

COSMOCHEMISTRY

Cosmochemistry is mainly concerned with the study of the chemical, isotopic and mineralogical composition of extraterrestrial materials such as meteorites, interplanetary dust particles (IDPs), cometary dust particles, lunar samples and, when they become available, samples from other bodies in the solar system. It is generally acknowledged that the emergence of cosmochemistry as a separate discipline stems from the seminal work by Urey, Suess and Brown in the late 1940s and early 1950s on the chemical processes involved in the origin of the solar system and on the abundances of the elements (e.g. Urey, 1952; Suess, 1947a,b; Brown, 1949).

Historically, some of the major objectives of cosmochemistry were to determine the solar system abundances of the elements, the shape of the elemental abundance curve as a function of mass number, the chemical behavior of the elements and their compounds in solar composition material, and the mechanisms (nebular and planetary) responsible for producing the different chemical fractionations and mineral phase assemblages seen in meteorites. At present some of the major research topics in cosmochemistry involve searches for preserved interstellar grains (e.g. SiC, graphite) in meteorites (Virag *et al.*, 1992), the origin of isotopic anomalies in oxygen and other elements in meteorites (Thiemens, 1988; Lee, 1988), and the origin of oxidizing conditions at high temperatures in the solar nebula (Palme and Fegley 1990).

This article summarizes two major results of cosmochemical studies, namely the determination of the solar system abundances of the elements and their chemical behavior in a solar composition (i.e. H₂-rich) system. These two topics are related because the observed elemental depletions in the different classes of primitive meteorites (the chondrites) are generally correlated with the volatility of the elements and/or their compounds in a solar composition system. A significant fraction of the research work in cosmochemistry during the past four decades has been concerned either directly or indirectly with these topics.

Another important area of cosmochemistry, namely studies of the isotopic composition of meteorites, their components (chondrules, matrix and inclusions) and IDPs is not covered here because of a lack of space. However, good introductions to cosmochronology, isotopic anomalies in meteorites and extinct radionuclides are found in several books such as Faure (1986) and in Kerridge and Matthews (1988). (See also Meteorite; Dating methods; Dust.)

Finally, several terms (i.e. nomenclature) used in the following sections will be briefly defined here. Chondrites (q.v.) are stony meteorites which generally contain small, glassy objects known as chondrules. The chondrites are primitive in the sense that they are composed of constituents (metal, silicate and sulfide grains) formed

In *Encyclopedia of Planetary Sciences* (1997), J. H. Shirley and R. W. Fairbridge, Eds. Chapman and Hall, London.

Table C13 Abundances of the elements in CI chondrites and the solar photosphere

Atomic Number	Element name and chemical symbol	CI chondrites (Si = 10 ⁶)	Solar photosphere (H = 10 ¹²)	Abundance in Orgueil CI chondrite
1	Hydrogen (H)	2.79 × 10 ¹⁰	1.00 × 10 ¹²	2.02%
2	Helium (He) ^a	2.79 × 10 ⁹	1.00 × 10 ¹¹	56 nL g ⁻¹
3	Lithium (Li)	57.1	14.45	1.49 μg g ⁻¹
4	Beryllium (Be)	0.73	14.13	24.9 ng g ⁻¹
5	Boron (B)	21.2	398	870 ng g ⁻¹
6	Carbon (C) ^a	9.90 × 10 ⁶	3.55 × 10 ⁸	3.45%
7	Nitrogen (N) ^a	2.60 × 10 ⁶	9.33 × 10 ⁷	3180 μg g ⁻¹
8	Oxygen (O) ^a	2.07 × 10 ⁷	7.41 × 10 ⁸	46.4%
9	Fluorine (F)	843	3.63 × 10 ⁴	58.2 μg g ⁻¹
10	Neon (Ne) ^a	3.28 × 10 ⁶	1.17 × 10 ⁸	203 pL g ⁻¹
11	Sodium (Na)	5.74 × 10 ⁴	2.14 × 10 ⁶	4900 μg g ⁻¹
12	Magnesium (Mg)	1.074 × 10 ⁶	3.80 × 10 ⁷	9.53%
13	Aluminium (Al)	8.49 × 10 ⁴	2.95 × 10 ⁶	8690 μg g ⁻¹
14	Silicon (Si)	1.00 × 10 ⁶	3.55 × 10 ⁷	10.67%
15	Phosphorus (P)	1.04 × 10 ⁴	2.82 × 10 ⁵	1180 μg g ⁻¹
16	Sulfur (S)	5.15 × 10 ⁵	1.62 × 10 ⁷	5.25%
17	Chlorine (Cl)	5240	3.16 × 10 ⁵	698 μg g ⁻¹
18	Argon (Ar) ^a	1.11 × 10 ⁵	3.98 × 10 ⁶	751 pL g ⁻¹
19	Potassium (K)	3770	1.32 × 10 ⁵	566 μg g ⁻¹
20	Calcium (Ca)	6.11 × 10 ⁴	2.29 × 10 ⁶	9020 μg g ⁻¹
21	Scandium (Sc)	34.2	1259	5.83 μg g ⁻¹
22	Titanium (Ti)	2400	9.77 × 10 ⁴	436 μg g ⁻¹
23	Vanadium (V)	293	1.0 × 10 ⁴	56.2 μg g ⁻¹
24	Chromium (Cr)	1.35 × 10 ⁴	4.68 × 10 ⁵	2660 μg g ⁻¹
25	Manganese (Mn)	9550	2.45 × 10 ⁵	1980 μg g ⁻¹
26	Iron (Fe) ^a	9.00 × 10 ⁵	3.24 × 10 ⁷	18.51%
27	Cobalt (Co)	2250	8.32 × 10 ⁴	507 μg g ⁻¹
28	Nickel (Ni)	4.93 × 10 ⁴	1.78 × 10 ⁶	1.10%
29	Copper (Cu)	522	1.62 × 10 ⁴	119 μg g ⁻¹
30	Zinc (Zn)	1260	3.98 × 10 ⁴	311 μg g ⁻¹
31	Gallium (Ga)	37.8	759	10.1 μg g ⁻¹
32	Germanium (Ge)	119	2570	32.6 μg g ⁻¹
33	Arsenic (As)	6.56	—	1.85 μg g ⁻¹
34	Selenium (Se)	62.1	—	18.2 μg g ⁻¹
35	Bromine (Br)	11.8	—	3.56 μg g ⁻¹
36	Krypton (Kr)	45	—	8.7 pL g ⁻¹
37	Rubidium (Rb)	7.09	398	2.30 μg g ⁻¹
38	Strontium (Sr)	23.5	794	7.80 μg g ⁻¹
39	Yttrium (Y)	4.64	174	1.53 μg g ⁻¹
40	Zirconium (Zr)	11.4	398	3.95 μg g ⁻¹
41	Niobium (Nb)	0.698	26.3	246 ng g ⁻¹
42	Molybdenum (Mo)	2.55	83.2	928 ng g ⁻¹
44	Ruthenium (Ru)	1.86	69.2	714 ng g ⁻¹
45	Rhodium (Rh)	0.344	13.2	134 ng g ⁻¹
46	Palladium (Pd)	1.39	49	556 ng g ⁻¹
47	Silver (Ag)	0.486	8.7	197 ng g ⁻¹
48	Cadmium (Cd) ^a	1.61	58.9	680 ng g ⁻¹
49	Indium (In)	0.184	45.7	77.8 ng g ⁻¹
50	Tin (Sn)	3.82	100	1680 ng g ⁻¹
51	Antimony (Sb)	0.309	10	133 ng g ⁻¹
52	Tellurium (Te)	4.81	—	2270 ng g ⁻¹
53	Iodine (I)	0.9	—	433 ng g ⁻¹
54	Xenon (Xe)	4.7	—	8.6 pL g ⁻¹
55	Cesium (Cs)	0.372	—	186 ng g ⁻¹
56	Barium (Ba)	4.49	135	2340 ng g ⁻¹
57	Lanthanum (La)	0.446	16.6	236 ng g ⁻¹
58	Cerium (Ce)	1.136	35.5	619 ng g ⁻¹
59	Praseodymium (Pr)	0.1669	5.1	90 ng g ⁻¹
60	Neodymium (Nd)	0.8279	31.6	463 ng g ⁻¹
62	Samarium (Sm)	0.2582	10	144 ng g ⁻¹
63	Europium (Eu)	0.0973	3.2	54.7 ng g ⁻¹
64	Gadolinium (Gd)	0.33	13.2	199 ng g ⁻¹
65	Terbium (Tb)	0.0603	0.8	35.3 ng g ⁻¹
66	Dysprosium (Dy)	0.3942	12.6	246 ng g ⁻¹
67	Holmium (Ho)	0.0889	1.8	55.2 ng g ⁻¹
68	Erbium (Er)	0.2508	8.5	162 ng g ⁻¹
69	Thulium (Tm)	0.0378	1	22 ng g ⁻¹

Table C13 Continued

Atomic Number	Element name and chemical symbol	CI chondrites (Si = 10 ⁶)	Solar photosphere (H = 10 ¹²)	Abundance in Orgueil CI chondrite
70	Ytterbium (Yb)	0.2479	12	166 ng g ⁻¹
71	Lutetium (Lu)	0.0367	5.8	24.5 ng g ⁻¹
72	Hafnium (Hf)	0.154	7.6	108 ng g ⁻¹
73	Tantalum (Ta)	0.0207	—	14.0 ng g ⁻¹
74	Tungsten (W)	0.133	12.9	92.3 ng g ⁻¹
75	Rhenium (Re)	0.0517	—	37.1 ng g ⁻¹
76	Osmium (Os)	0.675	28.2	483 ng g ⁻¹
77	Iridium (Ir)	0.661	22.4	474 ng g ⁻¹
78	Platinum (Pt)	1.34	63.1	973 ng g ⁻¹
79	Gold (Au)	0.187	10.2	145 ng g ⁻¹
80	Mercury (Hg)	0.34	—	258 ng g ⁻¹
81	Thallium (Tl)	0.184	7.9	143 ng g ⁻¹
82	Lead (Pb) ^a	3.15	89.1	2430 ng g ⁻¹
83	Bismuth (Bi)	0.144	—	111 ng g ⁻¹
90	Thorium (Th) ^a	0.0335	1.9	28.6 ng g ⁻¹
92	Uranium (U)	0.009	< 0.34	8.1 ng g ⁻¹

Elemental abundance compilations do not list the following radioactive elements which have no stable isotopes and are not found in meteorites: Technetium (43), Promethium (61), Polonium (84), Astatine (85), Radon (86), Francium (87), Radium (88), Actinium (89).

The abbreviations used for abundances in the Orgueil CI chondrite have the following meanings: % = mass %, nL g⁻¹ = 10⁻⁹ liters per gram, $\mu\text{g g}^{-1}$ = 10⁻⁶ grams per gram, pL g⁻¹ = 10⁻¹² liters per gram, ng g = 10⁻⁹ grams per gram.

The abundances in Table C13 are generally from Anders and Grevesse (1989) with the following values also being included:

^a The photospheric abundance is from Grevesse and Noels (1993).

in the solar nebula and little altered since that time by planetary processes. In particular, the chondrites have not been subjected to igneous differentiation on a planetary body. They are subdivided into several classes such as the carbonaceous, ordinary and enstatite chondrites on the basis of their major element compositions and mineralogy. In turn, these classes are further subdivided into different petrographic types. The most primitive chondrites, i.e. those which best reproduce the elemental abundances in the Sun, are the C1 (or CI) chondrites. This classification scheme and the properties of meteorites are described in more detail in the articles on meteorites.

Solar system abundances of the elements

One of the major triumphs of cosmochemistry is the determination of the abundances of the elements and of the shape of the elemental abundance curve as a function of mass number (Table C13; Figure C69). These first-order results are important for at least four reasons. First, they show that to a very good first approximation the abundances of the elements in the Sun, which constitutes over 99% of the mass of the solar system, are the same as those in the primitive meteorites known as the C1 (or CI) chondrites. The few exceptions to this generalization are (1) light elements and isotopes, such as Li and D, which are destroyed by thermonuclear reactions in the Sun; (2) the highly volatile elements such as H, O, C, N and the noble gases, which are incompletely condensed in meteorites; and (3) some rare elements such as Hg, Ge, Pb and W which are either difficult to analyze in the Sun, or in meteorites, or in both. To a somewhat lesser degree there is also a correspondence between the elemental abundances in the Sun and the elemental abundances in all chondrites. This similarity is an important factor which has led cosmochemists to believe that the chondrites are relatively unaltered samples of material formed in the solar nebula. As such, the chondrites contain a record which, if properly interpreted, will provide information about the chemical and physical conditions existing in the solar nebula.

Second, a good knowledge of the abundances of the elements is necessary for modeling the chemical fractionations which occurred in the solar nebula and which determined to a large extent the compositions of the planets, their satellites and the minor bodies (asteroids, comets and meteorites) in the solar system. Third, determination of the solar system abundances of the elements is important for comparisons to elemental abundances in other stars and the interstellar medium in our galaxy. This is useful for modeling galactic chemical evolution over time. Fourth, a firm knowledge of the solar system elemental abundances and of the shape of the

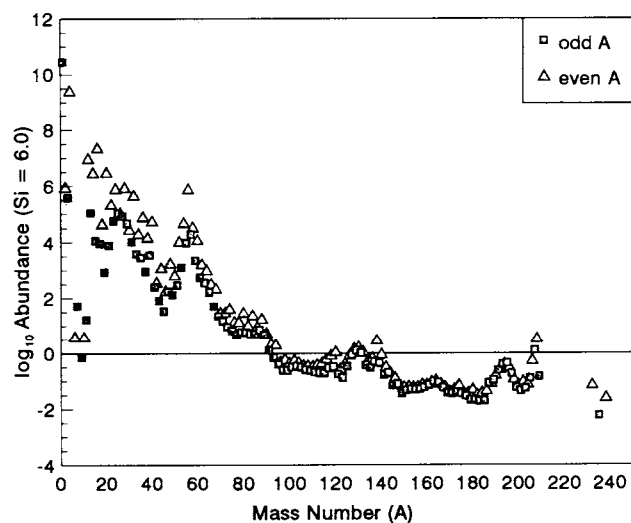


Figure C69 Abundances of the nuclides as a function of mass number (A). The even and odd mass number nuclides are indicated by separate symbols. The abundances, which are from Anders and Grevesse (1989), are plotted on a logarithmic scale normalized to Si = 6.00.

abundance curve as a function of mass number has been and continues to be an important constraint for models of nucleosynthesis in stars.

Attempts to determine the abundances of the elements date back at least to Clarke (1889), who attempted to find periodicities in the relative abundances of the elements in the Earth's crust. However, as we now know, the relative elemental abundances in the terrestrial crust have been modified by planetary differentiation and weathering processes and generally are not representative of the solar system abundances of the elements. Instead, it is necessary to analyze samples of primitive meteorites, such as the chondrites, which have been relatively unaltered by planetary processes, to obtain elemental abundances representative of the average composition of the solar system.

Chemical analyses of chondritic meteorites in the modern era date back to the work by Goldschmidt, the Noddacks and their colleagues in the 1920s and 1930s. This work was critically assessed by Goldschmidt (1937, 1954) who compiled the first table of elemental abundances in meteorites. This tabulation showed that to first approximation, the abundances of the non-volatile elements in meteorites and in the Sun were similar. It also served as a stimulus for the seminal work of Suess (1947a,b) who postulated that the abundances of the nuclides, and especially the odd mass number nuclides, are a smooth function of mass number.

Suess (1947a,b) used this postulate to adjust the elemental abundances to produce a smooth variation of abundance with mass number. In some cases, such as Re, adjustments of up to a factor of 100 were made and shown to be correct by subsequent chemical analyses of meteorites. A modern version of the elemental abundance curve as a function of mass number is shown in Figure C69. Many of the details of this curve are reviewed by Woolun (1988).

A later paper by Suess and Urey (1956) carried this approach even further and produced an influential table of solar system elemental abundances. One outcome of their table was the pioneering studies of stellar nucleosynthesis mechanisms by Burbidge *et al.* (1957). Another outcome was an increasing number of high-quality analytical studies of elemental abundances in chondritic meteorites. In the intervening 40 years the improvements in chemical analyses of meteorites, in the understanding of stellar nucleosynthesis mechanisms and in astronomical observations of elemental abundances in the Sun and other stars have led to vast improvements in our knowledge of the solar system abundances of the elements.

The result of all these efforts is displayed in Table C13, based on Anders and Grevesse (1989), which summarizes present knowledge of the solar system abundances of the elements. It shows the atomic abundances of the elements in CI chondrites (normalized to 10^{12} atoms of Si) in the solar photosphere (normalized to 10^{12} atoms of H), and elemental abundances by mass in the Orgueil CI chondrite. The abundance compilations by Cameron (1982), Anders and Ebihara (1982) and Anders and Grevesse (1989) describe the details involved in assessing the solar system abundance table. In addition, two compilations by Mason (1971, 1979) provide comprehensive references to the elemental analyses of the different types of meteorites. More recent papers on elemental abundances in meteorites can be found in the journals *Earth and Planetary Science Letters*, *Geochimica et Cosmochimica Acta*, and *Meteoritics*, while more recent papers on astronomical observations of elemental abundances in the Sun and other stars can be found in *Astronomy and Astrophysics* and the *Astrophysical Journal*.

Cosmochemical behavior of the elements

Our knowledge of the cosmochemical behavior of the elements is based upon analytical studies of meteorites, IDPs and lunar samples; remote sensing and spacecraft observations of the composition of evolved planetary bodies (e.g. Mercury, Venus and Mars) and primitive bodies such as comets, asteroids and icy satellites; *in situ* spacecraft analyses of volatiles emitted from comet P/Halley; and theoretical calculations of the equilibrium chemistry of solar composition material as a function of pressure and temperature.

The latter calculations are reviewed in detail elsewhere (Grossman and Larimer 1974; Larimer, 1988) and will not be described here except for the following. Most condensation calculations have been done at pressures of either 10^{-3} or 10^{-4} bars, and thus the results in Table C14 are given at 10^{-4} bars pressure. The early physical models of the solar nebula by Cameron gave pressures of this magnitude for the formation region of the terrestrial planets and asteroids. Current models of the P,T structure of the solar nebula also give similar pressures at high temperatures (Wood and Morfill, 1988). An exemplary P,T model of the solar nebula, based on the work by Lewis and colleagues, is given in Figures C70 and C71.

This large body of information provides us with a fairly detailed understanding of the chemical behavior of the elements (and/or their compounds) in a solar composition (i.e. H_2 -rich) system. In particular, it is now well established that volatility-controlled fractionations of the elements, or their stable compounds, in a H_2 -rich system was an important process which to a large extent determined the distribution of the elements on the different bodies (i.e. the planets, their satellites, the asteroids, comets, etc.) in the solar system (e.g. Larimer, 1988). Thus we will now review the cosmochemical classification of the elements, which is based upon their volatility in a H_2 -

rich system. The important points of this classification are summarized in Table C14 and in Figure C70, which form the basis for much of the subsequent discussion.

Overview

Elements which are either the first to condense from a hot gas with solar composition or are the last to vaporize from a solid with CI chondritic abundances are classified as refractory elements. Both siderophile elements (which geochemically prefer to be in a metallic phase) and lithophile elements (which geochemically prefer to be in an oxide or silicate phase) fall into this category. The condensation of iron metal and the magnesian silicates, which together constitute most of the rocky material in the solar system, is a dividing line which separates the refractory elements from the moderately volatile elements. In turn, the moderately volatile elements are separated from the highly volatile elements by the condensation of troilite, FeS, which occurs at the pressure-independent temperature of ~ 690 K (Figure C69). Finally, the highly volatile elements are separated from the atmophile elements (H, C, N and the noble gases) by water ice condensation. Each of these categories will now be discussed in more detail.

Refractory elements

Refractory lithophiles

The lanthanides (rare earth elements), the actinides, the alkaline earths, Al and elements in groups 3b (Sc, Y), 4b (Ti, Zr, Hf), and 5b (V, Nb, Ta) of the periodic table are included in this category. The refractory lithophiles are indicated by RL in Table C14. These elements constitute about 5% by mass of the total rocky material in a solar composition system. Extensive studies of the chemical composition of stony meteorites show that these elements behave as a group in most meteorites, that is, their abundances in different types of meteorites are either enriched or depleted by about the same factor.

The condensation chemistry of these elements is generally well known, with a few exceptions such as Be, Sr, Ba and Eu. The data in Table C14 for Be are based on the calculations by Lauretta and Lodders (1996), which are the latest ones available for this element. These calculations predict $Ca_2BeSi_2O_7$ condensation in melilite and $BeAl_2O_4$ condensation in spinel. However, the principal Be host phases (if any) in chondrites are unknown. Condensation temperatures in Table C14 for Sr, Ba and Eu assume ideal solid solution in perovskite $CaTiO_3$, but condensation calculations indicate that perovskite has already reacted away when condensation of these trace elements is calculated to occur. However, perovskite is observed to be a major host phase for these elements.

Large enrichments (on average 20 times solar elemental abundances) of the refractory lithophile elements are found in certain inclusions in the Allende meteorite and other carbonaceous chondrites. These inclusions are known as Ca, Al-rich inclusions or CAIs because they have a mineralogy dominated by Ca-, Al- and Ti-rich minerals such as hibonite $CaAl_{12}O_{19}$, melilite, a solid solution of gehlenite $Ca_2Al_2SiO_7$ and åkermanite $Ca_2MgSi_2O_7$, spinel, $MgAl_2O_4$ and perovskite $CaTiO_3$ (MacPherson, Wark and Armstrong, 1988). Condensation curves for two of these minerals (corundum Al_2O_3 and hibonite) are illustrated in Figure C70. The condensation curves for the other refractory phases fall in the same region at slightly lower temperatures. Details of their condensation chemistry are given by Kornacki and Fegley (1984).

In contrast to bulk meteorites, where they behave as a coherent group, the refractory lithophiles in CAIs sometimes display large chemical fractionations from one another. These fractionations are consistently explained by the relative volatilities of the different refractory lithophiles (Kornacki and Fegley 1986); fractionations among the lanthanides form a classification scheme for the CAIs (Martin and Mason, 1974; Fegley and Ireland, 1991).

Refractory siderophiles

The refractory siderophiles are the Pt-group metals (except Pd), Mo, W and Re. They are indicated by RS in Table C14. Like the refractory lithophiles, they are enriched to about 20 times solar elemental abundances (on average) in CAIs. Refractory metal nuggets, which are rich in Pt-group metals, and complex multiphase assemblages of metal, oxide and sulfide, known either as Fremdlinge or as opaque assemblages, are the two principal host phases for the refractory siderophiles in Ca, Al-rich inclusions in Allende and other

Table C14 Cosmochemistry of the elements in the solar nebula

Atomic number	Element name and chemical symbol	Condensation temperature (K) ($P = 10^{-4}$ bar)	Initial condensate in the solar nebula	Major gases in the solar nebula	Notes and sources
1	Hydrogen (H)	180	H ₂ O(s)	H ₂	A, 1
2	Helium (He) ^a	< 5	He(s)	He	A, 1
3	Lithium (Li)	1225	Li ₂ SiO ₃ in MgSiO ₃	LiCl, LiF	MV, 2
4	Beryllium (Be)	1490 (50%)	Ca ₂ BeSi ₂ O ₇	Be, Be(OH) ₂ , BeOH	MV, 3
5	Boron (B)	964 (50%)	CaB ₂ SiO ₂ O ₈	NaBO ₂ , KBO ₂ , HBO ₂ , HBO	MV, 3
6	Carbon (C) ^c	78	CH ₄ ·6H ₂ O(s)	CO, CH ₄	A, 1
7	Nitrogen (N) ^d	120	NH ₃ ·H ₂ O(s)	N ₂ , NH ₃	A, 1
8	Oxygen (O) ^e	–	–	CO, H ₂ O	A
9	Fluorine (F)	736	Ca ₅ (PO ₄) ₃ F	HF	MV, 4
10	Neon (Ne) ^a	~ 5	Ne(s)	Ne	A, 1
11	Sodium (Na)	970 (50%)	NaAlSi ₃ O ₈ in feldspar	Na, NaCl	MV, 4
12	Magnesium (Mg)	1340 (50%)	Mg ₂ SiO ₄ (s)	Mg	ME, 5, 13
13	Aluminium (Al)	1670	Al ₂ O ₃ (s)	Al, AlOH, Al ₂ O, AlS, AlH, AlO, AlF	RL, 6
14	Silicon (Si) ^f	1529	Ca ₂ Al ₂ SiO ₇ (s)	SiO, SiS	ME, 6
15	Phosphorus (P)	1151 (50%)	Fe ₃ P(s)	PO, P, PN, PS	MV, 4, 7
16	Sulfur (S)	713	FeS(s)	H ₂ S, HS	MV, 4, 12
17	Chlorine (Cl)	863 (50%)	Na ₄ [AlSiO ₄] ₃ Cl(s)	HCl, NaCl, KCl	MV, 4
18	Argon (Ar)	50	Ar·6H ₂ O(s)	Ar	A, 14
19	Potassium (K)	1000 (50%)	KAlSi ₃ O ₈ (s) in feldspar	K, KCl, KOH	MV, 4
20	Calcium (Ca)	1634	CaAl ₁₂ O ₁₉ (s)	Ca	RL, 6
21	Scandium (Sc)	1652 (50%)	Sc ₂ O ₃ (s)	ScO	RL, 8
22	Titanium (Ti)	1600	CaTiO ₃ (s)	TiO, TiO ₂	RL, 6
23	Vanadium (V)	1455 (50%)	Diss. in CaTiO ₃ (s)	VO ₂ , VO	RL, 8
24	Chromium (Cr)	1301 (50%)	Diss. in Fe alloy	Cr	MV, 9
25	Manganese (Mn)	1190 (50%)	Mn ₂ SiO ₄ in olivine	Mn	MV, 2
26	Iron (Fe)	1337 (50%)	Fe alloy	Fe	ME, 7, 9
27	Cobalt (Co)	1356 (50%)	Diss. in Fe alloy	Co	RS, 9
28	Nickel (Ni)	1354 (50%)	Diss. in Fe alloy	Ni	RS, 9
29	Copper (Cu)	1170 (50%)	Diss. in Fe alloy	Cu	MV, 2
30	Zinc (Zn)	684 (50%)	ZnS diss. in Fe	Zn	MV, 2
31	Gallium (Ga)	918 (50%)	Diss. in Fe alloy	GaOH, GaCl, GaBr	MV, 10
32	Germanium (Ge)	825 (50%)	Diss. in Fe alloy	GeS, GeSe	MV, 10
33	Arsenic (As)	1012 (50%)	Diss. in Fe alloy	As	MV, 10
34	Selenium (Se)	684 (50%)	FeSe diss. in FeS	H ₂ Se, GeSe	MV, 2
35	Bromine (Br) ^b	~ 350	Ca ₅ (PO ₄) ₃ Br(s)	HBr, NaBr	HV, 4
36	Krypton (Kr)	54	Kr·6H ₂ O(s)	Kr	A, 14
37	Rubidium (Rb) ^b	~ 1080	Diss. in feldspar	Rb, RbCl	MV, 5, 13
38	Strontium (Sr)	1217 (50%)	Diss. in CaTiO ₃ (s)	Sr, SrCl ₂ , Sr(OH) ₂ , SrOH	RL, 8
39	Yttrium (Y)	1622 (50%)	Y ₂ O ₃ (s)	YO	RL, 8
40	Zirconium (Zr)	1717 (50%)	ZrO ₂ (s)	ZrO ₂ , ZrO	RL, 8
41	Niobium (Nb)	1517 (50%)	Diss. in CaTiO ₃ (s)	NbO ₂ , NbO	RL, 8
42	Molybdenum (Mo)	1595 (50%)	Refractory metal alloy	MoO, Mo, MoO ₂	RS, 9
44	Ruthenium (Ru)	1565 (50%)	Refractory metal alloy	Ru	RS, 9
45	Rhodium (Rh)	1392 (50%)	Refractory metal alloy	Rh	RS, 9
46	Palladium (Pd)	1320 (50%)	Diss. in Fe alloy	Pd	MV, 9
47	Silver (Ag)	993 (50%)	Diss. in Fe alloy	Ag	MV, 2
48	Cadmium (Cd) ^b	430 (10 ⁻⁵ bars)	CdS in FeS	Cd	HV, 11
49	Indium (In) ^b	470 (50%)	InS in FeS	In, InCl, InOH	HV, 11
50	Tin (Sn)	720 (50%)	Diss. in Fe alloy	SnS, SnSe	MV, 2
51	Antimony (Sb)	912 (50%)	Diss. in Fe alloy	SbS, Sb	MV, 10
52	Tellurium (Te)	680 (50%)	FeTe diss. in FeS	Te, H ₂ Te	MV, 2
53	Iodine (I)	?	?	I, HI	MV/HV?
54	Xenon (Xe)	74	Xe·6H ₂ O(s)	Xe	A, 14
55	Cesium (Cs)	?	?	CsCl, Cs, CsOH	MV/HV?
56	Barium (Ba)	1162 (50%)	Diss. in CaTiO ₃ (s)	Ba(OH) ₂ , BaOH, BaS, BaO	RL, 8
57	Lanthanum (La)	1544 (50%)	Diss. in CaTiO ₃ (s)	LaO	RL, 8
58	Cerium (Ce)	1440 (50%)	Diss. in CaTiO ₃ (s)	CeO ₂ , CeO	RL, 8
59	Praseodymium (Pr)	1557 (50%)	Diss. in CaTiO ₃ (s)	PrO	RL, 8
60	Neodymium (Nd)	1563 (50%)	Diss. in CaTiO ₃ (s)	NdO	RL, 8
62	Samarium (Sm)	1560 (50%)	Diss. in CaTiO ₃ (s)	SmO, Sm	RL, 8
63	Europium (Eu)	1338 (50%)	Diss. in CaTiO ₃ (s)	Eu	RL, 8
64	Gadolinium (Gd)	1597 (50%)	Diss. in CaTiO ₃ (s)	GdO	RL, 8
65	Terbium (Tb)	1598 (50%)	Diss. in CaTiO ₃ (s)	TbO	RL, 8
66	Dyprosium (Dy)	1598 (50%)	Diss. in CaTiO ₃	DyO, Dy	RL, 8
67	Holmium (Ho)	1598 (50%)	Diss. in CaTiO ₃ (s)	HoO, Ho	RL, 8

Table C14 Continued

Atomic number	Element name and chemical symbol	Condensation temperature (K) ($P = 10^{-4}$ bar)	Initial condensate in the solar nebula	Major gases in the solar nebula	Notes and sources
68	Erbium (Er)	1598 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	ErO , Er	RL, 8
69	Thulium (Tm)	1598 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	Tm, TmO	RL, 8
70	Ytterbium (Yb)	1493 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	Yb	RL, 8
71	Lutetium (Lu)	1598 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	LuO	RL, 8
72	Hafnium (Hf)	1690 (50%)	$\text{HfO}_2(\text{s})$	HfO_2	RL, 8
73	Tantalum (Ta)	1543 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	TaO_2 , TaO	RL, 8
74	Tungsten (W)	1794 (50%)	Refractory metal alloy	WO, WO_2 , WO_3	RS, 9
75	Rhenium (Re)	1818 (50%)	Refractory metal alloy	Re	RS, 9
76	Osmium (Os)	1812 (50%)	Refractory metal alloy	Os	RS, 9
77	Iridium (Ir)	1603 (50%)	Refractory metal alloy	Ir	RS, 9
78	Platinum (Pt)	1411 (50%)	Refractory metal alloy	Pt	RS, 9
79	Gold (Au)	1284 (50%)	Fe alloy	Au	MV, 2
80	Mercury (Hg)	?	?	Hg	MV/HV?
81	Thallium (Tl) ^b	448 (50%)	Diss. in Fe alloy	Tl	
82	Lead (Pb) ^b	520 (50%)	Diss. in Fe alloy	Pb, PbS	HV, 11
83	Bismuth (Bi)	472 (50%)	Diss. in Fe alloy	Bi	HV, 11
90	Thorium (Th)	1598 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	ThO_2	RL, 8
92	Uranium (U)	1580 (50%)	Diss. in $\text{CaTiO}_3(\text{s})$	UO_2	RL, 8

The condensation temperatures either indicate where the condensate first becomes stable or where 50% of the element is condensed and 50% is in the gas. The 50% condensation temperature is generally used when solid solutions are formed.

The major gases vary as a function of temperature and total pressure. The gas chemistry in Table C14 is generally valid at the condensation temperature of each element, and was either taken from the original references below or calculated as part of this work.

Sources cited in Table C14: (1) Lewis 1972; (2) Wai and Wasson, 1977; (3) Lauretta and Lodders, 1996; (4) Fegley and Lewis, 1980; (5) Grossman and Larimer, 1974; (6) Kornacki and Fegley, 1984; (7) Sears, 1978; (8) Kornacki and Fegley, 1986; (9) Fegley and Palme, 1985; (10) Wai and Wasson, 1979; (11) Larimer, 1973; (12) Lauretta *et al.*, 1996; (13) Wasson, 1985; (14) Sill and Wilkening, 1978.

^a This temperature is below cosmic background and condensation will not occur.

^b The condensation temperature and initial condensate is uncertain and needs to be re-evaluated.

^c Kinetic inhibition of the CO to CH_4 conversion yields either $\text{CO}\cdot 6\text{H}_2\text{O}(\text{s})$ or $\text{CO}(\text{s})$ as the initial condensate.

^d Kinetic inhibition of the N_2 to NH_3 conversion yields either $\text{N}_2\cdot 6\text{H}_2\text{O}(\text{s})$ or $\text{N}_2(\text{s})$ as the initial condensate.

^e Oxygen is the most abundant element in rocky material and a separate condensation temperature is meaningless. The bulk of oxygen condenses as water ice; the remainder is present as CO or in rocky material.

^f Most Si condenses when the silicates MgSiO_3 and Mg_2SiO_4 form (e.g. 1340 K at 10^{-4} bar). See the MgSiO_3 condensation curve in Figure C70.

Key to abbreviations used for cosmochemical classification of the elements: A = atmophile, HV = highly volatile, ME = major element, MV = moderately volatile, RL = refractory lithophile, RS = refractory siderophile.

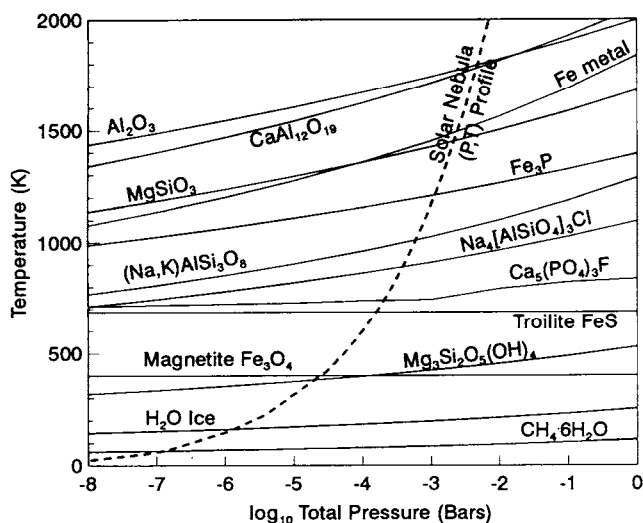


Figure C70 Condensation curves of some important minerals which are stable at chemical equilibrium in a gas of solar composition. The minerals are vaporized above the curves and are stable below the curves until they react away to form other species. The position of an exemplary P, T profile for the solar nebula is also illustrated. The condensation curves are taken from several papers (Fegley, 1988; Fegley and Lewis, 1980; Grossman and Larimer, 1974; Kornacki and Fegley, 1984; Lewis, 1972, 1974) which describe the computational details. The nebular P, T profile is taken from Lewis (1974) and Prinn and Fegley (1989).

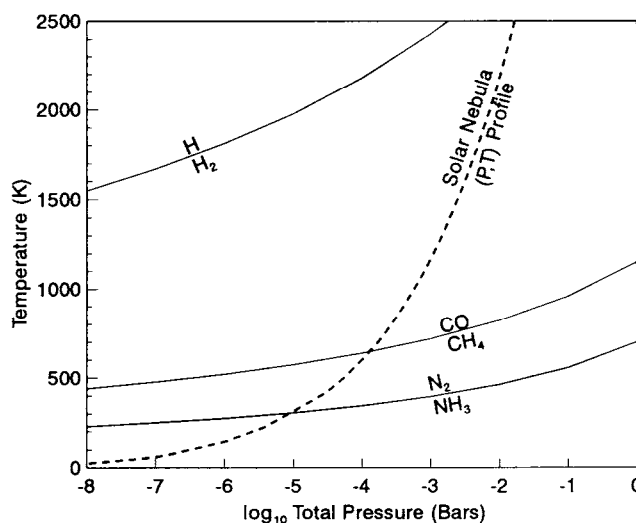


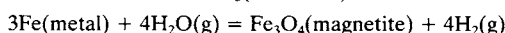
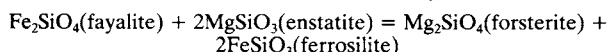
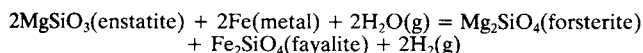
Figure C71 Important phase boundaries for H, C and N chemistry in a solar gas are compared with an exemplary P, T profile in the solar nebula. The different gases have equal abundances along the phase boundaries and are more abundant on their side of the boundary. Thus CO is the major carbon gas at high temperatures and low pressures, while CH_4 is the major carbon gas at low temperatures and high pressures. The nebular P, T profile is the same one shown in Figure C70.

carbonaceous chondrites (Palme and Wlotzka, 1976; Fuchs and Blander, 1980; El Goresy, Nagel and Ramdohr, 1978). The refractory metal nuggets are generally believed to be condensates from the solar nebula; their compositions are reproduced by equilibrium condensation calculations (e.g. Palme and Wlotzka, 1976; Fegley and Palme, 1985). The origin of the complex multiphase assemblages (Fremdlinge or opaque assemblages) is more controversial, and a variety of models ranging from formation in the meteorite parent bodies (e.g. Blum *et al.*, 1988), to condensation in the solar nebula (e.g. Bischoff and Palme, 1987), to formation by the partial evaporation and melting of interstellar dust aggregates (e.g. Fegley and Kornacki, 1984) have been proposed to explain their origin. While each of these models has some attractive features, none can easily explain all of the complexities observed in the Fremdlinge/opaque assemblages, and their origin is still somewhat enigmatic.

Iron alloy and magnesian silicates

The condensation of the major elements Fe, Mg and Si as metallic iron and the magnesian silicates is an important phase boundary because it is the point where most of the rocky materials in solar composition material condense. These elements are indicated by ME in Table C14. As illustrated in Figure C70, at pressures above about 10^{-5} bar iron metal condenses before magnesian silicates (represented by MgSiO_3 in Figure C70), while at lower pressures the magnesian silicates condense first. In both cases the separation between the metal and silicate condensation temperatures increases as the pressure is either increased or decreased from the crossover point.

The magnesian silicates which condense at high temperatures are essentially pure MgSiO_3 and Mg_2SiO_4 because the large excess of H_2 in solar gas leads to extremely low oxygen fugacities. The temperature dependent oxygen fugacity (f_{O_2}) of solar gas is given by the expression $\log_{10} f_{\text{O}_2} = 2 \log_{10} (\text{H}_2\text{O}/\text{H}_2) + 5.59 - 25\,598/T$ which is valid from 300 to 2500 K (Rubin, Fegley and Brett, 1988). As a result the FeO content of the magnesian silicates is predicted to be insignificant until low temperatures of about 400–600 K are attained where the reactions



become thermodynamically favorable (Larimer, 1967; Grossman and Larimer, 1974). At these temperatures olivine and pyroxene solid solutions containing several tens of mole percent of fayalite and ferrosilite are predicted to form, and any remaining Fe metal is predicted to form magnetite at a pressure independent temperature of about 400 K (see Figure C70).

However, recent work by Fegley (1988) and Palme and Fegley (1990) has questioned this picture because the slow solid-state diffusion at the required low temperatures will inhibit gas–solid and solid–solid reactions such as the formation of magnetite and FeO-rich silicates over the estimated 10^5 – 10^6 year lifetime of the solar nebula. Instead, they find that the observed textural features and chemistry of FeO-rich olivines are plausibly explained by high-temperature condensation under oxidizing conditions in the solar nebula. These conditions are proposed to result in dust-rich regions, such as the nebular midplane, where heating of the dust releases the oxygen in rock into the gas and increases the local O/H elemental ratio above the solar value. However, although many workers have now discarded the notion that FeO-rich silicates formed at low temperatures in the solar nebula, an origin by metamorphic reactions on the meteorite parent bodies is still being debated as an alternative to an origin under oxidizing conditions in the solar nebula.

Moderately volatile elements

By convention, the moderately volatile elements are defined as having condensation temperatures intermediate between those of the major elements Fe, Mg and Si and of troilite FeS. The elements in this group are geochemically diverse and include Na, K, Rb, Cr, Mn, Cu, Ag, Au, Zn, B, Ga, P, As, Sb, S, Se, Te, F and Cl. These elements are indicated by MV in Table C14. The condensation chemistry of many of these elements is not well known because of

uncertainties about the thermodynamic properties of the condensate minerals and their solid solutions in major host phases such as Fe metal, FeS and apatite minerals. For example, Ga is predicted to condense in solid solution in Fe metal, but Ga condensation in silicates such as feldspar cannot be modeled because the thermodynamic properties of the relevant minerals are unknown. Likewise, the thermodynamic properties of Rb aluminosilicates and their solid solutions with anorthite are also unknown. In some cases such as Cs, Br and I, periodic behavior suggests that an element should be classified as moderately volatile, but either no data are available on any plausible condensates (as is the case for Cs and I), or the available data suggest that the element is highly volatile (Br). However, despite these uncertainties, the calculated condensation temperatures are generally in accord with expectations based on observed elemental abundance trends in chondritic meteorites (e.g. Wai and Wasson, 1977).

Highly volatile elements

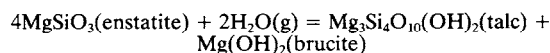
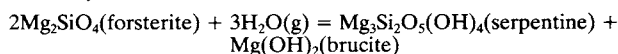
Only a few elements fall into this category. Mercury is probably a highly volatile element but it is calculated to condense as Hg(s) at temperatures below 200 K (Larimer, 1967). It is unlikely that Hg is as volatile as water ice, and the low condensation temperature is an artifact due to incomplete thermodynamic data on plausible condensates. However, apparently all of the analytical data for Hg in chondrites are subject to contamination problems, so neither its abundance or host phases (if any) are known. The other highly volatile elements are Br, Cd, In, Tl, Pb and Bi. All the highly volatile elements are indicated by HV in Table C14. The condensation chemistry of these elements is not well known. Br is calculated to condense as bromapatite $\text{Ca}_5(\text{PO}_4)_3\text{Br}$ at about 350 K, but its abundance in chondrites suggests a higher condensation temperature. The elements Tl, Pb and Bi are calculated to condense in solid solution in Fe metal while Cd and In are calculated to condense in solid solution in FeS. However, it is difficult to model the chemistry of these elements because of incomplete and uncertain thermodynamic data, and the poor knowledge of their host phases in meteorites.

Chemically reactive atmophile elements

Hydrogen

As Table C13 shows, hydrogen is the most abundant element and therefore H_2 is the most abundant gas in solar composition material. At sufficiently high temperatures, dissociation to atomic H occurs. However, as illustrated in Figure C71, the phase boundary where equal abundances of H_2 and H occurs is at lower pressures and higher temperatures than those expected in the solar nebula. Conversely, H_2 remains in the gas until temperatures of about 5 K, where it will condense out as solid hydrogen (Lewis, 1972). It is unlikely that temperatures this low were ever reached in the solar nebula.

About 0.1% of all hydrogen condenses out as water ice at temperatures of 150–250 K, depending on the total pressure (Figure C70). Hydrated silicates such as serpentine and talc are also predicted to form by reactions such as



at temperatures below 300 K at 10^{-4} bar (Figure C70). However, although they are thermodynamically favorable, these reactions probably did not occur in the solar nebula because the vapor phase hydration of rock in a near-vacuum is a very slow process (e.g. Fegley, 1988; Fegley and Prinn, 1989; Prinn and Fegley, 1989). Instead, the theoretical studies of hydration kinetics in the solar nebula and petrographic studies of water-bearing chondrites both suggest that the production of hydrated minerals occurred on the meteorite parent bodies. Thus it is very likely that water ice is the first H-bearing condensate to form.

Carbon

Carbon chemistry is significantly more complex. To a good first approximation, CO is the dominant carbon gas at high temperatures and low pressures and CH_4 is the dominant carbon gas at low temperatures and high pressures in solar composition material (Urey, 1953; Lewis, Barshay and Noyes 1979). The phase boundary where the abundances of CO and CH_4 are equal is shown in Figure C71. The

two gases are converted by the net thermochemical reaction $\text{CO}(\text{g}) + 3\text{H}_2(\text{g}) = \text{CH}_4(\text{g}) + \text{H}_2\text{O}(\text{g})$. Increasing the H_2 pressure (essentially the total pressure in solar material) and/or decreasing the temperature drives this reaction to the right and yields more CH_4 . As shown in Figure C71, the nebular P,T profile crosses the CO/CH_4 boundary at about 600 K. CO is more abundant at higher temperatures, and CH_4 is more abundant at lower temperatures.

Detailed modeling by Lewis, Barshay and Noyes (1979) also shows that at high temperatures, similar to those for the H/H_2 phase boundary, CO dissociates to the elements and C(g) becomes the dominant C-bearing gas. Conversely, at sufficiently low pressures, both CO and CH_4 decompose to form graphite (gr) via the reaction $\text{CO}(\text{g}) + \text{CH}_4(\text{g}) = \text{H}_2\text{O}(\text{g}) + \text{H}_2(\text{g}) + 2\text{C}(\text{gr})$. CO also disproportionates via the reaction $2\text{CO}(\text{g}) = \text{CO}_2(\text{g}) + \text{C}(\text{gr})$ to form CO_2 plus graphite at low temperatures and pressures. However, the graphite and CO_2 stability fields are at much lower pressures than those along the nebular P,T profile in Figure C71.

As first noted by Urey (1953), and later quantified by Lewis and Prinn (1980), the kinetics of the $\text{CO} \rightarrow \text{CH}_4$ conversion may be so slow under the (P,T) conditions expected in the solar nebula that CO cannot be converted to CH_4 within the lifetime of the solar nebula. An exception to this occurs in the giant protoplanetary subnebulae, which are higher density environments predicted around Jupiter and the other gas giant planets during their formation. The $\text{CO} \rightarrow \text{CH}_4$ conversion is predicted to take place in these environments (Prinn and Fegley, 1981, 1989; Fegley and Prinn, 1989).

At low temperatures in the outer solar nebula and the giant protoplanetary subnebulae, CO and CH_4 may react with water ice to form the clathrate hydrates $\text{CO}\cdot 6\text{H}_2\text{O}(\text{s})$ and $\text{CH}_4\cdot 6\text{H}_2\text{O}(\text{s})$. The condensation curve for $\text{CH}_4\cdot 6\text{H}_2\text{O}$ is illustrated in Figure C70, and the curve for $\text{CO}\cdot 6\text{H}_2\text{O}(\text{s})$ is only slightly lower. The formation of these clathrate hydrates requires sufficiently rapid diffusion of CO or CH_4 through the water ice crystal lattice. Theoretical models, which use experimentally determined activation energies for clathrate formation, predict that CH_4 clathrate hydrate can form in the giant protoplanetary subnebulae but that CO clathrate hydrate cannot form in the much lower density environment of the outer solar nebula (Fegley, 1988; Fegley and Prinn, 1989). However, other workers have argued that clathrate hydrate formation can still occur under special circumstances (Lunine, 1989).

Nitrogen

The most important features of nitrogen chemistry are shown in Figure C71, which displays the phase boundary where N_2 and NH_3 have equal abundances. At any pressure this boundary is at a lower temperature than the analogous phase boundary for CO and CH_4 . N_2 is the major nitrogen gas at high temperatures and low pressures while NH_3 is the major nitrogen gas at low temperatures and high pressures.

The two species are converted via the reaction $\text{N}_2 + 3\text{H}_2 = 2\text{NH}_3$, which is analogous to the reaction which converts CO and CH_4 . Reduction of N_2 to NH_3 is also predicted to be kinetically inhibited in the solar nebula and to be both thermodynamically favored and kinetically facile in the giant protoplanetary subnebulae (Lewis and Prinn, 1980; Prinn and Fegley, 1981, 1989; Fegley and Prinn, 1989). This is true even when the possible catalytic effects of Fe metal grains are taken into account. Thus N_2 is predicted to be the dominant nitrogen gas throughout the solar nebula and NH_3 is predicted to be the dominant nitrogen gas throughout the giant protoplanetary subnebulae.

At low temperatures in the outer solar nebula, $\text{N}_2\cdot 6\text{H}_2\text{O}(\text{s})$ becomes thermodynamically stable, but its formation is probably inhibited by two factors. One is the limited availability of water ice, which may already be totally consumed by reactions to form other hydrates and clathrates. The other is the expected kinetic inhibition of clathrate hydrate formation in the outer solar nebula (Fegley and Prinn, 1989). In this case N_2 , like CO, will not condense until temperatures of about 20 K (at 10^{-4} bar pressure), where the solid ices form. On the other hand, $\text{NH}_3\cdot \text{H}_2\text{O}$ formation is predicted in the giant protoplanetary subnebulae, because it is both thermodynamically favorable and kinetically facile.

Noble gases

The noble gases He, Ne, Ar, Kr and Xe display fairly simple chemistry in solar composition material. All are present in the gas as the monatomic elements and Ar, Kr and Xe undergo condensation to

either ices or clathrate hydrates at sufficiently low temperatures. Condensation of the pure ices will occur at slightly lower temperatures than condensation of the clathrate hydrates. The condensation temperatures for the noble gas clathrate hydrates in Table C14 are from Sill and Wilkening (1978). However, the formation of these species, like the clathrates of CO and N_2 , may be kinetically inhibited. Temperatures of about 20 K (at 10^{-4} bar pressure) are required for quantitative condensation of Ar, Kr and Xe as pure ices. Neither He nor Ne will condense out of the gas because temperatures of 5 K or below are required for this to happen (e.g. Lewis, 1972).

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Cross references

Carbon, carbon dioxide
 Chemical element
 Comet: structure and composition
 Interstellar grain
 Iron
 Silica, silicate
 Solar system: origin

CRATER

A circular to slightly polygonal depression formed on the surface of a solid body by the impact of an interplanetary body. Craters are ubiquitous throughout the solar system. They range in size from microns through kilometers to over 1000 km in diameter, with the corresponding impacting bodies ranging from interplanetary dust through meteorites, asteroids, comets to planetesimals. Craters result from the transfer of the kinetic energy contained in the impacting body to the target rocks. This energy can be considerable, as the impactor is generally travelling at velocities of kilometers to tens of kilometers per second. Energy transfer to the target is by means of a hemispherically propagating shock wave. This shock wave increases the internal energy of the target rocks (leading to so-called shock metamorphism) and also sets the target rocks in motion. This motion leads to the excavation and displacement of the target rocks, forming a cavity. Subsequent modification and collapse of this cavity results in the final observed crater.

Craters have two basic forms; so-called simple and complex craters. Simple craters consist of a bowl-shaped depression with an uplifted rim area. Larger, complex craters are a more modified and collapsed form with a flatter cross-sectional shape. They have uplifted central structures, in the form of a central peak(s) and/or rings and a structurally faulted rim area. The transition from simple to complex forms occurs at a specific diameter range, which varies with planetary