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PRECONDENSED MATTER: KEY TO THE EARLY SOLAR SYSTEM*

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Abstract. Chemical and isotopic anomalies in meteorites may be understandable in terms of the chemical fractionation routinely expected in the interstellar medium (ISM). Dust of distinct composition is idealized as being of three types: (1) thermal supernova condensates (SUNOCONS), (2) thermal condensation during other stellar mass-loss processes (STARDUST), and (3) nonthermal sticking processes in cold nebulae (NEBOCONS). Great depletions in ISM of Ca Al Ti are due to SUNOCONS, although STARDUST is about twice as abundant. An abundance table of interstellar SUNOCONS is presented. Parent bodies in the solar system are accumulated directly from the ISM. No hot solar condensation sequence is assumed. Only relatively volatile elements within NEBOCONS are vaporized in the warm solar accretion disk. Variations in the relative amounts of these components during accumulation processes plus subsequent solid chemistry may have produced such chemical anomalies as the meteoritic fractionation patterns and the Ca Al-rich inclusions. Isotopic anomalies result from four processes that selectively site specific isotopes: (1) extinct radioactivities, (2) distinct supernova shells, (3) gas-dust separation, and (4) gas-dust age difference. Planetary accumulation will have been fingerprinted by the chemical state of the ISM if this picture is correct.

1. Introduction

The purpose of this paper is to develop explicit astrophysical details of the following thesis: chemical and isotopic anomalies in primitive solar-system samples reflect routine initial chemical conditions within precondensed matter. No special events are invoked to prepare these initial conditions. The central feature of this theory concerns the chemical state of presolar dust, which I regard as never having been vaporized in the region where the most chemically primitive samples, carbonaceous meteorites, accumulated. I try to take advantage of the fact that this presolar dust is not of an arbitrary and unknowable composition, but rather that many features of its chemical state can already be qualitatively predicted. This is based on previous papers (Clayton, 1975a, b) regarding the role of chemical fractionation during thermal condensation in the expanding interiors of supernovae, where the nuclei of the refractory elements first came into being (cf. Arnett and Clayton, 1970). Small mineral grains precipitating during the initial expansions of this newly synthesized matter have continuously populated the interstellar medium with a component of refractory crystals that are characterizable by a thermal condensation sequence in a cooling gas. As a result, the initial chemical state of heavy atoms during meteoritic and planetary accumulation was distributed between a refractory-mineral component from high-temperature condensation and a volatile component resulting from cold matter adhering to preexisting grains. This bimodal distribution is important for the

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understanding of chemical peculiarities in primitive accumulates. The thermal condensates are also important as carriers of isotopic irregularities of a predictable type. Many of these irregularities have already been discovered, and many more will be. It is this way that the physical state of the precondensed matter provides the key to the origin of the planetary system. The development of this theory is in a series of papers (Clayton, 1975a, b; Clayton, 1967a, b; Clayton and Hoyle, 1976; Clayton and Ramadurai, 1977; Clayton, 1977a, b, c, d, e; Clayton, 1978). In addition to advancing new features of this theory here, I will attempt to lay out the astrophysical picture that guided its construction.

A central controversy concerns the thermal conditions in the solar nebula. Larimer (1967), Larimer and Anders (1967), and Grossman (1972) provided detailed arguments and calculations in favor of the slow cooling of a hot gaseous solar nebula as a way to fractionate elements according to volatility rather than according to other chemical properties. Observed fractionations in meteoritic abundances seems to support that view. For over a decade it has been fashionable to speak of the "high-temperature thermal condensation in the early solar system", and meteoriticists have almost come to refer to it as an established event rather than as a speculative model.

Larson (1969) showed that the hydrodynamic collapse of a protostar remains quite cold and that the early Sun is not very luminous. Cameron (1976) has conducted a modern astrophysical approach to the later evolution of the solar nebula, including an influential study (Cameron, 1973a) of the accumulation processes during collapse, and his models reveal temperatures no hotter than about 500 K for material outside that portion of the disk that ultimately accumulates in Martian orbit. Because I too can find no adequate way to concentrate an adequate energy density, I have preferred to drop the concept of a high-T solar system capable of vaporizing interstellar dust. I have preferred instead to specifically assume that the parent bodies of the carbonaceous meteorites (and even of the ordinary chondrites) were in fact cold accumulations of interstellar dust and gas that have been sufficiently heated in order to obtain their present chemical form. It is the solid chemistry within the initial accumulates that is relevant. The isotopic and chemical state of the precondensed matter is then also relevant.

How can one consider discarding the high-T solar system in the face of the traditional cosmochemical arguments? The key is the existence of *supernova condensates* and other thermal stellar condensates in the interstellar dust. The supernova condensation sequence should produce a large number of refractory-mineral grains, and this component of the later bimodal presolar condensates (PRESOLCONS) can logically replace the thermal condensates assumed from a hot solar nebula. In this spirit, Clayton (1977b) argued that the Ca Al-rich inclusions which bear superficial resemblance to high-T thermal condensates are in fact fused refractory assemblies rich in supernova condensates (SUNOCONS). They are Ca Al Ti-rich because the SUNOCONS themselves are so. The chemical fusion happened in the solar system and the fragments dispersed in such a way as to be found today primarily in C3 meteorites. Our model of Ca Al-rich inclusions as residues is similar to that advanced by Chou *et al.* (1976) with, however, the significant additional argument that the chemical fractionation was expected *ab initio*, so that the thermal conditions

needed to establish the residuals are less demanding than in their model. Chemical fractionation in the ISM according to volatility will emerge from this study as a previously unexplored phenomenon of considerable potential significance. During accumulation in the presolar nebula (Cameron, 1973a), the interstellar grains will gather other more volatile matter and remaining refractory gas as cold mantles that adhere during collisions in the cold nebula, thereby providing a physical separation into volatile and refractory elements as an initial condition. This fractionation will be idealized in terms of four distinct interstellar components. One can then try to interpret the fractionation patterns within meteorites in terms of the degree to which the volatile elements have been retained when the PRESOLCONS accumulated to become meteoritic parent bodies.

This model of a fractionated precondensed solar system was initially suggested by the discovery of the ^{16}O mixing anomaly (R. Clayton *et al.*, 1973) and the ^{22}Ne -rich Ne-E proposed by Black (1972) to be a presolar admixture. Clayton (1975a, b) then argued that these and many other isotopic anomalies should be routinely present in the ISM owing to condensation in the supernova interior during their early expansion, before dilution with the ISM was possible. Supernovae as a possible source of interstellar grains had been suggested by Cernushi *et al.* (1967) and by Hoyle and Wickramasinghe (1970), but it is their relevance to observable phenomena to which I call attention.

The model assumes that fractionation in the ISM can lead to later fractionation in meteorites, the samples we observe. The solar nebula remains cold enough in their region of formation that their parent bodies may be regarded as direct accumulations of cold ISM material. Both isotopic and chemical fractionation can occur naturally as these parent bodies accumulate in different places at different times. The fractions result from gas–dust separation, from fractionation of one type of dust from another, and from fracturing and reheating of volatile mantles. These processes and the transition from parent bodies to today's meteorites must for the present be somewhat unspecific. I will concentrate instead on building a description of fractionated precondensed matter, whose peculiarities offer hope of unlocking the early stages of planetary accumulation.

2. Fractionation in the Interstellar Medium

The interstellar medium (ISM) should *not* be well mixed with respect to chemical fractionation between dust phases and gas phases. Certain species prefer certain physical sites, a preference that arises not only out of chemical propensity but also out of varied circumstances of injection into the ISM. As an example, Ca, Al, and Ti form refractory oxides at such high temperatures (1700 K) that they probably cannot escape condensation in the expansion of the supernova interior where they were synthesized, so they must be found preferentially in interstellar dust. This conclusion has been offered (Clayton, 1977b, c) as an explanation of the very large depletion of Ca, Al, and Ti in the interstellar gas (Spitzer and Jenkins, 1975).

Because Ca resides overwhelmingly in interstellar dust, any physical fractionation of dust from gas can separate Ca from the bulk of the less-depleted elements. Oxygen, on

the other hand, must be largely in volatile forms because the total abundances of oxide-forming refractory metals is at most a few percent of the oxygen abundance. Only hydrogen is abundant enough to condense oxygen, which could therefore be solid within cold portions of the ISM. This ice would probably have to have accumulated in these cold regions, moreover, because thermally condensed (i.e. equilibrium) H_2O from stars will probably be ejected largely as a molecular gas rather than as 'snowflakes'. These two examples adequately illustrate the expectations of severe chemical fractionation among different phases of the ISM.

Examples of isotopic fractionation are well illustrated by the same two elements, O and Ca. Clayton (1975a) observed that the sites for forming the ^{16}O -rich carriers called for by R. Clayton *et al.* (1973) were probably the expansion-cooled supernova interiors. These provide a natural concentration of ^{16}O into the abundant high-T thermal condensates expected from those sites. For Ca, on the other hand, Clayton (1975b, 1977c) observed that its strong condensation propensity should cause $^{40,42}\text{Ca}$ to be mineralogically sited somewhat differently from other Ca isotopes and, even more dramatically, cause ^{41}K to be sited preferentially in Ca-bearing SUNOCONS owing to its explosive nucleosynthesis as a radioactive progenitor, ^{41}Ca ($1.3 \times 10^5 \text{ yr}$). An attempted measurement of this effect on a Ca-rich inclusion revealed no ^{41}Ca -richness (Begemann and Stegmann, 1976). Perhaps the chemistry of that bulk inclusion masks the enrichment, if it exists. Calcium anomalies have, on the other hand, been detected (McCulloch and Wasserburg, 1978) in certain Allende inclusions but not in most. A possible connection between these examples and the ISM requires attention to the following principle: *A description of the ISM must include not only chemical fractionation, but must also specify the isotopic composition of each phase.*

SUNOCONS are not the only high-T thermal condensates of interest in the ISM. Mass loss from other types of stars will also lead to thermal condensation. I call these collectively STARDUST. Woolf (1975) reviewed their general chemical properties and arguments showing that mass loss from giant stars can be an appreciable (perhaps the largest) source of interstellar dust. If these giant mass-shedding stars have undergone thermonuclear evolution, as is likely, the thermal condensates in their lost atmospheres will be enriched in whatever specific nucleosynthetic products of that star that have been mixed to its surface. Many such surface enrichments are observationally known. S stars, Ba stars and C stars reveal large overabundances of s-process nuclei in their atmospheres. Those elements will in those atmospheres be very much enriched in the s-process isotopes, so that dust forming there may fractionate s isotopes from r and p isotopes. Clayton (1968) contains a description of these isotopic designations. One may, for example, regard this as a likely cause of the large $^{202}\text{Hg}/^{196}\text{Hg}$ ratios observed by Jovanovich and Reed (1976) in some meteoritic samples. Consider the light element, carbon, as another example; $^{13}\text{C}/^{12}\text{C}$ ratios as large as 0.2 are seen by stellar spectroscopy in giant carbon stars, so graphite or CO molecules forming there will be some twenty-fold richer in ^{13}C than is average for solar-system carbon. Perhaps they could provide a source for the ^{13}C -richness within CO molecules. These examples illustrate that all sources of fresh ISM components,

along with their isotopic compositions, are needed for an accurate description of chemical fractionation in the ISM.

At the very least, two other considerations are needed to complete this description. It is clear that not all interstellar dust can be high-T thermal condensate during mass ejection from stars. Some interstellar dust, perhaps even most by mass fraction, will have grown because of cold atoms (or ions) and molecules adhering to the surfaces of preexisting dust. This component will not be expected to exist in the form of refractory minerals, but rather as a fluffy cold accumulate. This is true even if the element in question is potentially refractory. For example, Clayton (1977b), in applying these ideas to the chemistry of Mg and Al, reasoned that much interstellar Mg will be injected from supernovae as MgO molecular gas or tiny crystals. When these later accumulate in a dense cold nebula, such MgO will reside along with volatiles in a disequilibrium matrix, whereas perhaps 30% of Mg will reside as refractory MgAl_2O_4 or Mg_2SiO_4 . Interstellar Al, by contrast, should be contained entirely within refractory minerals, because during its nucleosynthesis it is surrounded by much more abundant Mg and O. This distinction may facilitate fractionation of Mg from Al in the formation of the Ca Al-rich inclusions found in Allende and other C3 meteorites (Clayton, 1977a, b, e).

One need not find surviving interstellar grains in order to find evidence of *interstellar grains*. These grains are expected to be small, say 10^{-5} to 10^{-6} cm, so that locating them individually in a meteorite would be difficult even if they had not been modified by the chemistry of accumulation. Even so, if the chemistry of certain small accumulates remains closed, bulk chemical and isotopic anomalies resulting from carrier grains can be preserved in macroscopic samples. The ISM has an ensemble of all these grains and an associated spectrum of chemical and isotopic compositions. Physical fractionation of these grains during their accumulation into larger grains (for example gas/dust fractionation or partial volatilization) can then lead not only to chemical but even to isotopic anomalies in the bulk accumulates. This property makes the theory powerful.

Leaving accumulation processes within the presolar nebula for later, and concentrating on the state of the ISM, we can write the density ρ of interstellar dust as

$$\rho = \rho(\text{SUNOCON}) + \rho(\text{STARDUST}) + \rho(\text{NEBCON}), \quad (1)$$

where SUNOCON is the supernova condensate, STARDUST is thermal condensate formed during mass ejection from other types of stars, and NEBCON is nebular condensate resulting when nebular atoms stick to preexisting grains. Physically the NEBCONS are probably not independent entities but are chemically unequilibrated mantles surrounding thermally condensed cores of STARDUST or SUNOCONS. I let STARDUST represent all thermal condensates in stellar envelopes except for the SUNOCONS, which I designate separately. STARDUST is an ensemble of many types of thermally condensed grains from many types of stars. Some of it, such as is condensed in mass loss from massive Main-Sequence stars, will be condensed in a solar composition and will have chemical and isotopic composition characteristic of the traditional solar condensation sequences (cf. Larimer, 1967). Other STARDUST, such as from highly evolved giants, may bear chemical and isotopic peculiarities.

Fig. 1. A schematic diagram of the structure and composition of a massive star prior to its explosive disruption is shown to the left of the central dashed line, whereas the postexplosion composition is shown on the right. Zones of nuclear evolution are identified by roman numerals, and the preexplosion temperatures and densities are given. The right half divides the explosive ejecta into those nuclear species that simply survive the explosion and those that are actually synthesized within it. The fraction of the postexplosive star, by mass, is for a massive star, $\sim 30 M_{\odot}$. The bulk of the nuclei between $A = 12$ and $A = 60$ are believed to originate in such stars. Figure from Clayton and Woosley (1974).

2.1. SUPERNOVA CONDENSATES

The SUNOCONS are also of many types, owing both to differences among the many supernova that have contributed to galactic nucleosynthesis and to condensation within separate nuclear shells of these supernovae. These shells are illustrated in Figure 1, which represents features of the presupernova structure and of the post-explosion composition of a highly evolved idealized star of perhaps $20 M_{\odot}$ to $60 M_{\odot}$. The presupernova structure has the usual theorist's layer cake: H envelope, He shell, C and O shells, Si shell and growing Ni core. The collapse of the core subsequently causes a shock wave to propagate through this layer cake, and the enhanced burning associated with the elevated post-shock temperature causes the nucleosynthesis products to assume their final form. The cosmochemically interesting species between carbon and nickel in atomic number seem to owe their origin to this explosive burning (Arnett and Clayton, 1970).

Their paper has an introduction to explosive nucleosynthesis, whereas Clayton and Woosley (1974) provide a more specialized review of the nuclear reactions of importance in determining the resulting abundance distributions. The point here is that if these separate zones cool to below 2000 K before they mix, SUNOCONS chemically and isotopically characteristic of each zone will precipitate thermally. The overheated supernova expands hydrodynamically, with the overpressure in each interior layer pushing the overlying layers to higher and higher velocity of expansion. In the absence of mixing instabilities, a velocity profile will be established in the ejected matter, with the outermost layers expanding at 10^4 km s^{-1} as observed in supernovae, whereas the deep burning shells may follow at 10^3 km s^{-1} . As a result, a pronounced radial composition gradient is established in the expanding supernova remnant.

The bulk of the SUNOCON precipitation occurs during the first year when the remnant interior is no more than a few hundred AU in size. The argument of Hoyle and Wickramasinghe (1970) is easy to follow. In the radiation dominated adiabat, the density and temperature fall during the expansion according to $\rho \propto T^3$. Thus an explosive shell at, for example, $\rho = 10^5 \text{ g cm}^{-3}$ and $T = 4 \times 10^9 \text{ K}$ will pass through $T = 2000 \text{ K}$ when $\rho \simeq 10^{-14} \text{ g cm}^{-3}$, or about 10^9 refractory atoms per cm^3 . The density $\rho \propto R^{-3}$, so that R^3 must increase by the factor 10^{19} before thermal condensation commences. If the initial $R_1 = 10^9 \text{ cm}$, the final $R = 10^9 \text{ cm} (10^{19})^{1/3} \simeq 2 \times 10^{15} \text{ cm}$ is reached after a time $R = Vt$, where $V \simeq 10^3 \text{ km s}^{-1}$ is the expansion velocity. This yields $t = 8$ months. Must faster dust growth in novae was advanced as evidence that nucleation can happen this rapidly (Clayton and Hoyle, 1976), whereas kinetic arguments show that the subsequent depletion times are of order one month.

The realization that dust precipitates so quickly encouraged me to present an extended interpretation of extinct radioactivities, suggesting that Xe-X and Ne-E were SUNOCON-carried extinct radioactivities from parents with halflives of a few years (Clayton, 1975a, b). With a different choice of parameters, condensation epochs differing from one year by an order of magnitude in either direction could be realized, but a year may still be a useful physical estimate. It may be, however, that some physical process prevents condensation in supernova interiors. Cameron (1975), apparently also unaware of Hoyle's and Wickramasinghe's (1970) paper, argued specifically that dust would *not* form in supernova ejecta; but later revised his opinion (Cameron and Truran, 1977). His major concern centered on energy input from the underlying pulsar. Lattimer *et al.* (1978), on the other hand, have argued that radioactivity in the ejecta may make grain formation impossible by delaying low temperatures until the density is too low for nucleation. Others have expressed concern over the survival of grains within the shock heating and sputtering in the supernova remnant.

At this point, the problem seems clearly enough in focus. A prescription for the SUNOCON content of the interstellar medium is needed. We need to know the percentage of each chemical element that resides in interstellar SUNOCONS, the chemical identity of the SUNOCONS, and the isotopic composition of that element within each SUNOCON type. I make a first attempt at such a program in this work. The procedure is

illustrated by some facets of the condensates in the explosive-carbon-burning case (Clayton, 1977a, b).

Because carbon burning is believed to be the primary nucleosynthetic source of ^{23}Na , $^{24,25,26}\text{Mg}$, ^{27}Al and $^{29,30}\text{Si}$, I have characterized C-burning ejecta by the solar abundances of these nuclides (except that one-quarter of Mg emerges from partially burned oxygen zones). Si and Ca are, on the other hand, less abundant in this zone relative to their solar values by factors of about 0.12 and 10^{-2} respectively, with the result that the usual silicates and Ca-rich melilite are respectively less important as condensation products than they were in the solar condensation sequences of Grossman (1972). From such condensation sequences, modified by greatly altered abundances of the supernova shells, I interpolated a mineral abundance table. Identification of probable minerals has recently been aided by new calculations (Lattimer *et al.*, 1978) explicitly giving several condensation sequences with peculiar starting abundances as befit the supernova shells. Such equilibrium calculations help to confirm the mineralogy one would expect; however, they do not give realistic final abundances, which are therefore not tabulated by Lattimer *et al.* The shortcoming of equilibrium theory is that it yields only the dominant mineral phases in a system to which chemical equilibrium applies, but it does not indicate when equilibrium fails. The temperature drop between 2000 K requires about one year for the model expansion described earlier, during which time the mass density decreases by a factor 8, and the gas density decreases even faster owing to the depletion into the forming minerals. In such rapidly changing conditions it is not an easy matter to determine the point at which equilibrium ceases to be a valid concept. One might hope to define a freeze-out temperature T_f having the property that the ejected mineralogy is frozen at that temperature because the rate of transmutation to new mineralogy becomes slower than the rate of change of the physical environment. However, calculating such a freeze-out temperature will not be easy, and may not itself be a good approximation even if possible. What will probably be required are dynamic models that follow the grain growth and their changing compositions, explicitly taking into account the rate of diffusion of deposited ions through the solid hot crystals. For example, in the calculations of Grossman (1972) and of Lattimer *et al.* (1978) corundum (Al_2O_3) does not survive, despite being an early condensate. It is instead converted to spinel (MgAl_2O_4) by the subsequent deposition of Mg and O; however, in the actual supernova expansion corundum may survive due to inadequate time for the transmutation to spinel to be completed. Chemical equilibrium offers no guide to that problem. Clayton (1977b) suggested that 2% of the Al is ejected in corundum and 98% in spinel, and his choice of 2% corundum survival was arbitrarily made in order to reproduce with corundum carriers the ^{26}Mg vs. Al/Mg correlation found by Lee *et al.* (1977). That alternative to live ^{26}Al would, if correct, be of importance in constructing a time scale for planetary accumulation, but it is also no way to decide how much corundum can survive.

Simple examination of time scales in the supernova expansion gives no sure clue to what will actually happen. Suppose, for example, that the Al and O are able to nucleate critical clusters of radius $3 \times 10^{-7}\text{cm}$ at a temperature of 1800 K when corundum

condensation becomes thermodynamically favored. An elementary geometrical calculation shows that if all Al atoms stick to these clusters when they strike them, the initial timescale for depletion of Al is approximately $[N_g(\text{cm}^{-3})]^{-1} \text{yr}$, where N_g is the space density of these small clusters. Thus the rate of depletion of Al depends upon a number that is physically hard to predict, namely the density of nucleation clusters of critical mass. Each critical nucleation of radius $a_0 = 3 \times 10^{-7} \text{cm}$ has a mass $3 \times 10^{-19} \text{g}$, which is about 1% the total Al mass density near 1700 K. Thus if $N_g > 10 \text{cm}^{-3}$, the Al will condense rapidly into a large number of small ($a \simeq 1.4 \times 10^{-6} \text{cm}$) corundum crystals, whereas if $N_g < 1 \text{cm}^{-3}$ the Al cannot condense before the Mg would be independently able to condense. The initial time scale for the depletion of Mg will, if the Al_2O_3 has been able to condense the Al, be about a factor of 10 faster. Thus it would appear that the condensible Mg, which is primarily MgAl_2O_4 and Mg_2SiO_4 , will condense rapidly enough if the Al_2O_3 has already done so. But that is in itself not enough to ensure that Mg and O atoms striking the surface of a solid Al_2O_3 grain will be able to convert it to MgAl_2O_4 within the year or so available. Since MgO will not itself condense until Al_2O_3 has done so its deposition maintains a skin on the corundum crystals, and further growth would seem to be regulated by the rate of chemical diffusion of MgO into the solid Al_2O_3 crystal. These are the types of questions that will determine the applicability of equilibrium calculations.

If chemical equilibrium is maintained during the expansion, the Al_2O_3 will not be in the ejecta because it will first have been converted to MgAl_2O_4 and later to other Al-bearing minerals, e.g. Al_2SiO_5 and $\text{NaAlSi}_3\text{O}_8$. The abundances of Na, Al, and each of the three Si isotopes are roughly equal in this shell of ejecta, each being roughly 5% of the Mg abundance. These Al-bearing silicates may be able to command a significant share of the Al when the temperature has fallen to $\sim 1000 \text{K}$ (Lattimer *et al.*, 1978); or conversely, they may not form at all if spinel has been able to trap all of the Al, which may be too immobile in that mineral form to react on the available timescale. There is nothing, other than C and O, abundant enough to condense the bulk of the Mg, on the other hand, so MgO, perhaps MgCO_3 , or Mg will by default be the dominant chemical form for Mg. This is a very significant difference from the solar condensation sequences studied in the past. It may explain why Mg is not as depleted in interstellar gas as are Al and Ca.

It may be premature to discuss the optical consequences of SUNOCONS, but they may be substantial. Relevant to the present discussion, for example, is Duley's (1976) attribution of the broad extinction bump at $2175 \text{\AA}$ to small MgO crystals, whose optical properties have been extensively surveyed in this regard by Huffman (1977); and Gillett *et al.* (1973) attributed all 11.3μ circumstellar feature to MgCO_3 .

The next step in the astrophysical scenario is to see that significant isotopic effects are frozen into these grains. Different explosions of carbon result in different Mg isotopic ratios (Pardo *et al.*, 1974), and a portion of the ^{24}Mg comes from the oxygen shell, so that individual Mg-bearing interstellar grains will differ in composition. However, any macroscopic (say $\gtrsim 0.1 \text{cm}$) accumulation contains many grains, so that the Mg isotopic composition in the SUNOCON portion of the accumulate will reflect its average composition.

This macroscopic average *may be* approximately equal to the isotopic composition of average solar Mg. Since most meteoritic samples measured have shown average Mg, one concludes that either they have equilibrated or else the fluctuations remain so finely distributed that they are not commonly discernible. However, interesting exceptions may persist in detectable ways. Since about 10^{-3} of the ^{26}Mg abundance was initially synthesized as ^{26}Al (Arnett, 1969), the Al-bearing minerals, such as Al_2O_3 or Al_2SiO_5 , will later carry large fractional excesses of ^{26}Mg , whereas the Al-poor phases, such as MgO crystals or Mg gas, will be systematically deficient in that component of ^{26}Mg . The former are potential carriers of the Al-correlated ^{26}Mg excess found in meteoritic minerals, whereas the latter deficiency in ^{26}Mg owing to physical fractionation between gas and refractory dust provides a ^{26}Mg -deficient pool which Clayton (1977b) called a ghost. Because ^{24}Mg from the oxygen shell may be more completely condensed than is the Mg from the carbon shell, the gas-phase Mg may be expected to be ^{24}Mg -poor with respect to average. Fluctuations in the deposition of this gaseous Mg could then produce anomalous macroscopic samples.

One can hardly expect the fast supernova condensation to initially form just those pure minerals identified by equilibrium sequences. A very difficult problem relates to the nucleation (Donn, 1976; Salpeter, 1977) if one considers that the mineral is assembled from molecules of gas. Al_2O_3 is not likely to exist as a gaseous molecule, for example, so that it cannot serve as a monomer for the *mineral* Al_2O_3 , which can only set after a sufficient nucleation and growth of molecule clusters containing Al and O. In the heavily oxidizing environment of zone III, suitable molecules should exist; however, the actual condensation temperature may be a lower one characterized by a sufficient density of some molecule, AlO as likely example, in the gas. At temperatures lower than those normally ascribed to Al_2O_3 condensation, Na, Mg and Si-bearing molecules may mix into the growing molecular paste, whose mineral composition once it is large enough to assume mineral forms will be constrained by the bulk composition of the assembly. The final minerals result from the annealing of nonequilibrium accumulates. For this reason, Al_2SiO_5 and $\text{NaAlSi}_3\text{O}_8$ may eventually be more abundant than the high-T corundum in the ejected condensates. That expectation lead Clayton (1977b) to a predicted correlation between excess ^{26}Mg carried by Mg-free Al and excess $^{29,30}\text{Si}$. Where Clayton (1977a, b) used corundum for prototype 1, one can also use these Al silicates for the charmed- ^{26}Mg carriers, if such a concept is justifiable. One needs only Mg-free condensed Al. Regardless of the validity of that controversial aspect of solar system chemistry, the chemical fractionation of the ISM can lead to isotopic anomalies in the later accumulates. Another example is Si, which is expected to be ^{28}Si -rich in the gas phase because zone-IV Si is less condensed than zone-III Si. Thus gas/dust fluctuations correlate excess ^{28}Si with a deficiency of ^{24}Mg similar to but different from the correlation carried by zone-III Al silicates. This illustrates an important point, namely that there is no single answer to predicted correlations in this model. They depend on the nature of the fractionation.

Clayton (1976b) and Clayton and Ramadurai (1977) first emphasized the important features of the SUNOCONS from zone IV of Figure 1, the explosive-oxygen-burning shell.

Four stages of burning of oxygen important for SUNOCON research can be readily identified from the thorough study by Woosley *et al.* (1973):

(1) Early O burning converts Na, Mg, Al primarily into ^{28}Si and $^{32,33,34}\text{S}$. Ejection before the Mg has been converted, which requires burning less than 1/3 of the O, results primarily in magnesium silicates, MgSiO_3 or Mg_2SiO_4 . Isotopically these SUNOCONS will be enriched in ^{24}Mg and in ^{28}Si . These carriers would produce a positive correlation between ^{24}Mg and ^{28}Si , again in contrast to the examples discussed above.

(2) Intermediate O burning finds Mg exhausted and O converting to Si, S, Ar and Ca, with a small but interesting amount of ^{46}Ti -rich titanium. The latter will be carried in perovskite (CaTiO_3) SUNOCONS, where the Ca is $^{40,42}\text{Ca}$ -rich and the O is, as always, ^{16}O . CaSiO_3 that is very ^{28}Si -rich will be a prominent SUNOCON. Clayton (1977c) studied other SUNOCON aspects of this burning stage.

(3) When more than 75% of O has been burned, the atmosphere becomes sulphurous rather than oxidizing and the iron-group rises in abundance. Clayton and Ramadurai (1977) emphasized the most important aspect of this, the expectation of abundant sulfides in the interstellar medium: CaS , TiS_2 , $(\text{CrFeNi})\text{S}$. This is probably the second-most-significant chemical anomaly likely to be found within the starting condensates for the solar system, because refractory sulfides are virtually nonexistent in the historical hot-gas approach. In that picture sulfides are formed late, when metals react with H_2S , which is assumed to be the dominant form for sulfur.

(4) Exhaustion of oxygen merges into silicon burning, wherein the 4N nuclei ^{28}Si , ^{32}S , ^{36}Ar and ^{40}Ca are slowly rearranged into Cr Fe Ni, much of which will also be ejected in the ^{32}S rich atmosphere. This is shown as zone V of Figure 1. Major SUNOCON components of interest will be $^{40}\text{Ca}^{32}\text{S}$, ^{32}S -rich interstellar 'troilite' FeS , and FeNi metallic droplets. The Fe is ^{54}Fe -rich in early silicon burning.

These few remarks illustrate considerations that guide my construction of an abundance table of interstellar minerals. Fuller nucleosynthetic understanding is to be found in the nucleosynthesis literature previously cited. However, there is one other SUNOCON component to call attention to at this time owing to its potential for illuminating cosmochemical history. These are heavy-noble-metal SUNOCONS. Although the astrophysical site of the rapid-neutron-capture *r* process of heavy element nucleosynthesis is yet to be located with assurance, I take it to be the innermost parts of zone V, where iron-peak nuclei have been neutronized by compression and partially decomposed by heat before reassembling in the rapid expansion. Such a scenario is consistent with the traditional picture of the *r*-process as converting a residual of iron-peak nuclei into heavy neutron-rich nuclei by the rapid addition of free neutrons (Seeger *et al.*, 1965). This material has barely escaped becoming trapped in the collapsed remnant, a neutron star or a black hole. The point of cosmochemical interest is that in the expansion of this material, the normal refractory materials are expected to be absent. Even Fe and Ni have been converted to heavy nuclei, whose relatively small abundances attest to the inefficiency or infrequency of these events. Included in these ejecta is the bulk of the heavy noble metals, Ta, W, Re, Os, Ir, Pt, which, being very refractory, will condense as either pure droplets or alloys of

TABLE I
Interstellar SUNOCON abundance^a (per 10⁵Si atoms from supernovae)

Element Z	(SUNOCON) _{zone} N(Si = 10 ⁶), % of element A ⁱ (Σ ≡ 100%)					
Mg	(MgAl ₂ O ₄) _{III} 3.3 × 10 ⁴ , 3.1% Al ₀ = (0.2, 99.8) Mg = (71, 14, 15)	(Mg ₂ SiO ₄) _{III} 5.3 × 10 ⁴ , 10% Si = (37, 38, 25) Mg = (71, 14, 15)	(MgO) _{III} 2.7 × 10 ⁵ , 26% Mg = (71, 14, 15)	Mg _{III} 2.7 × 10 ⁵ , 26% Mg = (71, 14, 15)	(MgCO ₃) _{III} 1.2 × 10 ⁵ , 11% C = (100, 0) Mg = (71, 14, 15)	(MgSiO ₃) _{IV} 2.6 × 10 ⁵ , 24% Si = (100, 0, 0) Mg = (100, 0, 0)
Al	(Ca ₂ Al ₂ SiO ₇) _{III} 280, 0.7% Al ₀ = (0.2, 99.8) Si = (37, 38, 25) Ca = (19, 19, 19, 19, 0.4, 24)	(Al ₂ SiO ₅) _{III} 4.25 × 10 ³ , 10% Al ₀ = (0.2, 99.8) Si = (37, 38, 25)	(NaAlSi ₂ O ₆) _{III} 8.5 × 10 ³ , 10% Al ₀ = (0.2, 99.8) Si = (37, 38, 25)	(Al ₂ O ₃) _{III} 850, 2% Al ₀ = (0.2, 99.8) Mg = (71, 14, 15)	(MgAl ₂ O ₄) _{III} 3.3 × 10 ⁴ , 77% Al ₀ = (0.2, 99.8) Mg = (71, 14, 15)	
Si	(Mg ₂ SiO ₄) _{III} 5.3 × 10 ⁴ , 5.3% Mg = (71, 14, 15) Si = (37, 38, 25)	(Al ₂ SiO ₅) _{III} 4.25 × 10 ³ , 0.4% Al ₀ = (0.2, 99.8) Si = (37, 38, 25)	(NaAlSi ₂ O ₆) _{III} 8.5 × 10 ³ , 1.7% Al ₀ = (0.2, 99.8) Si = (37, 38, 25)	(SiO + SiO ₂) _{III} 5.1 × 10 ⁴ , 5.1% Si = (37, 38, 25)	(SiO + SiO ₂) _{IV} 1.9 × 10 ⁵ , 19% Si = (100, 0, 0)	(CaSiO ₃) _{IV} 2.3 × 10 ⁴ , 2.3% Ca = (99, 1, 0, 0, 0, 0) Si = (100, 0, 0)
	(SiS ₂) _{IV} 4 × 10 ⁴ , 4% Si = (100, 0, 0) S = (91, 1, 8, 0)	(Si) _{IV} + V 3.1 × 10 ⁵ , 31% Si = (100, 0, 0)	(Fe ₃ Si) _V 5 × 10 ⁴ , 5% Si = (100, 0, 0) Fe = (11, 87, 2, 0)	(MgSiO ₃) _{IV} 2.6 × 10 ⁵ , 26% Mg = (100, 0, 0) Si = (100, 0, 0)		
Ca	(Ca ₂ Al ₂ SiO ₇) _{III} 280, 0.8% Si = (37, 38, 25) Ca = (19, 19, 19, 19, 0.4, 24)	(CaS) _{IV} 2.4 × 10 ⁴ , 33% S = (91, 1, 8, 0) Ca = (97, 0.5, 0, 2.5, 0, 0)	(CaSiO ₃) _{IV} 2.3 × 10 ⁴ , 32% Si = (100, 0, 0) Ca = (99, 1, 0, 0, 0, 0)	(CaS) _V 2.3 × 10 ⁴ , 32% S = (100, 0, 0, 0) Ca = (100, 0, 0, 0, 0, 0)	(CaTiS ₃) 1300, 1.8% S = (100, 0, 0, 0) Ti = (0, 0, 96, 4, 0) Ca = (97, 0, 0, 3, 0, 0)	

Table I (Continued)

Element Z	(SUNOCON) _{zone} $N(\text{Si} \equiv 10^6)$, % of element $A^i(\Sigma = 100\%)$			
S	(SiS ₂) _{IV} 4×10^4 , 16% Si = (100, 0, 0) S = (91, 1, 8, 0)	(CaS) _{IV} 2.4×10^4 , 4.8% Ca = (97, 0.5, 0, 2.5, S = (91, 1, 8, 0)	(CaS) _{IV} 2.3×10^4 , 4.6% Ca = (100, 0, 0, 0, 0) S = (100, 0, 0, 0)	(FeS) _V 1.5×10^5 , 30% Fe = (11, 87, 2, 0) S = (94, 0.5, 5.5, 0)
Ti	(MgTiO ₃) _{III} 427, 15% Mg = Ghost Ti = (0, 47, 0, 18, 35)	(CaTiO ₃) _{IV} 110, 4% Ca = (99, 1, 0, 0, 0, 0) Ti = (100, 0, 0, 0, 0)	(CaTiS ₃ + TiS ₂) _{IV} 110, 4% S = (96, 0.6, 3, 0) Ca = (99, 1, 0, 0, 0, 0) Ti = (100, 0, 0, 0, 0)	(TiS ₂) _V 830, 30% S = (100, 0, 0, 0)
Fe	(FeS) _V 1.5×10^5 , 18% S = (100, 0, 0, 0) Fe = (11, 87, 2, 0)	(Fe ₃ Si) _V 5×10^4 , 18% Si = (100, 0, 0) Fe = (11, 87, 2, 0)	(Fe) _V 5.3×10^5 , 64% Fe = (3, 95, 2, 0)	Ti = (0, 0, 96, 4, 0)

^a These abundances have been theoretically assigned. For dilution by STARDUST, see Section 2.3.

these metals. One is thus led to expect droplets of pure heavy metals, a prediction that I have regretted never having put into print, because El Goresy *et al.* (1977) have now discovered such droplets, which they call *Fremdlinge*, imbedded within Ca Al-rich inclusions of the Allende meteorite. Some droplets appear to be alloys of noble metals, whereas others seem to be nearly pure metal. The SUNOCON concept does not in itself explain the existence of pure noble metals unalloyed with other noble metals, but it may explain why they are not alloyed with FeNi. In the usual solar condensation sequence these metals are not expected in pure form but should condense instead in alloy with much more abundant FeNi, causing it in turn to condense at higher T (Palme and Wlotzka, 1976). If such SUNOCONS do indeed populate the ISM, they will be expected to be deficient in the relatively rare s -process isotopes of these largely r -process metals. Clearly we need isotopic analyses of these noble-metal *Fremdlinge*. Clayton (1978) showed that an average collection of r -process condensates may account for the Ba and Nd anomalies discovered by McCulloch and Wasserburg (1978).

2.2. A SUNOCON ABUNDANCE TABLE FOR THE MAJOR REFRACTORY ELEMENTS

In order to attack cosmogonical consequences of the chemical state of the interstellar medium I have constructed an abundance table of interstellar SUNOCONS. Because there are as yet no *clearly identifiable* abundance data of this type, the table must be a theoretical construction – a ‘theoretician’s sandcastle’. With this caveat also goes the conviction that such a theoretical, and often even arbitrary, construction is scientifically justifiable. Namely: (1) *The logical consequence of this abundance table have analogous consequences for the true abundance table*; (2) *Experimental information concerning the true interstellar composition can be better identified with the aid of a theoretical picture*. Not only the planning of new experiments but also the interpretation of the existing cosmochemical literature can be guided into new discoveries by a relevant model.

Table I lists the abundances N per molecule of major ejecta from supernovae. These are normalized to 10^6 newly synthesized Si atoms. In the next section I will consider the important question of the relative rates of input of refractory elements into the ISM from supernovae and from reinjection by other stars. But for the moment it is important to understand that the Table I abundances are per 10^6 Si atoms that have just come into existence by nucleosynthesis in supernova explosions. Following the abundance N in Table I is the percentage of that particular element to be found in that particular chemical form following explosive nucleosynthesis. For clarification consider the example of $(\text{MgAl}_2\text{O}_4)_{\text{III}}$, the first entry in the Mg row of Table I. The subscript III identifies this SUNOCON as having originated from the nucleosynthesis products of zone III of Figure 1, the explosive-carbon-burning shell of the supernova. The value $N = 3.3 \times 10^4$ molecules of MgAl_2O_4 (despite the technical point that the spinel mineral is not literally composed of such molecules as independent entities) represents 3.1% of all the newly synthesized Mg. Reference to the Al column of Table I shows the same entry, but in this case constituting 77% of all newly synthesized Al.

The remaining entries in Table I give the isotopic composition of the indicated

SUNOCONS. This is especially important, because it is the carriers of anomalous isotopic compositions that may provide experimental indicators of subsequent events. These isotopic compositions have been taken from papers previously cited on recent work in the theory of explosive nucleosynthesis. The SUNOCONS themselves have been identified from the literature pertaining to mineral condensation in a cooling gas (Lord, 1965; Larimer, 1967; Grossman, 1972; Lattimer *et al.*, 1978), modified by our own estimates of how the nonsolar elemental abundances in the nucleosynthesis zones are likely to have effected the unequilibrated residues of key condensates. These judgements were, as previously indicated, very difficult to make in the face of the many uncertainties that confront the entire picture. They are in the nature of suggestions rather than results of a quantitative theory of condensation residues.

One wants an isotopic representation for Equation (1). It can be projected into the form

$$\rho(Z)A(Z) = \sum_i \rho_i(Z)A^i(Z), \quad (2)$$

where i designates the several chemical forms in which element Z is found in the ISM, and A^i is an ordered set ('vector') for each i representing the isotopic composition of the element Z in that i th chemical form. Let $A(Z)$ be a 'unit vector' in the sense that its components sum to unity. Then in the displayed product, $\rho(Z)$ represents the density of species Z and $A(Z)$ its distribution among isotopes. In Table I I actually write these in terms of percentage rather than fraction, so that the components of $A(Z)$ sum to 100%. Equation (2) can be thought of as a complete description of the ISM, or it can be thought of as a description of one component of the ISM. Table I is of the latter type, since only the SUNOCON component is represented in the abundance table. A few examples of isotopic composition follow for clarity. Consider again the Mg row, where the silicon in $(\text{Mg}_2\text{SiO}_4)_{\text{III}}$ has the composition $A(\text{Si}) \equiv \text{Si} = (37, 38, 25)$ which is shorthand for the composition $^{28}\text{Si} = 37\%$, $^{29}\text{Si} = 38\%$, $^{30}\text{Si} = 25\%$. The magnesium isotopic composition is deficient in ^{24}Mg because of my estimate that 30% of ^{24}Mg emerges from the oxygen shell. In $(\text{MgAl}_2\text{O}_4)_{\text{III}}$, by contrast, $\text{Al}_0 = (0.2, 99.8)$ indicates that initially after nucleosynthesis, when the SUNOCONS formed, $^{26}\text{Al}/^{27}\text{Al}$ was 2×10^{-3} (Arnett, 1969; Truran and Cameron, 1978).

One important element, oxygen, does not have its isotopic composition entered in Table I. Interior to zone III the oxygen emerges as pure ^{16}O , so all of the SUNOCONS of Table I contain initially pure ^{16}O at ejection time; however, this purity is diluted by exchange during the slowing down processes in the ISM. I therefore take it that each SUNOCON is ^{16}O -rich but that its oxygen includes those exchange processes that have diluted the ^{16}O . To avoid repetition, it is not listed.

At this stage of theoretical speculation, it is counter-productive to attempt to include all chemical elements in the table. Therefore I have restricted myself to the elements Mg, Al, Si, S, Ca, Ti and Fe. They are the elements that dominate solid cosmochemistry, and provide the key diagnostics of meteorites. Because these elements are so overabundant

in the nucleosynthesis zones where they have originated, there is some reasonable hope of identifying plausible abundances for the key mineral products.

2.3. RELATIVE ABUNDANCE OF SUNOCONS AND STARDUST

The large ($\sim 10^3$) depletions of Ca, Al, and Ti in the ISM (Spitzer and Jenkins, 1975) appear to be associated with condensation in their site of nucleosynthetic origin. With this added concept of SUNOCONS, Clayton (1977a, b, c) enlarged Field's (1974) interpretation of the severe depletions as thermal condensates. The very first environment experienced by Ca, Al and Ti following their nuclear birth is a rapidly cooling dense gas dominated by O, Mg, Si, and S, elements ideally suited for complete condensation of Ca, Al, and Ti. By contrast, Mg and Si cannot condense so completely in refractory forms, because there are no ambient refractories of adequate abundance to do so. Mg and Si differ *ab initio* in their sites of origin, so they cannot condense each other.

Such SUNOCONS in the ISM will be incorporated into the birth of new stellar systems, however, at which time they will be vaporized within the new star. Most of these refractory atoms will be subsequently reinjected into the ISM when their host star becomes an evolved giant and loses a substantial distended atmosphere. At that time, many will again condense into mineral forms. Indeed, to retain the large CaAlTi depletions, those elements must again condense with high efficiency. The difference is that they will condense in different minerals and carry different isotopic composition. I call these secondary condensation sites STARDUST. They are composed of refractory elements thermally condensed in a process of chemical recycling rather than in a process of nucleosynthesis. Taking Ca as a specific representative, one sees that interstellar Ca grains will be of these two types. To create an abundance table for the interstellar medium, one must estimate the relative importance of these two condensation venues.

To this end I will take Salpeter's (1977) estimate that $1.5 M_{\odot} \text{ yr}^{-1}$ are returned from stars to the ISM. Taking the Ca mass fraction to be $X(\text{Ca}) = 8.4 \times 10^{-5} \text{ g g}^{-1}$ leads to the injection of $1.3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ of condensed Ca in the form of STARDUST. The rate of Ca injection from supernovae can be estimated from three lines of reasoning, all of which assume that nucleosynthesis in supernovae is an ongoing process: (1) The average supernova yield required by Clayton's (1973) model for producing a galactic mass of heavy elements is $8.7 \times 10^{-3} M_{\odot} \text{ Ca}$ per supernova, which at a current rate 0.025 yr^{-1} gives $2.2 \times 10^{-4} M_{\odot} \text{ Ca yr}^{-1}$; (2) Assuming that current nucleosynthesis is doubling the interstellar Ca concentration in $5 \times 10^9 \text{ yr}$ leads to $6.8 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ of new Ca; (3) Taking Talbot and Arnett's (1973) self-consistent models as showing that 6×10^{-3} of the matter going into stars emerges as new heavy elements, and taking Salpeter's (1977) estimate of $2 M_{\odot} \text{ yr}^{-1}$ going into stars, leads to $5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ of new Ca. Adopting the middle value as representative, I would construct the abundance table for the complete ISM with

$$\frac{f_{\text{SN}}}{f_*} \equiv \frac{\text{SUNOCON CaAlTi}}{\text{STARDUST CaAlTi}} = \frac{6.8 \times 10^{-5}}{1.3 \times 10^{-4}} \simeq \frac{1}{2}.$$

That is, $f_{\text{SN}} = \frac{1}{3}$ of interstellar Ca resides in SUNOCONS and $f_* = \frac{2}{3}$ resides in STARDUST condensed during mass loss from other types of stars. The reader will appreciate that this simple estimate will not stand up numerically to continuing scrutiny, but the principles I have used to obtain it may find lasting utility.

The estimate seems clear enough for the elements Ca, Al, and Ti, whose very refractory mineral compounds make it likely that they will in fact be injected in condensed forms from all types of stellar mass loss. For other less refractory elements it is likely that the fraction f_{SN} condensed following nucleosynthesis in supernova will differ from the fraction f_* condensed during mass loss. In that case the ratio of refractory thermal condensates for that element will not be $\frac{1}{2}$; however, that ratio may still be taken as the ratio of mass ejection from the separate events. This is true at least for the major species, which are synthesized in their average cosmic abundance ratio in supernovae and ejected in their average cosmic abundance ratio from other types of stellar mass loss. Consider again the important example of Mg to clarify these ideas. Most of it is ejected from supernova zone III as MgO molecules or MgO crystals, because there is in that nucleosynthesis zone no other refractory element abundant enough to condense the Mg. In stellar mass loss, however, Si is equally abundant, so that most of the Mg that is to be condensed can be condensed as magnesium silicates. One sees thereby that for Mg the SUNOCON and STARDUST carriers are chemically distinct. The MgO molecules ejected from supernova will be later dissociated by the interstellar ultraviolet radiation and will therefore be effectively atomic, whereas the MgO crystals may survive as such. In stellar mass loss, on the other hand, the fraction of Mg condensed can be quite variable and difficult to estimate. Cases characterizable by hydrodynamic expansion of an optically thick envelope will condense most of the Mg as silicates, but cases driven by an intense radiation flux through an optically thin envelope may eject Mg in primarily gaseous form. These uncertainties make it difficult to estimate the chemical composition of the Mg ejecta from stars. Nonetheless, because of the average cosmic abundance ratio involved, we may still take it that twice as much Mg is ejected from stars per unit time as is created in supernovae per unit time. Table I, normalized as it is to 10^6 newly synthesized Si nuclei, could be enlarged to include all stellar ejection by adding the chemical abundances representing 2×10^6 Si atoms ejected from stars.

The SUNOCONS and STARDUST are also isotopically distinct. If the isotopes are each synthesized in explosive nucleosynthesis, the total isotopic composition may be the same in both ejecta; however, the isotopic composition of different specific minerals will vary. If one isotope is made elsewhere, say in giant stars, the supernova and stellar ejecta will be isotopically different in bulk. Both cases are expected to occur and lead to observable results. Probably the single most important isotopic example is oxygen. In SUNOCONS interior to zone III it is pure ^{16}O (except for exchange processes after ejection), whereas in evolved red giants one may find ^{17}O and ^{18}O surface enrichments to the isotopically normal oxygen from which that star originally formed. The details of this latter enrichment depend on the extent to which CNO-burning shells have been mixed to the surface and upon the history of stellar mass loss. Such mass loss may yield MgSiO_3

STARDUST, for example, with isotopically normal Mg and Si but $^{17,18}\text{O}$ -enriched oxygen. The chemically identical MgSiO_3 SUNOCON is also expected from zone III (although I chose Mg_2SiO_4 in Table I), and in this case $^{29,30}\text{Si}$ -rich silicon and pure ^{16}O are associated with heavy Mg. Isotopic difference between STARDUST and SUNOCONS is a ubiquitous feature of this theory.

I will not enlarge Table I to include the stellar ejecta. The mineralogy is that identified by condensation in a solar gas (Lord, 1965; Larimer, 1967; Grossman, 1972) and the isotopic composition is normal except for a few specific exceptions such as C and O mentioned previously. Taking 2×10^6 Si atoms in a solar condensation sequence (if the STARDUST is fully condensed) and adding it to the entries of Table I would result in a combined abundance table for supernova ejecta and stellar ejecta. Clearly the sum would be then normalized to 3×10^6 Si atoms. I prefer to leave this step for future research, when more is known of the extent of mineral condensation during stellar mass loss.

2.4. NEBULAR CONDENSATES (NEBCONS)

All of the interstellar solid material does not consist of thermally condensed minerals from stars. At any one time about half of the interstellar medium is to be found in large (10^3 – $10^5 M_\odot$) cold (10 K–100 K) molecule-rich clouds having perhaps 10^3 – 10^5 particles cm^{-3} (Scoville and Solomon, 1975; Burton and Gordon, 1976). Since exchange between the rare phase of the ISM and dense clouds is a common feature of galactic evolution, the average grain or particle spends about half its life in the rare ISM and half its life in the dense clouds. Simple collision rates then indicate that many more atoms and molecules should strike grains in the dense clouds than in the rare ISM; i.e. the dust should be expected to grow in primarily the dense clouds. Watson (1975) has argued that the average time required for an interstellar atom to strike a grain is $t_a \approx (10^9 \text{ cm}^{-3}/n_{\text{H}}) \text{ yr}$, so that whenever $n_{\text{H}} \geq 10^2$ all atoms will strike grains within the roughly 10^7 yr lifetime probably applicable to the dense cloud. Since the temperatures are so low, most species will be expected to be found in solid forms there if they stick to the grains. The resulting condensate should bear little resemblance to a high-T mineral. Ices and hydrocarbons and fluffy snowflake-like structures should be common. I call these nebular condensates, or NEBCONS.

Salpeter (1977) has reviewed these numbers to conclude that the the rate of NEBCON growth may be about 10^3 times greater than the rate of growth of high-T thermal condensates in stars. We may therefore expect that $\rho(\text{NEBCONS}) \gg \rho(\text{STARDUST})$ in the decomposition suggested by Equation (1). We should not, however, conclude from this that the NEBCONS contain most of the very refractory elements. The ISM is highly depleted in these very refractory elements, so even if the condensible gas does adhere to grains in the dense clouds, there was little of the refractory atoms to be condensed in the first place. They had already been substantially condensed following their nucleosynthesis in supernovae and following their ejection from stars. For this reason, most Ca, Al and Ti is probably in SUNOCONS and STARDUST. Most Ar, at another extreme, will be in NEBCONS or remain in the gas. The other elements lie between these limits. For an

arbitrary major element like Si, which is not expected to be totally condensed within SUNOCONS and STARDUST, it may be a long and difficult problem to determine the relative amount of Si in NEBCONS.

Snow (1975) has argued that, for some elements at least, much of the depletion does occur in the ISM; he presents evidence suggesting that the greatest depletions occur in the densest portions of the ISM. Snow also suggests that such growth of NEBCONS may be more influenced by ionization potentials than by thermal chemistry. The existence of this effect, and even the sign of the charge to be expected on grains, is not clear, but such physical considerations may play a role in physical fractionation of the NEBCON component.

The cosmochemically significant distinction concerning the NEBCONS is that they can be evaporated at relatively low temperature. Since they formed by sticking processes when cold atoms strike cold grains, the fragile low-T structures created can probably be evaporated by returning the NEBCONS to higher temperature. If the grains are heated to several hundreds of degrees around forming stars, for example, the NEBCON component will partially evaporate. The actual chemistry of such processes will of course be very complicated. A SiO molecule for example, that previously had stuck to a cold growing NEBCON may not evaporate when the icy matrix in which it is imbedded does so. New mineral forms will undoubtedly be generated by such processing. But the key cosmochemical point is that *the ISM is fractionated with respect to volatile and refractory elements*. Even when all elements have been condensed, a volatile element (Pb, say) will be predominantly in the NEBCON phase whereas a refractory element (Ca, say) will be primarily in SUNOCONS and STARDUST. Any process separating SUNOCONS from NEBCONS will separate Ca from Pb.

3. Solar-System Chemical Anomalies

An *anomaly*, chemical or isotopic, is not an absolute concept; it exists only in relation to a man-made picture. An anomaly is a fact that cannot be understood with respect to that picture. In that sense I may be close to current practice by defining chemical and isotopic anomalies as facts that cannot be, at least easily, understood within a picture of an initially hot homogeneous gas. These 'anomalies' are here interpreted as fundamental data of the accumulation processes.

3.1. ACCUMULATION PROCESSES IN THE PRESOLAR NEBULA

I will assume that the solar system was born during a fragmentation process associated with the gravitational collapse of a typical cold interstellar cloud. The initial compression that caused the cloud to be unstable against collapse is assumed to be whatever natural process nature has used most often for that star-formation instability, *e.g.* compression by density waves, as the leading candidate. During the dynamics of collapse, the temperature maintains the low value near 10 K (Larson, 1969), although it will later be heated to values near 100 K by the standing shock wave surrounding the pressure-supported central

regions. The nebula, in short, begins and remains cold. Within this very picture, augmented by the important argument that the early nebula is turbulent, Cameron (1973a) has presented a thorough discussion of the process by which particles accumulate into larger bodies. I adopt Cameron's description as the basic model within which early solar-system chemistry can be analyzed. The only feature I have added, albeit a decisive feature, is the intense chemical fractionation of the ISM as outlined in the previous section. I take matter to be of four forms: GAS, NEBCONS, STARDUST, and SUNOCONS. The distribution of chemical elements and their isotopes among these forms is the initial condition that may provide a key to unlocking the accumulation of planetary systems.

I summarize Cameron's detailed analysis into four stages: (1) In the very beginning stages of collapse, the condensible atoms in the gas adhere to preexisting grains; this amounts to growing larger NEBCON mantles on the dust. This is the last stage at which the solid particles could be referred to as interstellar dust, but I prefer calling these pre-solar condensates PRESOLCONS. The PRESOLCONS are the spectrum of solid particles at the time when the easily condensible chemical species have been removed from the gas phase. (2) Owing to the turbulence, grains from one turbulent cell are propelled against grains from colliding cells, leading to growth of mm-to-cm sized accumulates of PRESOLCONS. The first stages of this accumulation may overlap to some degree the last stages of gas depletion, so that within the accumulates the relative amounts of NEBCON, including trapped solar gas, STARDUST, and SUNOCON may be variable. This physical fractionation may be quite important, because the *average* PRESOLCON accumulate will by definition have average solar abundances for the totally condensed elements, but individual PRESOLCON accumulates may reveal fluctuations from that average. (3) The PRESOLCON accumulates of cm size can rather quickly settle through the gas to a concentration in a disk. A physical sorting mechanism not discussed by Cameron is the faster settling of larger accumulates, so that if they have different average chemical composition than the smaller ones; another dynamical mechanism for chemical fractionation results. (4) The gravitational instabilities of such a solid-particle disk quickly cluster the smaller accumulates into planetary, cometary or meteoritic masses (Goldreich and Ward, 1973). The onset of this instability will overlap the termination of the settling process, so that the first massive clustering may preferentially contain the larger PRESOLCON accumulates.

The competition between depletion of the gas phase and accumulation of grains into grain clusters leads to one of the solar fractionations – the fraction f_A of the condensed nuclide that was from the beginning already condensed in interstellar dust. The fraction of a condensed volatile nuclide that was already condensed in interstellar dust will fall in time to a low value as the bulk of that volatile species is depleted from the interstellar gas, whereas the initially condensed component of a more refractory species falls to only a moderate fraction of the total abundance (cf. Figure 1 of Clayton, 1975a). The precondensed fraction of Ca, Al, and Ti will remain near unity because such a small fraction of these elements remains to be depleted from the gas. Gradients in both time and space play a role in these depletion fractions. Thermal effects may be important in the continued condensation of the more volatile species, because, although the early collapse is

quite cold, higher temperatures can arise as the viscous accreting disk becomes opaque to its own radiation. Cameron's (1976) model estimate is that outside the asteroid belt the temperature was never higher than about 300 K. Viscous dissipation is the major heat source.

Volatile-refractory fractionation is achieved by any dynamic process that alters the average ratio of NEBCONS to the STARDUST and SUNOCONS. Space and time gradients in gas/dust ratio are the simplest possibility. Another may be turbulence-driven grain-grain collisions that might conceivably fracture volatile NEBCON mantles, partially dispersing them, and leaving refractory cores sticking together. Cameron (1973a) has estimated that these collisions occur with relative velocities ranging from tens of meters per second in initial collapse phases to 10^3 m s^{-1} in later convection zones. Other possibilities lie in the rapid accumulation of parent bodies by gravitational instabilities in the disk. Collisionally dispersed NEBCON mantles may not then have time to recondense before numerous refractory cores have quickly come together in a collective process.

3.2. CHEMICAL ANOMALIES

Whether some primitive accumulates remain today, as perhaps in carbonaceous chondrites, or whether they have all been chemically modified by internal temperature within accumulated solids, there exist chemical facts that are hard to understand with the usual model of a thermal solar condensation sequence. Let us briefly look at some of the most important of these, in no particular order.

(1) Gypsum: In the most primitive C1 meteorites, much of the element Ca appears as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). This is not easily understandable in the hot solar-system condensation model (Wood, 1975), where all Ca is immediately locked up as oxides. But Table I shows CaS to be the dominant SUNOCON, which may be accumulated, oxidized to a sulphate, and hydrated even in a cold solar system. It would then be an alteration product of a different type than in the usual picture.

(2) Magnetite: Fe_3O_4 is common in carbonaceous chondrites. Wood (1975) has argued that the Ni-free nature of this magnetite argues against oxidation of metallic FeNi alloys and in favor of low-temperature condensation from a vapor. This may be possible in a cold solar system, wherein Fe gas may condense directly as such an oxide. The gaseous Fe might be that which existed before it was depleted onto NEBCONS in the cold cloud, or it may more likely have been regenerated by vaporization of cold mantles in the warm disk. On the other hand, magnetite may be a complicated alteration product of little relevance here.

(3) Refractory-element abundance patterns: Ca, Al, and Ti and several refractory trace elements are depleted in ordinary and enstatite chondrites relative to carbonaceous chondrites by mean factors of 0.69 and 0.50 respectively. Instead of the usual interpretation (Larimer and Anders, 1970), it seems simpler to assume that the carbonaceous chondrites accumulated with a higher SUNOCON/NEBCON ratio, perhaps by accumulating in a different time and plane than the ordinary chondrites.

(4) CaAl-rich inclusions: Clayton (1977b, e) argued for fusing the high-T condensates

already present within interstellar grains. A fast process of this type also allows survival of isotopic anomalies that have been found in these inclusions and for their enrichment by factors of 10 to 24 (Grossman, 1973) in the refractory heavy trace elements, which remained through the sudden heating event that fused the inclusions. Many refractory noble metals even appear as very small droplets, or *Fremdlinge* (El Goresy *et al.*, 1977), that were trapped within the major fusing minerals. The principal astrophysical problem remains that of clarifying the nature of the heating event, which had to be sudden enough to avoid isotopic equilibration in a melt. Clayton (1977b, e) suggested high speed collisions of PRESOLCON accumulates accelerated by the gravitational field of accumulating protoplanets.

(5) Layer-lattice silicates: Wood (1975) called attention to the inability of forming the layer-lattice silicates, which are the chief minerals of the C1 and C2 chondrites, in a condensation sequence within a hot gas of solar elemental abundances. Perhaps their formation as alteration products happens more naturally in a heated assembly of dust with NEBCON icy mantles than in a hot solar system.

(6) 'Planetary' and 'solar' noble gas abundance patterns: Signer and Suess (1963) showed that two components of noble gas abundance patterns occur in meteorites. One is close to solar composition and is generally regarded as having been implanted by solar wind into the soil of a meteorite parent body. The other type is strongly fractionated in elemental abundances, like the Earth's atmosphere, and is therefore called 'planetary'. The very cold but turbulent conditions leading to accumulation processes in the early solar nebula (Cameron, 1973a) offers a new chance to understand these patterns. I suggest the following: the turbulent motion of grains through the nebula may have allowed implantation of the solar component; in any case, the heavy noble gases (Ar, Kr, Xe) are partially condensed, and therefore strongly fractionated from He and Ne, at the very cold (10 K) temperatures found in the early stages of accumulation. A portion of this condensed Ar, Kr, Xe was not outgassed until internal *protoplanetary* atmospheres were formed. The actual chemical carriers of these planetary gases in the meteorites may have been formed in a parent body after first being brought there by the PRESOLCONS. A large internal atmosphere of planetary gases may be freed by a modest heat of accumulation, only to be trapped again in new minerals forming in the presence of this internal atmosphere. *The present carriers of presolar noble-gas patterns do not themselves have to be presolar.*

(7) Refractory-volatile abundance patterns: Larimer and Anders (1967) showed that the abundances of whole classes of elements in meteorites cluster into volatility groups. Instead of a condensation sequence in the solar system, these patterns may represent physical fluctuations in the ratio of NEBCONS, which carry the most volatile elements, and SUNOCONS and STARDUST, which carry part of the moderately volatile elements (cf. Wai and Wasson, 1977; Anders 1977). In a solar system in which accumulation is very cold, it seems that one must rely on the chemical fractionation that naturally exists in the ISM or in reheating events at some later stage. The 'mysterite' which Higuchi *et al.* (1977) describe as a late condensate in a solar condensation sequence is in my view an

accumulation rich in the NEBCON component. Concentration in the NEBCON component can also explain the striking correlation between the two chemically dissimilar elements In and Xe, as discovered by Tandon and Wasson (1967).

(8) Rare-earth abundance patterns: Boynton (1975) has demonstrated that very peculiar abundance patterns were generated in the rare-earth elements. These patterns are probably impossible to achieve starting with a homogeneous solar gas. A highly fractionated initial condition offers more opportunities for expecting differing rare-earth patterns in different chemical components of the cold nebula.

(9) Enstatite meteorites: It has always been a problem to account for these relatively reduced meteorites in a solar nebula beginning as a hot homogeneous gas. Much chemical variety exists in the nebula; for example, sulfides are common in place of oxides, and metallic FeNi droplets are also common. Cold accumulation offers many opportunities for avoiding oxidation. These same observations are also relevant to discussions of the initial state of Fe oxidation when considering the Earth's core.

(10) Carbonaceous compounds and life: The carbonaceous material that gives the carbonaceous chondrites their name is largely a complex mix of organic compounds. The origin of these compounds is unclear, but Anders *et al.* (1973) regard them as having been very late products of a chemistry that became possible once the initially hot and gaseous solar system had cooled sufficiently. With that physical model the carbon begins as the stable diatomic molecule CO. If the solar nebula was actually never hotter than 300–600 K, most of these organic compounds may instead be survivors from the interstellar medium which is rich in organic molecules (Zuckerman and Palmer, 1974). Organic molecules should adhere as a NEBCON component to preexisting grains. Greenberg has speculated that the polymerizing effect of interstellar ultraviolet radiation will result in a series of 'oily plastics' in the grains. It seems possible that such phenomena are the origins of the meteoritic carbonaceous material.

Hoyle and Wickramasinghe (1977) have discussed the possibility that a primitive life could evolve in the ISM from the formation and destruction of clumps of grains coated with organic polymers. The possibility must therefore be faced that not only our atoms but also the seeds of our organic complexity could be survivors of the intense unequilibrated fractionations of the ISM.

3.3. ISOTOPIC ANOMALIES

While the cold ISM accumulated in the protosolar nebula, fractionation in the relative amounts of GAS, NEBCON, STARDUST and SUNOCON occurred. Each of these components of the ISM is characterized by its own isotopic composition, so that these fluctuations lead to isotopic anomalies even though a macroscopic collection of all condensibles must by definition possess the average isotopic composition of the solar system. Rewriting Equation (2) for the average isotopic composition of element Z in the ISM gives

$$\rho(Z)\langle A(Z) \rangle = \sum_i \rho_i(Z) A^i(Z), \quad (3)$$

where the sum i is now over the four phases of the ISM listed above and $\langle \mathbf{A}(Z) \rangle$ is its average isotopic composition.

The usual approach to isotopic anomalies is to postulate some special event that effectively adds a specific component to an otherwise homogeneous solar system. My approach is to interpret the anomalies in terms of variations in the fractional abundance $f_i(Z) = \rho_i(Z)/\rho(Z)$ of basic phases. In this view of the early solar system, no special event is to be postulated until its need is specifically demonstrated. I adopt the view (Clayton, 1977a) that presolar carriers constitute the single best explanation of isotopic anomalies, and I attempt to utilize it as the *only* explanation. Only to the degree that it demonstrably fails does one require one of the special-event models – an energetic solar-particle irradiation (Fowler *et al.*, 1962; Heymann and Diczkaniec, 1976; D. Clayton *et al.*, 1977) or a supernova trigger for the formation of the solar system (Cameron, 1962; Cameron and Truran, 1977; Clayton, 1977a). This choice provides the simplest explanation, namely that the isotopic anomalies result from the natural initial conditions expected for accumulation processes. Then, in terms of the fluctuations f_i in the relative densities we have

$$\langle \mathbf{A}(Z) \rangle + \delta \mathbf{A}(Z) = \sum_i \mathbf{A}^i(Z) [\langle f_i(Z) \rangle + \delta f_i], \quad (4)$$

where $\langle f_i(Z) \rangle$ is the average fractional concentration of element Z in phase i , and $\delta \mathbf{A}(Z)$ and δf_i are fluctuations about the average resulting from a fractionation in the assembly of the four components. The first terms on the left- and right-hand sides formally cancel. For each isotope, here designated as a component of the vector $\mathbf{A}$, the fractional anomaly that results is given by $\delta A / \langle A \rangle$. Since by definition $\sum_i f_i = 1$, we have also the normalization $\sum_i \delta f_i = 0$. However, when each δf_i is weighted by the anomalous isotopic composition $\mathbf{A}^i$ of phase i , sizeable bulk anomalies result. The anomalies so far detected are mostly of order $\delta A / \langle A \rangle \simeq 10^{-3}$ to 10^{-2} in magnitude, although ^{16}O anomalies are as large as 5×10^{-2} (R. Clayton *et al.*, 1977), xenon anomalies are as big as unity in the chemical separations discovered by Lewis *et al.*, (1975), and $\delta^{22}\text{Ne}$ in the Ne-E suggested by Black (1972) as having been carried in unvaporized presolar grains is about a factor of eight.

Equation (4) is intended to describe a PRESOLCON accumulate, perhaps a first-generation planetesimal. It need not describe inclusions in which most anomalies have been found or any other sample currently in our terrestrial laboratories, because it does not include any subsequent chemistry that has modified the accumulate. This reservation can be illustrated by the Ca-rich inclusions. These samples are clearly NEBCON-deficient, but they may be so either because NEBCONS were deficient in the accumulates or because the NEBCON component was vaporized or otherwise lost by the heating event. In either case Equation (4) may apply, but in the second case the heating event can not remove or dilute *exactly* the NEBCON component. Clearly chemical effects will play a role in a heating event, so that volatility and presolar history cannot be the whole story. This chemistry has the effect of leaving some volatile species (e.g. C1) rich in some inclusions. That problem is, however, less severe for the present model than for one that assumes them to be high-T condensates within a gaseous solar nebula. In either model, a

complicated history of accumulation plus subsequent chemistry is indicated. But the present point is that Equation (4), which describes a bulk accumulation of interstellar components, does not take this subsequent chemistry into account. The inclusions themselves are here suggested to be chemically altered fragments of a disrupted SUNOCON-rich parent body to which Equation (4) was applicable.

Equation (4) is written in terms of the four bulk components i of the ISM; however, the sum over i can be generalized to a more complete description. The relative SUNOCON abundances given in Table I may have been chemically altered in the formation of new minerals. For example, the Si found in Al silicates may be chemically enriched in $(\text{Al}_2\text{SiO}_5)_{\text{III}}$ relative to the Si in $(\text{SiO})_{\text{IV}}$. This would have the effect of chemically rendering those silicates $^{29,30}\text{Si}$ -rich. Those resulting silicates would then have an isotopic anomaly that was carried by SUNOCONS although the sample itself is not a SUNOCON. Fluctuations with respect to the Si in STARDUST and NEBCONS would produce a similar isotopic effect.

There is one case where Equation (4) retains its validity in the face of subsequent chemistry. If an accumulation of PRESOLCONS is heated sufficiently for some chemical reactions, Equation (4) may still apply in bulk if the system evolves *as a closed system*. In that case, each mineral separate of the bulk sample will reflect its chemistry, but the bulk sum may nonetheless show a simpler pattern. A case in point is the coarse-grained inclusions in Allende, which Grossman *et al.*, (1977) find to be uniformly enriched in trace refractory elements even though individual mineral separates show large variations in elemental abundance ratios. This can be understood as if the accumulation processes resulted in a uniform enrichment of refractory elements in a bulk sample, which was then chemically rearranged in a closed system into the samples of coarse-grained inclusion that one studies today. I describe the accumulation as having occurred within a cold precondensed nebula, of course, whereas Grossman *et al.* (1977) describe it within a condensation sequence in a hot solar nebula. If closed-system rearrangement has occurred chemically, isotopic anomalies within mineral separates can still be understood, but less easily than in the case of pure fractionation during accumulation. For example, Clayton (1977a, b) regarded the Al-rich minerals as having fused from SUNOCON grains in such a way that the excess ^{26}Mg could not be diffusively separated from the Al. Such specialized chemistry will need to be studied in great detail if in fact the mineral separates were indeed fused rapidly from a disequibrated collection of interstellar grains.

In the cold accumulation model there appear to be four physical effects that are likely producers of isotopic anomalies:

(1) *Extinct radioactivities*: Condensation in SUNOCONS fractionated short-lived parents ($\tau_{1/2} \gtrsim 1 \text{ yr}$) from the daughter element, resulting in single-spike anomalies in SUNOCON carriers (Clayton, 1975a, b). The mechanism was first advanced to account for already known anomalies in the noble gases, but it also predicted correlations to be explained in terms of ^{26}Al , ^{41}Ca , ^{44}Ti , ^{53}Mn and ^{57}Ni . The xenon interpretations remain controversial, but the ^{22}Na SUNOCON interpretations of Ne-E and the excess ^{40}Ar due to presolar ^{40}K decay (cf. Clayton, 1977c; and Jessberger *et al.*, 1977) provide support for

the mechanism. Perhaps the clearest support would derive from the establishment of the special ^{144}Nd anomaly (Clayton, 1978, study of McCulloch and Wasserburg, 1978). This fractionation would have resulted from the arrest of r -process ejecta at 285d ^{144}Ce . Accurate measurements of Nd capture cross sections are needed to establish this anomaly, however. Additional predictions within the r -process nuclei (Clayton, 1978) allow ample opportunities to confirm this astrophysical process. Lee *et al.* (1978) have detected Ca anomalies which may be related to $^{40}\text{Ca}/^{44}\text{Ca}$ variations (Clayton, 1975b), but the Ca spectrum seems very complex at the present time. It must be appreciated that in this model a ^{44}Ca anomaly from extinct ^{44}Ti should not be expected to correlate with Ti elemental abundance, because, for technical nucleosynthetic reasons, the ^{44}Ti synthesis appears to be separated from that of the more abundant ^{48}Ti . As a result, the ^{44}Ca -rich SUNOCONS are distinct from the major Ti-bearing SUNOCONS.

(2) *Time- and position-dependent gas-dust separations*: In the very early solar nebula the relative densities of gas and dust must have varied both in space and in time. The condensable gas adhered as a NEBCON component, but the relative amount of initial gas and dust will vary in different accumulates. There are specific cases where one expects this fractionation to separate individual isotopes of a given element. Drozd and Podosek (1976) coupled this idea to Clayton's (1975a) advocacy of ^{129}Xe concentration in grains in an attempt to account for the large $^{129}\text{Xe}/^{132}\text{Xe}$ variations in the trapped Xe component. Clayton (1975a) had made a similar interpretation of Xe-X, and Clayton (1975b) extended it to Ar. All the PRESOLCON carriers of noble gases need do is carry their excesses into a sizeable accumulate, where the resulting internal atmosphere will be anomalous. New minerals forming in such a planetesimal will trap the exotic gas, so that the resulting carriers are not necessarily presolar even though they then carry presolar anomalies. Clayton (1977b) extended this concept to other elements important for cosmochemistry, arguing that ^{26}Mg was deficient relative to ^{25}Mg in the gas (a *Ghost*), that $^{87}\text{Sr}/^{86}\text{Sr}$ is augmented in the gas, and that Pb variations between dust and gas are expected. These questions cause one to doubt, as Cameron (1973b) had done on other grounds, that the large time differences inferred for accumulation of differing meteorites are real. It seems likely that gas-dust separation also plays a role in the enhancements of the r -process isotopes of Ba and Nd as discovered by McCulloch and Wasserburg (1978). The s - and r -components of heavy elements are ejected in quite different chemical surroundings, so it is not to be expected that they will be equally condensed in the ISM.

(3) *Average age difference between dust and gas*: Clayton (1975a, 1977b, c) raised the question of the relative ages of nuclei in interstellar gas and interstellar dust. Gas atoms should, averaged over galactic history, more easily escape star-formation than can dust grains, which will concentrate somewhat more in the galactic midplane. If that is so, U and K atoms in dust may be slightly younger than U and K atoms in gas. Because ^{235}U and ^{40}K are short-lived in comparison with the mean age of the nuclei, these two isotopes would then be significantly enhanced in dust. This may be the explanation of the ^{235}U -enhanced meteoritic samples isolated by Arden (1977). These two elements are clearly the best ones for searching for such an effect.

(4) *Condensates within distinct supernova shells*: If the first few months of the hydrodynamic expansion of the supernova interior are sufficiently stable, SUNOCONS will precipitate within distinct shells prior to gaseous mixing. This assumption predicated the construction of Table I. Those SUNOCONS are rife with isotopic anomalies, and if nature has indeed stored them in the ISM, we may expect a rich future for isotopic studies of meteoritic minerals. For example, $(\text{NaAlSi}_2\text{O}_6)_{\text{III}}$ carries positive correlation between $^{26}\text{Mg}^*$ and the two heavy isotopes of silicon, and that correlation can in some cases survive the chemical transformation to meteoritic minerals. Every SUNOCON has similar potential, and that potential is greatly amplified if the condensates actually occur in unmixed shells (Figure 1).

This approach offers hope of understanding new anomalies as they are discovered, and to illustrate that point we consider the new discovery of sulfur anomalies by Rees and Thode (1977). They found that the last 3.5% of sulfur leachable by HCl from samples of Allende was noticeably enriched in ^{33}S . In Table I there are *no* ^{33}S -rich SUNOCONS, in the sense that $^{33}\text{S}/^{32}\text{S}$ is not enriched relative to solar more than $^{34}\text{S}/^{32}\text{S}$ is. In fact, the sum of the SUNOCONS listed contains only about 60% of the solar complement of ^{33}S , whereas it does contain the solar complement of ^{32}S and ^{34}S . This comes about because I listed there only the major forms of each chemical element, which for sulfur arise from zones IV and V. Our analysis of explosive oxygen burning (zone IV) showed that ^{34}S is synthesized more readily than ^{33}S (Woosley *et al.*, 1973). The complement to this set of SUNOCONS are rare phases that must be ^{33}S -rich, and ^{36}S -rich as well. These are to be found in zone III, where Howard *et al.* (1972) showed ^{36}S originated. Pardo, Couch and Arnett (1974) found the sulfur of those zones to be ^{33}S rich, and in fact approaching the solar yield of ^{33}S if the peak explosive temperature is as great as $T_9 = 2.1$, as is likely for some explosions. It therefore is likely that a small part of total S, but a significant part (say 40%) of ^{33}S , was ejected from zone III. This SUNOCON was too rare for inclusion in Table I, but we should search for it in the ejecta of the explosive carbon shell. Perhaps carbonaceous carriers can grow in the carbon ejecta even though simple chemical arguments suggest that all such carbon will be locked up as CO.

4. Summary

I emphasize the chemical fractionation in the interstellar medium as being relevant to primitive objects formed early in the history of the solar system. Correctness of the above picture would establish the following: (1) The elements were indeed synthesized in explosions; otherwise anomalies due to short-lived extinct radioactivities would not be condensible. (2) Major chemical depletions of ISM gas occurred simultaneously with ejection following explosive nucleosynthesis. (3) The heavy elements within the early solar system were never a hot gas, enabling precondensed chemical carriers of isotopic anomalies to survive. (4) Since CaAl-rich inclusions cannot be first condensates from a hot solar nebula, they must instead carry new information about presolar accumulation processes. (5) Chronological restrictions derived from variable initial $^{26}\text{Mg}/^{24}\text{Mg}$, $^{87}\text{Sr}/^{86}\text{Sr}$, $^{207}\text{Pb}/^{206}\text{Pb}$, $^{129}\text{Xe}^*/^{127}\text{I}$, and $^{40}\text{Ar}/^{36}\text{Ar}$ have been eliminated or liberalized.

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