109**, 347 (1949).

[65] H. Suess, Zeits. f. Natur. **2a**, 606 (1947).

† Professor L. Spitzer, Jr. has informed the author that he has recently determined approximate upper limits for the lithium and beryllium concentrations in interstellar space. He finds

$$\text{atoms Li/atoms Na} < 0.1$$
$$\text{atoms Be/atoms Na} < 10^{-4}.$$

[66] O. Struve, J. Wash. Acad. Sci. **31**, 217 (1941).

[67] B. Strömgren, Astrophys. J. **108**, 242 (1948).

[68] L. Spitzer, Astrophys. J. **108**, 276 (1948).