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CHEMICAL PROCESSES IN THE EARLY SOLAR SYSTEM: A DISCUSSION OF METEORITES AND ASTROPHYSICAL MODELS

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ABSTRACT

The chondritic meteorites display a number of compositional trends - the separation of certain lithophile elements from others and the separation of siderophile elements from non-siderophiles - which, like many isotopic properties, almost certainly reflect nebular processes. Models based on equilibrium thermodynamics, when constrained by considerations of kinetic factors and the effects of secondary alteration which are petrographically observable, provide a remarkably successful means of understanding certain aspects of these trends, as well as explaining a plethora of more detailed observations. For a number of reasons, mainly associated with astrophysical concepts concerning maximum temperatures in the primordial nebula, equilibrium thermodynamic models have fallen into disfavour. However, recent astrophysical models suggest that turbulence and radial transport of material were important processes in the nebula from which the solar system eventually formed and these provide plausible conditions for equilibrium thermodynamic processes of the sort required by the meteorite data to occur. New insights into the processes occurring during the formation of the solar system now seem possible through a careful assimilation of meteorite observations and astrophysical models.

INTRODUCTION

The chondritic meteorites are the largest class of meteorites falling on earth, and those which bear the best evidence of early solar system processes. Unlike the small achondrite classes, terrestrial and lunar samples, the chondrites are essentially solar in composition, differing only in the proportions of the most volatile elements, H, He, O, N and inert gases. The chondrites are also the oldest rocks known, having formation ages of 4.6 Ga, which are comparable with the ages of the Earth and Moon, and with the Sun. Finally, the chondritic meteorites contain a number of petrographic and mineralogical properties which indicate a lack of planetary processing on the scale observed for terrestrial and lunar rocks. In short, the chondritic meteorites are relics of the processes by which our solar system formed, and in principle should provide a unique and powerful window on the chemical and physical processes occurring during the formation of the solar system.

The chondrites are, however, complex, consisting of nine distinct chemical classes and with each chondrite consisting of 4 major structural components. In addition, diverse physical processes, such as shock, brecciation and metamorphism, have affected the whole assemblage and its components to varying degrees. It is not surprising, therefore, that many of the details of chondrite history and formation are controversial. However, while attention seems to focus on areas of disagreement, there are several points which seem well established and have important implications for nebular models. Some of these were alluded to above: (1) while they are essentially solar in composition, chondrites show subtle compositional variations which enable division into the nine classes; (2) the classes identified on the basis of major element abundances often have distinct isotopic composition, and certain components within chondrites

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show a great number of uncorrelated isotopic anomalies; and (3) they consist of four structural components, chondrules, calcium-aluminum inclusions (CAI), matrix and metal.

CLASSES AND SUMMARY OF COMPOSITIONAL PROPERTIES

The composition of the solar photosphere is compared with two classes of chondrites, the CI and L chondrites, in Fig. 1. While both the CI and L class are solar to a good approximation, the L chondrites show significant differences in composition, such as a depletion in "siderophile" elements (see below). Similar plots could be drawn for the other 7 chondrite

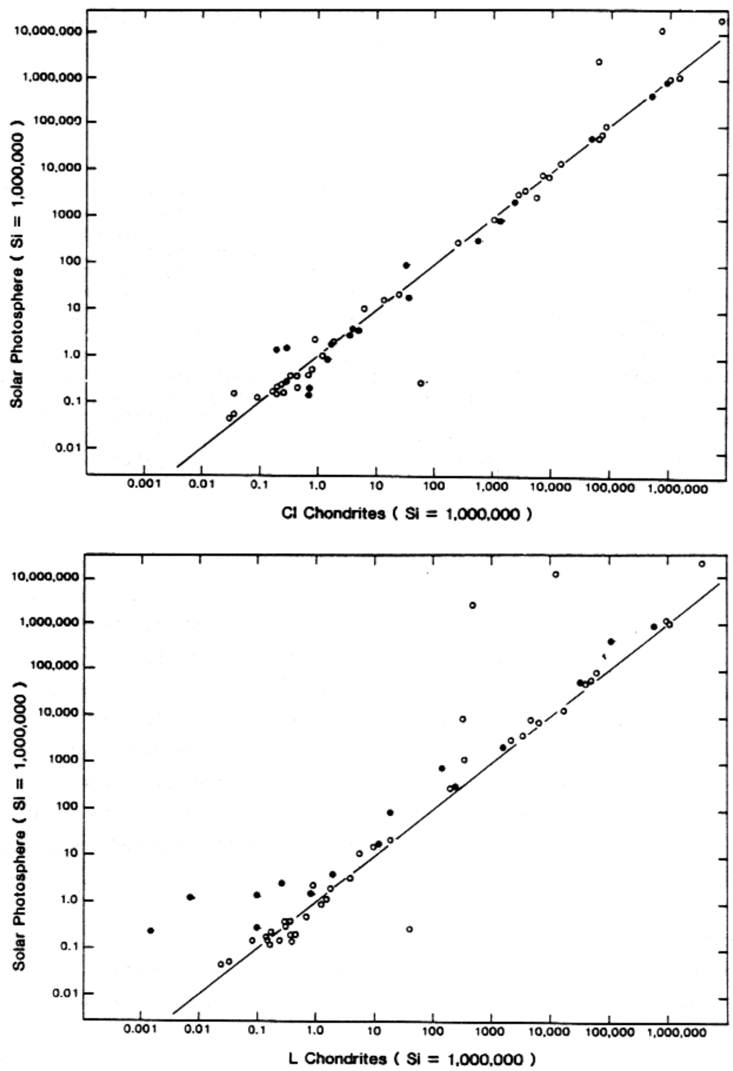

Fig. 1 Plots of photospheric composition against (a) CI chondrites and (b) the largest ordinary chondrite class, the L chondrites. The CI chondrites closely resemble the photosphere in all but the most volatile elements, or elements which form stable volatile compounds, (H, N, O and the inert gases). The L chondrites are also essentially solar in composition but show subtle and significant differences. Siderophile and chalcophile elements (filled symbols) are depleted by about 20% and there are differences in lithophile elements. Li is noticeably depleted in the photosphere since it is unstable in stellar interiors and is produced by interstellar nuclear reactions. (Figures from Sears, 1987; data from Ross and Aller, 1976; and Mason, 1979).

classes which show that they also are essentially solar in composition with subtle differences which are characteristic of each class (Table 1). The history of the discovery of these chemical trends is long and complicated, but generally followed improvements in analytical techniques.

Lithophile Elements

Separating the chondrites into classes in the broadest sense are differences in the proportion of certain lithophile elements (Ahrens et al., 1968). The lithophile elements (Ca, Al, Mg, Sc, Na, K) are those which tend to concentrate in the silicate phases. A histogram of Mg/Si values (Fig. 2a) has three peaks, which leads to the definition of the "carbonaceous",

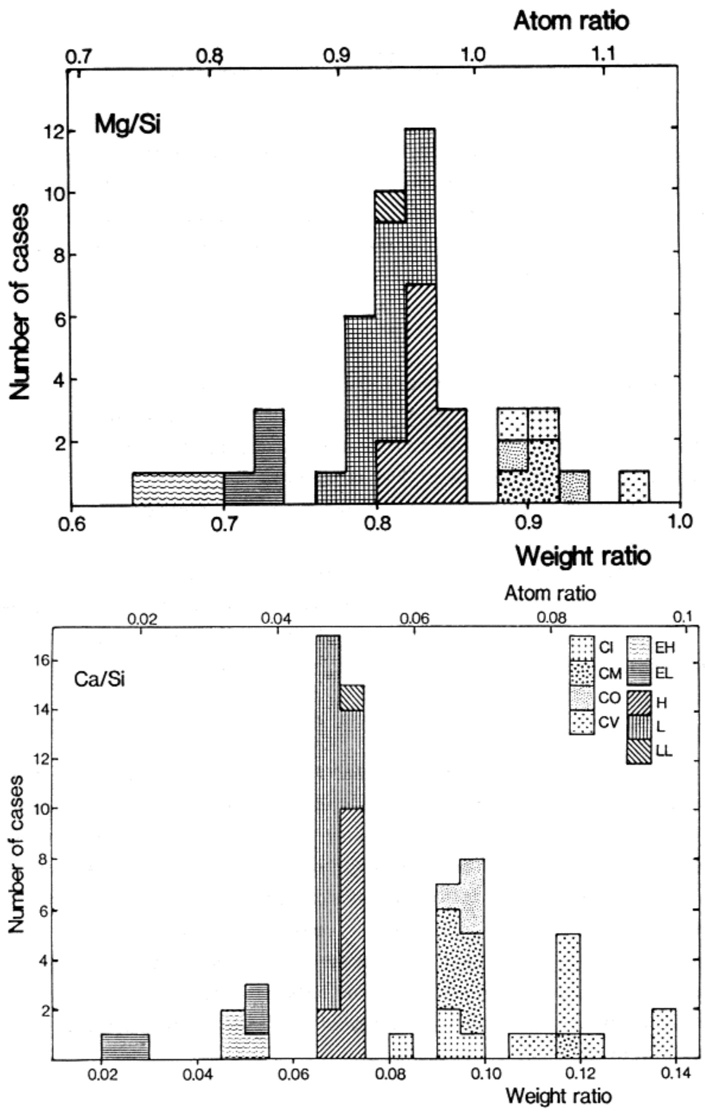

Fig. 2 Histograms of (a) the Mg/Si ratio and (b) the Ca/Si ratio in chondritic meteorites. Both ratios divide the chondrites into groups of carbonaceous, ordinary and enstatite chondrites while the Ca/Si ratio further identifies one of the carbonaceous groups known as CV chondrites. (Figure from Sears, 1987; data from Von Michaelis et al., 1969; and Van Schmus and Hayes, 1974).

Table 1 Chondrite classes and properties. (Data Von Michaelis et al., 1969; Anders and Ebihara, 1982; Sears and Axon, 1976; Sears and Weeks, 1986; Wiik, 1969; Mason, 1966; and R.N. Clayton, 1981 and per. comm.)

Group	Mg/Si (a/a)	Ca/Si (a/a)	Fe/Si (a/a)	Co in Fa (mol%)	Kamacite (mg/g)	Fe met/ Fe_t	$\delta^{18}O$ (‰)	$\delta^{17}O$ (‰)
CI	1.05	0.062	0.86	-	-	0	~16.4	~8.8
CM	1.05	0.067	0.80	-	-	0	~12.2	~4.0
CO	1.05	0.068	0.77	-	-	0-0.2	~-1.1	~-5.1
CV	1.03	0.059	0.87	-	-	0-0.3	~0	~-4.0
H	0.96	0.050	0.81	16-20	5.2	0.11	4.1	2.9
L	0.93	0.046	0.57	22-25	10.6	0.29	4.6	3.5
LL	0.94	0.049	0.52	27-32	22.9*	0.58	4.9	3.9
EH	0.77	0.035	0.95	-	-	0.76	5.6	3.0
EL	0.83	0.026	0.62	-	-	0.83	5.3	2.7

* While many of the LL chondrites cluster around the value indicated, they show a "tail" up to 110.0 mg/g.

"ordinary" and "enstatite" chondrites. (The names given to meteorite classes are a matter of colourful historical development; they are sometimes helpful, and sometimes misleading.) Other lithophile element ratios produce the same groups, but refractory (i.e. non-volatile) lithophile element ratios like Ca/Si (Fig. 2b), cause the carbonaceous chondrites to break down into another class, the CV chondrites.

Siderophile Elements

Totally unrelated to the Mg/Si-produced groups are subdivisions produced by siderophile elements (Urey and Craig, 1953; Sears et al., 1982; Kallemeyn and Wasson, 1981; Sears and Weeks, 1986). The siderophile elements, those tending to concentrate in the metal phase (Fe, Ni, Co, Au, Ir, As, and Ge), produce groupings within those produced by the lithophile elements. Fe/Si is the ratio most frequently used, but all siderophiles show similar behaviour, the trends being more marked for the more refractory elements. On such plots the enstatite chondrites are divided into the EL and EH classes, and the ordinary chondrites into H, L and LL classes. The carbonaceous chondrites can also be divided into four smaller divisions on the basis of Fe/Si, Mg/Si and Ca/Si. However, other properties, notably the abundances of volatile elements, produce sharper subdivisions; they produce the CI, CM, CV and CO classes.

Oxidation State

The third major compositional trend observed in the chondrites concerns their bulk oxygen content (or "oxidation state"). Carbonaceous chondrites contain highly oxidised mineral assemblages (all the Fe is in the form of Fe_3O_4 or silicates), while the enstatite chondrites are highly reduced (no Fe in oxide form, although some is in the sulphide form). The ordinary chondrites are in an intermediate state of oxidation, with some Fe in the metallic and sulfide form and some in the silicate form, and show a systematic increase in oxidation state along the series H, L and LL (Muller et al., 1971). The Urey-Craig (1953) plot (Fig. 3) is a classic in meteorite research, displaying both oxidation and bulk siderophile trends. Oxidation state plays a major role in determining the mineralogy of the assemblages, so that mineralogical data may often be sufficient to classify a meteorite.

The origin of the bulk compositional trends is widely attributed to nebular processes (e.g. Larimer and Anders, 1971; Wasson, 1972), and there is at least a reasonable concensus as to the general nature of the processes. The lithophile element patterns reflect the redistribution of mineral phases which are relatively refractory, while the Fe/Si and other siderophile element trends almost certainly reflect the separation of metal and silicate grains before aggregation into the chondrites now observed; the processes affecting each set of elements acted separately.

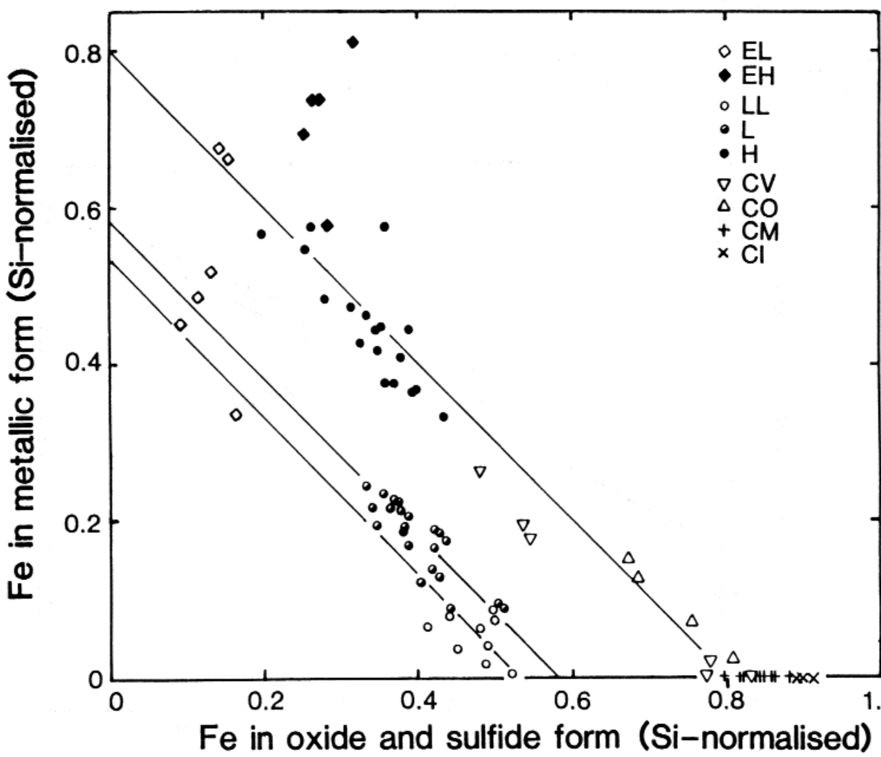

Fig. 3 Plot of Fe/Si ratios for Fe in the "reduced" phase (i.e. metal) against Fe in the "sulphurised" or "oxidised" phases (FeS, Fe_3O_4 and Fe-silicates). Redox reactions move the data along the diagonals, while the bulk Fe/Si ratios fix the position of the diagonal. Enstatite chondrites (EH and EL) are highly reduced with a major difference in bulk Fe/Si, while carbonaceous chondrites (CI, CM, CO, CV) are highly oxidised with a modest range of Fe/Si. Ordinary chondrites are intermediate in oxidation state and form a sequence (H, L, and LL) of decreasing bulk Fe/Si and increasing oxidation. (Data from Wiik, 1969; Mason, 1966; Jarosewich, 1966.)

Volatile Elements

Elements of moderate volatility (say, As, Sb, Zn, Cu, Cd) are typically depleted in ordinary chondrites by about 20%. Although the ideas concerning the mechanism (and the fine detail in the depletion patterns) are controversial, there seems to be agreement that the depletions reflect a nebular process. The situation is qualitatively similar for the enstatite and carbonaceous chondrites, and the same arguments have been made.

The situation for the highly volatile elements (e.g. In, Tl, Bi and Pb) is altogether different. Their depletion is considerably greater than for the moderately volatile elements, up to ~10^3-fold, and correlates with the degree of metamorphism experienced. Thus it seems likely that the depletion of highly volatile elements reflects their loss during metamorphism, but it is also possible that the relationship between metamorphism and highly volatile element content is indirect, both reflecting burial depth in the meteorite parent body. According to Ikramuddin et al. (1977a,b), annealing experiments are most consistent with metamorphism for the enstatite chondrites and nebular accretion for the ordinary chondrites.

Oxygen Isotopes

The chemical classes of chondrites were well established and widely interpreted as reflecting nebular processes by the time the oxygen isotope distribution was discovered by Clayton et al. (1976). Except for the EH and EL chondrites, which show different but overlapping ranges, each of the chondrite classes contains oxygen with unique proportions of the three isotopes (Fig. 4). The distributions cannot be attributed entirely to chemical and

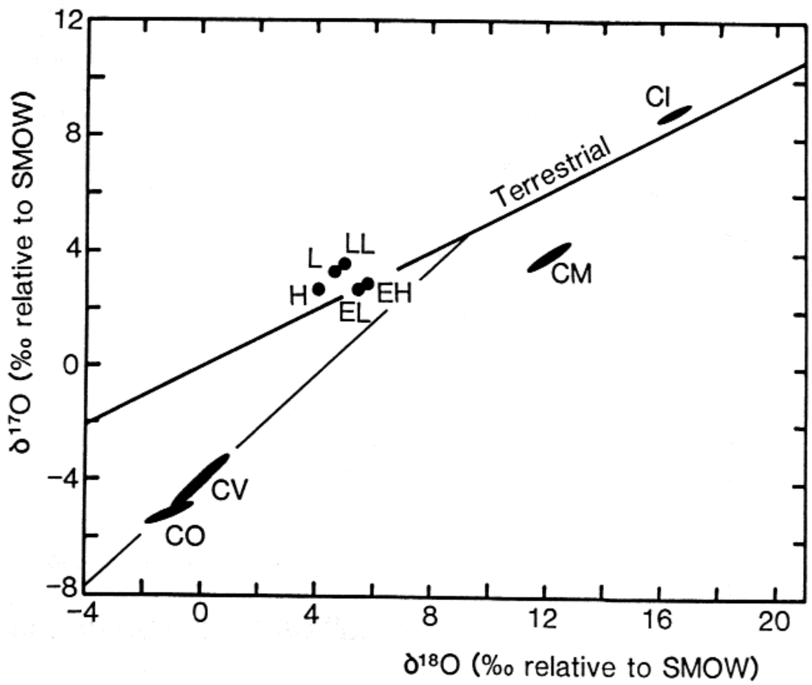

Fig. 4 Plot of $^{17}O/^{16}O$ against $^{18}O/^{16}O$ for various meteorite classes, expressed in δ units relative to standard mean ocean water (SMOW).

$$(\delta\, ^{17}O = \frac{(^{17}O/^{16}O)\ \text{sample} - (^{17}O/^{16}O)\ \text{standard}}{(^{17}O/^{16}O)\ \text{standard}} \times 1000)$$

A slope ½ line (e.g. the "terrestrial" line) is produced by chemical and physical processing of a given sample, while the slope 1.0 line (on which components from CV chondrites plot) reflects mixtures or exchange between ^{16}O-rich solid and relatively heavy oxygen. (Figure from Clayton, 1981; Clayton et al., 1984a,b).

physical processes acting on a single starting material as these would result in a line with a slope of ~0.5, like the "terrestrial" line, but must reflect differences in the starting material. The data are therefore remarkable confirmation of the interpretations of the chemical classes in terms of nebular processes. Furthermore, components removed from certain individual chondrites, most notably the CAI from the Allende CV chondrite, plot along a line with slope equal one indicating various mixtures of, or various degrees of exchange between, an ^{16}O-rich solid and relatively ^{16}O-poor gas. The CAI have not been isotopically homogenized with the rest of the meteorite since its formation, although a few individual CAI may have experienced chemical and physical processing. There are many instances of unusual isotope ratios for other elements in the CAI, but they do not appear to be correlated with each other in any obvious way (Clayton, 1978). Isotopic "anomalies" are not restricted to CAI, but are displayed by a number of classes including the little-metamorphosed ordinary chondrites (Pillinger, 1984).

SUMMARY OF PETROGRAPHIC DATA

Major Structural Components

The major structural components of chondrites are the chondrules, matrix and metal/sulfide assemblages. In certain classes, additional important components are the calcium-aluminum rich inclusions (CAI).

Chondrules are silicate assemblages, a millimeter or less in size, which have experienced partial or complete melting. A great diversity of theories have been proposed to account for these objects, but there is currently a widespread feeling that they formed by the flash melting of pre-existing dust grains (rather than by condensation of liquid droplets, by the flash melting of diffuse nebula dust, or by meteorite impact on a parent body, for example). There are many examples of "relic grains", grains which survived the melting process. The main argument for flash-heating as the event which produced chondrules and CAI are their rapid cooling rates (Wood, 1985). If the temperatures involved represent ambient nebula temperatures, then the cooling rates associated with transport from a hot to a cold region would be much slower than observed.

The distinctive chondrule morphologies of certain classes, and the "complimentary" compositions of the components in Murchison (neither the chondrules nor matrix have solar Fe/Si but the mixture has solar composition), are further arguments Wood makes for rapid aggregation with little long-distance transport. Note, however, that these arguments, which are all very strong, only preclude transport of material during or subsequent to chondrule-formation and do not rule out the possibility of transport of material prior to chondrule formation. Wood also assumes that the oxidation state was fixed at the time of chondrule formation to argue for considerable enhancement of dust in the chondrule-forming region. While Wood (1985) does not define the nature of the high-energy event which produced the chondrules, Safronov and Vitjazev (1986), who describe a very similar scenario for chondrule formation, suggest that it may be the collisions of bodies at the stage of planetesimal formation. Taylor et al. (1983) recently reviewed scenaria for chondrule formation and argued against impact mechanisms, however their discussion relates to fairly late impacts on existing parent bodies rather than early collisions on planetesimals. Both Wood (1987) and Safronov and Vitjazev (1986) imply that the chemical classes could result from these events, but neither go into detail. However, it is very unlikely that the chemical classes could have been made this way because of the diversity and complexity of the chemical trends. If one assumes a common starting material, and produces the Mg/Si variations by degassing during chondrule formation, then there would be a broad correlation between Mg/Si and Fe/Si, which, as we see from the chondrite classes described above, is not the case.

The matrix is a fine-grained opaque material which "cements" the chondrules, metal and other components of the chondrites. In CI and CM chondrites it consists of hydrated lattice layer silicates, but in the type 3 chondrites it is poorly characterized.

Metal and sulphide grains are an important constituent of the chondrites, both in terms of their abundance and the part they play in establishing the chemical trends. However, the petrology and composition of the metal and sulphide grains generally reflects metamorphic processes, since these phases are highly susceptible to low-temperature reactions. An exception might be the Si-bearing metal found by Rambaldi et al. (1980) in Semarkona, Bishunpur and Krymka. Rambaldi et al. (1980) suggested that the metal was formed at temperatures higher than required for the condensation of silicates, so that there were no silicates to form a sink for the Si in the gas. Soon after formation, the silicates became encased in sulphide which prevented any subsequent reaction. On the other hand, Gooding et al. (1980) suggest that the Si-bearing metal was made by reduction during a flash melting similar to that responsible for the formation of the chondrules. CAI are abundant in CV chondrites, and account for the enrichment in refractory lithophiles in the class; they are also present in minor amounts in CM chondrites and are present in trace amounts in ordinary chondrites.

The CAI are <1 cm aggregates of Ca and Al rich minerals which resemble the first solids predicted to form when a gas of solar composition is cooled from ~2000K. The inclusions contain a great many isotopic anomalies; instances where the proportion of isotopes of a given element differ from those encountered in terrestrial, lunar and most meteoritic material and not explicable in terms of radioactive decay, cosmic ray interactions or fractionations during chemical processes. The isotopic anomalies in the CAI indicate that the early solar system was not hot enough to completely homogenize elemental and isotopic proportions.

The once-popular theory for origin of the CAI was that they were the first solids to condense in the solar nebula as it cooled down; interstellar grains, with their unusual isotopic signatures, may have acted as nucleation sites. However, rare-earth element patterns suggest a more complicated history than this, involving the loss of a high temperature component. Some inclusions also show signs of having once been melted, and some have received a component of volatile material. It has also been suggested that the inclusions are the residues of a distillation process, the opposite to high temperature condensation. A variety of physical settings have been proposed for these evaporation/condensation processes.

Petrographic Types and Metamorphism

Most ordinary chondrites experienced temperatures of ≳1000°C subsequent to, or during, accretion. These temperatures obliterated original structures, homogenized mineral compositions, and caused recrystallisation of many phases. It may also have driven off volatiles, like water, inert gases, carbon compounds and certain trace elements (see above). Van Schmus and Wood (1967) proposed division of the chondrites into petrologic types 1 to 6, the value reflecting increasing levels of metamorphism. Ordinary and enstatite chondrites occupy types 3-6, while carbonaceous chondrites are, with a few exceptions, types 1-3. On the basis of thermoluminescence measurements, and a variety of detailed petrographic observations, Sears et al. (1980) subdivided the type 3 ordinary chondrites into types 3.0-3.9. The temperatures associated with each petrologic type are poorly known; estimates based on mineral thermodynamics suggest the following: 6, >1000°C; 5, >800°C; 4, >600°C; 3, 400-600°C with a few <400°C (Dodd, 1981). Phase transformations in feldspar, which affect the TL emission, show that types 3.3-3.5 did not equilibrate above 500-600°C (Guimon et al., 1985).

Aqueous Alteration

Chondrites of types 1 and 2 contain sulfate and carbonate minerals, sometimes in veins, hydrous silicates and magnetite with morphologies similar to those deposited by aqueous processes on earth (McSween, 1979). It has recently been argued that ordinary chondrites of types 3.0-3.1 are aqueously altered equivalents of type 3.2. They have anomalous TL properties which can be reproduced by hydrothermal annealing experiments, and Semarkona (L3.0) contains calcite, water with non-terrestrial H isotopes and hydrous silicates (Guimon et al., 1988; Hutchison et al., 1987).

Shock and Brecciation

Most chondrites have suffered brecciation to some extent, the mixing of pre-existing rocks to produce a "new" rock with a complex structure. Sometimes the breccia consists of light clasts of normal chondritic material surrounded by dark matrix material with unusual chemical and physical properties which show that it was once part of a regolith (the loosely consolidated surface material on a planet). At other times, the brecciation mechanism appears to have been quite different; often it is associated with meteorite impact. The subject of meteorite brecciation was reviewed by Keil (1981).

Most meteorite classes contain members which have experienced severe shock, transient excursions to high pressures and temperatures caused by impact. Shock causes relatively few petrographic changes, such as phase transformations and mechanical deformation, but the associated temperature pulse produces many physical changes; the low melting point minerals are mobilised and certain highly volatile elements are totally volatilized. The subject was recently reviewed by Haq et al. (1987) in their study of the effects of shock on TL properties.

SUMMARY OF CHRONOLOGICAL DATA

Formation Ages

The point in time at which the solids came together to form the chondrites, the formation age, is probably the most reliably dated. Wetherill and co-workers have published ages based on Rb-Sr whole-rock isochrons for the H, L, LL and E chondrites and internal isochrons for several individual E and H chondrites (Wetherill, 1975). Gray et al. (1973) have published an internal isochron for the Guarena H5 chondrite. Formation ages are 4.6 Ga for all classes although the carbonaceous and heavily shocked ordinary chondrites failed to yield a meaningful isochron, probably due to redistribution of the Rb by aqueous alteration and shock, respectively.

Other chronometers yield similar results unless the system has been disturbed, in which case the age of the disturbance can sometimes be determined. This is particularly true of systems involving gaseous daughter products. The ^{40}Ar-^{39}Ar method enables the extent of gas-loss to be evaluated and unshocked meteorites with no gas-loss also yield ages of 4.6 Ga (Turner et al. 1978; Bogard, 1979).

Extinct Nuclides, Formation Periods and Formation Intervals

Excess amounts of ^{129}Xe, heavy isotopes of Xe in the proportions produced by fission of ^{244}Pu, and ^{26}Mg indicate the one-time presence of short-lived ^{129}I ($t_{1/2}$ = 18 Ma), ^{244}Pu ($t_{1/2}$ = 80 Ma), and ^{26}Al ($t_{1/2}$ = 0.71 Ma) in meteorites or certain meteoritic components. Evidence for a variety of other short-lived nuclides in the meteorite at the time of its formation have been found or are being sought (Wasserburg and Papanastassiou, 1982). If the abundance of these nuclides at the end of nucleosynthesis and at the time of the formation of the meteorite can be determined, then the time interval between these events (the formation period) can be determined. The ^{26}Al chronometer is complicated by the presence of excess ^{26}Mg in the early solar system which is of non-radiogenic origin, and the ^{244}Pu chronometer by the lack of a stable isotope against which to compare the ^{244}Pu to normalise-out the effect of chemical processes on the Pu abundance. The ^{129}I chronometer yields a formation period of 380 million years for the achondrites (Podosek, 1972), but such large values seem incompatible with the presence of ^{26}Al in the meteorites at their formation. Long-lived isotopes of U and Th have also been studied in this connection, but the data are also poorly understood.

Although much remains to be done before precise values for the formation period can be determined, it is clear that the value is in the order of Ma rather than Ga and that, in comparison with the age of the solar system, the time interval between the end of nucleosynthesis and meteorite formation was very brief.

Uncertainty over the nucleosynthetic ^{129}I value does not preclude relative formation ages to be determined by this isotope with great precision. The relative amount of ^{129}Xe in ordinary chondrites has enabled Drozd and Podosek (1976) to show that 20 ordinary chondrites accreted within a very short period (within 20 Ma of each other).

Metamorphism Age

The Guarena H5 chondrite has an initial $^{87}Sr/^{86}Sr$ value higher than unmetamorphosed meteorites which Gray et al. (1973) attributed to a resetting of the Rb-Sr system by metamorphism. If this interpretation is correct, then the metamorphism suffered by ordinary chondrites occurred within 78 Ma of their formation.

Shock Ages

One-half to one-third of the L chondrites, and a significant proportion of the other classes, suffered a major shock event. When the severity was sufficient to cause total loss of radiogenic ^{40}Ar, it is possible to date the event. The ^{40}Ar-^{39}Ar method provides both a check on the extent of degassing and an age. The event which shocked the L chondrite occurred 500 Ma ago, and the H chondrites were shocked around 3500 Ma ago (Bogard, 1979; Turner et al., 1978).

Cosmic Ray Exposure Ages

Cosmic rays can penetrate only a few meters into the meteorite in space, so that the products of cosmic-ray bombardment enable an estimate of the time during which the meteorites were meter-sized. The major uncertainty is in the production rate for the isotopes, which has to be estimated in a number of indirect ways. Production rates and age estimates based on various cosmic ray products are in good agreement, and it seems that cosmic ray exposure ages are now fairly reliable. Chondritic meteorites have ages of ~1 Ma to ~100 Ma, generally ~20-40 Ma. A peak at 4 Ma in the histogram of cosmic ray exposure ages for H chondrites indicates that a significant number of this class were members of the same object prior to break-up at that time.

ASTROPHYSICAL ASPECTS OF THE EARLY SOLAR SYSTEM

Formation of the Primordial Solar Nebula

The formation of the sun and its planetary system began with the gravitational collapse of an interstellar cloud. Gravitational heating occurred as the opacity rose until the internal pressure matched the gravitational collapse and the protosun formed. This continued to accrete material, the central temperature rising until hydrogen fusion occurred in the core and the sun became a normal main sequence star. Since the infalling material possessed angular momentum, it probably formed an "accretion disk" around the Sun, within which differences in rotational velocity caused a redistribution and heating of nebular gases. At times the rate of infall of material was so high that the material was in a state of free-fall, and a standing shock wave may have been established as the gas fell into the nebula. If the total angular momentum was large (10^{19} cm^2/s), then the nebula to protosun ratio will have been large and the nebula will have broken down into a number of large gaseous sun-like protoplanets, multiple systems, rings, bars or spirals. On the other hand, a small total angular momentum and small nebula to protosun ratio will have resulted in a stable nebula in which solid grains formed and grew into large bodies (Cameron, 1978; Cassen and Summers, 1983). Cassen et al. (1985) claim that the present size of the solar system and the agreement between planetary masses predicted by the adiabat in Fig. 7 (see below) and those observed are "substantive arguments" for a low-mass nebula.

As a result of their circular motion and gravitational pull of the protosun, the grains will fall to the midplane of the nebula. There they form a gravitationally unstable disk which will break up into kilometer-sized planetesimals. Shortly thereafter, the nebula became dispersed, probably by being driven off by the intense solar wind of the sun as it passed through the T-Tauri phase.

The Angular Momentum Problem

Of the numerous solar system properties which have to be explained by a successful model for the formation of the solar system, that which has presented the biggest challenge is the angular momentum distribution. The Sun, which possesses 99.9% of the solar system mass, has only 0.5% of its angular momentum; apparently a highly efficient coupling mechanism existed to transfer the angular momentum from the Sun to the planets. A number of mechanisms have been proposed, but that which is most effective during the final stages of collapse leading to star formation is turbulence.

Astronomical Models for the Primordial Solar Nebula

Attempts to model the final stages of the formation of the Sun and planets with special attention to the angular momentum problem were recently reviewed by Cameron (1978) and Morfill (1985). Lynden-Bell and Pringle (1974) have shown that angular momentum can be transferred from the inner to the outer part of the nebula if there is a frictional force which dissipates energy. This force also results in considerable radial transport. By equating centrifugal force and gravity (modified by a frictional force) they show that the process may be described by

$$F \frac{dh}{dR} = \frac{-\partial g}{\partial R} \tag{1}$$

where F is the flux of material moving through radial distance R, g is the couple between the inner and outer material at R, and h is the specific angular momentum given by

$$h = R\Omega = [GMR + \frac{h}{2} \frac{GMoR^2}{R_o}]^{1/2} \tag{2}$$

where Ω is the angular velocity and M is the central mass and Mo and Ro are disk mass and radius. The coupling, g, is given by

$$g = 4hR^2 nsA \tag{3}$$

where n is the viscosity of the gas (1/3 the product of the turbulent velocity and mixing length), s the number density and A the local rate of shearing

$$A = \frac{1}{2} R \frac{d\Omega}{dR} \tag{4}$$

Crucial to the success of the models in redistributing angular momentum is the size of ν, that is, the turbulence in the nebula. Several mechanisms are conceivable for generating the turbulence; convective instability, residual turbulence from the collapsing gas, rotational flows behind curved shocks, a mismatch in the angular momentum of the gas and dust, and meridional circulation flow patterns. Morfill (1985), for example, described two models in which the effects of turbulence were included, one in which an accretion zone was assumed to become turbulent due to convective instabilities and one in which turbulence was added in an ad hoc fashion. Other authors have treated the problem in other ways, and the models make very different predictions for the distance dependence of many physical properties of the nebula, but agree in an essential feature of the early solar system, the temperature gradient.

Radial Transport

A major consequence of a turbulent protoplanetary disk, however created, is that there will have been radial transport of material in the primordial solar nebula and this has considerable cosmochemical implications. As an example of the sort of relationships involved, Cassen and Summers (1983) give the radial mass flux within the disk of a small mass nebula as

$$2\pi\dot{m} = -6r^{1/2}\frac{\delta}{\delta R}(\sigma\upsilon R^{1/2}) - \frac{2\pi\sigma R^2}{t} \quad (5)$$

Low-mass nebula models predict considerable radial transport of material since gas falls into the protosun and then moves out into the disk (Fig. 5). On the other hand, high-mass nebula

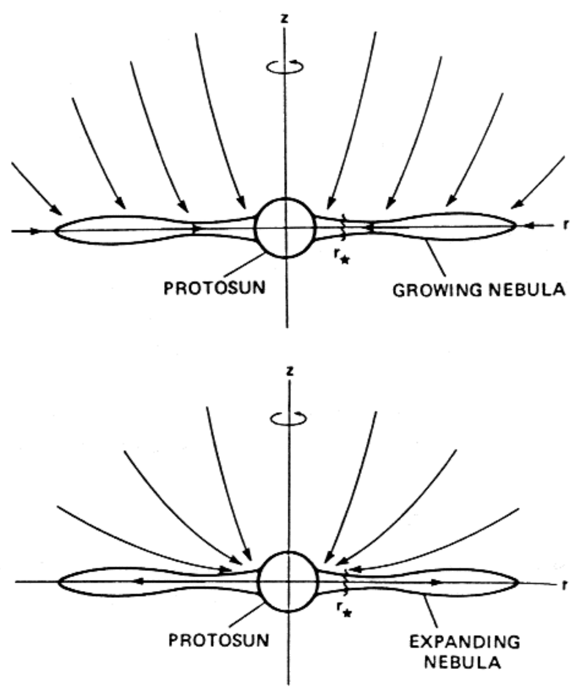

Fig. 5 The details of the evolution of the primordial solar nebula are governed primarily by the mass of the nebula. "Low-mass" nebula, or, more precisely, minimum angular momentum nebula (upper Fig., disk mass less than or equal to one solar mass) grow by accreting mass to the protosun and then transferring matter radially to the disk. Nebulae with much more angular momentum than presently observed ("high-mass" nebula, disk greater than one solar mass) grow by accreting matter to the disk and transporting it radially into the protosun. High-mass nebulae are gravitationally unstable, and fragment into rings, giant protoplanets, multiple star systems, spirals or bars. (Figures from Cassen and Summers, 1983.)

models predict accretion directly onto the disk with radial transport inwards towards the protosun. However there are many processes acting to cause radial transport of the dust, besides the growth mechanisms of the nebula as a whole. The interaction between dust and gas, for instance, and the turbulence responsible for angular momentum transfer between protosun and disk. A fully quantitative treatment has yet to be made, although semi-empirical models have been developed (e.g. Morfill, 1983).

COSMOCHEMICAL PROCESSES IN THE EARLY SOLAR SYSTEM AND THE ORIGIN OF METEORITES

Equilibrium Condensation

The decade or so beginning ~1965 saw the development of elaborate thermodynamic models for the condensation of a gas of solar composition; the period was once described as the "heroic days of cosmochemistry." The models provide a successful means of understanding many of the major properties of chondrites (and planets) and a plethora of the detailed observations. However, the fundamental underpinning of the models was removed by the development of astrophysical models for the primordial solar nebula and the discovery of isotopic anomalies. Apparently, the nebula was never hot enough to totally vaporise and homogenise solids, chemically or isotopically, in the vicinity of the asteroid belt. Thus throughout the late 1970's and early 1980's there was a move away from equilibrium thermodynamic calculations as a means of explaining chondrite origins, especially their bulk compositions, despite their successes and the failure of alternatives.

Thermodynamic models are based on a series of mass-balance equations in which the partial pressure of a given element is set equal to the pressure of each of its molecular forms, thus for oxygen

$$P_t(0) = \frac{2A(0)}{A(H)} P_T = + P(0) + 2P(0_2) + P(CO) + P(CO_2) + P(H_2O) + \ldots \qquad (6)$$

where $P_t(0)$ is the partial pressure of oxygen in the nebula, P_T is the total nebula pressure and A(0) and A(H) are cosmic abundances of oxygen and hydrogen. The most recent compilation of cosmic abundances is that of Anders and Ebihara (1982). The P(M) terms are the pressure of each gaseous form of oxygen, and these can be replaced by expressions involving the pressure of the atomic species (C, O and H in this case), and the equilibrium constants. Since

$$2H(0) + 0(g) = H_2O(g) \qquad (7)$$

for which the equilibrium constant is K_{H_2O}, then

$$P(H_2O) = K_{H_2O}\, P(H)^2\, P(0) \qquad (8)$$

Thus a series of mass-balance equations analogous to (6) can be written, one for each element being considered, and expressed in terms of the pressures of monoatomic elements using equations analogous to (8). The result is a series of irregular polynomial equations which can be solved simultaneously using numerical methods, usually that of Newton-Raphson. When the pressure for a given species exceeds the vapour pressure of that species in the solid form, condensation occurs and the A(E) term, A(0) in the above example, has to be adjusted to allow for the fraction condensed. The P(E) term then becomes equal to the vapour pressure, or activity multiplied by vapour pressure if the condensate goes into solid solution with an earlier-formed solid. Fig. 6 describes the equilibrium pathways, thus calculated, for a gas of solar composition. At high temperatures the stable solids are a number of mineral phases rich in refractory elements. At moderate temperatures metal and the major magnesian minerals appear, while at 700-500 K minerals of more volatile elements become stable and metal reacts with H_2O and H_2S in the nebular gases to form sulphides and oxides. At still lower temperatures carbonaceous compounds and ices become stable.

There are several ways in which small deviations from equilibrium should be expected. One is that physical processes probably occur which move solids with respect to gases, and the removal of solids as they form could change subsequent reaction pathways. At low temperatures, departures from equilibrium are to be expected due to kinetic difficulties. There is also the possibility that solids which formed at one temperature (and location) could be mixed with those which formed at other temperatures. For example, "high temperature" products such as CAI, or the reduced mineral phases in enstatite chondrites, appear to have been mixed with "low-temperature" (highly oxidised, volatile-rich) material in CV and E chondrites, respectively (Sears, 1980).

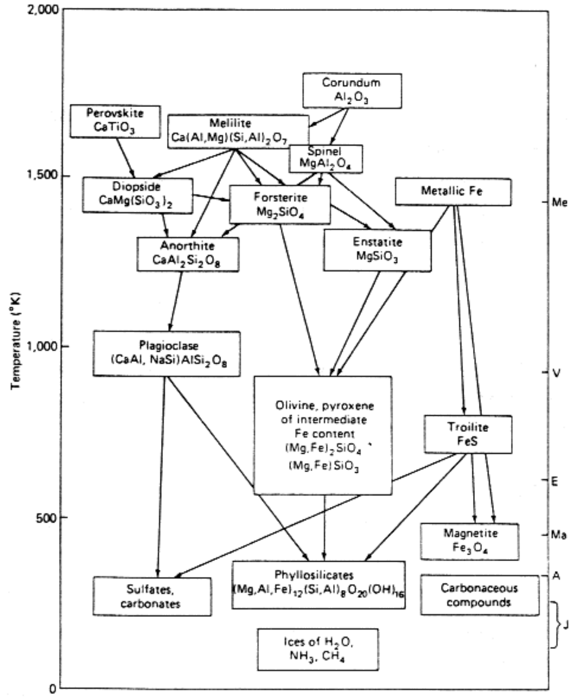

Fig. 6 Sketch of the equilibrium condensation pathways in a gas of cosmic composition. The first solids to form are refractory-rich, then a major phase of condensation occurs which produces metal and Mg-silicates. At lower temperatures, H_2S and H_2O react with metal, carbonaceous compounds form, probably by non-equilibrium methods, and eventually water, methane and ammonia ice form. Equilibrium thermodynamics provides a means of explaining the Mg/Si and Fe/Si fractionations in chondrites and their relative oxidation states since removal of high temperature condensation could produce the Mg/Si and Ca/Si trends in Fig. 2 and separation of metal and silicate just before or during oxidation could produce the Fe/Si in oxidation state trends in Fig. 3. (Figure from Wood, 1979.)

As far as the formation of the nine chondrite chemical classes are concerned several points stand out very clearly: (1) the considerable range of mineral compositions present under various conditions closely parallels the range observed in the various chondrite classes; (2) the opportunity for separating non-volatile lithophile elements in order to achieve the differences between enstatite, ordinary and carbonaceous chondrites is possible through the removal of high-temperature condensates; (3) metal and silicates co-exist over a considerable temperature range, which include the temperatures over which oxidation occurs, so that it is possible to separate silicates and metal without any change in the oxidation state of the metal (as in the EH and EL chondrites) or with correlated changes in oxidation state and Fe/Si (as in the H, L, and LL chondrites). The scenarios of the kind described by Wood (1985, 1987) and Safronov and Vitjazev (1986), involving a number of isolated high-energy events, almost certainly account for the chondrules and perhaps have relevance to the formation of CAI. However, equilibrium thermodynamic calculations provide the most straight-forward and successful means of understanding the most fundamental properties of chondrites; that they are essentially solar in composition, but with subtle fractionations in major non-volatile elements and oxidation state which were not due to a simple single process.

The predictions of equilibrium thermodynamics are slightly pressure-dependent. Fig. 7 is a plot of temperature against pressure for the major condensation reactions shown in Fig. 6.

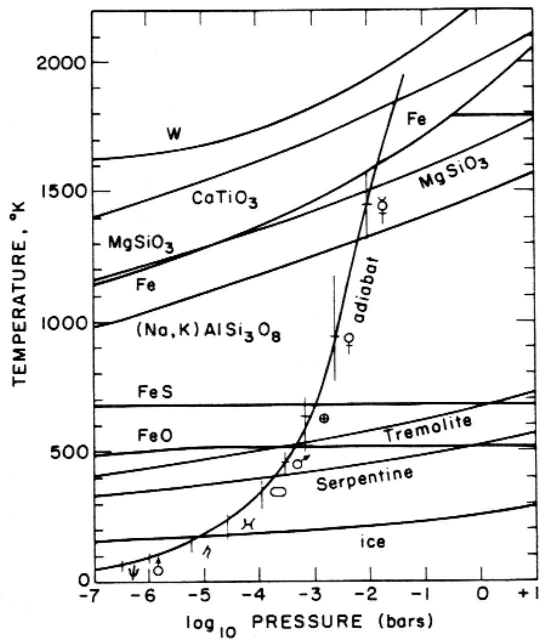

Fig. 7 Condensation (or reaction) temperatures as a function of pressure for phases in a condensing nebula of solar composition. The curve indicated W represents a number of refractory elements and oxides (e.g. Os, Sc_2O_3, and ZrO_2), while $CaTiO_3$ resembles the curves for Al, V, U, Th and the rare-earths. The horizontal line at 1790 K refers to the melting point of iron; above this liquid Fe forms. The adiabat is that predicted by a low-mass primordial solar nebula (from Cameron, 1973), along which are indicated the positions at which the predicted condensates have densities comparable to the planets and asteroids (Lewis, 1974). (Figure from Barshay and Lewis, 1976.)

Except for the oxidation and "sulphurisation" reactions, most reactions occur at higher temperatures under higher pressures. The data in Fig. 7 were used by Lewis (1974) to explain planetary densities. Assuming an adiabat appropriate to the low-mass solar nebula (taken from Cameron, 1973), the predicted densities of the condensates match very closely those of the terrestrial planets and the satellites of the major planets.

Predicted Pressures and Temperatures

Fig. 8 shows the temperature gradients for several theoretical models, including that deduced by Lewis (1974) from condensation theory and planetary densities. All models predict that photospheric temperatures fell from a few thousand degrees near the Sun to less than 100 degrees several AU away, and mid-plane temperatures would have been greater by a factor of ~2. There is good agreement between the temperature estimates based on thermodynamics with those based on planetary composition by Lewis (1974).

Meteorite Parent Bodies - Evidence for Structure, Number and Size

It is clear that prior to their fall to earth, meteorites were parts of much larger objects (meteorite parent bodies). It was presumably while on these larger objects that they experienced the elevated temperatures responsible for the metamorphism and contact with liquid water responsible for the aqueous alteration. Brecciation and shock are also processes associated with parent body surfaces and break-up. Evidence for such parent objects is strong.

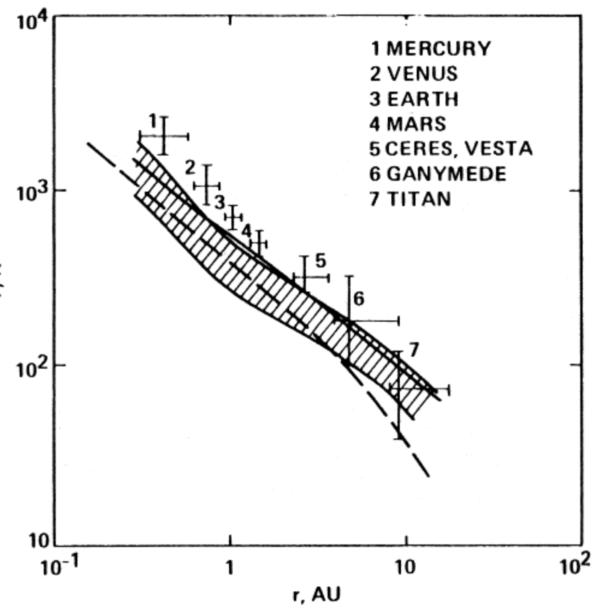

Fig. 8 Temperature profiles predicted by three low-mass nebula models and formation temperatures for the planets and asteroids inferred by Lewis (1974) from the compositions of the planets. The three profiles (solid line, Lin, 1984; dashed line, Cassen and Summers, 1983; shaded region, Morfill, 1983) model viscosity in different ways but predict very similar temperature profiles. (Figure from Casson, et al., 1985.)

First, meteorite cosmic ray exposure ages are very much less than their formation ages, showing that for most of their existence, meteorites were part of larger bodies so that they could be shielded from cosmic rays. Secondly, meteorites of a given class sometimes show a preference for a particular cosmic ray exposure age, showing that they became exposed to cosmic rays at the same time; the best example is probably the H chondrites, a significant proportion of which have 4 Ma cosmic ray exposure ages. Third, one third of the L chondrites suffered a major shock reheating 500 Ma ago, as indicated by the large number of L chondrites with ages around this value.

It can also be argued that compositional data provide evidence for several meteorite parent objects. On plots such as the oxygen three-isotope plot, the Ca/Si and Mg/Si plots, and the Urey-Craig diagram, tight clusters are observed which indicate a common or closely related ancestry. Thus there may have been nine discrete chondrite parent bodies.

If extent of metamorphism is related to burial depth, then it is possible to envisage a stratified meteorite parent body with type 6 at the center and type 3 on the surface. Such might be the case, for instance, if the source of heat for metamorphism were the long-lived radioisotopes of U, Th and K and the parent objects were several hundred kilometers in size. Type 6 clasts are found in regolith breccias, indicating that at least some were located near enough to the surface to be excavated without extensive shock. Alternatively, if the $^{26}Al/^{27}Al$ ratio in chondrites at the time of accretion was the same as in CAI, then the ^{26}Al would have been sufficient to cause reheating of 5 km objects and then metamorphic temperatures could reflect amount of ^{26}Al rather than depth.

Comets, Asteroids and Orbits

Only 3 meteorite orbits are known with great precision because accurate orbit determination requires the meteorite's fireball to be photographed from three locations. They have perihelia of 0.8-0.97 and aphelia in or beyond the asteroid belt, similar to Apollo asteroids and short-period comets. A further 40-50 orbits have been estimated from fall times and locations, which are generally similar to the 3 based on photographs (Semenenko, 1975). Such orbits are highly unstable, and in 10^7 a, typically, the objects are thrown onto Venus-crossing orbits where they have a life-time against ejection from the solar system of only 10^5 a (Wetherill, 1975). Apparently, meteorites did not originate with earth crossing orbits, but were placed on them very recently.

It is widely believed that the chondritic meteorites originated in the main asteroid belt, but until recently it was unclear how material could be extracted. Orbital resonances with Jupiter provides one means, but the efficiency is low, suggestive perhaps that only the irons and achondrites were sent to earth this way (Zimmerman and Wetherill, 1973). However Wisdom (1983) recently discovered that "chaotic zones" should have existed, which yield a flux sufficient to account for the chondrites.

Compositional data exist for the asteroids in the form of the spectra of reflected sunlight. It is clear that several compositional classes of asteroids exist; one of the two major classes resemble the C chondrites and many of the smaller classes recently iron, stony-iron and achondrite classes (Chapman, 1976). However, one of the major spectral types and one of the major chondrite classes have no matches and it is unclear how this should be interpreted.

There is little support for the idea of a simple direct link between comets and meteorites. What little is known about comet composition is consistent with bulk chondritic composition, especially if meteorite dust collected in the stratosphere is cometary in origin (Brownlee et al., 1987). However, the complex chemical fractionations observed among chondritic meteorites seem to require inner solar system temperatures (see above), and it seems unlikely that comets could have acquired the abundance of solar wind gases observed in gas-rich chondrites (Anders, 1975; Zimmerman and Wetherill, 1973).

Chemical Changes in a Turbulent Nebula

Morfill (1983, 1985) has pointed out that condensation and evaporation accompanying turbulent movement as material moves from one temperature regime to another could produce major element fractionation of the sort upon which chondrite classifications are based. Morfill assumes that matter falls onto the disk directly and is then thrown outwards by turbulence, but his arguments are equally applicable to material moving radially outwards from the protosun.

Around the protosun there will be a number of concentric "condensation fronts", one for each solid condensate. Their number and the solids involved can be determined from the equilibrium thermodynamic calculations and their location can be estimated from Fig. 6. Condensates moving radially inwards will evaporate, those moving outwards will not, so that significant wide scale chemical heterogeneities in the major elements will result (Fig. 9). Thus behind each condensation front the abundances of elements involved in a given condensate will abruptly rise, the less so for more refractory condensates, and then slowly fall.

The enstatite, ordinary and CV chondrites came from these regions of elemental heterogeneity, the enstatite and ordinary chondrites receiving less than cosmic compliments of Mg relative to Si, while the CV received cosmic Mg/Si but a considerable enhancement in Ca

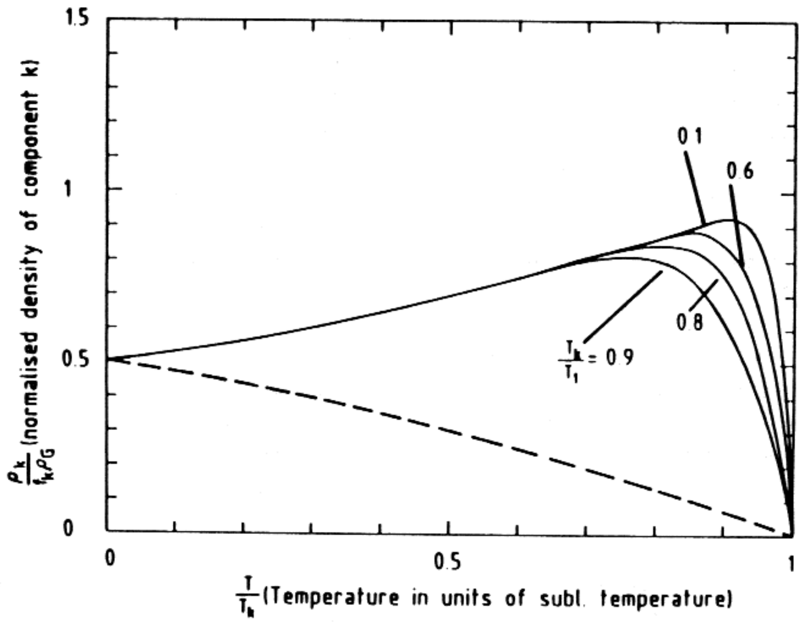

Fig. 9. Abundance of a component (element or compound) k, normalised to cosmic, as a function of nebular temperature (relative to its condensation or sublimation temperature, T_k). The broken line refers to the condensation curve ignoring transport effects. Radial transport enhances abundances at distances where temperatures are just under the sublimation/condensation temperature by an amount dependent on the volatility of the substance; the ration T_k/T_1 refers to the sublimation-condensation temperature relative to that of the most refractory substance. (Figure from Morfill, et al., 1985.)

relative to Si (Fig. 2). The other carbonaceous chondrites suffered only minor changes in composition, CI chondrites receiving a cosmic compliment of most elements. The effects of one condensation front may be superimposed on another, so that the Mg/Si fractionations could be present in material which later became affected by the front at which the oxidation of Fe or the Fe/Si fractionation occurred to give the trends in Figs. 3 and 4.

Morfill argues that the major phases of condensation (formation of metal, Mg-silicates, FeS, Fe_3O_4 and hydrous silicates) may have triggered the formation of Mercury, Venus, Earth and Mars, so the location of each planet reflects the location of the appropriate condensation front. He also points out that certain CAI, with zoned structures suggestive of successive layers of condensation at different temperatures, may be evidence for transport of the sort envisaged. Wood's (1985) argument that CAI have not been transported large distances depends on estimated cooling rates which may reflect a subsequent event experienced by the CAI, rather than its formation.

The oxygen isotope data cannot be interpreted in terms of chemical processes in the primordial solar nebula, but must signal a component in the dust which did not experience the evaporation and homogenization associated with passage through the protosun. The picture created, therefore, is one of essentially a low-mass nebula, with most material accreting to the protosun, with a steady rain of material falling directly to the disk from outside. In other words, the true situation was a mixture of both models shown in Fig. 8, but leaning strongly towards the upper model.

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