

# 1.03

## Solar System Abundances of the Elements

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### 1.03.1 ABUNDANCES OF THE ELEMENTS IN THE SOLAR NEBULA

#### 1.03.1.1 Historical Remarks

At the beginning of the twentieth century attempts were made to define the average

composition of cosmic matter, utilizing compositional data on the Earth's crust and meteorites. This led to the discovery by Harkins (1917) that elements with even atomic numbers are more abundant than those with odd atomic numbers, the so-called Oddo–Harkins rule, best exemplified for the rare earth elements (REEs). During the

1920s and 1930s Victor Moritz Goldschmidt and his colleagues in Göttingen, and later in Oslo, measured and compiled a wealth of chemical data on terrestrial rocks, meteorites, and individual phases of meteorites. On the basis of these data Goldschmidt (1938) set up a cosmic abundance table which he published in 1938 in the ninth volume of his *Geochemische Verteilungsgesetze der Elemente (The Geochemical Laws of the Distribution of the Elements)* entitled *Die Mengenverhältnisse der Elemente und der Atom-Arten (The Proportions of the Elements and the Various Kinds of Atoms)*. Goldschmidt believed that meteorites would provide the average composition of cosmic matter. He used the word “cosmic” because, in citing contemporaneous astronomers, he thought that meteorites represent interstellar material from outside the solar system. In his book he mentioned a second reason for using meteorite data. Most meteorites will be representative of average cosmic matter, because they have not been affected by physicochemical processes (e.g., melting and crystallization), although chondrules within them have experienced melting and crystallization, the meteorites as a whole have not. In contrast, the crust of the Earth, which formed by the melting of the mantle, provides only a very biased sampling of elemental abundances in the bulk Earth. Goldschmidt calculated the average concentrations of elements in cosmic matter by using a weighted mean of element abundances in meteorite phases: metal (two parts), sulfide (one part), and silicates (10 parts). In this way he obtained the cosmic abundances of 66 elements.

It was during the same time that astronomers began to extract quantitative information about elemental abundances in the Sun by solar absorption spectroscopy and it was soon realized that the compositions of the Sun and the whole Earth are similar, except for hydrogen and other extremely volatile elements (see Russell, 1941).

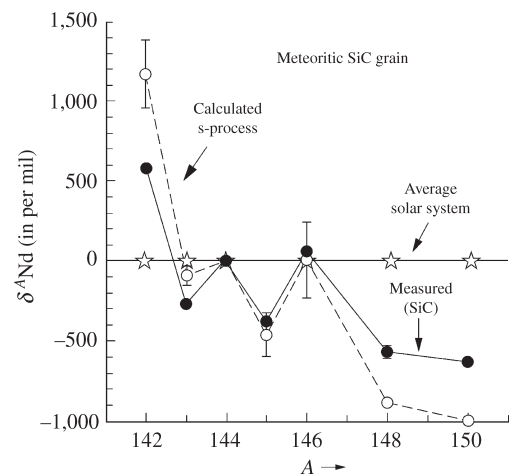
Almost 20 years after Goldschmidt, Suess and Urey (1956) published a new abundance table, which in part relied on solar abundances. In addition, Suess and Urey (1956) introduced arguments based on nucleosynthesis. Their so-called semiempirical abundance rules, primarily the smooth abundance variation of odd-mass nuclei with increasing mass number, were applied to estimate abundances for elements for which analytical data from meteorites were not available or had large errors. The Suess and Urey compilation was very influential for theories of nucleosynthesis and for the development of nuclear astrophysics in general. Later compilations by Cameron (1973), Anders and Grevesse (1989), Palme and Beer (1993), and others took into account improved analytical data on meteorites and the more accurate determination of elemental abundances in the solar photosphere. Over the

years there has been a continuous convergence of abundances derived from meteorites and those obtained from solar absorption line spectroscopy. The agreement is now better than  $\pm 10\%$  for most elements, as described below.

### 1.03.1.2 Solar System Abundances of the Elements

#### 1.03.1.2.1 Is the elemental and isotopic composition of the solar nebula uniform?

In the past it was assumed that the Sun, the planets and all other objects of the solar system formed from a gaseous nebula with well-defined chemical and isotopic composition. The discovery of comparatively large and widespread variations in oxygen isotopic compositions has cast doubt upon this assumption (see Begemann, 1980 and references therein). In addition, evidence for incomplete mixing in the primordial solar nebula is provided by isotopic anomalies for a variety of elements in the refractory inclusions of carbonaceous chondrites and by detection of the huge isotope anomalies of carbon, nitrogen, silicon, and some heavy elements in tiny grains of meteorites, such as silicon carbide, nanodiamond, and graphite grains (e.g., Anders and Zinner, 1993; Chapter 1.02). A good example for such isotope anomalies is given in Figure 1, where the unusual isotopic composition of neodymium in an aggregate of SiC grains from the Murchison carbonaceous chondrite is shown (Richter *et al.*, 1992). The neodymium isotopic compositions of all other



**Figure 1** Nd isotopes in an aggregate of meteoritic SiC from Murchison. The deviation of the Nd isotopic composition from normal is given in per mil ( $\delta$ ). All ratios are normalized to  $^{144}\text{Nd}$ . Full symbols are measured ratios. Error bars are in most cases smaller than symbol sizes. Calculated s-process productions are indicated. All previous analyses of Nd isotopes in terrestrial, lunar, or meteorite samples fall along the line marked “average solar system,” which is used for normalization (source Richter *et al.*, 1992).

solar system materials analyzed (i.e., terrestrial, lunar, and meteoritic samples) are indistinguishable within the scale of Figure 1 and these other materials would fall on the line designated “average solar system.” Such s-process components have also been found for other elements: For example, Nicolussi *et al.* (1998) identified nearly pure s-process molybdenum in some SiC grains (see Chapter 1.02, figure 10). These findings confirm the presence of material of distinct nucleosynthetic origins at the time of accretion of meteorite parent bodies. However, such isotope anomalies are confined to a very small fraction (a few ppm) of the bulk of a meteorite, i.e., this material is truly exotic. Moreover, it is likely that the more widespread oxygen isotope anomalies are not of nucleosynthetic origin but were produced by fractionation processes within the solar nebula or a precursor molecular cloud (Chapter 1.06), it is still a reasonable working hypothesis that the bulk of the matter of the solar system formed from a chemically and isotopically uniform reservoir, the primordial solar nebula. The composition of this nebula, the average solar system composition, is well known and carries the signatures of a variety of nucleosynthetic processes in stellar environments.

Although the elemental composition of the solar system is roughly similar to that of many other stars, in particular with respect to the relative abundances of the nongaseous elements, there are, in detail, compositional differences among stars and there are, in addition, truly exotic stars that make the term “cosmic abundances of elements” questionable. We will therefore use the term “solar system abundances of the elements” in this chapter.

### 1.03.1.2.2 *The composition of the solar photosphere*

The quantitative determination of elemental abundances in the Sun involves three steps: (i) construction of a numerical model atmosphere; (ii) calculation of an emitted spectrum based on the model atmosphere; and (iii) comparison of this spectrum with the observed spectrum (Cowley, 1995). Another assumption usually made in calculating solar abundances is that of local thermodynamic equilibrium (LTE), i.e., “the quantum-mechanical states of atoms, ions, and molecules are populated according to the relations of Boltzmann and Saha, valid strictly in thermodynamic equilibrium” (Holweger, 2001). It is not clear if, in the highly inhomogeneous and dynamic plasma permeated by an intense, anisotropic radiation, the LTE assumption is justified. In recent calculations effects of NLTE (nonthermal local equilibrium thermodynamics) and of photospheric granulation are taken into account (Holweger, 2001). Another important factor in the accuracy of solar abundance determinations are

transition probabilities determined in laboratory experiments. The main need for improving solar abundance data is more accurate transition probabilities (Grevesse and Sauval, 1998).

In Table 1, the composition of the solar photosphere as obtained by absorption spectroscopy is given. Abundances are normalized to  $10^{12}$  H atoms, the usual practice in astronomy. Most of the data are from Grevesse and Sauval (1998), which is an update of the photospheric abundance table by Anders and Grevesse (1989). For nitrogen, magnesium, silicon, and iron new photospheric abundances from Holweger (2001) were used. These data are marked H in Table 1. Their uncertainties range from about 30% for nitrogen to 12% for silicon. The accuracy of iron is given as 20%. The standard deviations listed by Holweger (2001) are, in all cases except silicon, larger than those given by Grevesse and Sauval (1998). Holweger ascribes this to his more conservative procedure for calculating errors. A new determination of the solar lead is included (Biemont *et al.*, 2000) and marked B in Table 1. The oxygen abundance was taken from a paper by Allende Prieto *et al.* (2001), marked A1 in Table 1. The solar oxygen abundance has gone down considerably, from  $8.93 \pm 0.35$  (Anders and Grevesse, 1989) and  $8.83 \pm 0.06$  (Grevesse and Sauval, 1998) to  $8.736 \pm 0.078$  (Holweger, 2001) and  $8.69 \pm 0.05$  (Allende Prieto *et al.*, 2001). This 50% decrease is important because, based on the old value, it was thought that the interstellar medium (ISM) must have had a different H/O ratio than the Sun (see below). The carbon abundance has also been revised downward, as indicated in Table 1 (Allende Prieto *et al.*, 2002). The new carbon and oxygen lead to a higher C/O ratio of  $0.50 \pm 0.07$  compared to the earlier ratio of  $0.43 \pm 0.06$  (Anders and Grevesse, 1989), although both values overlap within error bars. This implies a somewhat more reducing nebular gas, as all C is present as CO, and the higher C/O ratio thus reduces the number of O<sub>2</sub> molecules.

Rare gases have no appropriate lines in the solar spectrum. The helium abundance of Grevesse and Sauval (1998) is derived from standard solar models. The helium abundance in the outer layers of the Sun seems to have decreased over the lifetime of the Sun, from  $N_{\text{He}}/N_{\text{H}} = 0.098$  at the beginning of the solar system to the present value of  $N_{\text{He}}/N_{\text{H}} = 0.085$  corresponding to an abundance of  $10.93 \pm 0.004$  (Grevesse and Sauval, 1998), which is given in Table 1. A detailed discussion of the solar helium abundance can be found in Lodders (2003).

The abundance of neon was calculated from an Ne/Mg abundance ratio of  $3.16 \pm 0.07$  derived from emerging magnetic flux regions observed in Skylab spectroheliograms. This value is thought to be representative of the Ne/Mg abundance

**Table 1** Solar photospheric abundances and meteorite derived solar system abundances (log abundance  $a(\text{H}) = 12$ ).

	<i>Element</i>	<i>Solar photosphere</i>	<i>SD</i>		<i>Meteorite (CI)</i>	<i>SD</i>	<i>Sun/meteorite</i>
1	H	12.00					
2	He	10.99 <sup>a</sup>	0.02	G <sup>b</sup>			
3	Li	1.10	0.10	G	3.30	0.04	0.006
4	Be	1.40	0.09	G	1.41	0.04	0.98
5	B	2.70	-0.12, +0.21	C	2.77	0.04	0.74
6	C	8.39	0.04	A2	7.39	0.04	9.90
7	N	7.93	0.11	H	6.32	0.04	40.6
8	O	8.69	0.05	A1	8.43	0.04	1.82
9	F	4.56 <sup>a</sup>	0.3	G	4.45	0.06	1.29
10	Ne	8.00 <sup>a</sup>	0.07	H			
11	Na	6.33	0.03	G	6.30	0.02	1.07
12	Mg	7.54	0.06	H	7.56	0.01	0.94
13	Al	6.47	0.07	H	6.46	0.01	1.02
14	Si	7.54	0.05	H	7.55	0.01	0.99
15	P	5.45	(0.04)	G	5.44	0.04	1.02
16	S	7.33	0.11	G	7.19	0.04	1.37
17	Cl	5.5 <sup>a</sup>	0.3	G	5.26	0.06	1.74
18	Ar	6.40 <sup>a</sup>	0.06	G			
19	K	5.12	0.13	G	5.11	0.02	1.03
20	Ca	6.36	0.02	G	6.33	0.01	1.07
21	Sc	3.17	0.10	G	3.08	0.01	1.22
22	Ti	5.02	0.06	G	4.95	0.04	1.18
23	V	4.00	0.02	G	3.99	0.02	1.02
24	Cr	5.67	0.03	G	5.67	0.01	0.99
25	Mn	5.39	0.03	G	5.51	0.01	0.75
26	Fe	7.45	0.08	H	7.49	0.01	0.92
27	Co	4.92	0.04	G	4.90	0.01	1.05
28	Ni	6.25	0.04	G	6.23	0.02	1.05
29	Cu	4.21	0.04	G	4.28	0.04	0.85
30	Zn	4.60	0.08	G	4.66	0.04	0.87
31	Ga	2.88	(0.10)	G	3.11	0.02	0.59
32	Ge	3.41	0.14	G	3.62	0.04	0.62
33	As			G	2.35	0.02	
34	Se			G	3.40	0.04	
35	Br			G	2.61	0.04	
36	Kr	3.30 <sup>a</sup>	0.06	P			
37	Rb	2.60	(0.15)	G	2.40	0.04	1.59
38	Sr	2.97	0.07	G	2.88	0.04	1.22
39	Y	2.24	0.03	G	2.21	0.04	1.06
40	Zr	2.60	0.02	G	2.59	0.04	1.02
41	Nb	1.42	0.06	G	1.39	0.04	1.07
42	Mo	1.92	0.05	G	1.95	0.04	0.93
44	Ru	1.84	0.07	G	1.80	0.04	1.11
45	Rh	1.12	0.12	G	1.10	0.08	1.05
46	Pd	1.69	0.04	G	1.68	0.04	1.01
47	Ag	(0.94)	(0.25)	G	1.23	0.04	
48	Cd	1.77	0.11	G	1.75	0.04	1.05
49	In	(1.66)	(0.15)	G	0.80	0.04	
50	Sn	2.00	(0.3)	G	2.12	0.04	0.76
51	Sb	1.00	(0.3)	G	1.00	0.04	0.99
52	Te			G	2.22	0.04	
53	I			G	1.50	0.08	
54	Xe	2.16 <sup>a</sup>	0.09	P			
55	Cs			G	1.12	0.04	
56	Ba	2.13	0.05	G	2.21	0.04	0.83
57	La	1.17	0.07	G	1.21	0.02	0.91
58	Ce	1.58	0.09	G	1.62	0.02	0.90
59	Pr	0.71	0.08	G	0.80	0.04	0.81
60	Nd	1.50	0.06	G	1.48	0.02	1.04
62	Sm	1.01	0.06	G	0.98	0.02	1.08
63	Eu	0.51	0.08	G	0.55	0.02	0.92

(continued)

**Table 1** (continued).

	Element	Solar photosphere	SD		Meteorite (CI)	SD	Sun/meteorite
64	Gd	1.12	0.04	G	1.08	0.02	1.10
65	Tb	(−0.1)	0.3)	G	0.34	0.04	
66	Dy	1.14	0.08	G	1.16	0.02	0.96
67	Ho	(0.26)	0.16)	G	0.50	0.04	
68	Er	0.93	0.06	G	0.96	0.02	0.93
69	Tm	(0.00)	0.15)	G	0.15	0.04	
70	Yb	1.08	(0.15)	G	0.95	0.02	
71	Lu	0.06	0.10	G	0.13	0.04	0.85
72	Hf	0.88	(0.08)	G	0.74	0.04	1.37
73	Ta			G	−0.14	0.06	
74	W	(1.11)	0.15)	G	0.66	0.04	
75	Re			G	0.29	0.04	
76	Os	1.45	0.10	G	1.38	0.04	1.18
77	Ir	1.35	(0.10)	G	1.36	0.02	0.97
78	Pt	1.80	0.30	G	1.67	0.06	1.36
79	Au	(1.01)	0.15)	G	0.84	0.02	
80	Hg			G	1.15	0.08	
81	Tl	(0.9)	0.2)	G	0.81	0.04	
82	Pb	2.00	0.06	B	2.05	0.04	0.89
83	Bi			G	0.69	0.06	
90	Th				0.07	0.04	
92	U	(< −0.47)		G	−0.52	0.04	

SD—standard deviation in dex: 0.1–12%, 0.2–60%, 0.3–100%. Meteorite data:  $\log a_E + 1.546$ ;  $a_E$  abundances relative to  $10^6$  Si atoms (see Table 3). Solar data: A1—Allende Prieto *et al.* (2001); A2—Allende Prieto *et al.* (2002); B—Biemont *et al.* (2000); C—Cunha and Smith (1999); G—Grevesse and Sauval (1998); H—Holweger (2001); P—Palme and Beer (1993).

<sup>a</sup> Abundances are not derived from the photosphere. <sup>b</sup> Average Sun; outer layers of Sun are 10% lower in He; values in parenthesis are defined as uncertain by Grevesse and Sauval (1998).

ratio in the solar photosphere (Reames, 1998). Following Holweger (2001) we adopt a value of  $\log A_{\text{Ne}} = 8.001 \pm 0.069$  calculated from the Ne/Mg and Ne/O ratios of Reames (1998). The argon value is based on data from coronal spectra and a more precise SEP (solar energetic particles) value by Reames (1998), as discussed in Grevesse and Sauval (1998).

For krypton and xenon abundances were derived from computer fits of  $\sigma N$  (neutron capture cross-section times abundance) versus mass number. Nuclei that are shielded from the r-process, so-called s-only nuclei, were used for the fit and the abundances of  $^{82}\text{Kr}$  and  $^{128}\text{Xe}$  were calculated. From these data, and the isotopic composition of the solar wind, the krypton and xenon elemental abundances were calculated (Palme and Beer, 1993) and are listed in Table 1. The meteorite data given in Table 1 will be discussed in a later section.

### 1.03.1.3 Abundances of Elements in Meteorites

#### 1.03.1.3.1 Undifferentiated and differentiated meteorites

There are two different groups of meteorites—undifferentiated and differentiated. The undifferentiated meteorites are pieces of planetesimals that have never been heated to melting temperatures. Their chemical and isotopic composition should

be representative of the bulk parent planetesimal from which the meteorites were derived. Differentiated meteorites are pieces of planetesimals that were molten and differentiated into core, mantle, and crust. A sample from such a body will not be representative of the bulk planet and it is not a trivial task to derive, from the samples available, the bulk composition of the parent planet. Undifferentiated meteorites reflect, at least to some degree, the composition of the solar nebula from which they formed. There are, however, variabilities in the composition of undifferentiated meteorites, which must reflect inhomogeneities in the solar nebula or disequilibrium during formation of solids from gas, or both. A more comprehensive discussion of meteorite classification is given by Krot *et al.* (Chapter 1.05).

#### 1.03.1.3.2 Cosmochemical classification of elements

Many of the processes that are responsible for the variable chemical composition of primitive meteorites are related to the temperature of formation of meteoritic components. Although it is difficult to unambiguously ascertain the condensation origin of any single meteoritic component, it is clear from the elemental patterns that condensation processes must have occurred in the early solar system and that the volatilities of

the elements in the solar nebula environment were important in establishing the various meteorite compositions. Condensation temperatures provide a convenient measure of volatility. These temperatures are calculated by assuming thermodynamic equilibrium between solids and a cooling gas of solar composition. Major elements condense as minerals while minor and trace elements condense in solid solution with the major phases. The temperature where 50% of an element is in the solid phase is called the 50% condensation temperature (Wasson, 1985; Lodders, 2003). Within this framework five more or less well-defined components that account for the variations in the elemental abundances in primitive meteorites may be defined (Table 2). In addition, the state of oxidation of a meteorite is an important parameter that adds to the complex textural variability among chondritic meteorites. According to the condensation temperatures the following components are distinguished:

(i) *Refractory component.* The first phases to condense from a cooling gas of solar composition are calcium, aluminum oxides, and silicates associated with a comparatively large number of trace elements, such as REEs, zirconium, hafnium, and scandium. These elements are often named refractory lithophile elements (RLEs), in contrast to the refractory siderophile elements (RSEs) comprising metals with low vapor pressures, e.g., tungsten, osmium, and iridium condensing at similarly high temperatures as multicomponent metal alloys. Both RLEs and RSEs are enriched in Ca–Al-rich inclusions (Chapter 1.08) by a factor of 20 on average, reflecting the fact that the refractory component makes up ~5% of the total condensible matter (Grossman and Larimer, 1974). Variations in Al/Si, Ca/Si, etc., ratios of bulk chondritic

meteorites may be ascribed to the incorporation of variable amounts of an early condensed refractory phase.

(ii) *Magnesium silicates.* The major fraction of condensible matter is associated with the three most abundant elements heavier than oxygen—silicon, magnesium, and iron. In the reducing environment of the solar nebula iron condenses almost entirely as metal, while magnesium and silicon form forsterite ( $\text{Mg}_2\text{SiO}_4$ ), which is, to a large extent, converted to enstatite ( $\text{MgSiO}_3$ ) at lower temperatures by reaction with gaseous SiO. As forsterite has an atomic Mg/Si ratio twice the solar system ratio, loss or gain of a forsterite component is the most simple way for producing variations in Mg/Si ratios. Thus, variations in Mg/Si ratios of bulk meteorites are produced by the incorporation of various amounts of early-formed forsterite.

(iii) *Metallic iron.* Metal condenses as an Fe–Ni alloy at about the same temperature as forsterite, the sequence depending on pressure. At pressures above  $10^{-4}$  bar iron metal condenses before forsterite and at lower pressures forsterite condenses ahead of metal (Grossman and Larimer, 1974). Variations in the concentrations of iron and other siderophile elements in meteorites are produced by the incorporation of variable fractions of metal.

(iv) *Moderately volatile elements.* These have condensation temperatures between those of magnesium silicates and FeS (troilite). The most abundant of the moderately volatile elements is sulfur, which condenses by reaction of gaseous sulfur with solid iron at 710 K, independent of pressure. Other moderately volatile elements condense in solid solution with major phases. Moderately volatile elements are distributed among sulfides, silicates, and metals.

**Table 2** Cosmochemical classification of the elements.

	<i>Elements</i>	
	<i>Lithophile (silicate)</i>	<i>Siderophile + chalcophile (sulfide + metal)</i>
Refractory	$T_c = 1,850\text{--}1,400$ K Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Re, Os, W, Mo, Ru, Rh, Ir, Pt, Rh
Main component	$T_c = 1,350\text{--}1,250$ K Mg, Si, Cr, Li	Fe, Ni, Co, Pd
Moderately volatile	$T_c = 1,230\text{--}640$ K Mn, P, Na, B, Rb, K, F, Zn	Au, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
Highly volatile	$T_c < 640$ K Cl, Br, I, Cs, Tl, H, C, N, O, He, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg

$T_c$ —Condensation temperatures at a pressure of  $10^{-4}$  bar (Wasson, 1985; for B, Lauretta and Lodders, 1997).

Their abundances are in most cases below solar, i.e., they have lower element/silicon ratios than the Sun or CI chondrites, they are depleted (see below). In Figure 2, abundances of moderately volatile elements in CV3 meteorites relative to those in CI meteorites are plotted. Increasing depletions correlate with decreasing condensation temperatures but are independent of the geochemical properties of the elements. Depletions of moderately volatile elements in meteorites are produced by incomplete condensation. The amount and the relative abundances of these elements in meteorites are probably the result of removal of volatiles during condensation (Palme *et al.*, 1988).

(v) *Highly volatile elements.* These have condensation temperatures below that of FeS (Table 1). The group of highly volatile elements comprises elements with very different geochemical affinity, such as the chalcophile lead and the atmophile elements nitrogen and rare gases. Similar processes as those invoked for the depletion of moderately volatile elements are responsible for variations in these elements. In addition, heating on small parent bodies may lead to loss of highly volatile elements.

(vi) *Oxygen fugacity and oxygen isotopic composition.* The oxygen fugacities recorded in meteoritic minerals are extremely variable, from the high oxygen fugacity recorded in the magnetite of carbonaceous chondrites to the extremely reducing conditions in enstatite chondrites, reflected in the presence of substantial amounts of metallic silicon dissolved in FeNi. The oxygen

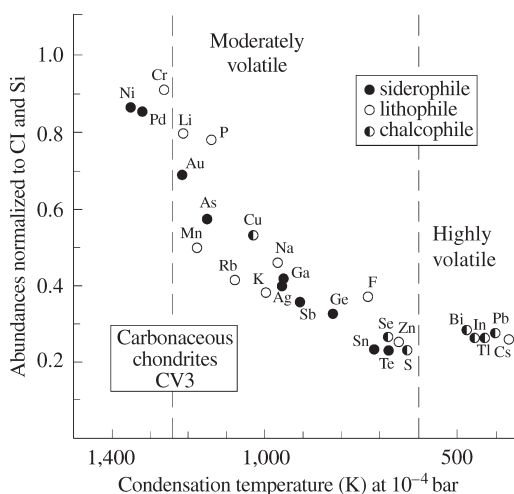
fugacity of a meteorite is, however, not well defined. Large variations in oxygen fugacity are often recorded in individual components of a single meteorite. The various components of primitive meteorites apparently represent extreme disequilibrium. Oxygen isotopes give a similar picture (Clayton, 1993). It has been suggested that variations in  $\Delta^{17}\text{O}$  were produced by reaction of  $^{16}\text{O}$ -rich material with a gas rich in  $^{17}\text{O}$  and  $^{18}\text{O}$  (Clayton, 1993). The gas phase may be considered an additional independent component of meteorites. Thus, the extent of the gas–solid reaction at various temperatures, and possibly also fluid–solid reactions, on a parent body determine the degree of oxidation and the oxygen fugacity of meteoritic components and bulk meteorites (Chapter 1.06).

### 1.03.1.4 CI Chondrites as Standard for Solar Abundances

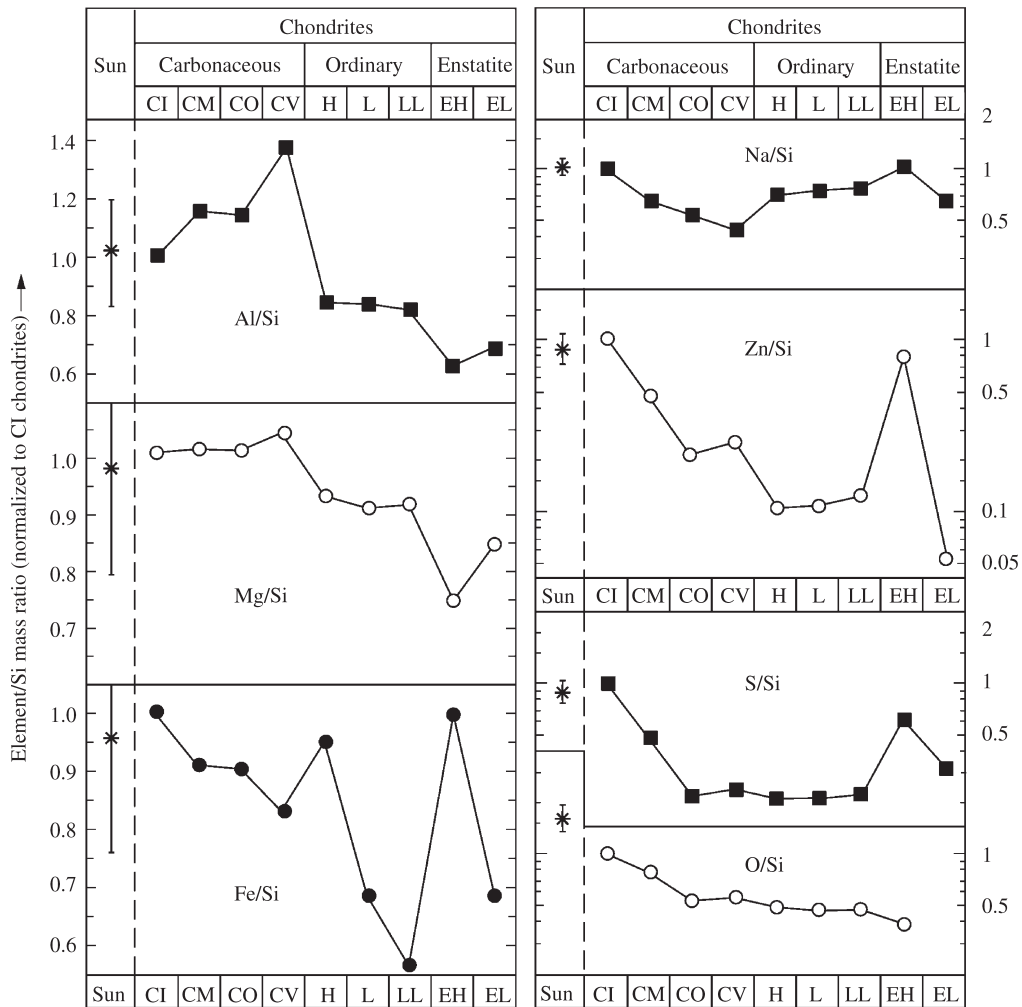
#### 1.03.1.4.1 Chemical variations among chondritic meteorites

In Figure 3 the variations of selected element ratios in the different groups of chondritic meteorites are shown. All ratios are normalized to the best estimate of the average solar system ratios, the CI ratios (taken from Table 3, see below). Meteorite groups are arranged in the sequence of decreasing bulk oxygen contents, i.e., decreasing average oxygen fugacity. Element ratios in the solar photosphere determined by absorption line spectroscopy are shown for comparison (Table 1).

In Figure 3, aluminum is representative of refractory elements in general and the Al/Si ratios indicate the size of the refractory component relative to the major fraction of the meteorite. It is clear from this figure that the Al/Si ratio of CI meteorites agrees best with the solar ratio, although the ratios in CM (Type 2 carbonaceous chondrites) and even OC (ordinary chondrites) are almost within the error bar of the solar ratio. The errors of the meteorite ratios are below 10%, in many cases below 5%. A very similar pattern as for aluminum would be obtained for other refractory elements (calcium, titanium, scandium, REEs, etc.), as ratios among refractory elements in meteorites are constant in all classes of chondritic meteorites, at least within  $\sim 5$ –10%. The average Sun/CI meteorite ratio of 19 refractory lithophile elements (Al, Ca, Ti, V, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Lu, see Table 2) is 1.004 with a standard deviation of 0.12. The accuracy of the solar abundance determination of each of these elements is better than 25% (see Table 1). Elements with larger errors were not considered. Calculating the standard error of the mean for the average refractory element/silicon ratio leads to an uncertainty of about  $\pm 0.03$  in the



**Figure 2** Abundances of volatile elements in CV3 chondrites (e.g., Allende) normalized to CI chondrites and Si. There is a continuous decrease of abundances with increasing volatility as measured by the condensation temperature. The sequence contains elements of very different geochemical character, indicating that volatility is the only relevant parameter in establishing this pattern (source Palme, 2000).



**Figure 3** Element/Si mass ratios of characteristic elements in various groups of chondritic (undifferentiated) meteorites. Meteorite groups are arranged according to decreasing oxygen content. The best match between solar abundances and meteoritic abundances is with CI meteorites (see text for details).

ratio of refractory elements between CI meteorites and the Sun. Thus the absolute level of refractory elements (measured by refractory element/silicon ratios) and ratios among refractory elements are the same in CI meteorites and the Sun. The level of refractory elements in other chondritic meteorites is higher in CM (by 13%) and in CV (by 25%) and lower in H chondrites (by 10%) and enstatite chondrites (by 20%). Thus, the agreement between refractory elements in the Sun and in CI meteorites is statistically significant and all other groups of meteorites will not match solar refractory element abundances. The CR meteorites (Renazzo type meteorites) have CI ratios of Al/Si (Bischoff *et al.*, 1993) (not shown in Figure 3). However, these meteorites are depleted in volatile elements relative to CI meteorites, disqualifying them as a solar system standard.

The Mg/Si ratios of CI chondrites also match with the solar abundance ratio (Figure 3). This is,

however, less diagnostic, as all groups of carbonaceous chondrites have the same Mg/Si ratio (Wolf and Palme, 2001). The OC and the EC have significantly less magnesium. The error of the solar ratio is  $\sim 19\%$  (combining the errors of silicon and magnesium, Table 1) and thus covers the range of all classes of chondrites except EH chondrites.

Until recently, the range of the bulk iron content in chondritic meteorites varied by about a factor of 2, with most meteorite groups being depleted in iron (Figure 3). There are new, recently discovered subgroups of carbonaceous chondrites, with large excesses of iron (see Chapter 1.05). These CH and CB chondrites indicate that metal behaves as an independent component, some groups of chondritic meteorites are enriched in iron and other siderophile elements, others are depleted. The excellent agreement of CI meteorite abundance ratios with solar abundance ratios is



**Table 3** Solar system abundances based on CI meteorites.

Element	<i>Palme and Beer (1993, updated)</i>				<i>Anders and Grevesse (1989)</i>		
	Mean CI abundance (by weight)	Lit.	Estimated accuracy (%)	Atoms per $10^6$ atoms of Si	Mean CI abundance (by weight)	Atoms per $10^6$ atoms of Si	
1	H	2.02 (%)	*	10	$5.27 \times 10^6$	2.02 (%)	
2	He	56 (nL g <sup>-1</sup> )	*			56 (nL g <sup>-1</sup> )	
3	Li	1.49 (ppm)		10	56.5	1.50 (ppm)	57.1
4	Be	0.0249 (ppm)		10	0.727	0.0249 (ppm)	0.73
5	B	0.69 (ppm)	Z	13	16.8	0.870 (ppm)	21.2
6	C	3.22 (%)	*	10	$7.05 \times 10^5$	3.45 (%)	$1.01 \times 10^7$
7	N	3,180 (ppm)	*	10	$5.97 \times 10^4$	0.318 (%)	$3.13 \times 10^6$
8	O	46.5 (%)	*	10	$7.64 \times 10^6$	46.4 (%)	$2.38 \times 10^7$
9	F	58.2 (ppm)		15	806	60.7 (ppm)	843
10	Ne	203 (pL g <sup>-1</sup> )	*			203 (pL g <sup>-1</sup> )	
11	Na	4,982 (ppm)		5	$5.70 \times 10^4$	5,000 (ppm)	$5.74 \times 10^4$
12	Mg	9.61 (%)		3	$1.04 \times 10^6$	9.89 (%)	$1.074 \times 10^6$
13	Al	8,490 (ppm)	W	3	$8.27 \times 10^4$	8,680 (ppm)	$8.49 \times 10^4$
14	Si	10.68 (%)		3	$\equiv 10^6$	10.64 (%)	$\equiv 10^6$
15	P	926 (ppm)	W	7	$7.86 \times 10^3$	1,220 (ppm)	$1.04 \times 10^4$
16	S	5.41 (%)	D	5	$4.44 \times 10^5$	6.25 (%)	$5.15 \times 10^5$
17	Cl	698 (%)		15	$5.18 \times 10^3$	704 (ppm)	$5.24 \times 10^3$
18	Ar	751 (pL g <sup>-1</sup> )	*			751 (pL g <sup>-1</sup> )	
19	K	544 (ppm)		5	$3.66 \times 10^3$	558 (ppm)	$3.77 \times 10^3$
20	Ca	9,320 (ppm)	W	3	$6.12 \times 10^4$	9,280 (ppm)	$6.11 \times 10^4$
21	Sc	5.90 (ppm)		3	34.5	5.82 (ppm)	34.2
22	Ti	458 (ppm)	W	4	$2.52 \times 10^3$	436 (ppm)	$2.40 \times 10^3$
23	V	54.3 (ppm)		5	280	56.5 (ppm)	293
24	Cr	2,646 (ppm)		3	$1.34 \times 10^4$	2,660 (ppm)	$1.35 \times 10^4$
25	Mn	1,933 (ppm)		3	$9.25 \times 10^3$	1,990 (ppm)	$9.55 \times 10^3$
26	Fe	18.43 (%)		3	$8.68 \times 10^5$	19.04 (%)	$9.00 \times 10^5$
27	Co	506 (ppm)		3	$2.26 \times 10^3$	502 (ppm)	$2.25 \times 10^3$
28	Ni	1.077 (%)		3	$4.82 \times 10^4$	1.10 (%)	$4.93 \times 10^4$
29	Cu	131 (ppm)		10	542	126 (ppm)	522
30	Zn	323 (ppm)		10	$1.30 \times 10^3$	312 (ppm)	$1.26 \times 10^3$
31	Ga	9.71 (ppm)		5	36.6	10.0 (ppm)	37.8
32	Ge	32.6 (ppm)		10	118	32.7 (ppm)	119
33	As	1.81 (ppm)		5	6.35	1.86 (ppm)	6.56
34	Se	21.4 (ppm)	D	5	71.3	18.6 (ppm)	62.1
35	Br	3.50 (ppm)		10	11.5	3.57 (ppm)	11.8
36	Kr	8.7 (pL g <sup>-1</sup> )				8.7 (pL g <sup>-1</sup> )	
37	Rb	2.32 (ppm)		5	7.14	2.30 (ppm)	7.09
38	Sr	7.26 (ppm)		5	21.8	7.80 (ppm)	23.5
39	Y	1.56 (ppm)	J2	3	4.61	1.56 (ppm)	4.64
40	Zr	3.86 (ppm)	J2	2	11.1	3.94 (ppm)	11.4
41	Nb	0.247 (ppm)	J2	3	0.699	0.246 (ppm)	0.698
42	Mo	0.928 (ppm)		5	2.54	0.928 (ppm)	2.55
44	Ru	0.683 (ppm)	J1	3	1.78	0.712 (ppm)	1.86
45	Rh	0.140 (ppm)	J1	3	0.358	0.134 (ppm)	0.344
46	Pd	0.556 (ppm)		10	1.37	0.560 (ppm)	1.39
47	Ag	0.197 (ppm)		10	0.480	0.199 (ppm)	0.486
48	Cd	0.680 (ppm)		10	1.59	0.686 (ppm)	1.61
49	In	0.0780 (ppm)		10	0.178	0.080 (ppm)	0.184
50	Sn	1.68 (ppm)		10	3.72	1.720 (ppm)	3.82
51	Sb	0.133 (ppm)		10	0.287	0.142 (ppm)	0.309
52	Te	2.27 (ppm)		10	4.68	2.320 (ppm)	4.81
53	I	0.433 (ppm)		20	0.897	0.433 (ppm)	0.90
54	Xe	8.6 (pL g <sup>-1</sup> )				8.6 (pL g <sup>-1</sup> )	
55	Cs	0.188 (ppm)		5	0.372	0.187 (ppm)	0.372
56	Ba	2.41 (ppm)		10	4.61	2.340 (ppm)	4.49
57	La	0.245 (ppm)		5	0.464	0.2347 (ppm)	0.4460
58	Ce	0.638 (ppm)		5	1.20	0.6032 (ppm)	1.136

(continued)

Table 3 (continued).

Element	Palme and Beer (1993, updated)				Anders and Grevesse (1989)		
	Mean CI abundance (by weight)	Lit.	Estimated accuracy (%)	Atoms per 10 <sup>6</sup> atoms of Si	Mean CI abundance (by weight)	Atoms per 10 <sup>6</sup> atoms of Si	
59	Pr	0.0964 (ppm)		10	0.180	0.0891 (ppm)	0.1669
60	Nd	0.474 (ppm)		5	0.864	0.4524 (ppm)	0.8279
62	Sm	0.154 (ppm)		5	0.269	0.1471 (ppm)	0.2582
63	Eu	0.0580 (ppm)		5	0.100	0.0560 (ppm)	0.0973
64	Gd	0.204 (ppm)		5	0.341	0.1966 (ppm)	0.3300
65	Tb	0.0375 (ppm)		10	0.0621	0.0363 (ppm)	0.0603
66	Dy	0.254 (ppm)		5	0.411	0.2427 (ppm)	0.3942
67	Ho	0.0567 (ppm)		10	0.0904	0.0556 (ppm)	0.0889
68	Er	0.166 (ppm)		5	0.261	0.1589 (ppm)	0.2508
69	Tm	0.0256 (ppm)		10	0.0399	0.0242 (ppm)	0.0378
70	Yb	0.165 (ppm)		5	0.251	0.1625 (ppm)	0.2479
71	Lu	0.0254 (ppm)		10	0.0382	0.0243 (ppm)	0.0367
72	Hf	0.107 (ppm)		5	0.158	0.104 (ppm)	0.154
73	Ta	0.0142 (ppm)	J2	6	0.0206	0.0142 (ppm)	0.0207
74	W	0.0903 (ppm)	J1	4	0.129	0.0926 (ppm)	0.133
75	Re	0.0395 (ppm)	J1	4	0.0558	0.0365 (ppm)	0.0517
76	Os	0.506 (ppm)	J1*	2	0.699	0.486 (ppm)	0.675
77	Ir	0.480 (ppm)	J1	4	0.657	0.481 (ppm)	0.661
78	Pt	0.982 (ppm)	J1	4	1.32	0.990 (ppm)	1.34
79	Au	0.148 (ppm)	J1	4	0.198	0.140 (ppm)	0.187
80	Hg	0.310 (ppm)		20	0.406	0.258 (ppm)	0.34
82	Tl	0.143 (ppm)		10	0.184	0.142 (ppm)	0.184
82	Pb	2.53 (ppm)		10	3.21	2.470 (ppm)	3.15
83	Bi	0.111 (ppm)		15	0.140	0.114 (ppm)	0.144
90	Th	0.0298 (ppm)		10	0.0338	0.0294 (ppm)	0.0335
92	U	0.00780 (ppm)		10	0.0086	0.0081 (ppm)	0.0090

Data from Palme and Beer (1993), except: rare gases in nL g<sup>-1</sup> or pL g<sup>-1</sup> at (STP) from Anders and Grevesse (1989), elements marked D (Dreibus *et al.*, 1995), J1 (Jochum, 1996), J1\* Os is calculated from the average carbonaceous chondrite ratio Ir/Os of 0.0949 from Jochum (1996); J2 (Jochum *et al.*, 2000); W (Wolf and Palme, 2001); Z (Zhai and Shaw, 1994); \* elements incompletely condensed in CI meteorites. Average CI abundances from Anders and Grevesse (1989), Table 1, columns 6 and 2, except C, N, O and rare gases He, Ne, Ar, Kr, Xe which are only from Orgueil.

obvious, although the formal error of the solar iron abundance is quite large (Table 1). However, the same argument that has been applied to refractory elements can be used here. The patterns of nickel and cobalt are identical to that of iron and the errors in the solar abundances of nickel and cobalt are only half of the error in the iron abundance determination (Table 1). The combined error associated with the solar/CI meteorite ratio for these three metals is then below 10%, assuming constant ratios between the three metals. Thus only CI, H, and EH chondrites have solar Fe/Si ratios. As H and EH chondrites have very different refractory element contents, they are not suitable meteorites for representing solar abundances.

In Figure 3, sodium, zinc, and sulfur are representative of the abundances of moderately volatile elements (Figure 2 and Table 2). Abundance variations reach a factor of 5 for sulfur and 10 for zinc. All three elements show excellent agreement of solar with CI abundances, in contrast to other groups of chondritic meteorites, except for the enstatite chondrites, which reach the level of CI abundances. However, enstatite chondrites

cannot be representative of solar abundances because of their low refractory element contents and their fractionated Mg/Si ratios (Figure 3).

The new photospheric lead determinations (Table 1) show that there is now agreement between the CI lead and the solar lead abundance. Thus the excellent match of CI chondrites with the solar photosphere can be extended to some of the highly volatile elements.

The CI chondrites not only have the highest contents of volatile elements but also the highest content of oxygen (a large fraction in the form of water) of all chondritic meteorites. However, in contrast to other highly volatile elements, such as lead, the amount of oxygen contained in CI meteorites is still a factor of 2 below that of the solar photosphere (Figure 3), implying that water is not fully condensed. The concept of incomplete condensation of volatile elements in most meteorite groups is supported by the observation that there is no group of meteorites that is enriched in these elements relative to the average solar system abundances. There was no late redistribution of volatiles, for example, by reheating. In CI meteorites,

the moderately volatile elements and some of the highly volatile elements are fully condensed; other groups of chondrites acquired lower fractions of volatiles because the solar gas dissipated during condensation (Palme *et al.*, 1988).

In summary, there is only one group of meteorites, the CI chondrites, that closely match solar abundances for elements representing the various cosmochemical groups and excluding the extremely volatile elements such as the rare gases, hydrogen, carbon, oxygen, and nitrogen and also the element lithium, which will be discussed in Section 1.03.1.5.3. All other chondrite groups deviate from solar abundances and the deviations can be understood, at least in principle, by gas–solid fractionation processes in the early solar system.

#### 1.03.1.4.2 CI chondrites

Among the more than twenty thousand recovered meteorites there are only five CI meteorites: Orgueil, Ivuna, Alais, Tonk, and Revelstoke. These meteorites are very fragile and are easily fragmented on atmospheric entry. In addition, their survival time on Earth is short. All five CI meteorites are observed falls. Most analyses have been performed on the Orgueil meteorite, simply because Orgueil is the largest CI meteorite and material is easily available for analysis. However, problems with sample size, sample preparation, and the mobility of some elements are reflected in the chemical inhomogeneities within the Orgueil meteorite, and often make a comparison of data obtained by different authors difficult. This contributes significantly to the uncertainties in CI abundances.

The chemical composition of CI chondrites as shown in Figure 3 is the basis for designating CI meteorites as primitive or unfractionated. Texturally and mineralogically they are far from being primitive. CI meteorites are microbreccias with millimeter to submillimeter clasts with variable composition. Late stage fractures filled with carbonates, hydrous calcium, and magnesium sulfate demonstrate that low temperature processes have affected the meteorite. The CI meteorites have no chondrules and thus consist almost entirely of extremely fine-grained hydrous silicates with some magnetite. High temperature phases such as olivine and pyroxene are frequently found (Dodd, 1981). Although the CI meteorites undoubtedly match solar abundances very closely, processes that occurred late on the Orgueil parent body have largely established their present texture and mineralogy. On a centimeter scale these processes must have been essentially isochemical, otherwise the composition of Orgueil would not be solar for so many elements.

#### 1.03.1.4.3 The CI abundance table

The CI abundance table given here (Table 3) is largely based on the compilation by Palme and Beer (1993). Relevant data published after 1993 are incorporated as described below. In addition, the widely used CI data of Anders and Grevesse (1989) are listed for comparison.

In the 1993 compilation rhodium was the only element that had not been determined in the Orgueil meteorite. Jochum (1996) reported a value of 134 ppb for his Orgueil analysis, in good agreement with the value listed in the 1993 compilation, estimated from rhodium in other meteorites. The values for ruthenium, tungsten, rhenium, osmium, iridium, platinum, and gold were all taken from the paper by Jochum (1996) and are marked J1 in Table 3. The difference between the new data from Jochum (1996) and the old data listed in the Palme and Beer (1993) compilation is in all cases below 5%.

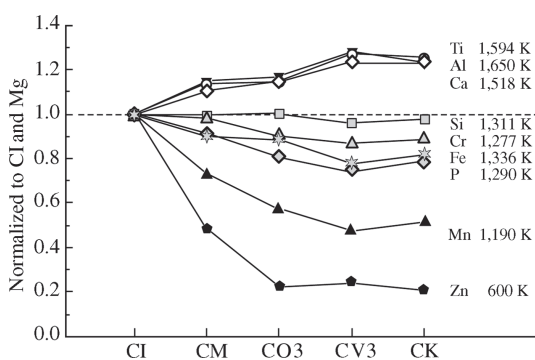
New sulfur and selenium data for CI chondrites were obtained by Dreibus *et al.* (1995) in a study of sulfur and selenium in chondritic meteorites. With the measured CI contents of 5.41% for sulfur and 21.4 ppm for selenium in Orgueil a CI S/Se ratio of 2,540 is obtained. A nearly identical S/Se ratio of  $2,560 \pm 150$  was calculated as average of carbonaceous chondrites, considering only observed meteorite falls. The average ratio of all meteorite falls analyzed by Dreibus *et al.* (1995) was  $2,500 \pm 270$ . These data suggest that the new sulfur and selenium content of Orgueil provides a reliable estimate for the solar system average. The new CI sulfur content is slightly higher than the sulfur content given in the Palme and Beer (1993) compilation and significantly lower than the sulfur content of 6.25% in the compilation of Anders and Grevesse (1989). The corresponding change in selenium is to 21.4 from 21.3 ppm in Palme and Beer (1993) and from 18.6 ppm in Anders and Grevesse (1989).

New phosphorus and titanium XRF data for CI chondrites were reported by Wolf and Palme (2001). The change in phosphorus is significant. The new CI abundance is 926 ppm, which is much lower than the values in the older compilations, 1,105 ppm in Palme and Beer (1993) and 1,200 ppm in Anders and Grevesse (1989), respectively. The new phosphorus contents are considered to be more reliable. The changes in titanium are small. Wolf and Palme (2001) also reported major element concentrations of CI meteorites and other carbonaceous chondrites. Their magnesium and silicon contents were almost identical to those given by Palme and Beer (1993): 10.69% versus 10.68% (for silicon) in Palme and Beer (1993) and 9.60% versus 9.61% (for magnesium) in Palme and Beer (1993). The aluminum, calcium, and iron concentrations

of Palme and Beer (1993) were, however, slightly different. The average between the new data and those listed earlier in Palme and Beer (1993) was used in the present compilation.

Figure 4 is a plot of some refractory and moderately volatile elements in the various types of carbonaceous chondrites. Calculated condensation temperatures at a pressure of  $10^{-4}$  bar (Wasson, 1985) are indicated to the right. There is a trend for increasing depletions (decreasing abundances) with decreasing condensation temperatures (see also Figure 2). However, the sequence of decreasing condensation temperatures for silicon, chromium, iron, and phosphorus does not match with the depletions observed in carbonaceous chondrites. The differences are small; however, the condensation temperatures of phosphorus and chromium are not well known and the condensation temperature of iron (condensing as metal) relative to silicon and other lithophile elements is dependent on nebular pressure (Grossman and Larimer, 1974). These minor discrepancies do not change the basic conclusion that these depletions are related to condensation temperatures. A number of conclusions with regard to the CI abundances can be drawn from Figure 4.

(i) The Mg/Si weight ratio, 0.90, is constant within one percent in bulk carbonaceous chondrites, except for a three percent depletion of magnesium in CV chondrites. There is no apparent trend that would suggest volatility related depletion of silicon, comparable to the depletions observed for chromium, manganese, zinc, etc.



**Figure 4** Abundances of refractory and moderately volatile elements in various groups of carbonaceous chondrites, normalized to CI and Mg. Refractory elements increase from CI to CV3 chondrites while Mg/Si ratios are constant in all groups of carbonaceous chondrites. Although the elements Cr, Fe, and P are significantly less depleted than Mn and Zn, they show a similar behavior, suggesting volatility related depletions of Cr, Fe, and P in carbonaceous chondrites of higher metamorphic grades (source Wolf and Palme, 2001).

(ii) There is a clear trend of decreasing Fe/Mg ratios with the increasing depletion of moderately volatile elements, suggesting that the variations in iron contents are probably related to the volatility of iron. Thus in defining the CI ratio for iron one cannot rely on other carbonaceous chondrites. There is an uncertainty of  $\sim 5\%$  in the CI Fe/Mg ratio of 1.92 (by weight) given in Table 1. This uncertainty reflects variable iron contents in CI samples and it will be difficult to obtain more accurate CI iron contents.

(iii) A similar problem is encountered with refractory elements. Wolf and Palme (2001) noted a 20% variation in the calcium content of various CI meteorite samples. The corresponding aluminum contents are fortunately much more constant and the Al/Mg ratio of 0.0865 is estimated to be accurate to within 2%. As a result there is some uncertainty in the solar system Ca/Al ratio, from  $\sim 1.07$  to 1.10. Members of the reduced subgroup in CV chondrites have Ca/Al ratios at least 10% below those of other carbonaceous chondrites (Wolf and Palme, 2001). In general, however, ratios among refractory elements in other chondritic meteorites may be used to improve the accuracy of chondritic refractory element ratios, which are variable in CI meteorites due to inhomogeneous distribution. An extreme example for CI variability is U. Rocholl and Jochum (1993) found Th/U ratios in CI chondrites varying from 1.06 to 3.79. The variability is primarily a result of low temperature mobilization of uranium under aqueous conditions. As other chondritic meteorites are also variable, although to a lesser extent, the CI uranium content is not too well determined. Rocholl and Jochum (1993) suggest a value of  $3.9 \pm 0.2$ . Other elements, such as barium, caesium, and antimony, may also be affected by alteration processes on parent bodies, although to a lesser extent (Rocholl and Jochum, 1993).

(iv) The geochemically similar, but cosmochemically dissimilar elements magnesium and chromium are fractionated in carbonaceous chondrites: chromium behaves as a slightly more volatile element than magnesium (Figure 4). The Fe/Cr ratio is apparently less variable than the Mg/Cr ratio reflecting the volatility related behavior of iron in carbonaceous chondrites (Figure 4). Wolf and Palme (2001) found an average Mg/Cr ratio in CI of 36.52 compared to 40.75 in CO chondrites, but Fe/Cr ratios of 70.89 for CI and 71.05 for CO. Much stronger variations are found for other moderately volatile elements, such as manganese, sodium, potassium, sulfur, zinc, selenium, etc. (see Figures 2–4). The concentrations of these elements in other carbonaceous chondrites cannot be used to infer or improve their CI abundances.

#### 1.03.1.4.4 Comparison with Anders and Grevesse abundance table

A comparison with the Anders and Grevesse (1989) compilation (Table 3) shows that there are few elements for which the difference between this compilation and that of Anders and Grevesse (1989) exceeds five percent. This is not surprising as both compilations rely, at least in part, on the same sources of data. Differences above 10% are found for phosphorus, sulfur, and selenium. The new values listed, as discussed above, are more reliable. Differences between 5% and 10% are found for carbon, strontium, antimony, cerium, praseodymium, rhenium, and mercury. The rare earth abundances in CI meteorites reported here are the same as those in Palme and Beer (1993), which are based on data by Evenson *et al.* (1978). There is an excellent agreement of the REE data of Evenson *et al.* (1978) with those in two Orgueil samples determined by Beer *et al.* (1984), except for a small difference of a few percent in the light REE. Because of this general agreement the hafnium, barium, strontium, rubidium, and caesium concentrations of Beer *et al.* (1984) were used in the present compilation. The Anders and Grevesse (1989) REE and strontium data were obtained by averaging data sets of various authors. The absolute concentrations of the REEs are slightly lower, exceeding 5% for strontium, cerium, and praseodymium. The differences in carbon and antimony concentrations between Palme and Beer (1993) and Anders and Grevesse (1989) are related to the selection of data literature. Mercury abundances in CI chondrites are extremely variable. The high contents of mercury in Orgueil may reflect contamination (Palme and Beer, 1993). A single analysis of Ivuna (0.31 ppm) was therefore used in the present compilation. The value of 0.31 ppm is in agreement with a mercury content inferred from nuclear abundance systematics (Palme and Beer, 1993).

#### 1.03.1.5 Solar System Abundances of the Elements

##### 1.03.1.5.1 Comparison of meteorite and solar abundances

In Table 1 the Si-normalized meteorite abundances of Table 3 ( $\log A_{\text{Si}} = 6$ ) are converted to the H-normalized abundances ( $\log A_{\text{H}} = 12$ ). The conversion factor between the two scales was calculated by dividing the H-normalized solar abundances by the Si-normalized meteorite abundances. The comparison was made for all elements with an error of the corresponding photospheric abundance of less than 0.1 dex, i.e., less than  $\sim 25\%$ . Thirty-four elements qualified for this procedure, and the log of the average ratio of solar abundance per  $10^{12}$  H

atoms/meteorite abundance per  $10^6$  silicon atoms is  $1.546 \pm 0.045$ . As each of the solar and meteorite abundance measurements are independent the error of the mean may be used which gives  $1.546 \pm 0.008$ , corresponding to a ratio of  $35.16 \pm 0.65$ . Thus,

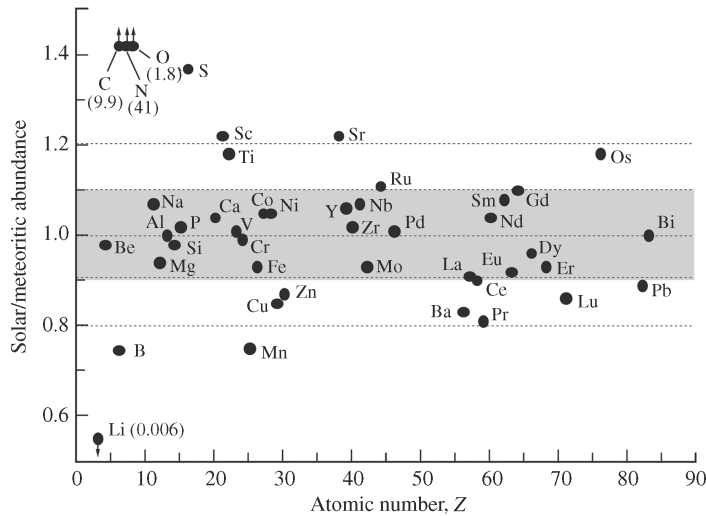
$$\log A_{\text{ast}} = \log A_{\text{met}} + 1.546$$

This yields a silicon abundance on the astronomical scale of  $\log A_{\text{ast}}(\text{Si}) = 7.546$  and a hydrogen abundance on the meteoritic scale of  $\log A_{\text{met}}(\text{H}) = 10.45$  or  $2.84 \times 10^{10}$  which is given in Table 3. Anders and Grevesse (1989) calculated a value of 1.554 for the ratio of solar to meteoritic abundances, which leads to a hydrogen abundance of  $2.97 \times 10^{10}$  on the meteoritic scale. Lodders (2003) used a conversion factor of 1.540 based on the ratio of photospheric and meteoritic silicon.

In column 6 of Table 1, the meteorite data are given on the astronomical scale and in column 8 the ratios of the photospheric abundances to the meteoritic abundances are listed. These ratios are displayed in Figure 5. The solar abundances of carbon, nitrogen, and oxygen are higher because these elements are incompletely condensed in CI meteorites. Although the new solar oxygen abundance is 50% lower than the old value, the solar oxygen abundance is still a factor of 2 above the meteorite value, which is, however, significantly less than the depletion of nitrogen (factor 41) and of carbon (factor 9.9). A major revision in photospheric abundances was found for beryllium which is now in good agreement with meteoritic abundances (Grevesse and Sauval, 1998). As the photospheric abundance of boron appears to fit with meteorite data, at least within a factor of 2, which is also the error assigned to the photospheric boron determination by Grevesse and Sauval (1998), lithium is the only light element that is strongly depleted in the Sun. "The Li-Be-B problem is now reduced to explaining how the Sun can deplete Li by a factor of 160 whereas Be and B are not destroyed" (Grevesse and Sauval, 1998).

The recent revision of the photospheric lead abundance brought this element into agreement with meteoritic lead abundances to within 10% (Biemont *et al.*, 2000).

In comparing meteorite with solar abundances in Figure 5 only ratios are plotted where the error of the photospheric abundances is below 0.1 dex, i.e., below 25%. In the Figure 5  $\pm 10\%$  variation is indicated. The largest discrepancy between solar and meteoritic abundances is now found for sulfur, scandium, strontium, and manganese, the only elements where the difference between solar and meteoritic abundances exceeds 20%. The solar sulfur and scandium abundances had been revised by Grevesse and Sauval (1998). Their new values are higher than those of



**Figure 5** Comparison of solar and meteoritic abundances (see Table 1). The elements C, N, and O are incompletely condensed in meteorites. Li is consumed by fusion processes in the interior of the Sun, but not Be and B. Solar and meteoritic abundances agree in most cases within 10%. Only the four elements S, Mn, Sc, and Sr differ by more than 20% from CI abundances. The difference is below 10% for 27 elements. Only elements with uncertainties of less than 25% in the photosphere are plotted.

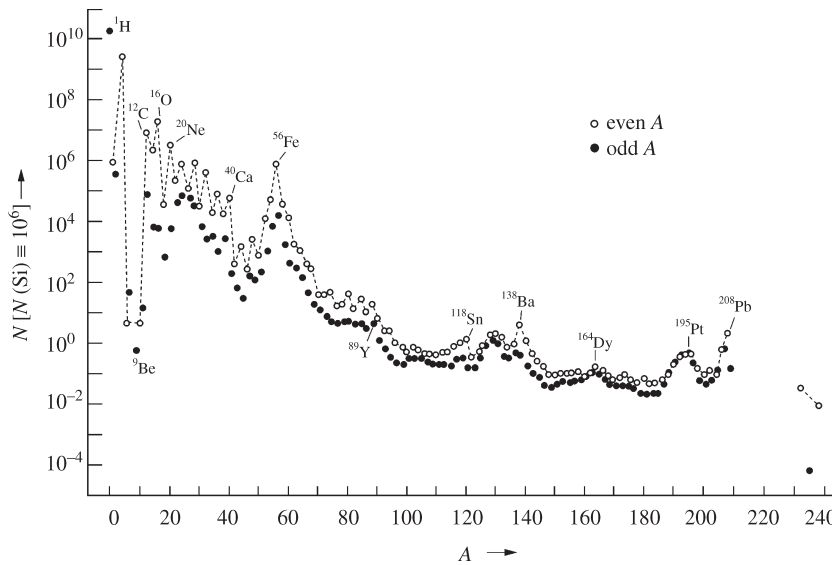
Anders and Grevesse (1989), which had agreed to within 5% with CI abundances. The error in the photospheric abundance of strontium is 17% according to Grevesse and Sauval (1998) and the difference is thus not significant. The only element that has consistently shown a major deviation within the stated error is manganese (Figure 5). In the compilation of Grevesse and Sauval (1998) an uncertainty of 7% is assigned to the manganese abundance. Recently Prochaska and McWilliam (2000) pointed out that there are so far unrecognized problems in the photospheric determination of manganese by incorrect treatment of hyperfine splitting. These authors also mention that similar problems may be involved with the photospheric abundance determination of scandium. The errors associated with the photospheric abundances of the other elements are all in excess of 10%, some are considerably higher, e.g., praseodymium with 20%.

The agreement between meteoritic and solar abundances must be considered excellent and there is not much room left for further improvements. Obvious candidates for redetermination of the solar abundances are manganese and sulfur.

#### 1.03.1.5.2 Solar system abundances versus mass number

The isotopic compositions of the elements are not discussed in this chapter. The compilation by Palme and Beer (1993) contains a list of isotopes and their relative abundances. Lodders (2003) has prepared a new compilation. From

these data the abundances for individual mass numbers can be calculated using the elemental abundances as given in Table 1. Figure 6 is a plot of abundances versus mass number. The generally higher abundance of even masses is apparent. Plots for even and odd mass numbers are more or less smooth, the latter forming a considerably smoother curve than the former. Historically, the so-called abundance rules, established by Suess (1947), postulating a smooth dependence of isotopic abundances on mass number  $A$ , especially of odd- $A$  nuclei, played an important role in estimating unknown or badly determined abundances. Later this rule was modified and supplemented by two additional rules (Suess and Zeh, 1973) in order to make the concept applicable to the now more accurate abundance data. However, the smoothness of odd- $A$  nuclei abundances itself has been questioned (Anders and Grevesse, 1989; Burnett and Woolum, 1990). Figure 7(a) is an enlargement of a part of Figure 6. The high abundance of  $^{89}\text{Y}$  (Figure 7(a)), an apparent discontinuity (Burnett and Woolum, 1990), reflects the low neutron capture cross-section of a dominantly s-process nucleus with a magic neutron number (50). Also, there are major breaks in the abundance curve of odd- $A$  nuclei in the region of molybdenum, rhodium, indium, tin, and antimony (Figure 7(a)). In detail there is therefore no smoothness of odd- $A$  nuclei with mass number. Similar arguments apply to the abundances of odd- $A$  isotopes of neodymium, samarium, and europium (Figure 7(b)). They do not follow a smooth trend with the lower abundance of samarium.



**Figure 6** Solar system abundances by mass number. Atoms with even masses are more abundant than those with odd masses (Oddo–Harkins rule) (source Palme and Beer, 1993).

### 1.03.1.5.3 Other sources for solar system abundances

Emission spectroscopy of the solar corona, solar energetic particles (SEP) and the composition of the solar wind yield information on the composition of the Sun. Solar wind data were used for isotopic decomposition of rare gases. Coronal abundances are fractionated relative to photospheric abundances. Elements with high first ionization potential are depleted relative to the rest (see Anders and Grevesse, 1989 for details).

The composition of dust grains of comet Halley has been determined with impact ionization time-of-flight mass spectrometers on board the Vega-I, Vega-II, and Giotto spacecrafts. The abundances of 16 elements and magnesium, which is used for normalization, are on average CI chondritic to within a factor of 2–3, except for hydrogen, carbon, and nitrogen which are significantly higher in Halley dust, presumably due to the presence of organic compounds (Jessberger *et al.*, 1988). There is no evidence for a clear enhancement of volatile elements relative to CI.

Many of the micron-sized interplanetary dust particles (IDPs) have approximately chondritic bulk composition (see Chapter 1.26 for details). Porous IDPs match the CI composition better than nonporous (smooth) IDPs. On an average, IDPs show some enhancement of moderately volatile and volatile elements (see Palme, 2000). Arndt *et al.* (1996) found similar enrichments in their suite of 44 chondritic particles (average size  $17.2 \pm 1.2 \mu\text{m}$ ). The elements chlorine, copper, zinc, gallium, selenium, and rubidium were enriched by factors of 2.2–2.7. In addition, these

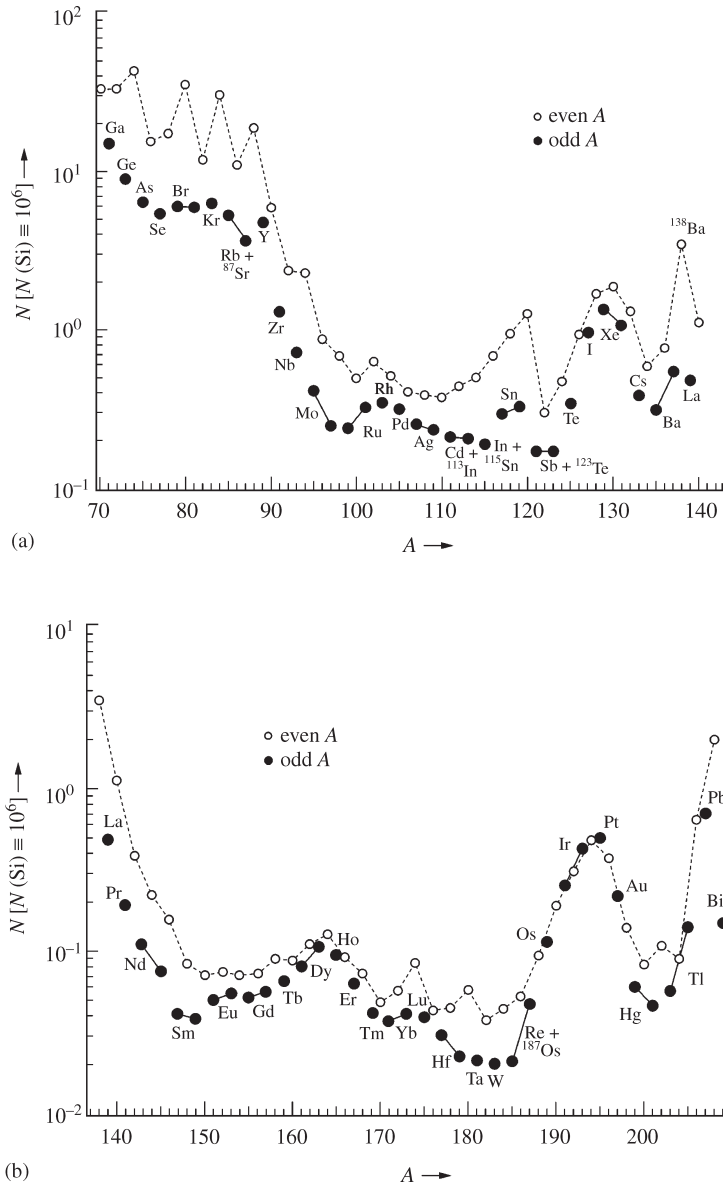
authors also reported very high enrichments of bromine ( $29 \times \text{CI}$ ) and arsenic ( $7.4 \times \text{CI}$ ), perhaps acquired in the Earth's atmosphere.

These particles probably come from the asteroid belt (Flynn, 1994). They are brought to Earth by the action of the Poynting–Robertson effect. Perhaps they are derived from sources that contain uncondensed volatiles from the inner part of the nebula. This would be the only example of a clear enhancement of moderately volatile elements in solar system material.

## 1.03.2 THE ABUNDANCES OF THE ELEMENTS IN THE ISM

### 1.03.2.1 Introduction

The solar system was formed as the result of the collapse of a cloud of pre-existing interstellar gas and dust. We should therefore expect a close compositional relationship between the solar system and the interstellar material from which it formed. If we make the assumption that the composition of the ISM has remained unchanged since the formation of the solar system, we can use the local ISM as a measure of the original pre-solar composition. Differences between the solar system and current local ISM would imply that fractionation occurred during the formation of the solar system, that the local ISM composition changed after solar system formation or that the solar system formed in a different part of the galaxy and then migrated to its present location. Studies of solar system and local ISM composition are therefore fundamental to the formation of the



**Figure 7** Enlarged parts of Figure 6: (a) mass range 70–140 and (b) mass range 138–209. The abundances of odd mass nuclei are not a smooth function of mass number, e.g., Y and Sn.

solar system, the nature of the local ISM and the general processes leading to low-mass star formation.

The discovery of presolar grains in meteorites has, for the first time, enabled the precise chemical and isotopic analysis of interstellar material (e.g., Anders and Zinner, 1993; Chapter 1.02). The huge variations in the isotopic compositions of all the elements analyzed in presolar grains is in stark contrast to the basically uniform isotopic composition of solar system materials (see Figure 1). This uniformity would have required an effective isotopic homogenization of all the material in the solar nebula, i.e., gas and dust, during the early stages of the formation of the solar system.

### 1.03.2.2 The Nature of the ISM

The ISM is the medium between the stars. For present purposes, we will also consider the media immediately surrounding stars (generally considered as circumstellar media) as part of the ISM. Most of the matter in the ISM is in the form of a very tenuous gas with densities of less than one hydrogen atom per  $\text{cm}^3$  to perhaps a million hydrogen atoms per  $\text{cm}^3$ . For comparison the terrestrial atmosphere contains about  $10^{19}$  hydrogen atoms per  $\text{cm}^3$ .

Interstellar matter is comprised of both gas and dust. The gas consists of atomic and polyatomic ions and radicals, and also of molecules. It is the



form of hydrogen in the ISM that is used to describe its nature, i.e., ionized ( $H^+$ ), atomic ( $H$ ), or molecular ( $H_2$ ), with increasing density from the ionized to the molecular gas. The dust is primarily composed of amorphous carbons and silicates and makes up  $\sim 1\%$  of the mass of the ISM. The dust particles have sizes in the nanometer to micrometer range (e.g., Mathis, 1990). The total amount of absorption and scattering along any given line of sight is called the interstellar extinction. The degree of extinction depends upon the wavelength, the size of the dust grains and their composition.

### 1.03.2.3 The Chemical Composition of the ISM

#### 1.03.2.3.1 The composition of the interstellar gas and elemental depletions

The elements incorporated into grains in the ISM cannot be observed directly. They are under-represented in or depleted from the gas phase. Only the fraction of an element that remains in the gas phase can be detected in the ISM, provided that the element has accessible and observable transitions. Initial measurements of the abundances of elements in the gas phase date back to the mid-1960s, when with the advent of space missions, it became possible to eliminate the absorbing effects of the Earth's atmosphere (e.g., Morton and Spitzer, 1966). With the sensitive spectrographs onboard the International Ultraviolet Explorer (IUE) and the Hubble Space Telescope (HST, e.g., the Goddard High Resolution Spectrometer, GHRS, and more recently the Space Telescope Imaging Spectrograph, STIS) many lines of sight have now been studied for a large number of elements (e.g., Savage and Sembach, 1996; Howk *et al.*, 1999; Cartledge *et al.*, 2001).

Hydrogen and helium are the most abundant elements in the ISM gas phase. To date some 30–40 elements heavier than helium have been observed and their gas phase abundances determined. Based on the existing data (e.g., Savage and Sembach, 1996; Howk *et al.*, 1999; Sofia and Meyer, 2001) the local ISM sampled out to a few kiloparsecs from the Sun appears to be rather uniform in chemical composition.

As an example we show the results of abundance determinations along the line of sight towards  $\zeta$  Oph ( $\zeta$  Ophiuchus), a moderately reddened star that is frequently used as standard for depletion studies. Molecules are observed along this line of sight and the material is a blend of cool diffuse clouds and a large cold cloud. The atomic hydrogen column density is  $\log N(H) = 21.12 \pm 0.10$ . In Table 4 all data are normalized to  $10^{12}$  atoms of hydrogen and in the

last column the ratios of the  $\zeta$  Oph abundances to the solar abundances are given. In Figure 8 these ratios are plotted against condensation temperatures (see Savage and Sembach, 1996 for details). The abundances of many of the highly volatile and moderately volatile elements up to condensation temperatures of around 900 K (at  $10^{-4}$  bar) are, within a factor of 2, the same in the ISM and in the Sun, independent of the condensation temperatures. This suggests that these elements predominantly reside in the gas phase in the ISM and that their elemental abundances in the ISM are similar to those of the solar system. At higher condensation temperatures a clear trend of increasing depletions with increasing condensation temperatures is seen. The more refractory elements are condensed into grains in the outflows of evolved stars or perhaps in the ejected remnants associated with supernovae explosions.

There are several elements whose abundances deviate from the general trend (e.g., phosphorus and arsenic in Figure 8). It will be important to find out during the course of future work whether these deviations reflect problems with the extremely complex analyses or whether they are true variations that indicate particular chemical processes in the ISM or are characteristic of condensation in stellar outflows.

It should be emphasized that the depletion pattern in the ISM does not reflect thermodynamic equilibrium between dust and gas. The temperature in the ISM is so low that virtually all elements, including the rare gases, should be condensed in grains if thermodynamic equilibrium between dust and gas is assumed. The depletion pattern rather reflects conditions at higher temperatures established during the condensation of minerals in the outflows of dying stars or supernovae explosions. This pattern is then frozen in the cold ISM.

#### 1.03.2.3.2 The composition of interstellar dust

As concluded in the previous section, the dust in the ISM is primarily composed of the elements carbon, oxygen, magnesium, silicon, and iron. This argument is based on the elemental make-up of the solid phase in the ISM determined from the depletions. However, the exact chemical and mineralogical composition of the dust in the ISM can be determined through infrared observations of the absorption of starlight by cold dust ( $T \approx 20$  K) along lines of sight toward distant stars, and also by the emission features from hot dust ( $T \approx$  a few hundred kelvin) in the regions close to stars. Such observations reveal the spectral signatures of amorphous aliphatic and

**Table 4** Abundances of elements in the gas phase of the ISM in the direction of  $\zeta$  Ophiucus.

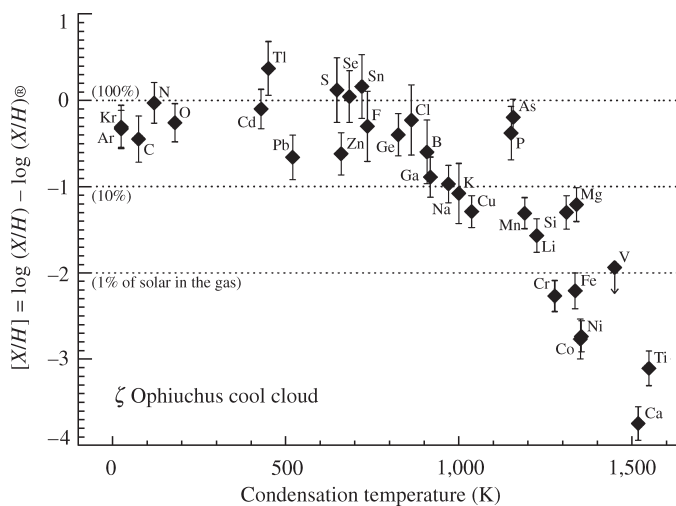
Element	$T_c$ (K)	Solar system		$\zeta$ Ophiucus cool			$\zeta$ Ophiucus cool/solar
		$\log X$	SD (%)	$\log X$	SD (%)	Lit.	
<i>Highly volatile elements</i>							
Ar	25	6.40	5	6.08	45	(1)	0.48
Kr	25	3.30	15	2.97	15	(1)	0.47
C	75	8.39	30	8.14	35	(1)	0.56
N	120	7.93	30	7.90	15	(1)	0.93
O	180	8.69	20	8.48	15	(1)	0.62
Pb	427	2.05	15	1.34	40	(1)	0.19
Cd	429	1.77	30	1.67	10	(2)	0.79
Tl	448	0.81	60	1.27	30	(1)	2.9
<i>Moderately volatile elements</i>							
S	648	7.19	30	7.45	90	(1)	1.8
Zn	660	4.66	20	3.98	30	(1)	0.21
Te	680	2.22		<3.01		(1)	<6.2
Se	684	3.40		3.45	70	(1)	1.1
Sn	720	2.12	90	2.16	25	(1)	1.1
F	736	4.45	90	4.26	60	(3)	0.65
Ge	825	3.62	40	3.01	10	(1)	0.25
Cl	863	5.26	90	5.27	60	(1)	1.0
B	908	2.87	90	1.95	25	(1)	0.12
Ga	918	3.11	25	1.99	15	(1)	0.076
Na	970	6.30	5	5.36	25	(1)	0.11
K	1,000	5.11	35	4.04	80	(1)	0.085
Cu	1,037	4.28	10	2.92	5	(1)	0.044
As	1,135	2.35	??	2.16	25	(1)	0.65
P	1,151	5.44	10	5.07	75	(1)	0.43
Mn	1,190	5.51	5	4.08	5	(1)	0.037
Li	1,225	3.30	10	1.73	15	(1)	0.027
<i>Mg-silicates and metallic FeNi</i>							
Cr	1,301	5.67	5	3.4	5	(1)	$5.3 \times 10^{-3}$
Si	1,311	7.55	15	6.24	5	(1)	$4.9 \times 10^{-2}$
Fe	1,337	7.49	20	5.24	5	(1)	$5.7 \times 10^{-3}$
Mg	1,340	7.56	15	6.33	5	(1)	$5.9 \times 10^{-2}$
Ni	1,354	6.23	10	3.51	5	(1)	$1.9 \times 10^{-3}$
Co	1,356	4.90	10	2.15	30	(1)	$1.8 \times 10^{-3}$
<i>Refractory elements</i>							
V	1,455	3.99	5	<2.06		(1)	$<1.2 \times 10^{-2}$
Ca	1,518	6.33	5	2.61	15	(1)	$1.9 \times 10^{-4}$
Ti	1,598	4.95	14	1.91	10	(1)	$9.2 \times 10^{-4}$

$T_c$ —condensation temperatures at  $10^{-4}$  bar (Wasson, 1985), except B (Lauretta and Lodders, 1997);  $\log X$ —log of abundances relative to  $10^{12}$  atoms of H; SD's are given to the nearest 5%. (1) Savage and Sembach (1996); (2) Sofia *et al.* (1999); (3) Snow and York (1981).

aromatic hydrocarbons and amorphous silicates. In dense clouds (densities of the order of  $10^3$ – $10^5$  hydrogen atoms per  $\text{cm}^3$ ), where the matter is well-shielded from the destructive effects of stellar UV-light, we observe molecular species such as  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and  $\text{CH}_3\text{OH}$ .

The interstellar carbon grains contain both aliphatic and aromatic C—H and C—C bonds; both are observed in absorption and emission in the ISM, but beyond this their exact composition is not known. Given the seemingly uniform elemental abundances in our local ISM we might expect that the dust composition would also be chemically uniform. However, the inferred elemental composition of silicates in the ISM

indicates that they have an olivine-type stoichiometry where the depletions are largest, and a mixed oxide/silicate stoichiometry where lower depletions indicate that some dust erosion has occurred (e.g., Savage and Sembach, 1996; Jones, 2000 and references therein). In the lower density regions above the galactic plane we clearly see a different dust stoichiometry (e.g., Savage and Sembach, 1996). This change in composition is presumably a reflection of the effects of shock waves that have lifted interstellar clouds high above the plane and that have, at the same time, eroded and destroyed some fraction of the dust incorporated into these clouds.



**Figure 8** Abundances of elements along the line of sight towards  $\zeta$  Oph ( $\zeta$  Ophiuchus), a moderately reddened star that is frequently used as standard for depletion studies. The ratios of  $\zeta$  Oph abundances to the solar abundances are plotted against condensation temperatures. The abundances of many of the highly volatile and moderately volatile elements up to condensation temperatures of around 900 K are, within a factor of 2, the same in the ISM and in the Sun. At higher condensation temperatures a clear trend of increasing depletions with increasing condensation temperatures is seen. It is usually assumed that the missing refractory elements are in grains (source Savage and Sembach, 1996).

#### 1.03.2.3.3 Did the solar system inherit the depletion of volatile elements from the ISM?

Most meteorites are depleted in moderately volatile and highly volatile elements (see Figures 2–4). The terrestrial planets Earth, Moon, Mars, and the asteroid Vesta show similar or even stronger depletions (e.g., Palme *et al.*, 1988; Palme, 2001). The depletion patterns in meteorites and in the inner planets are qualitatively similar to those in the ISM. It is thus possible that the material in the inner solar system inherited the depletions from the ISM by the preferential accretion of dust grains and the loss of gas during the collapse of the molecular cloud that led to the formation of the solar system. There is, however, little support for this hypothesis:

(i) The general uniformity of the isotopic compositions of solar system materials and the extreme variations in presolar grains suggest isotopic and elemental homogenization at the beginning of the solar system.

(ii) This applies likewise to all systems involving radioactive nuclei that are used for dating. For example, the extremely uniform strontium isotopic composition in all solar system materials at the beginning of the solar system, 4.566 billion years ago, indicates that the strontium isotopes were homogenized at that time, including  $^{87}\text{Sr}$ , the decay product of  $^{87}\text{Rb}$  ( $T_{1/2} = 5 \times 10^{10}$  yr). In the ISM, the refractory strontium is in grains and the volatile rubidium in the gas phase. The separation of these

two elements over hundreds of millions of years without thorough remixing at the beginning of the solar system, would produce a large range in initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios at the beginning of the solar system and should have been observed in solar system materials (see Palme, 2001).

#### 1.03.2.3.4 The ISM oxygen problem

Snow and Witt (1996) and others argued that the composition of the ISM is different from the composition of the Sun. Based on stellar compositional data, these authors concluded that heavy elements in the Sun are only two-thirds of the solar composition, with the implication that the heavy elements either fractionated from hydrogen during formation of the Sun (Snow, 2000) or that the Sun was formed in a different place in the Milky Way where the heavy element abundances were higher. Another possibility was that there were additional “hidden” reservoirs. In particular, there was a problem of too much interstellar oxygen when using the solar oxygen abundance as standard. Where could that excess oxygen be stored? Some 20% of the solar oxygen abundance must have been combined with magnesium, silicon, and iron, etc. in the form of the amorphous silicates observed in the ISM. Another 40% was directly observed in the gas as atomic oxygen (Meyer *et al.*, 1998). The “missing” 40% of oxygen remained elusive; it could not be in the form of molecules, e.g.,  $\text{H}_2\text{O}$  and  $\text{CO}$ , because they were not observed in

sufficient abundance. The recent re-evaluation of the solar oxygen abundance (Holweger, 2001; Allende Prieto *et al.*, 2001), and of interstellar oxygen (Sofia and Meyer, 2001), has resolved this problem. The new solar oxygen is now only ~60% of its previous value and so there is, and indeed never was, a problem. Recent interstellar abundance determinations using observations of solar-type F and G stars in the galactic neighborhood (Sofia and Meyer, 2001) suggest that many elemental abundances in the ISM are close to solar abundances.

### 1.03.3 SUMMARY

Updated solar photospheric abundances are compared with meteoritic abundances. It is shown that only one group of chondritic meteorites, the CI chondrites, matches solar abundances in refractory lithophile, siderophile, and volatile elements. All other chondritic meteorites differ from CI chondrites. The agreement between solar and CI abundances for all elements heavier than oxygen and excluding rare gases has constantly improved since Goldschmidt (1938) published his first comprehensive table of cosmic abundances.

The abundances of 39 nongaseous elements in the Sun have assigned errors below 30%. Only the four elements sulfur, manganese, scandium, and strontium differ by more than 20% from CI abundances. The difference is below 10% for 27 of these elements. The agreement between meteoritic and solar abundances must therefore be considered excellent and there is not much room left for further improvements. Obvious candidates for redetermination of solar abundances are manganese and sulfur. The limiting factor in the accuracy of meteorite abundances is the inherent variability of CI chondrites, primarily the Orgueil meteorite.

The ISM from which the solar system formed has volatile and moderately volatile elements, within a factor of 2, the same composition as the Sun. The more refractory elements of the ISM are depleted from the gas and are concentrated in grains.

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