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## Compositions of chondrites

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A compilation of data on 78 elements in the nine groups of chondrites shows each to be isochemical with the exception of a few volatiles. With the exception of the most volatile elements, the groups have solar abundances to within a factor of two. The solar abundances and the chemical and physical properties of phases in the least-altered chondrites indicate formation by grain agglomeration in the preplanetary nebula.

Planets formed by the gradual growth of bodies in the solar nebula. Because there is no evidence for the formation of non-chondritic bodies in the nebula, the simplest model calls for the bulk compositions of the terrestrial planets to be chondritic. Mercury is enriched in metal, perhaps either because of high loss of silicates due to enhanced radial drag in the innermost part of the nebula, or because of enhanced accretion of metallic cores from disrupted asteroids. Chondritic compositions should be considered as boundary conditions for planetary models.

### INTRODUCTION

The first compilation of chemical composition data for the chondrite groups is the book edited by Mason (1971); this compilation was updated by Mason (1979). Later, Anders & Ebihara (1982) and Wasson (1985) compiled complete data for the volatile-rich CI chondrites. Since Mason (1971) was compiled, the classification of chondrites has been revised: C3 chondrites were divided into CV and CO groups, and the E4, E5 and E6 chondrites assigned to EH and EL groups. A summary of chondrite classification is given in table 1.

Listed in table 1 as examples of taxonomic parameters are abundances (i.e. element/Si ratios) of a refractory lithophile element (Al), a common lithophile element showing some refractory properties (Mg), a siderophile element (Ni) and a volatile oxide- or sulphide-forming element (Zn). The bulk  $\text{FeO}_x/(\text{FeO}_x + \text{MgO})$  ratio is a measure of the degree of oxidation;  $\text{FeO}_x$  includes Fe present as FeO and  $\text{FeO}_{1.5}$ . The O-isotope data (expressed in per mille deviations from the composition of ocean water) are the most recent addition to the list of classificational parameters. Only the EH and EL O-isotope compositions fall on the terrestrial fractionation line defined by the O-isotope compositions of terrestrial rocks, waters, biota, etc.

The H, L and LL groups are closely related, and constitute the ordinary chondrite clan. The EH and EL chondrites are analogously related and constitute the enstatite chondrite clan. The carbonaceous chondrites appear to form three clans CV, CM–CO and CI. The body of reliable compositional data has been gradually increasing, especially during the past two decades. Our research group has contributed by analysing about 30 elements by neutron activation in representative observed falls from the nine groups. Our results on the four carbonaceous chondrite (Kallemeyn & Wasson 1981) and the two enstatite chondrite (Kallemeyn & Wasson 1986) groups have been published; a comprehensive chemical–petrographic study of ordinary

TABLE 1. THE CLASSIFICATION OF CHONDRITES AND A LISTING OF SOME KEY TAXONOMIC PARAMETERS

group	Al/Si	Mg/Si (normalized ratios)	Ni/Si	Zn/Si	$\frac{\text{FeO}_x}{\text{FeO}_x + \text{MgO}}$ (mol%)	$\text{d}^{17}\text{O}$ (‰)	$\text{d}^{18}\text{O}$ (‰)
CV	1.34	1.00	0.85	0.25	35	-3	1
CO	1.07	0.97	0.87	0.21	33	-4	0
CM	1.10	0.97	0.92	0.48	43 <sup>a</sup>	1	7
CI	$\approx 1.00$	$\approx 1.00$	$\approx 1.00$	$\approx 1.00$	45 <sup>a</sup>	9	17
H	0.80	0.89	0.94	0.092	17	3.0	4.2
L	0.78	0.84	0.64	0.088	22	3.5	4.6
LL	0.75	0.84	0.53	0.080	27	3.8	4.9
EH	0.58	0.68	1.04	0.49	0.05 <sup>a</sup>	2.9	5.7
EL	0.67	0.81	0.69	0.030	0.05	2.9	5.7

<sup>a</sup> Estimated  $\text{FeO}_x/(\text{FeO}_x + \text{MgO})$  for equilibrium assemblage.

chondrites is being prepared for publication. These large sets of data from our group form the core of the compiled data. Because the same controls were used throughout these studies, intergroup biases are minimal.

A sizeable body of evidence indicates that the chondritic meteorites formed in the solar nebula. They have solar compositions of the condensable elements. They show the fractionations expected from the mechanical segregation of materials forming over a range of temperatures from a solar mixture of the elements. Their compositions are grossly different from those of igneously formed rocks, and the temperature range over which they become molten is much greater than those for igneous rocks.

Chondrites appear to be the materials from which the inner planets were constructed. The compositional variations among groups appear to reflect differences in the processes that led to the formation of planetesimals at different times and different distances from the Sun. After the formation of chondritic planetesimals, there are no obvious and well-investigated accretional processes that would lead to the formation of Mercury to Earth-size planets having compositions that are not broadly chondritic.

#### COMPOSITIONS OF THE CHONDRITE GROUPS

Mean elemental compositions of the 9 chondrite groups are listed in table 2; data are given for 78 elements including all atomic numbers from 1 to 83 except the five rare gases and the missing elements 43 and 61. These means are calculated from data published through June 1987. Deviant values were discarded, and extra weight was given to certain large, high-quality data sets. A few data sets were multiplied by constant factors to bring them more nearly in line with more accurate data sets. Details can be found in Kallemeyn & Wasson (1988).

Five trace elements are still not well determined in the chondrite groups. Two (Be and Nb) are probably unstudied because their nuclear properties make them almost impossible to determine by neutron activation, and two others (Rh, Ta) are relatively difficult to study by this technique. Many studies of Hg have been done, but the data show extreme scatter, apparently as a result of ubiquitous laboratory contamination. An important goal for analysts would be the development of sensitive, contamination-free techniques for the determination of these elements, and the analysis of several representative samples of each meteorite group.

## COMPOSITIONS OF CHONDRITES

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TABLE 2. MEAN COMPOSITIONS OF THE CHONDRITE GROUPS

	CI	CM	CO	CV	H	L	LL	EH	EL
H/(mg g <sup>-1</sup> )	20	14	0.7	2.8	—	—	—	—	—
Li/(μg g <sup>-1</sup> )	1.57	1.36	1.2	1.24	1.7	1.8	2.1	2.1	0.58
Be/(ng g <sup>-1</sup> )	27	—	—	—	51	43	51	—	—
B/(μg g <sup>-1</sup> )	1.2	0.6	—	0.3	0.5	0.4	—	—	—
C/(mg g <sup>-1</sup> )	32	22	4.5	5.6	1.1	0.9	1.2	4.0	3.6
N/(μg g <sup>-1</sup> )	1500	1520	90	80	48	43	70	—	—
O/(mg g <sup>-1</sup> )	460	432	370	370	357	377	400	280	310
F/(μg g <sup>-1</sup> )	64	38	30	24	32	41	63	238	180
Na/(mg g <sup>-1</sup> )	4.9	4.1	4.1	3.3	6.4	7.0	7.0	6.8	5.8
Mg/(mg g <sup>-1</sup> )	97	117	145	145	140	149	153	106	141
Al/(mg g <sup>-1</sup> )	8.6	11.8	14.3	17.5	11.3	12.2	11.9	8.1	10.5
Si/(mg g <sup>-1</sup> )	105	129	159	156	169	185	189	167	186
P/(mg g <sup>-1</sup> )	1.02	0.90	1.04	0.99	1.08	0.95	0.85	2.00	1.17
S/(mg g <sup>-1</sup> )	59	33	20	22	20	22	23	58	33
Cl/(μg g <sup>-1</sup> )	680	160	240	210	80	76	130	660	210
K/(μg g <sup>-1</sup> )	560	400	345	310	780	825	790	800	735
Ca/(mg g <sup>-1</sup> )	9.2	12.7	15.8	19.0	12.5	13.1	13.0	8.5	10.1
Sc/(μg g <sup>-1</sup> )	5.8	8.2	9.6	11.4	7.9	8.6	8.4	5.7	7.4
Ti/(μg g <sup>-1</sup> )	420	580	780	980	600	630	620	450	580
V/(μg g <sup>-1</sup> )	55	75	92	96	74	77	75	54	60
Cr/(mg g <sup>-1</sup> )	2.65	3.05	3.55	3.60	3.66	3.88	3.74	3.15	3.05
Mn/(mg g <sup>-1</sup> )	1.90	1.70	1.65	1.45	2.32	2.57	2.62	2.20	1.63
Fe/(mg g <sup>-1</sup> )	182	210	248	235	275	215	185	290	220
Co/(μg g <sup>-1</sup> )	508	575	688	655	810	590	490	840	670
Ni/(mg g <sup>-1</sup> )	10.7	12.0	14.0	13.4	16.0	12.0	10.2	17.5	13.0
Cu/(μg g <sup>-1</sup> )	121	115	125	100	82	90	80	185	110
Zn/(μg g <sup>-1</sup> )	312	185	100	116	47	50	46	250	17
Ga/(μg g <sup>-1</sup> )	9.8	7.8	7.1	6.0	6.0	5.7	5.0	16	11
Ge/(μg g <sup>-1</sup> )	33	23	21	17	13	10	9.0	42	28
As/(μg g <sup>-1</sup> )	1.84	1.80	1.95	1.60	2.05	1.55	1.35	3.45	2.20
Se/(μg g <sup>-1</sup> )	19.6	12.7	7.6	8.3	7.7	9.0	9.9	25.5	13.5
Br/(μg g <sup>-1</sup> )	3.6	2.6	1.3	1.5	0.5	0.8	0.6	2.4	0.8
Rb/(μg g <sup>-1</sup> )	2.22	1.7	1.45	1.25	2.9	3.1	3.1	2.6	2.5
Sr/(μg g <sup>-1</sup> )	7.9	10.1	12.7	15.3	10.0	11.1	11.1	7.2	8.2
Y/(μg g <sup>-1</sup> )	1.44	2.0	2.4	2.4	2.2	2.1	2.0	1.3	—
Zr/(μg g <sup>-1</sup> )	3.8	8.0	7.8	8.3	6.3	5.9	5.9	4.9	5.2
Nb/(ng g <sup>-1</sup> )	270	(370)	(450)	(540)	(360)	(390)	(370)	(250)	—
Mo/(ng g <sup>-1</sup> )	920	1500	1900	2100	1700	1300	1100	—	—
Ru/(ng g <sup>-1</sup> )	710	883	1090	1130	1100	750	—	915	831
Rh/(ng g <sup>-1</sup> )	134	—	—	250	220	—	—	—	—
Pd/(ng g <sup>-1</sup> )	560	640	703	705	870	560	530	885	690
Ag/(ng g <sup>-1</sup> )	208	157	97	107	45	65	72	236	23
Cd/(ng g <sup>-1</sup> )	650	368	8	373	17	11	37	494	27
In/(ng g <sup>-1</sup> )	80	50	25	33	11	7.0	12	58	2.3
Sn/(μg g <sup>-1</sup> )	1.72	1.01	0.89	0.90	0.86	0.71	—	0.80	—
Sb/(ng g <sup>-1</sup> )	153	115	105	85	70	68	60	196	90
Te/(μg g <sup>-1</sup> )	2.4	1.91	0.90	1.02	0.26	0.48	0.49	2.23	0.80
I/(ng g <sup>-1</sup> )	500	425	200	188	68	53	—	150	53
Cs/(ng g <sup>-1</sup> )	183	125	80	95	120	280	180	200	100
Ba/(μg g <sup>-1</sup> )	2.3	3.3	4.29	4.9	4.2	3.7	4.8	2.6	—
La/(ng g <sup>-1</sup> )	236	317	387	486	295	310	315	235	190
Ce/(ng g <sup>-1</sup> )	616	838	1020	1290	830	900	907	660	300
Pr/(ng g <sup>-1</sup> )	92.9	129	157	200	123	132	122	94	—
Nd/(ng g <sup>-1</sup> )	457	631	772	990	628	682	659	460	233
Sm/(ng g <sup>-1</sup> )	149	200	240	295	185	195	200	140	135
Eu/(ng g <sup>-1</sup> )	56.0	76	94	113	73	78	76	54	54
Gd/(ng g <sup>-1</sup> )	197	276	337	415	299	310	303	214	107
Tb/(ng g <sup>-1</sup> )	35.5	47	57	65	53	57	48	35	—
Dy/(ng g <sup>-1</sup> )	245	330	404	475	343	366	351	240	139
Ho/(ng g <sup>-1</sup> )	54.7	77	94	110	73	81	77	50	—
Er/(ng g <sup>-1</sup> )	160	218	266	315	226	248	234	166	97
Tm/(ng g <sup>-1</sup> )	24.7	33	40	45	39	39	34	25	—
Yb/(ng g <sup>-1</sup> )	159	222	270	322	205	220	220	160	165
Lu/(ng g <sup>-1</sup> )	24.5	33	40	48	31	33	33	24	24
Hf/(ng g <sup>-1</sup> )	120	186	178	194	180	170	150	140	150
Ta/(ng g <sup>-1</sup> )	16	(22)	(27)	(32)	22	23	(22)	(15)	—
W/(ng g <sup>-1</sup> )	100	140	160	190	160	110	—	—	—
Re/(ng g <sup>-1</sup> )	37	46	55	65	70	40	33	52	47
Os/(ng g <sup>-1</sup> )	490	640	790	825	820	515	400	654	589
Ir/(ng g <sup>-1</sup> )	460	595	735	760	760	490	360	565	525
Pt/(ng g <sup>-1</sup> )	990	1100	1200	1250	1400	1050	850	1200	—
Au/(ng g <sup>-1</sup> )	144	165	184	144	215	162	140	330	225
Hg/(ng g <sup>-1</sup> )	380	—	—	—	—	—	—	—	—
Tl/(ng g <sup>-1</sup> )	142	92	42	46	3.7	2.0	7.2	103	5.0
Pb/(μg g <sup>-1</sup> )	2.4	1.7	2.2	1.4	0.24	0.37	—	1.1	—
Bi/(ng g <sup>-1</sup> )	110	75	33	48	17	14	16	88	12
Th/(ng g <sup>-1</sup> )	29	40	(45)	60	42	43	43	30	35
U/(ng g <sup>-1</sup> )	8.2	11	13	17	12	13	13	9	10

The CI chondrites are the most volatile-rich chondrites, and their compositions appear to be representative of mean nebular condensable material. Most compilations of solar abundances (e.g. Cameron 1982) use CI data for all elements listed in table 2 with the exception of four that were incompletely condensed: H, C, N and O. Compilations of CI data were published by Anders & Ebihara (1982) and by Wasson (1985). Wasson noted that his CI concentrations agreed with those of Anders & Ebihara (1982) to within  $\pm 5\%$  except for 9 elements. Six of these (C, S, Y, Nb, Sb, Os) are within  $\pm 10\%$  of the Anders–Ebihara set, whereas three (N, P, I) are, respectively, 12% lower, 20% higher and 13% lower in Anders & Ebihara (1982) than in Wasson (1985). The present listing of CI data corresponds exactly with that in Wasson (1985) with the exception of Na and V, which were changed slightly because of the inclusion of new CI data produced since Kallemeyn & Wasson (1981).

The elements can be divided on the basis of their inferred behaviour under nebular conditions into broad cosmochemical classes. The three major elements Si, Mg and Fe vaporize or condense at very similar nebular temperatures. At a  $p_{H_2}$  pressure of 0.1 Pa their 50%-condensation temperatures are in the range 1183–1203 K (Wasson 1985). These common elements serve as benchmarks on the volatility scale, and because they condense in the same range, the minor elements Cr, Co and Ni can also be designated common elements. Elements that vaporize or condense at higher temperatures are called refractory elements, and those that vaporize or condense at lower temperatures, volatile elements. These classes of elements can again be subdivided into the lithophiles that condense as oxides, and siderophiles that condense as metals. A few additional minor categories are excluded from this simplified discussion.

If large samples are analysed, concentrations of refractory and common elements show very little variation from chondrite to chondrite within a given group. In contrast, volatile concentrations often show large variations from one group member to the next, the magnitude of the variations generally increasing with increasing elemental volatility.

When the concentration ranges are large, one must decide how to weight individual values to obtain a mean. After discarding obvious outliers, we find that the ranges in the four carbonaceous chondrite groups are generally less than a factor of two; the arithmetic mean seems a reasonable choice, one with a relative uncertainty of up to 15% at 70% confidence.

In the H, L, LL and EH groups most of the concentration ranges of volatile elements often span an order of magnitude, and maximum:minimum ratios of some elements approach 1000. There is moderately strong evidence that these large variations were produced by metamorphic heating; in many cases volatile concentrations are negatively correlated with petrographic type (Wasson 1972). It cannot be ruled out that some of the highest concentrations were enhanced by the condensation of volatiles in other regions of the parent body (or planetesimal), although there is no direct evidence (such as volatile-rich veins) that this has indeed occurred. It seems probable that much of the volatiles lost from the high petrographic types left the parent body-planetesimal. For this reason we calculated mean volatile contents from sets limited to type-3 chondrites and the more volatile-rich members of type 4. The resulting maximum–minimum ranges are generally less than four, and the resulting uncertainties in the means are up to 30% of the mean.

The refractory lithophile elements have the same interelement ratios in all chondrite groups except EL. Two of the unstudied elements (Nb, Ta) are refractory lithophile; thus their concentrations can be inferred by assuming that they are unfractionated relative to well-determined refractory lithophile elements such as Al, Ca, Sc or Sm. These inferred values are enclosed in parentheses in table 2.



## INTERGROUP DIFFERENCES AND CHONDRITE FORMATION

In figure 1 we compare Si-normalized lithophile abundances for the chondrite groups. On the vertical axis we show ratios of group abundances to CI abundances. The elements are arranged along the horizontal axis with volatility increasing to the right. Because CI chondrites are used for normalization, their pattern consists of a horizontal line with an abundance ratio of unity. The LL group is not plotted because LL abundances have lower precisions than L abundances, and the two groups cannot be resolved on this diagram.

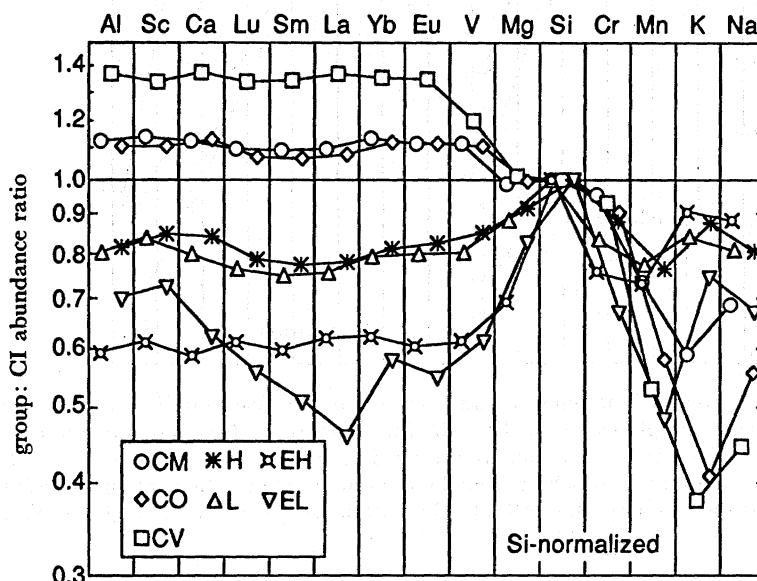


FIGURE 1. Si-normalized group:CI abundance ratios for lithophile elements in the chondrite groups, except LL. The elements are arranged from left to right in order of increasing volatility. CI chondrites are plotted on a horizontal line at unity. The LL group is not plotted because it is unresolvable from the L group and available data are of lower precision. All groups, except EL, have a flat refractory lithophile element pattern, implying that these elements were in the same nebular component.

Abundance ratios of siderophiles and other elements (mainly those that form sulphides in a nebula of solar composition) are shown in figures 2 and 3. In figure 2, Si is the normalizing element, in figure 3 it is Ni. On both diagrams, the CI-chondrite pattern is again a line at unity. The LL chondrite data are plotted and are completely resolved from the L group on figure 2, and partly resolved on figure 3.

Before we discuss the nebular fractionations that produced the patterns observed in figures 1–3 we need to outline a model of the solar nebula. The solar system formed by collapse of an interstellar cloud fragment. Because of the evidence for high-temperature processes, the collapse process was probably rapid enough (several  $10^{-6} M_{\odot} \text{ a}^{-1}$ ) to generate steady-state temperatures greater than 1000 K at 2.5 AU from the Sun. In addition, each parcel of infalling material reached still higher temperatures when it encountered the nebula gas. Most infalling materials vaporized at distances up to 2.5 AU from the Sun, but some refractory materials survived; the fraction that survived increased with increasing distance from the Sun and during the final period when the infall rate had decreased.

At most times and places the chemical composition of the nebula was solar. The degree of

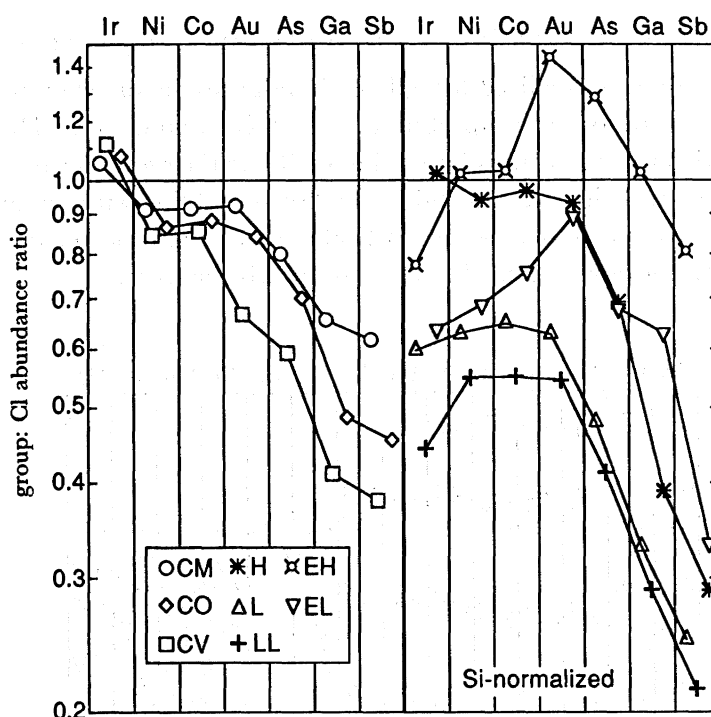


FIGURE 2. Si-normalized group:Cl abundance ratios for siderophile elements in the chondrite groups. The carbonaceous chondrites are plotted on the left half of the diagram and the ordinary and enstatite chondrites on the right half. The elements in each half are arranged in order of increasing volatility. The carbonaceous chondrites have simple patterns in which the abundance ratios decrease with increasing volatility. The patterns are more diverse for the ordinary and enstatite chondrites, most notably the high Au abundance ratio in EH.

oxidation of materials equilibrating with the nebula was controlled by a  $p\text{H}_2\text{O}/p\text{H}_2$  ratio that was about  $5 \times 10^{-4}$  at temperatures of at least 800 K. Some recent studies (e.g. Fegley & Palme 1985) suggest that some chondritic materials formed under more oxidizing conditions, but there seems to be no basis for assuming that the oxidizing medium was the nebular gas.

During the cooling of the nebula major and minor elements formed phases and the trace elements partitioned among these phases. The relative stability of phases changed with decreasing temperature, and some redistribution of elements among phases occurred. Because gas-phase transport was no longer possible, redistribution was possible only if the phases were in the same assemblage.

Chondrule formation occurred after the nebula had cooled to temperatures up to 600 K (Grossman & Wasson 1983). A widely accepted view is that chondrules formed in the nebula by flash melting grain assemblages (see, for example, Taylor *et al.* 1983) although some workers (e.g. Hutchison, this symposium) interpret the evidence to require a planetary setting to form most chondrules. Most of the volatiles in ordinary chondrites are found in chondrule interiors; thus it appears that little volatile loss occurred during the melting of chondrules (Gooding *et al.* 1980; Grossman & Wasson 1983).

Following chondrule formation, chondrites formed by particle agglomeration and compaction. The agglomeration step is not well understood, but the most promising mechanism seems to be the gravitational collapse in the dusty nebula midplane of particle

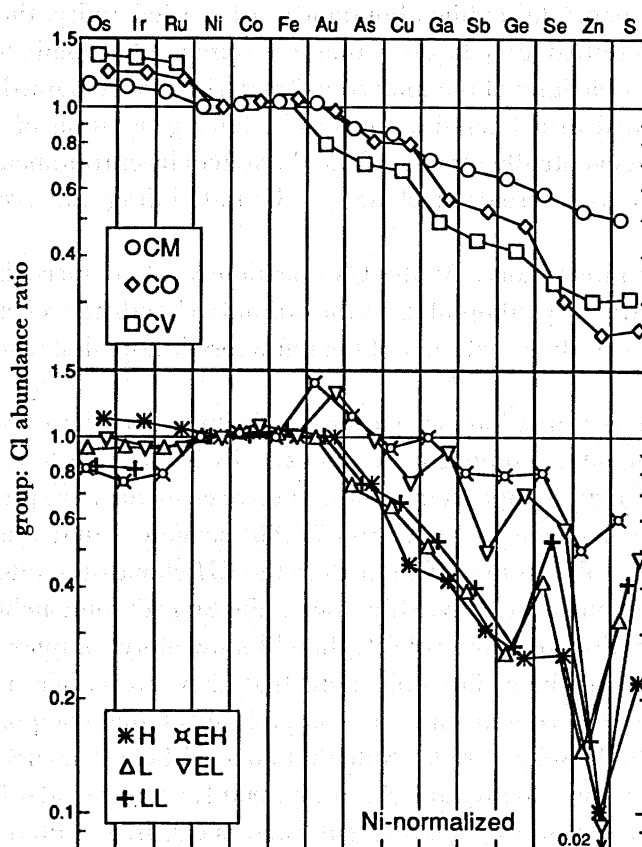


FIGURE 3. Ni-normalized group:CI abundance ratios for siderophile and other non-lithophile elements in the chondrite groups. The carbonaceous chondrites have patterns that decrease monotonically with increasing volatility. The abundance ratio patterns for ordinary and enstatite chondrites are complex. The most striking difference is the 30–40% enhancement of the Au/Ni ratio in the EH and EL groups relative to carbonaceous and ordinary chondrite groups.

clouds to form  $10^{13}$ – $10^{16}$  g planetesimals. After planetesimal formation no further interaction between grains and nebular gases was possible.

The chemical fractionations shown in figures 1–3 can be understood in terms of the above scenario. After the particles settled to the nebula midplane it was no longer possible to produce fractionations, because the collapse process captured all the particles within a cloud. This has stimulated me and my co-workers (see, for example, Wai and Wasson 1977; Kallemeyn & Wasson 1981) to explain all observed fractionations in terms of settling efficiencies that varied from one nebular component to the next, resulting in differing accretion efficiencies for different nebular components.

For example, in figure 1 the very similar abundance ratios of the refractory lithophiles within each group except EL implies that these elements were all in the same nebular component (a component is one or more phases that are mutually attached and thus remain coherent during mechanical fractionations). Abundance ratios greater than unity (e.g. *ca.* 1.4 in CV) imply that the fraction of the refractory lithophile component was higher than the fraction of the common lithophile component that settled to the midplane, i.e. that a significant fraction of the grains carrying Si, Mg, etc., were suspended in the gas when planetesimals formed. For ordinary



chondrites that have refractory lithophile abundance ratios below unity, the opposite is true: the refractory component settled less efficiently than the common lithophile component. There would seem to be two possible fates of the unaccreted material that remained suspended in the nebula: either (1) it settled at a later time to form a later generation of planetesimals; or (2) it never settled but was eventually removed from the system by entrainment with plasma, by accretion onto the surfaces of asteroids or planets, or by radial drag that eventually caused it to accrete to the Sun.

Two lithophiles are semirefractory. At the CV location V is enhanced by about half the factor that affected the refractory lithophiles. At the ordinary chondrite and enstatite chondrite locations the Mg depletion is about half that of the refractory lithophiles, whereas V shows the full depletion.

The EL chondrites show a fractionated pattern indicating that the refractory lithophiles were not all in the same nebular component. As discussed by Kallemeyn & Wasson (1986) and Larimer & Ganapathy (1987), it appears that some of these elements were present as refractory sulphides, especially CaS. Kallemeyn & Wasson (1986) suggested that the fractionated EL pattern indicates that these objects formed later than the EH chondrites, after the nebula had evolved by selective accretion (or selective drag loss to the Sun) of some nebular components.

The lithophile elements that are more volatile than Si show more complex patterns. We will not attempt to explain them here, but only note that they are either in several nebular components, or if in a single component, the composition of this component varied from location to location within the solar nebula. Note that none of these elements is highly volatile. The condensation temperatures for K and Na are *ca.* 900 K; that for Mn is *ca.* 1100 K at a nebular pressure of 0.1 Pa (Wasson 1985). Elements such as Cd, In and Pb that form sulphides in an unfractionated nebula have condensation temperatures below 600 K. The minima at Mn in the EH and EL chondrites imply (figure 1) that Mn becomes more volatile than the alkali elements under the reducing and S-rich nebular conditions at this location.

The moderately large fractionation of siderophiles from silicates is shown on the Si-normalized diagrams of figure 2. The three carbonaceous chondrite groups show simple patterns in which abundance ratios decrease with increasing volatility. The abundance ratio of Ni, the chief common siderophile, is roughly 0.9 in all three groups.

Most patterns are much more diverse at the locations where the ordinary and enstatite chondrites formed. The H-group pattern is simple, and very similar to those of the carbonaceous chondrites. This is a chief argument for the H-group having formed earlier than the L or LL chondrites. The related L group pattern is also quite smooth, but the Ir abundance ratio is resolvably lower than that of Ni; the LL group shows a still lower Ir/Ni ratio. The more complex EH and EL patterns will be discussed in connection with figure 3. The patterns for the elements Ir-Ga on figure 2 are quite similar, but the EL Ni abundance is only *ca.* 0.6 times that for EH.

In figure 3 are plotted additional siderophiles and also some elements (S, Se, possibly Zn) that condense as sulphides. The abundances are Ni-normalized, which allows us to see intergroup siderophile/Ni fractionations. Again, the carbonaceous chondrites show very regular patterns with abundance ratios monotonically decreasing with decreasing nebular condensation temperature. The refractory siderophile/Ni ratios are quite similar to the refractory lithophile/Si ratios, implying that much of the excess of both sets of refractory elements were in the same nebular component.

The abundance ratio patterns for the ordinary and enstatite chondrites in figure 3 are too complex to discuss in detail. The systematic decrease in the refractory siderophile/Ni ratio wherein  $H > L > LL$  is very clear, and is accompanied by a systematic increase in the element/Ni ratios of the volatile siderophiles Cu, Ga, As and Ge. It is clear that there was a variety of nebular siderophile components at the ordinary chondrite formation locations.

The closely related EH and EL groups chiefly differ in terms of the Zn abundance in EL which is a factor of 25 lower than in EH. Relative to other groups, refractory siderophiles are about 20 % lower in EH, and volatile siderophiles are about 20–30 % lower in EL than in EH. A striking difference between these groups and all other chondrite groups is the large, 30–40 % Au enhancement. This is the only case where a bulk volatile:common element ratio is significantly greater than the CI ratio. No simple explanation has been proposed to account for this enhancement. The enstatite chondrites clearly formed under nebular conditions that were subsolar, i.e.  $pH_2O/pH_2$  was lower and  $pH_2S/pH_2$  was higher than at other locations. It is conceivable that Au/Ni was also enhanced at this location. Additional cosmochemical explanations involving enhanced radial transport of particles at the EH, EL location may also be possible.

#### COMPOSITIONAL LINKS BETWEEN CHONDRITES AND PLANETS

The idea that the planets are chondritic is not new; Urey (1956) and Ringwood (1959) both suggested that the Earth had a bulk composition identical to CI chondrites. Others (e.g. Turekian & Clark 1969; Ganapathy & Anders 1974) have treated the cosmochemical components (common metal, common silicates, refractories, etc.) as time- or space-separated nebular entities, and generated compositional models for the planets based on this assumption. We find this latter approach unjustified, because there is no meteoritic evidence that these nebular components ever formed separate planetesimals. They are found only in chondrites, always mixed with other components to produce a bulk composition that, except for volatiles, has elemental abundances within a factor of two of those in the Sun.

The simplest plausible approach to estimating the bulk compositions of the planets is to link them to chondrites on the basis of compositional clues. It is important, however, to recognize that the set of chondrites in our museums is grossly incomplete. The large compositional hiatus between the chondrite groups are surely the reflection of incomplete sampling of what must have originally been a continuum. Thus, even though it is quite probable that some chondrite groups formed nearer to the Sun than Mars (see discussion in Wasson & Wetherill 1979), we may not now have samples of chondrites that formed in the Earth's formational zone at *ca.* 0.85 to *ca.* 1.3 AU from the Sun. For this reason we must be willing to interpolate some properties when generating chondritic compositional models of the planets. And, as discussed in Wänke (this symposium), it is probable that chondritic matter having differing compositions contributed matter to each of the terrestrial planets. In particular, it is probable that chondrite-like cometary matter formed a late veneer on each of these planets.

There are three other processes that could lead to planets having compositions different from those of chondrites and their interpolated siblings. (1) If the fine material that was not incorporated into planetesimals was still present when bodies reached dimensions above 100 km, it could have accreted gravitationally to these large bodies. (2) If asteroids were heated and differentiated before the final formation of the planets, then appreciable loss of volatiles by

episodic outgassing may have occurred. (3) As discussed earlier, the interpolation of chondrite properties may not be sufficient at the innermost edge of the nebula, where mechanical separations may have been more pronounced than those recorded in chondrites. For this reason it is plausible that the high metal:silicate ratio in Mercury reflects a mechanical enhancement in metal that was endemic to planetesimals forming at this location.

Chondrite compositions are now relatively well known. Understanding the valuable clues that they offer regarding the origins of planets largely remains a challenge for the future.

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#### REFERENCES

- Anders, E. & Ebihara, M. 1982 Solar-system abundances of the elements. *Geochim. cosmochim. Acta* **46**, 2363-2380.
- Cameron, A. G. W. 1982 Elementary and nuclidic abundances in the solar system. In *Essays in nuclear astrophysics* (eds C. A. Barnes, D. N. Schramm & D. D. Clayton), pp. 23-43. Cambridge University Press.
- Fegley, B. & Palme, H. 1985 Evidence for oxidizing conditions in the solar nebula from Mo and W depletions in refractory inclusions in carbonaceous chondrites. *Earth planet. Sci. Lett.* **72**, 311-326.
- Ganapathy, R. & Anders, E. 1974 Bulk compositions of the moon and earth, estimated from meteorites. In *Proc. 5th Lunar Sci. Conf.*, pp. 1181-1206.
- Gooding, J. L., Keil, K., Fukuoka, T. & Schmitt, R. A. 1980 Elemental abundances in chondrules from unequilibrated chondrites: evidence for chondrule origin by melting of pre-existing materials. *Earth planet. Sci. Lett.* **50**, 171-180.
- Grossman, J. N. & Wasson, J. T. 1983 The compositions of chondrules in unequilibrated chondrites: An evaluation of models for the formation of chondrules and their precursor materials. In *Chondrules and their origins* (ed. E. A. King), pp. 88-121. Houston: Lunar Planetary Institute.
- Kallemeyn, G. W. & Wasson, J. T. 1981 The compositional classification of chondrites. I. The carbonaceous chondrite groups. *Geochim. cosmochim. Acta* **45**, 1217-1230.
- Kallemeyn, G. W. & Wasson, J. T. 1986 Compositions of enstatite (EH3, EH4, 5 and EL6) chondrites: implications regarding their formation. *Geochim. cosmochim. Acta* **50**, 2153-2164.
- Kallemeyn, G. W. & Wasson, J. T. 1988 Mechanisms for elemental fractionation among the carbonaceous chondrites. *Space Sci. Rev.* (Submitted.)
- Larimer, J. W. & Ganapathy, R. 1987 The trace element chemistry of CaS in enstatite chondrites and some implications regarding its origin. *Earth planet. Sci. Lett.* **84**, 123-134.
- Mason, B. 1971 *Handbook of elemental abundances in meteorites*. New York: Gordon and Breach. (555 pages.)
- Mason, B. 1979 Cosmochemistry. In *Data of geochemistry*, chap. B (ed. M. Fleischer), Washington: U.S. Printing Office, B1-B124.
- Ringwood, A. E. 1959 On the chemical evolution and densities of the planets. *Geochim. cosmochim. Acta* **15**, 257-283.
- Taylor, G. J., Scott, E. R. D. & Keil, K. 1983 Cosmic setting for chondrule formation. In *Chondrules and their origins* (ed. E. A. King), pp. 262-278. Houston: Lunar and Planetary Institute.
- Turekian, K. K. & Clark, S. P. 1969 Inhomogeneous accumulation of the earth from the primitive solar nebula. *Earth planet. Sci. Lett.* **6**, 346-348.
- Urey, H. C. 1956 Diamonds, meteorites, and the origin of the solar system. *Astrophys. J.* **124**, 623-637.
- Wai, C. M. & Wasson, J. T. 1977 Nebular condensation of moderately volatile elements and their abundances in ordinary chondrites. *Earth planet. Sci. Lett.* **36**, 1-13.
- Wasson, J. T. 1972 Formation of ordinary chondrites. *Rev. Geophys. Space Phys.* **10**, 711-759.
- Wasson, J. T. 1985 *Meteorites: their record of early Solar-System history*. New York: W. H. Freeman. (288 pages.)
- Wasson, J. T. & Wetherill, G. W. 1979 Dynamical, chemical and isotopic evidence regarding the formation locations of asteroids and meteorites. In *Asteroids* (ed. T. Gehrels), pp. 926-974. University of Arizona.