

CHEMICAL PROCESSES IN THE SOLAR NEBULA

by

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INTRODUCTION

Urey (1952) was probably the first person to emphasize that both the chemical and physical processes occurring in the solar nebula have to be understood in order to develop a holistic model of the origin of the solar system bodies such as the planets, satellites, asteroids, and meteorites. In the four decades since Urey's pioneering efforts, a large literature devoted to the physics and chemistry of solar nebula processes has developed [e.g., see reviews by Grossman and Larimer (1974) and Fegley and Prinn (1989)].

After some general remarks on meteorites and their significance as indicators of solar nebula processes, we will highlight several issues connected with chemical processes and physical conditions in the solar nebula. One is the clear indication in meteorites for high temperatures and high oxygen fugacities in the inner solar nebula. This type of evidence is important because it can be used to constrain theoretical models for the formation and evolution of the primordial solar system. The second issue is the nature of the low temperature condensates in the outer solar nebula. This question is of importance because predicted condensates such as clathrates are believed to have been responsible for carbon and nitrogen retention in the solid grains that accreted to form comets and the icy satellites of the outer planets. The third issue is the chemical reprocessing of pure solar grains in the solar nebula. Recent meteorite studies show that chemically and isotopically anomalous grains are present at low levels in primitive meteorites and it is important to understand the processes which led to the survival of these grains in the solar nebula.

1 HIGH TEMPERATURES IN THE SOLAR NEBULA

1.1 Meteoritic Evidence for Solar Nebula Processes

The history of a meteorite may be characterized by three steps: a.) formation within the solar system (processing of interstellar material, evaporation, condensation, etc.) b.) evolution inside a parent body (thermal metamorphism, melting, chemical alteration etc.) and c.) history in space as a single object. To obtain information on conditions in the solar nebula during formation of meteoritic matter requires that a meteorite was, if at all, only slightly affected by processes inside a planetesimal. Such meteorites are called primitive or chondritic meteorites. Their composition and mineral assemblages provide clues to pressure, temperature and degree of oxidation of the solar nebula from which these materials must have formed. Although it is sometimes difficult to distinguish between the results of processes that occurred within the solar nebula and the effects of alteration in the interior of a parent body, evidence for nebular processes in meteorites or in components of meteorites has accumulated in recent years. It is now clear that chondritic meteorites and their components have formed under a variety of physico-chemical conditions that must have prevailed at some place or some time in the early solar nebula.

Inferences concerning the solar nebula may be directly made from the chemical and isotopic compositions and from mineral assemblages of meteoritic components. Conditions of the solar nebula derived from these data may, however, be relevant only for a small fraction of the solar nebula. It is, for example, conceivable that high temperature components such as Ca,Al-rich inclusions from carbonaceous chondrites formed near the Sun and they thus may only be indicative for conditions of formation for a comparatively small part of the solar nebula. In order to obtain a more representative picture of the early solar nebula it is necessary to consider not only the bulk composition of meteorites but take also into account the much more massive inner planets. Estimates for the bulk composition of the earth including trace elements have improved to a degree that justifies a detailed comparison with meteorite compositions.

1.2 Cosmochemical Classification of Elements.

Before going into more detail it is necessary to introduce a classification scheme of chemical elements that is appropriate for meteorites. In cosmochemistry elements are arranged according to condensation temperatures in a gas of solar composition at some pressure between 10^{-3} and 10^{-6} atm. These temperatures are a measure of volatility and they provide a convenient reference scheme. Application of condensation temperatures does not necessarily imply that meteorites did indeed solely form by condensation from a hot solar gas, it merely reflects the fact that the most important chemical differences among meteorites are related to the volatility of chemical elements or compounds. A useful compilation of condensation temperatures is found in Wasson (1985).

Based on their condensation temperatures chemical elements can be divided into four groups (see also Larimer, 1988):

- a.) Refractory elements, Ca, Al and Ti-oxides and silicates including trace elements such as REE (Rare Earth Elements), Be, V, Sc, Sr, Ba, Y, Zr, Hf, Nb, Ta, U, and Th and the refractory metals W, Re, Os, Ir, Mo, Ru, Pt and Rh. All these elements have condensation temperatures above those of the major components in meteorites: metallic FeNi and Mg-silicates. There is, nevertheless, a significant variation in condensation temperatures among refractory elements as shown in Fig. 1. The refractory component comprises about 5% of the total condensible matter.
- b.) Mg-silicates (forsterite Mg_2SiO_4 , enstatite $MgSiO_3$) and metal (FeNi) representing the major fraction of solid matter. Trace elements associated with these phases are Cr and Li as lithophiles and Co and Pd as siderophiles.
- c.) Moderately volatile elements with condensation temperatures below Mg-silicates and FeNi and above the condensation temperature of troilite: Au, Mn, As, P, Rb, Cu, K, Na, Ag, Ga, Sb, Ge, F, Sn, Se, Te, Zn, and S. Elements are listed in order of decreasing condensation temperatures and it is important to note that this sequence contains lithophile, siderophile and chalcophile elements and that the sequence of

depletion (ratios of elements relative to solar ratios, i.e. C1-chondrites) in most classes of chondritic meteorites broadly follows the same sequence. This indicates that abundances only depend on volatility and not on the geochemical properties (Palme et al., 1988).

d.) Highly volatile elements with condensation temperatures below FeS: Cl, Br, I, Cs, In, Tl, Pb, Cd and Hg. Several years ago there was a heated debate whether abundance variations of these elements reflect differences in condensation temperatures or increasing degrees of metamorphism leading to increasing losses of highly volatiles (see Wasson, 1974). The problem is still unresolved.

1.3 Significance of Bulk Composition of Meteorites as Indicators for Solar Nebula Processes

The chemical composition of chondritic meteorites is to a first approximation the same as that of the solar photosphere for elements heavier than oxygen and with the exception of noble gases. However, only the composition of type 1 carbonaceous chondrites (CI-meteorites, e.g., Orgueil) matches precisely (within 10%) the composition of the Sun (see Anders and Grevesse, 1989). All other groups of primitive meteorites show a more or less fractionated abundance pattern probably reflecting fractionation processes in the early solar nebula.

The main fractionation trends in chondritic meteorites are documented in Table 1. They are:

a.) Variations in abundances of refractory elements, when normalized to Si (almost a factor of three). Although ratios of Ca/Si vary by a factor of 2.6 between enstatite and type 3 carbonaceous chondrites, the relative abundances of refractory elements are the same, i.e., the ratios of Ca to Al, Ti, Sc, REE, etc. are the same in all types of chondritic meteorites. This is not so in some components of carbonaceous chondrites, such as, for example, Ca,Al-rich inclusions where occasionally large

fractionations among refractory elements are observed (see Fig. 3). These variations reflect variable volatilities of refractory elements as will be discussed later.

- b.) Variations in Mg/Si ratios by about 30% presumably indicating accumulation of variable amounts of forsteritic olivine (Mg_2SiO_4), the first major silicate phase that condenses from a gas of solar composition (Larimer, 1979).
- c.) Variable contents of Fe and some siderophile elements by about 40%. Loss or incomplete accretion of metallic iron accounts for these variations.
- d.) Variations in absolute (factor of 5) and relative abundances of moderately volatile elements as, for example, indicated by S, in Table 1.
- e.) Large variations (factor of 100) in the contents of highly volatile elements.

In addition to variable elemental abundances there are large differences in the degree of oxidation among chondritic meteorites, as reflected in the amount of metallic iron and water present in meteorites. The extremes are on one hand CI-chondrites (Orgueil) with several percent of water and on the other hand enstatite chondrites with no oxidized iron at all but instead more than one percent of metallic Si dissolved in iron metal. However, it is important to realize that even within a single meteorite there are components reflecting a wide range of oxygen fugacities, demonstrating that primitive meteorites are not equilibrium assemblages. This is also apparent from the oxygen isotopic composition which is variable, not only within different groups of chondrites, but even more so among components of individual meteorites. Variations in oxygen isotopic composition between calcite formed at low temperatures and high temperature components in Murchison, for example, are larger than between any two groups of bulk meteorites (Clayton and Mayeda, 1984). It is of some importance to point out that there is no simple relationship between any two of these fractionation trends. For example, the most reduced and the most oxidized meteorites i.e. enstatite and type 1 carbonaceous chondrites are both enriched in volatile elements compared to all other groups of chondritic meteorites. Any simple model producing reduced meteorites by heating from oxidized meteorites fails.

The most pronounced differences among chondritic meteorites are those of moderately volatile and highly volatile elements. This depletion in volatile elements is also a characteristic signature of the bulk composition of the inner planets (e.g., Earth and Moon) and of smaller differentiated planetesimals (e.g., eucrite parent body). It may therefore be concluded that the loss or incomplete sampling of volatiles must have been an important process in the early solar nebula when solid matter was formed. It is further remarkable that only depletions in volatile element abundances are observed but never enrichments. Volatile elements may have been lost by evaporation of condensed silicates or they are depleted because of incomplete condensation. Temperatures in the range of 1200 K are in both cases required to achieve these fractionations (Palme et al., 1988).

1.4 Evidence from Individual Components in Meteorites

Due to improved techniques for separating and analysing individual components of meteorites a large amount of compositional and isotopic data on single mineral grains and on, sometimes extremely small, inclusions have been obtained during the last years. As it is impossible to review all these data in the present contribution we will restrict ourselves describing the main trends and give a few examples.

A large body of literature exists on Ca,Al-rich inclusions from carbonaceous chondrites (see McPherson et al., 1988). These inclusions provide unequivocal evidence for having been processed at high temperatures of, in some cases, up to 2000 K, either by condensation or by evaporation of originally chondritic material. A tiny grain, one micrometer in diameter, was, for example, identified in the Ornam's carbonaceous chondrite that may represent such an early condensate from the solar nebula (Palme et al., 1982). This grain has high contents of the most refractory lithophile elements Hf, Sc, and Lu (Figs. 1 and 2) and at the same time it also contains only the most refractory metals, with the exception of W. The separation of Lu from Yb by gas-solid equilibrium requires quite high temperatures as can be seen from Fig. 1. While this type of inclusions could either represent an early condensate or a residue from evaporation, other inclusions provide unequivocal evidence

for condensation processes. These are inclusions much more common than the superrefractory grains. They lack this first condensate i.e. they are low in the most refractory elements Hf, Sc and Lu, but high in the more volatile refractories La, Sm, Ta, Nb. These, so called, group II patterns require separation of an earlier superrefractory component (Boynton, 1975). This type of trace element pattern cannot be produced by evaporation of chondritic material. It is the best chemical evidence for condensation processes in the solar nebula.

Tiny grains of alloys of low-vapor pressure metals (Ir, Re, Os, Mo etc.) are found in Ca,Al-rich inclusions (Palme and Wlotzka, 1976). There is again good evidence that these alloys formed by condensation. In order to allow formation and growth of these nuggets a time span in the order of several hundred years is required.

Individual forsterite crystals are commonly found in the Allende meteorite and other carbonaceous chondrites. These forsterites formed most likely by condensation from a gas. Their trace element composition as well as their ^{16}O content, which is higher than that of chondrules, exclude an origin by crystallization inside chondrules (Palme and Fegley, 1990; Weinbruch et al., 1990)). Time scales of days are required to form these crystals by condensation.

Although forsteritic olivines are low in FeO, their FeO-contents are still much higher than one would expect for condensates from a gas of solar composition (Wood 1985, Palme and Fegley, 1990). A gas enriched in oxygen (enhanced oxygen fugacity) is required to explain the forsterite crystals by condensation. Forsterites often have fayalite-rich rims that formed by condensation from a gas with still higher oxygen partial pressure (e.g., Weinbruch et al., 1990; Palme and Fegley 1990).

High temperature must have also prevailed during chondrule formation. Estimates by Hewins et al. (1988) indicate chondrule formation temperatures of up to 1600 K and chondrule cooling rates from 100° to 2000°C/hr , too slow for cooling by radiation into space but faster than the time scale for Ca,Al-rich inclusion or their components as indicated above. It is therefore likely that the chondrule forming process records a different

event than high temperature gas-solid equilibria. In addition, there is good evidence that the formation of chondrules affected preexisting compositionally heterogeneous matter (Grossman, 1988), suggesting that the formation of chondrules occurred later after solid solar-system material was formed by condensation processes.

There is, therefore, abundant additional evidence for high temperature processes inside the solar nebula occurring at oxygen fugacities considerably above those expected for a gas of solar composition (see Rubin et al., 1988). In addition fractionation of Si and Mg isotopes in inclusions from Allende reflect evaporation and condensation processes requiring rather high temperatures (Clayton et al., 1985). However, to reiterate a point made before, high temperature events must have affected most of the solid matter now in the inner solar system.

2 LOW TEMPERATURE CHEMISTRY

2.1 The Water Ice Evaporation Front

A major dividing line in the solar nebula is the water ice evaporation front. Inward of this front, at higher temperatures, gas-grain reactions in the solar nebula primarily involve carbonaceous, metal, oxide, and/or silicate particles reacting with the nebular gas. Outward of this front, at lower temperatures, gas grain reactions primarily involve "icy" particles reacting with the nebular gas.

The saturated water vapor pressure over crystalline ice is given by

$$\log_{10}P_{\text{H}_2\text{O}} = 7.62 - 2683/T \quad (1)$$

from 175 to 225 K. Assuming that all carbon is in the form of CO and that the oxygen bound up in rock can be represented as the sum of $\text{MgO} + 2\text{SiO}_2$, the equation for the water ice evaporation front is

$$T_{\text{ice}} = 2683/(11.17 - \log_{10}P_{\text{T}}) \quad (2)$$

where P_{T} is the total pressure in the solar nebula. For $P_{\text{T}} \sim 10^{-3} - 10^{-7}$ bars, the water ice evaporation front is at temperatures of 190 to 150 K. Because of the presence of water ice on the Galilean satellites Europa, Ganymede, and Callisto (Pilcher et al., 1972; Lebofsky, 1977), the water ice evaporation front is generally placed at 5 A.U. in nebular models; however, the position of this front obviously varies with distance during thermal evolution of the solar nebula (e.g., Cameron, 1978; Lin and Papaloizou, 1985; Ruden and Lin, 1986) and first moves outward as the nebula warms up and later moves inward as the nebula cools. Also, the water ice evaporation front, like the refractory mineral evaporation fronts (Cameron and Fegley, 1982) is closer to the proto-Sun at higher and lower regions off the midplane of the nebula. Neither the vertical structure nor the radial variation with time of the water ice evaporation front has been explored in detail, but both factors are important for understanding a variety of problems such as the survival of HDO-bearing ice grains in the solar nebula.

2.2 Deuterium Exchange

The problem of survival of HDO-bearing ice grains is relevant because recent spectroscopic observations of CH₃D in the atmospheres of Jupiter, Saturn, Uranus, Neptune, and Titan (deBergh et al., 1986, 1988, 1990; Gautier and Owen, 1989 and references therein) and of HDO in comet P/Halley (Eberhardt et al., 1987) show evidence for two distinct reservoirs of deuterium in the outer solar nebula (Owen et al., 1986; Lutz et al., 1990).

One reservoir, which was composed of gaseous hydrogen, had the protosolar D/H value of 34 ± 10 ppm (Anders and Grevesse, 1989) and was the dominant reservoir. Evidence for this reservoir is seen in Jupiter and Saturn, which have an average D/H ratio of 20 ± 15 ppm (Gautier and Owen 1989). The second reservoir, which was smaller, was composed of D-rich compounds which remained solid under the low temperatures prevailing in the outer solar nebula. Evidence for this reservoir is seen in Uranus, Neptune, Titan, and comet P/Halley, all of which are more "ice"-rich than Jupiter and Saturn. The latter four bodies have D/H atom ratios of 72 (+72,-36) ppm (Uranus), 120 (+120,-80) ppm (Neptune), 165 (+165,-80) ppm (Titan), and 60-480 ppm (comet P/Halley).

If the hypothesis of Owen and colleagues is correct, then any D-rich ices, such as HDO, have to be kept cold enough to prevent thermochemical isotope exchange reactions such as



from diluting their high deuterium contents. Note that this approach is just the reverse of the classical picture of deuterium exchange which envisions increasing deuterium enrichment in hydrides such as H₂O, NH₃, CH₄, etc. with decreasing temperature. However, calculations by Grinspoon and Lewis (1987) show that both gas-phase and grain catalyzed D/H exchange reactions are so slow that they cannot proceed to completion over the 10¹³ second lifetime of the solar nebula.

Instead it is better to regard deuterium exchange as a back-reaction in which D-rich hydrides are losing deuterium to the surrounding nebular H_2 . Then, the maximum exposure temperatures for hydrides such as HDO-ice can be estimated from equations such as

$$\log_{10}\alpha = -0.12 + 196/T \quad (4)$$

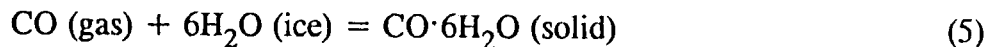
for HDO, where α is $[(D/H)_{ice}/(D/H)_{gas}]$ and thermodynamic data are taken from Richet et al. (1977). In this example, we merely note that the highest possible exposure temperature for HDO-ice is the water ice evaporation front, and that temperatures of 190 to 150 K for the front correspond to deuterium enrichments in HDO-ice of ~ 8 -15 times the protosolar value. Thus, in principle, the observed D/H ratios in Uranus, Neptune, Titan, and comet P/Halley can be supplied from a mixture of HDO-ice and nebular hydrogen. Furthermore, the terrestrial D/H ratio of 160 ppm can itself be supplied by the accretion of either HDO-ice or of hydrated silicates formed from it on meteorite parent bodies in the asteroid belt. In this regard, we suggest that a determination of the D/H ratio in the ice on the Galilean satellites and in the hydrated silicates on asteroids such as 1 Ceres would be very valuable for constraining the two component deuterium reservoir model of Owen and colleagues.

2.3 Clathrates and Ammonia Hydrate

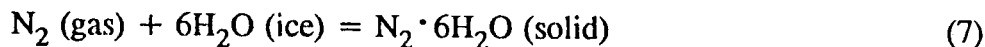
More volatile compounds, which are formed at lower temperatures and thus greater radial distances in the solar nebula, are clathrates and possibly ammonia hydrate. The potential importance of these compounds for retention of carbon and nitrogen in solid grains was probably first recognized by Urey (1953) who concluded that $NH_3 \cdot H_2O$ could condense in the solar nebula, and Miller (1961) who suggested the importance of methane clathrate $CH_4 \cdot 6H_2O$ for carbon retention.

As reviewed by Fegley and Prinn (1989), CO and N_2 are predicted to be the dominant carbon and nitrogen gases in the solar nebula, while CH_4 and NH_3 are predicted to be the dominant carbon and nitrogen gases in the subnebulae formed around the giant

protoplanets. Thus, in the solar nebula, CO and N₂ clathrate formation via reactions exemplified by

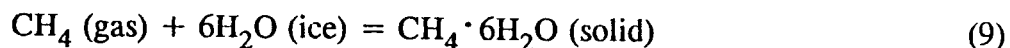


$$\log_{10}P_{\text{CO}} \sim 5.00 - 763/T \quad (6)$$

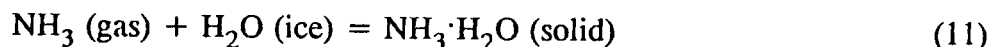


$$\log_{10}P_{\text{N}_2} \sim 4.86 - 729/T \quad (8)$$

are predicted to be important, while in the subnebulae around the giant protoplanets, CH₄ clathrate and NH₃ hydrate formation via reactions exemplified by



$$\log_{10}P_{\text{CH}_4} \sim 4.83 - 939/T \quad (10)$$



$$\log_{10}P_{\text{NH}_3} \sim 8.05 - 2088/T \quad (12)$$

are predicted to be important (Fegley and Prinn, 1989). As a result, the composition of the low temperature condensates formed in the solar nebula and in the giant protoplanetary subnebulae are predicted to be diagnostic of their environments (e.g., Prinn and Fegley, 1989).

However, as noted by Fegley (1988, 1990) and Fegley and Prinn (1989), CO and N₂ clathrate formation are predicted to occur at such low temperatures (~60 K) and pressures (~10⁻⁷ bars) in the solar nebula that kinetic inhibition will probably prevent the formation of any significant amount of CO and N₂ clathrates over the lifetime of the solar nebula. Approximately 6% of all CO must collide with ice grains in order to form stoichiometric CO·6H₂O. This process is fairly rapid (~11 hours) under conditions required for CO clathrate formation in the outer nebula, but only a small fraction of the collisions that possess the necessary activation energy E_a lead to CO clathrate formation. Following the treatment for gas-grain reactions given by Fegley (1988), this fraction is given by

$$f_i = \nu_i \exp(-E_a/RT) \quad (13)$$

where ν_i is the total number of collisions of CO molecules with all ice grains in each cm^3 of the nebula and is given by the equation

$$\nu_i = 10^{25.42} [P_{\text{CO}}/(M_{\text{CO}}T)^{1/2}] A \quad (14)$$

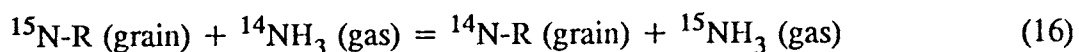
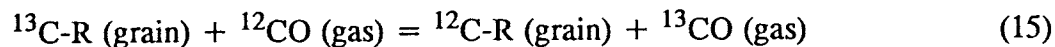
where P_{CO} and M_{CO} are the CO partial pressure and molecular weight, T is the temperature (Kelvins), and A is the total surface area of all ice grains per each cm^3 of the solar nebula.

Assuming spherical geometry and a radius of 1 mm for the ice grains, it is simple to calculate that a CO clathrate formation time $< 10^{13}$ seconds (the estimated lifetime for the solar nebula) requires $E_a < 8$ kJ/mole. Larger activation energies will lead to longer clathrate formation times and it will not be possible to make CO clathrate in the solar nebula. In fact, the activation energy for CO clathrate formation is almost certainly larger than 8 kJ/mole because the experimentally measured E_a for CO_2 clathrate formation is ~ 25 kJ/mole (Miller and Smythe, 1970). Similar kinetic constraints exist for the formation of N_2 clathrate. Thus, it is unlikely that either CO or N_2 clathrate formed in the solar nebula because it took too long to do so.

Instead, in the solar nebula, it is more likely that carbon and nitrogen were retained in solid grains by a combination of processes such as disequilibrium organic compound formation (Fegley, 1988; Fegley and Prinn, 1989), absorption/adsorption onto water ice grains (Lunine, 1989), and direct condensation of CO and N_2 ices in the coldest nebular regions. On the other hand, kinetic modelling of CH_4 clathrate and NH_3 hydrate formation in the subnebulae around the giant protoplanets show that clathrate and hydrate formation are kinetically favorable in these higher pressure environments. The consequences for the bulk compositions of icy satellites and for their outgassed volatiles have been discussed in detail in several articles (Fegley and Prinn, 1989; Prinn and Fegley, 1989). All of these predictions are potentially testable by a combination of laboratory experiments and improved Earth-based and spacecraft observations.

3 SURVIVAL OF PRESOLAR GRAINS

Finally, we close by noting that another important class of gas-grain chemical reactions in the environment of the solar nebula (i.e., the accretion shock, the nebula itself, and giant protoplanetary subnebulae) are those controlling the survival of presolar grains. Fegley (1988) noted that several different types of reactions fall into this broad category. For example, isotopically anomalous materials (e.g., D-rich or ^{13}C -rich, or ^{15}N -rich phases) may back-react with the surrounding nebular gas and thus become less anomalous or isotopically "average" as they tend toward equilibrium at the ambient temperature. An example of this type of reaction was given above for HDO-bearing ice; however, analogous reactions for C and N are schematically illustrated by the reactions



between presolar organic (-R) grains and the surrounding gas phase in the solar nebula and in giant protoplanetary subnebulae. Likewise, thermally labile materials such as ices and volatile organics may evaporate with increasing temperature until they eventually disappear.

However, perhaps the most interesting reactions are those involving chemically anomalous grains that are out of thermochemical equilibrium with the nebular gas. As noted by Fegley (1988), these grains "may be thermally reprocessed with increasing temperature until they no longer preserve chemical and/or isotopic signatures of their presolar origin. In particular, presolar grains such as carbides, nitrides, and sulfides, which formed in chemically reducing environments (e.g., carbon stars) will be oxidized at high temperatures in the nebular gas. Their survival will therefore depend on their rate of oxidation versus their

rate of removal to a thermochemically inactive region, for example, by mixing to cooler regions or by accretion into a meteorite parent body."

Writing shortly after the discovery of interstellar SiC grains in the Murray carbonaceous chondrite by Bernatowicz et al. (1987) and Zinner et al. (1987), Fegley (1988) noted that SiC is thermodynamically unstable in solar composition gas and will be oxidized via the net reaction

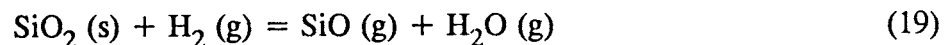


in the solar nebula. Reaction (17) is highly favorable thermodynamically; e.g., the equilibrium constant calculated for α -SiC oxidation to high cristobalite is

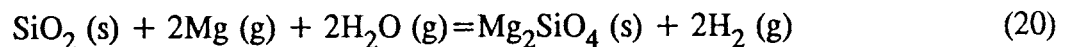
$$\log_{10}K_{17} = 4.93 + 10\,165/T \quad (18)$$

Although the equilibrium constant for oxidation of radiation damaged SiC grains having a different crystal structure may be slightly different, the process will still be very thermodynamically favorable. On the other hand, evaporation of SiC grains is much less thermodynamically favorable and insignificant vapor pressures of SiC and other species will be present at 2000 K and below in the solar nebula. Thus, oxidation by water vapor is the primary thermochemical process that destroys SiC grains in the solar nebula.

However, as noted by Fegley (1988), the destruction process is likely to be complex because the protective silica coating that forms on the SiC grains (thus inhibiting further oxidation by diffusion constraints) can also undergo reaction itself. For example, the SiO₂ may either evaporate by reaction with H₂



or react with more refractory metal vapors such as Mg



As noted by Fegley (1988), reaction (19) tends to destroy the protective SiO_2 coating while reactions (20) and (21) tend to replace it with more refractory coatings. Experimental studies of SiC oxidation are needed to determine the rates of these different reactions and to determine the detailed mechanisms involved in the net thermochemical processes. When this is done it will be possible to determine quantitatively why the SiC grains in meteorites survived and to use them as chemical probes of conditions in the solar nebula.

Figure Captions:

- Fig. 1: Calculated condensation temperatures for refractory elements. Calculations were performed according to programs described by Fegley and Palme (1985) and Kornacki and Fegley (1986).
- Fig. 2: Superrefractory pattern of refractory elements in a tiny inclusion from the Ornans meteorite (Palme et al., 1982).
- Fig. 3: Patterns of refractory elements in bulk Allende, a large Allende inclusion A4 with uniform enrichment factors for all refractory elements and a fractionated inclusion with a group II pattern (see text). Unpublished data MPI-Mainz, Cosmochemistry.

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Table 1: **Composition of the Major Groups of Chondritic Meteorites**

	Refractory elements	Magnesium silicates	Iron	Volatiles	
	Ca/Si	Mg/Si	Fe _{tot} /Si	S/Si	O/S
Carbonaceous					
I (Orgueil)	1	1	1	1	1
CM (Murchison)	1.14	1.02	0.92	0.47	0.76
CO (Ornans)	1.15	1.03	0.89	0.25	0.54
CV (Allende)	1.42	1.10	0.88	0.26	0.56
Ordinary					
LL (Saint Severin)	0.78	0.93	0.62	0.23	0.47
L (Leedy)	0.80	0.93	0.68	0.22	0.47
H (Richardton)	0.82	0.96	0.96	0.22	0.49
Enstatite					
EH (Indarch)	0.57	0.71	1.12	0.61	0.40
EL (St. Marks)	0.54	0.78	0.76	0.31	

Average elemental weight ratios are normalized to CI-ratios. Examples of meteorites representing various meteorite classes are given in parentheses. For sources of data see Palme (1988).

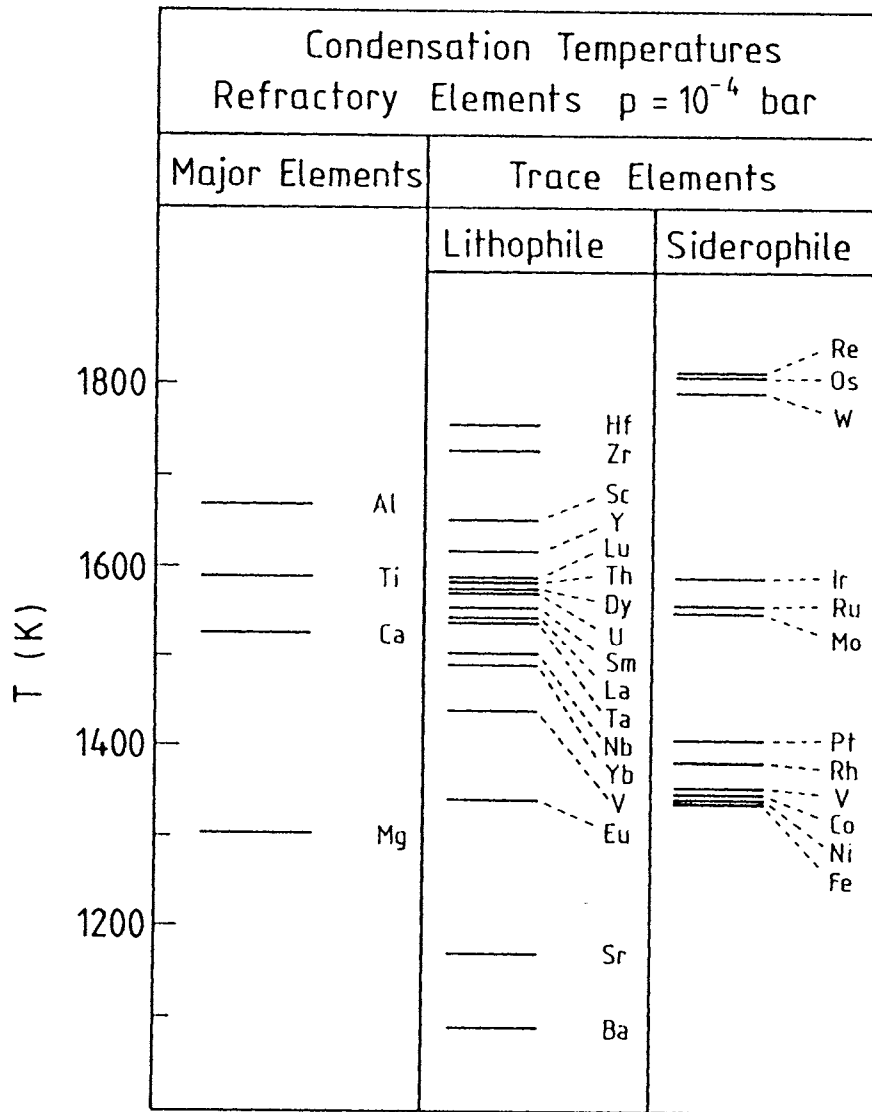


Fig. 1

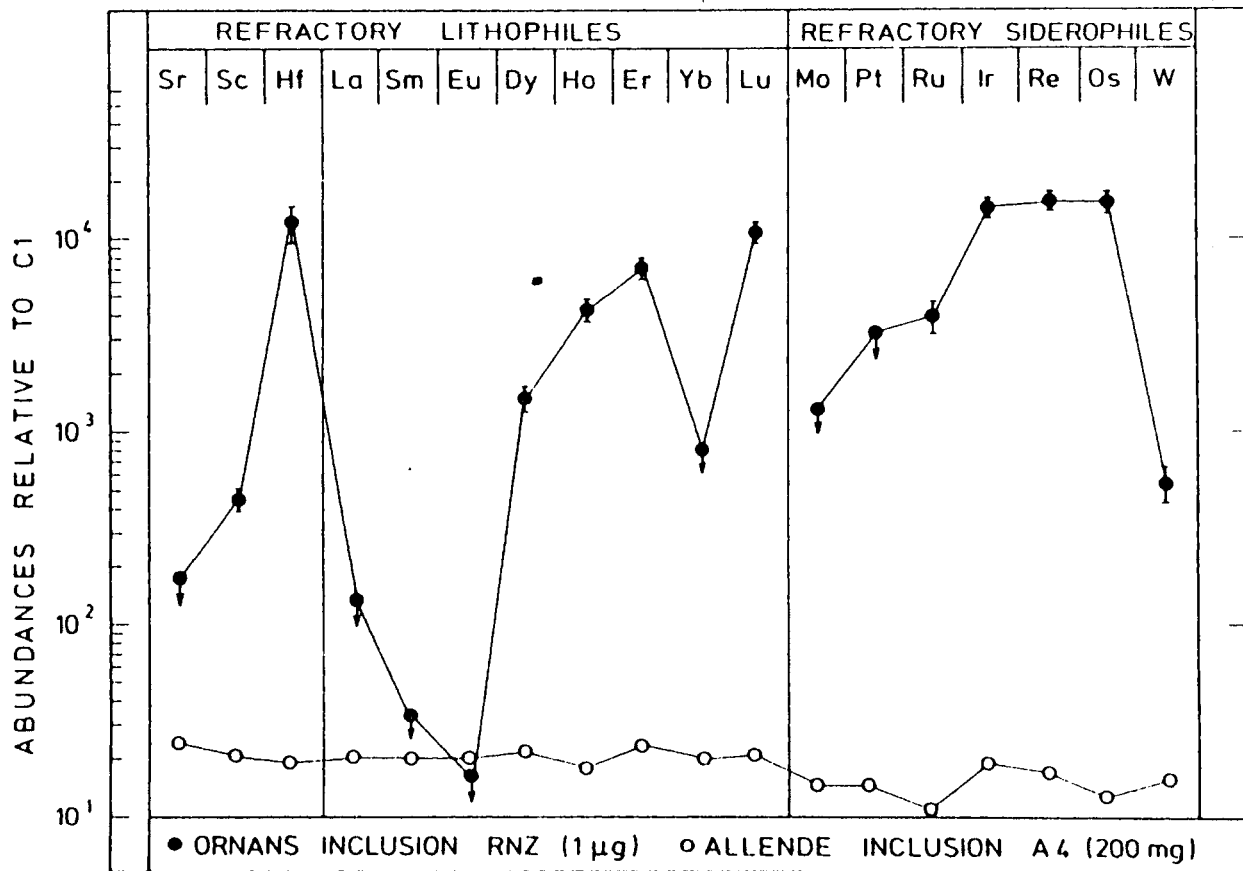


Fig. 2

