SUPERNOVAE AND THE ORIGIN OF THE SOLAR SYSTEM

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Abstract. This review concentrates on recent ideas involving a relationship between the early solar system and supernova explosions. It summarizes briefly the data that has helped inspire those ideas. Because the true relationship is still unknown and generates controversy, the distinct ideas are introduced singly in the historical context of their origins, and the active sense of surprise and controversy is visible. Quotations from pivotal papers are used as part of the exposition. The subject involves equally the isotopic anomalies detected in meteorites and the dynamic events of galactic evolution, nucleosynthesis, and protosolar collapse. Whatever the correct situation is, new connections have been found between the origin of the elements and the formation of the solar system. The objective of this review is to enable interested space scientists to quickly identify the competing points of view and the experiments and theories that have led to them.

1. Introduction

At first glance it may seem surprising that connections, real or imagined, between supernovae and the origin of the solar system should be one of the most exciting and competitive areas of space science research. Supernovae are, after all, the most violent known heavenly events outside of galactic nuclei and the big bang itself, whereas the stately solar system seems the epitome of good natured permanence. Upon inspection, the connecting threads are many, however, and it will be the purpose of this review to recount them. As we shall see, it is too early to know which connections have truly happened and which serve only as temporary models, destined for discard. Our objective, therefore, will be to attempt a clear discussion of the main themes, acknowledging both their historical origins and hopes for future clarifications.

At least it is poetic that these two great astrophysical topics find a modern unity, because they did share roles, by happenstance, as intellectual stimulants to celebrated aspects of our culture. Tycho Brahe, whose detailed observations of the Martian motions were prerequisites to a dynamical view of the solar system, was stimulated to his astronomical career by the 'new star' which appeared in Cassiopeia in 1572 and which faded from the brightness of Venus to invisibility over the next few years. Tycho's travels through northern Europe after observing and writing about this new star led to the endowment of his observatory at Uraniborg by King Frederick II. Tycho worked there on his observations for twenty-one years, moving finally to Prague in 1597, four years before his death.

Johannes Kepler, whose brilliant insights into planetary motion were the springboard to a modern dynamical theory of the solar system (and were made from Tycho's data), wrote about 'new stars' that appeared in 1600 and in 1604, the latter

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now commonly called 'Kepler's supernova'. This same supernova also gripped Galileo's attention, so that he, the celebrated prototype of the modern scientist, developed also a lifelong interest in astronomy. Unwittingly, supernovae had played thereby a role in mankind's historical understanding of the dynamics that govern today's solar system.

But this review is to be the story of the 1970's, when new types of experimental information have stimulated new connections between supernovae and the days of the birth of our solar system. There have been, in this reviewer's assessment, five main concurrent themes that have dominated this new solar-system science. All have some connection to supernovae. We here list these themes, later to return to their details:

THEME 1. *Radioactive half-lives as clocks for the nucleosynthesis of solar-system nuclei.* This theme has a rich history concerned with the abundances of radioactive species in the solar system and associated implications for the nucleosynthesis history of those nuclei. The extinct radioactivities ^{129}I and ^{244}Pu have in the past decade stimulated many discussions of the rate of nucleosynthesis during the few $\times 10^8$ yr before formation of the solar system. The new evidence that solids existed even before radioactive ^{26}Al, which has the (astronomically speaking) short half life $\tau_{1/2} = 0.72 \times 10^6$ yr, had totally decayed to ^{26}Mg suggested that a neighboring supernova explosion essentially contemporary with the formation of the solar system injected freshly synthesized ^{26}Al into the parent cloud of the solar nebula. This line of reasoning rests on the conclusion that the ^{26}Al was still live when the CaAl-rich inclusions of C3 meteorites were formed. That conclusion rests in turn on an assumption, often unstated and never yet proven, that the Ca Al-rich inclusions in question were once molten so that the Mg isotopes would have been homogeneously equilibrated when the inclusions solidified. The total argument remains the major evidence, perhaps the only evidence, in favor of such a supernova injection. The isotopic counterevidence against, or difficulty with, direct supernova injection is the normality of the isotopic composition of other elements in most of the same CaAl-rich inclusions. The alternative model, if any, to live ^{26}Al injection appears to lie in Theme 2.

THEME 2. *Isotopic anomalies as residuals of presolar interstellar grains.* Isotopically anomalous elements have been found in carbonaceous-meteorite minerals, the most important element being the excess ^{16}O mixed into their refractory minerals. These ^{16}O excesses were interpreted at discovery as perhaps representing a certain type of interstellar grain containing excess ^{16}O that was not vaporized in the solar nebula and that was admixed variably into different meteoritic samples. The supernova connection came from the later realization that condensation within the expanding interiors of past galactic supernovae was potentially the most prolific source of isotopically anomalous interstellar grains. These carriers can cause isotopic anomalies even if the parent cloud has a homogenous bulk composition.

THEME 3. *Bulk Composition fluctuations in the interstellar medium.* Because nucleosynthesis occurs in discrete events, particularly supernovae, fluctuations in the bulk composition of the interstellar medium exist from place to place and from time to time. If mechanisms exist to allow some of these fluctuations to survive even in a mass as small as that destined to become our planetary system, a generator of isotopic anomalies is produced. An alternative is to somehow form macroscopic solids in different volumes of a larger system, say different parts of a massive cold cloud, and to then somehow gather those solids into accumulating solar system samples.

THEME 4. *Depletion of elements from the gas phase of the interstellar medium.* Ultraviolet absorption lines, observed primarily by the *Copernicus* satellite, have confirmed older and less detailed optical observations suggesting that the more refractory elements are less gaseous in the interstellar medium. They are presumably in dust grains instead, since it is unreasonable to suppose that such large abundance variations can be maintained in interstellar gas. By increasingly refractory we will mean having a higher vaporization temperature (the term being also used to mean a higher melting temperature). For example, from vapor pressure data the mineral Al_2O_3 would not vaporize below about 1600 K in the ISM, whereas alkali feldspars (Na, K) $AlSi_3O_8$ would remain condensed only below about 1000 K. These considerations impact questions of correlations of volatility and abundance in meteorites and questions of which presolar grains (in Theme 2) are most likely to survive any hot gaseous state encountered in the solar system.

THEME 5. *Supernova-induced star formation.* Astronomical observations show generally the need of increased external pressures to force diffuse clouds to collapse to the point of gravitational collapse and fragmentation. Leading candidates are galactic spiral shock waves, new H II regions, and supernova ejecta. Evidence for all three exists, and the astronomical observations suggesting that supernovae shock waves have caused star formation elsewhere have added plausability to the suggestion that one has also caused our solar system. These are basically dynamic arguments, but they also impact the problem of isotopic anomalies. The astrophysical context has been much enriched by the recent analyses showing that supernova remnants are even an important hot phase of the general interstellar medium, comprising of order half of its volume. Clayton (1978a) describes the medium succinctly.

These five themes are not mutually exclusive. Indeed, the number of them relevant to the formation of the solar system may lie anywhere between zero and five! General astrophysical scenarios involving blends of these themes are now commonly discussed. But it is useful to recognize these themes, so that any new presentation utilizing them can be seen as the blend it is of ideas that have previously arisen singly. Nor is it possible to set apart discussion of dynamics of the solar formation from the chemical and isotopic evidence that has stimulated these discussions. In one sense, the topic of supernovae and the origin of the solar system is almost the same topic as isotopic anomalies in meteorites, because it is the latter that are spurring astrophysical reexaminations of a subject that has forever tickled mankind's fancy. The main body of this review, therefore, will necessarily move back and forth among these themes and will shift suddenly from astrophysical arguments to chemical anomalies. But that's the way the science is today, and we can only attempt a more orderly appraisal of it than one usually finds in the research papers themselves.

Because much of the chemical evidence comes from isotopic studies of so-called CaAl-rich inclusions from type C3 meteorites, especially Allende, the various themes stated above find correspondence or dual themes in the nature of the origin of these strange and wonderful inclusions. Their history is not known, and certain postulated histories fit better into some astrophysical themes than others. Therefore the debate concerning the astrophysical relevance of supernovae is not really separable from the debate concerning the origin of these inclusions. To begin this review it seems advisable to first examine the basic ideas concerning these samples.

2. The CaAl-Rich Inclusions

The fall of the Allende meteorite in Mexico in 1969 provided the samples that stimulated the discoveries of isotopic anomalies. Today it appears that there is nothing special about Allende except that it provided a very large sample (tons) in good condition of a type 3 carbonaceous chondrite (C3). About 8% by volume of this meteorite consists of white assemblages consisting primarily of very refractory minerals rich in Ca, Al, and Ti (their oxides and silicates). The predominant mineral is the Al-rich melilite called gehlenite ($Ca_2Al_2SiO_7$) containing from 5 to 35 mole percent of the Mg-rich melilite Akermanite ($Ca_2MgSi_2O_7$). Prominent also are nearly-iron-free spinels ($MgAl_2O_4$) and clinopyroxene, either $CaMgSi_2O_6$ or $CaTiAl_2O_6$. Perovskite ($CaTiO_3$) is also a common accessory mineral, particularly if the pyroxenes are not themselves Ti-rich.

In their initial discussion of this important fall, Marvin *et al.* (1970) observed that the enrichment of the refractory elements (Ca, Al, Ti) in these minerals compared to Mg and Si resembles the highest-temperature mineral condensations from a cooling solar gas. These high-T mineral condensates had been identified by Lord (1965) and by Larimer (1967), and they were then recalculated in more detail by Grossman (1972). Grossman (1972 and subsequently) has argued quite strongly that the existence of these inclusions suggests that the solar system began as a hot gas which, upon cooling and condensation, gathered together the first high-T condensates as the basic material of the inclusions. This model has been popular among cosmochemists, who commonly refer to the hot gaseous solar system as an actual event rather than a speculative model. Grossman (1975) classified these inclusions into several common types: (Type A) coarse grained, consisting of 0.1-to-5 mm bodies of melilite, spinel and perovskite; (Type B coarse grained) type B1 are 1–2 cm concentrically zoned bodies with gehlenite mantles enclosing cores of Ti-rich pyroxene, anorthite ($CaAl_2Si_2O_8$), melilite and spinel, and type B2 are 5–10 mm unzoned bodies composed of melilite, Ti-rich pyroxene, anorthite, and spinel; and (Type B fine grained) irregular alkali-rich aggregates up to 5 mm in size containing spinel, perovskite, anorthite, nephaline ($NaAlSiO_4$), sodalite, and pyroxene. Wark and Lovering (1977) have described layered rims enclosing these inclusions and providing important but poorly understood clues to their origin.

When heavy elements present in trace amounts are examined, it is found that the most refractory heavy elements, those that would condense from a cooling gas above about 1400 K, are also enriched in the CaAl-rich inclusions by factors of about 20 or so, and relatively uniformly enriched too (Grossman, 1973; Wänke *et al.*, 1974; Grossman and Ganapathy, 1976). Their uniform enrichment strengthens the identification of the inclusions as being bodies enriched, for whatever reason, in those elements (e.g. Ca, Al, Ta, Ir, etc) that exist in solid forms at temperatures above about 1400 K. A good review of the *chemical argument that this enrichment is explained by the condensation within a hot and gaseous solar nebula* is provided by Grossman and Larimer (1974). Table I (Grossman, 1972) shows the condensation temperatures of major minerals under the assumption of chemical equilibrium within a cooling gas of solar composition and a total pressure of 10^{-3} atmospheres. This condensation sequence does not depend very strongly on the pressure within such a cooling nebula. Reduction of the pressure by a factor of 10 lowers the condensation temperatures by about 100 K. What one sees is that compounds of Ca, Al, and Ti are the first that are able to totally condense. Note that although some Mg and Si are contained in some of these compounds, their total abundance is not great enough to condense much Mg or Si. That awaits condensation of Forsterite (Mg_2SiO_4) near 1440 K, about 200 K cooler than the condensations of Ca, Al, and Ti. The fraction of Si condensed in the various phases is shown in Figure 1. Table 3 of

TABLE I

Condensation of major elements at 10^{-3} atmospheres pressure in a cooling nebula of solar composition[a]

Phase name	Phase formula	Condensation temp. (K)	Phase name	Phase formula	Condensation temp. (K)
Corundum	Al_2O_3	1758	Enstatite	$MgSiO_3$	1349
Perovskite	$CaTiO_3$	1647	Eskolaite	Cr_2O_3	1294
Melilite	$\{Ca_2Al_2SiO_7$-	1625	Metal Co	Co	1274
(mix)	$Ca_2MgSi_2O_7$		Alabandite	MnS	1139
Spinel	$MgAl_2O_4$	1513	Rutile	TiO_2	1125
Metal	(Fe, Ni)	1473	Feldspar	(Na, K)	~1000
Diopside	$CaMgSi_2O_6$	1450		$AlSi_3O_8$	
Forsterite	Mg_2SiO_4	1444	Troilite	FeS	700
Ti-oxide	Ti_3O_5	1393	Magnetite	Fe_3O_4	405
Anorthite	$CaAl_2Si_2O_8$	1362	Ice	H_2O	≤200

[a] From Grossman (1972). Because equilibrium is assumed, these solid phases disappear by transforming into new solid phases as the temperature is reduced. More detailed results were recalculated by Lattimer *et al.* (1978).

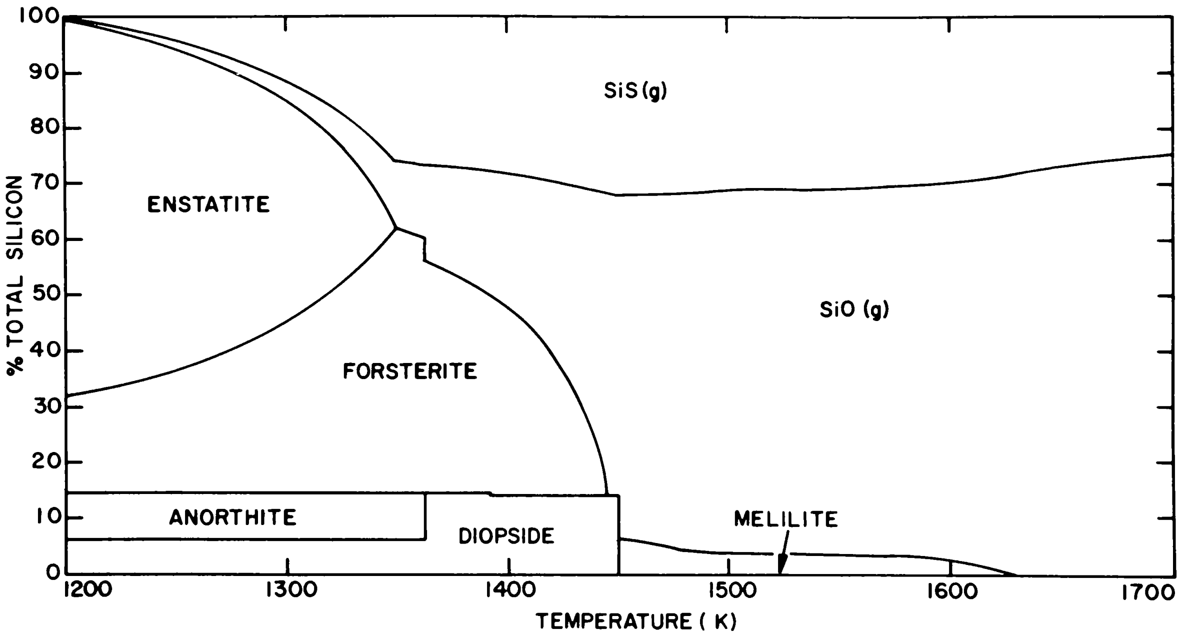

Fig. 1. The distribution of silicon between crystaline and vapor phases in thermodynamic equilibrium. The density for this calculation was taken to be 10^{-3} atmospheres of total pressure (~H + He pressure) in a gas of solar composition (Grossman, 1972). Less than 10% can be condensed by Ca-bearing melilite until the temperature has fallen to almost 1400 K, where the magnesium silicates, forsterite and enstatite, become stable. These figures are regarded as a guide to a model of the early solar system as a cooling hot gas. Large changes in pressure produce small translations of the temperature scale.

Grossman and Larimer (1974) gives analogous model computations for heavy trace elements.

Somewhat different views of the origin of these inclusions are possible. Almost from the beginning Kurat (1970) suggested that they were residues of chondritic material that had been severely heated. If chemical equilibrium applies, the composition at a fixed temperature and density would be independent of the past history. Kurat imagined that less refractory elements were evaporated by impact heating on the surface of a parent body, but his model is not detailed and did not have the advantage of subsequent knowledge. Chou *et al.* (1976) pushed the residue concept much further, but with a difference. They supposed that the solar nebula became just hot enough to vaporize most, but not all, of the preexisting interstellar dust. Again, one finds the most refractory elements remaining in the solid state, which accumulates into inclusions. They argue that the size distribution shows time-dependent nonequilibrium features of the subsequent cooling.

The next significant step was the argument (Clayton, 1977b) that in the interstellar medium the refractory elements are much more thoroughly depleted from the gas into dust than are the other elements (e.g. Field, 1974), so that accumulations of interstellar dust as it is observed are already Ca, Al, Ti-rich compared to Mg and Si. Furthermore, argued Clayton (1977b, c, e, 1978d) the heavy CaAlTi depletions from interstellar gas can only be understood easily if they condensed in refractory forms while leaving supernovae in which they were first synthesized, so that the CaAl *etc.* in interstellar dust already resides in refractory forms best able to resist sudden heating. He described the origin of the refractory minerals found today as sudden heating events (collisions) that fused refractory fields from the refractory-rich component of the interstellar dust.

A persistent problem with the thermal condensation picture has been the presence of relatively volatile elements (e.g. Na, Cl) in quite substantial amounts. Their presence has been attributed to condensation under nonequilibrium conditions (Arrhenius and Alfvén, 1971), to low-T reactions between the cooled gas and the surfaces of the inclusions (Grossman and Larimer, 1974), metamorphic reactions between the inclusions and the Allende matrix (Grossman, 1972), and nebular mixing of later low-T condensates with earlier high-T condensates (Grossman, 1975). A related problem is the entrapment of micron-sized particles called *Fremdlinge* by El Goresy *et al.* (1978) within the fields of refractory minerals. Fremdlinge are complex objects consisting of Fe and Ni metal, sulfides, Pt-metal grains of various compositions, Ca phosphates, and volatile-bearing silicates like nephaline and sodalite. El Goresy *et al.* argue that the enormous variability in chemical composition of *Fremdlinge* preclude their formation in equilibrium condensation along with the major minerals, arguing instead for a mechanical assembly of unequilibrated components. In the author's model (Clayton, 1977b; Clayton, 1978d), on the other hand, the quick heating that fuses the major minerals during formation of the inclusions allows them to encapsulate low-T *Fremdlinge* if they can be trapped in the brief semi-liquid flow.

The textural qualities of the inclusions have defied a definitive statement concerning whether they were ever molten. Many look to the eye as if they have melted. Still others show small crystals arranged haphazardly together in such a way as to suggest either mechanical accumulation or condensation from a vapor phase, or both (Grossman *et al.*, 1975). Blander and Fuchs (1975) present arguments for liquid origin, including many beautiful photographs of mineral assemblages. The work of El Goresy *et al.* (1978) presents perhaps the strongest evidence against a liquid origin. The chemical and petrographic evidence constraining the origin of the inclusions in carbonaceous chondrites has been evaluated by McSween (1977). This work, like most chemical discussions to date, has not taken into account the preferential siting of Ca, Al, and Ti in refractory interstellar dust as an initial condition for the presolar cloud. The current situation seems too confusing and complicated to predict a winning entry in the contest to explain the inclusions. Progress is rapid, at least in the form of new data, even if theoretical understanding progresses much more slowly than the data itself.

Table II has summarized some data relevant to the major refractory elements in these inclusions (Mg, Al, Si, Ca, and Ti). The first two columns give average abundances per 10^6 Si atoms in inclusions of type A and type B, as adapted from Grossman and Ganapathy (1976). The next column gives the relative abundances in condensed matter at 1500 K in thermal equilibrium with a bulk system of solar composition (Grossman and Larimer, 1974). Because Forsterite (Mg_2SiO_4) has not

TABLE II

Major abundances in CaAl-rich inclusions, in the 1500 K equilibrium condensate from a solar gas, in the solar system, and in interstellar refractory dust

Element	Ca-rich inclusions[a] Type *A*	Type *B*	1500 K[b] condensate	Solar[c] system	Log interstellar[d] depletion *re*, Na, P, K
Mg	4.3×10^5	1.0×10^6	5.1×10^5	1.1×10^6	−0.5
Al	1.0×10^6	1.0×10^6	1.1×10^6	8.5×10^4	−2.3
Si	1.0×10^6	1.0×10^6	1.0×10^6	1.0×10^6	−0.6
Ca	1.7×10^6	7.5×10^5	1.9×10^6	7.2×10^4	−2.6
Ti	3.4×10^4	1.1×10^5	6.0×10^4	2.8×10^3	−1.4

[a] From Grossman and Ganapathy (1976). Averages of two type *A* and of three type *B*.
[b] From Grossman and Larimer (1974). *T* chosen for best fit.
[c] From Cameron (1973), based on type C1 meteorite abundances.
[d] From Morton (1975). For example, the ratio N(Al)/N(Na, P, K) in the gas within this H I cloud is $10^{-2.3}$ times the solar ratio.

yet condensed, the elements Ca, Al, and Ti are at this T much enriched in the condensate relative to Mg and Si. It is this similarity to the inclusions that has led chemists to the view that the solar nebular was once a hot gas and that the inclusions are accumulated predominantly from 1500 K condensates. The next column gives the solar abundances (Cameron, 1973a). The final column gives a measure of the depletion from interstellar gas in an H I region in the direction of ζ Ophiuchi (Morton, 1975). Morton found that even volatile elements (C, N, Ar) were depleted relative to H by at least a factor 3, which one may perhaps take to illustrate the effectiveness of cold depletion in the cloud. The elements Na, P, and K, which might be expected to thermally condense near 1000 K in hot sources, are depleted by yet another factor of about 3. What the last column in Table I lists specifically is the logarithm of the gaseous abundance of the very refractory species relative to those of the group Na, P, K when compared to the solar ratio. It is the extra depletion, if you will, of the very refractory elements relative to the depletion of moderately refractory ones. Clayton (1978d) summarized the author's thesis that this extra depletion argues in favor of mineral condensation in the expanding supernova interiors that had first synthesized the refractory nuclei. It is this qualitative argument that suggests that the refractory parts of interstellar dust make a good parent for the inclusions, which were, in that view, presumably fused together by events accompanying the formation of the solar system.

Finally a word should be added about the total chemical constitution of the meteorites in which these inclusions are imbedded. The carbonaceous chondrites are regarded as our best indication of the relative abundances of the nonvolatile elements in the solar system, leading to their utilization (especially Cl's) in the construction of abundance tables (Suess and Urey, 1956; Cameron, 1973a; Trimble, 1975). The heavy elements are easily studied by neutron activation, and a recent study (Anders *et al.* 1976) of 17 trace elements in the C3 meteorites (where the inclusions are found) shows a progressive pattern of depletion (relative to C1 chondrites) with volatility of these heavy elements. Such information and the arguments it engenders will not concern us further in this review, except to say that the origin of the inclusions must clearly be compatible with the origin and history of the total meteorite.

The purpose in this review of this very brief discussion of the CaAl-rich inclusions is that they are the objects that have revealed elements with anomalous isotopic compositions. As we turn to that story, we will bear in mind that any connection between supernovae and the origin of the solar system must pass through the rather muddy waters of the origin of these inclusions. And one must bear in mind that all CaAl-rich inclusions do not show the same anomalies. The majority show clearly only ^{16}O excesses and ^{26}Mg excesses in Al-rich minerals, whereas two special inclusions, called C1 and EK1 for historical reasons, seem to be anomalous in all elements. The different causes of these two types of anomalous inclusions are subjects of hot debate.

3. Presolar Carriers of Isotopic Anomalies

It is perhaps not surprising that cosmochemists have long maintained that the solar system began as a hot gas, considering the successes of its postulated thermal condensation sequence in offering an explanation of certain chemical abundance patterns in meteorites. The paper of Larimer and Anders (1967) argued especially effectively that groups of elements have been fractionated from other groups because of differences in their equilibrium volatilities rather than other chemical properties. Grossman and Larimer (1974) also review much of the basics of this line of argument. The high temperature gaseous solar system came to be confidently spoken of as an actual event rather than a speculative model.

The astrophysical justification of such an assumption has always been shaky. Star formation is observed to occur in cold dusty clouds rather than in hot ionized gas. Proponents of a hot-vapor model must call upon the gravitational energy released by the collapsing sun and the transfer of that energy to more distant parts of the nebula wherein the meteorites are forming. The problem is formidable, and it has seemed increasingly plausible in the past few years that the accretion disk at several AU from the center will never have been hotter than 1000 K, if that hot. Frequent reference is made in the cosmochemical literature to the ongoing studies of Cameron and collaborators. Aware of the chemical argument that the initial dust was somehow ionized, these workers commented that their nebular models offered some hope of a gaseous nebula, especially if the Sun could be initially formed at high luminosity atop a Hayashi track. Calculations of collapse dynamics (e.g. Larson, 1969, 1973) showed that the top of the Hayashi track is probably an unreal initial condition, not likely to be achieved by actual rotating collapsing clouds. Collapse calculations of rotating interstellar clouds (see also Woodward, 1978) have not even progressed to the point of forming a sun, so formidable are the physics problems.

Cameron and Pine (1973) constructed a solar nebular (as opposed to disk), in an attempt to circumvent this wide gap and found that temperatures of 2000 K could be achieved near the center, but which are nowhere near great enough to evaporate all dust at great distances from the center where the carbonaceous meteorites probably formed. Nonetheless their paper is frequently referred to as partial justification for assuming a hot nebula. The latest of his models described by Cameron (1978) involves an optically thick (at its midplane) accretion disk heated by viscous interactions that are transporting angular momentum outward. Peak temperatures outside the Martian mass do not exceed 500 K, so that refractory interstellar dust will not be vaporized. The basic problem is the lack of a ready supply of energy to heat the entire nebula or disk, so that one is left with schemes that instead concentrate what available energy there is in the attempt to heat and vaporize a selected fraction of the interstellar dust. Thus the best argument that the solar system was once a hot gas is the chemical argument that this is the best way to fractionate element abundances in meteorites according to their volatilities. Convincing as it is to chemists who have been conditioned by years of acceptance of this model, it is unlikely to be accepted by astrophysicists until dynamic collapse calculations indicate the physical plausibility of such a hot gaseous state in matter where meteorites probably form.

A second reason why it was commonly believed that the presolar dust was once evaporated is that the isotopic composition of elements in various meteorites is almost uniform. It was felt that if any classes of meteorites assembled from dust grains that partly preexisted, isotopic differences would persist. Suess (1965) summarized this chemical evidence bearing on the origin of the solar system as follows:

> "Among the very few assumptions which, in the opinion of the writer, can be considered well justified and firmly established is the notion that the planetary objects were formed from a well-mixed primordial nebula of chemically and isotopically uniform composition. At some time between the formation of the elements and the beginning of condensation of the less volatile material, this nebula must have been in the state of a homogeneous gas mass of a temperature so high that no solids were present. Otherwise, variations in the isotopic composition of many elements would have to be anticipated."

Today, after isotopic anomalies have been detected, this argument is no longer valid. Furthermore it is now realized that the meteorites could have assembled from such small isotopically anomalous grains that these individual grains have not been well sampled, even if they still exist. Closed-system chemistry within such an accumulate could have formed newer and larger mineral forms that appear to be isotopically normal because they were constructed from such a large number of smaller grains.

3.1. Excess ^{16}O

Although it was not the first isotopic anomaly that was discovered, the detection of anomalous oxygen in the refractory minerals of carbonaceous meteorites turned thinking around on this problem. It was a discovery of unusual significance in the history of solar-system science, made in the Chicago laboratory of R. N. Clayton, who had for many years been using oxygen-isotope analysis to examine mass-dependent isotopic fractionation effects that provide clues to the thermal origins of various objects, both terrestrial and extraterrestrial. Most studies had measured $^{18}O/^{16}O$ ratios, which can be enhanced in any chemical process (for example, evaporation) that concentrates the heavier isotope. The $^{17}O/^{16}O$ ratio was not so routinely measured because of its small mass difference and much smaller abundance ratio, but it had been measured often enough to know that the fractional enhancement of ^{17}O is half that of ^{18}O. This is exactly what was expected for small fractionation effects, because $A = 17$ is only half as far removed in mass from $A = 16$ as $A = 18$ is. For small fractionation effects, only the first term in a Taylor expansion of the mass dependence is nonnegligible, leading to this simple result.

It was astonishing to find (Clayton *et al.*, 1973) that the anhydrous minerals found in type C2 and C3 carbonaceous meteorites do not satisfy that relation between mass-18 and mass-17 variations. Figure 2 illustrates the relationship between the *fractional excesses* in the $^{17}O/^{16}O$ ratio when compared to standard mean ocean water (SMOW). The fractional excess

$$^{A}\delta \equiv \{[(^{A}N/^{16}N)_{\text{sample}}/(^{A}N/^{16}N)_{\text{SMOW}}]-1\}\times 10^{3}$$

is expressed in parts per thousand, so that the largest observed variations ($\delta \simeq -50$) corresponds to a 5% deficiency in that ratio compared to SMOW. The well known mass-fractionation line for terrestrial materials is shown, having a slope of $\frac{1}{2}$ as expected. The refractory anhydrous minerals from C2 and C3 meteorites, as found in the CaAl-rich inclusions, plot instead along a line of slope 1. Such precisely

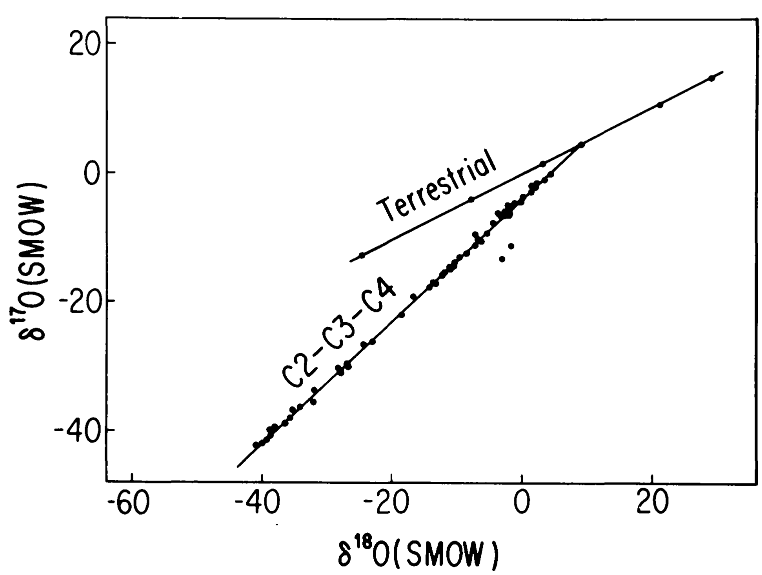

Fig. 2. The range of isotopic compositions of terrestrial oxygen is contrasted to the isotopic compositions of the refractory minerals within carbonaceous meteorites. $\delta^{17}O$ and $\delta^{18}O$ are respectively the deviations in parts per thousand of the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ abundance ratios when compared to standard mean ocean water (SMOW). The size of the error bars is comparable to the size of the points. Terrestrial minerals define a line of slope $\frac{1}{2}$, reflecting mass-dependent isotopic fractionation during a complicated chemical history. The C2–C3–C4 minerals, on the other hand, define a line of unit slope which is interpreted as varying mixtures of normal oxygen with an ^{16}O-rich counterpart. Unpublished figure provided by R. N. Clayton as update of data first published by Clayton *et al.* (1973). See also Figure 11.

correlated decreases in the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios can only be easily explained as a varying admixture of extra isotopically pure ^{16}O. In their abstract the discoverers state 'This component may predate the solar system and may represent interstellar dust with a separate history of nucleosynthesis.' They also attribute the idea that interstellar dust should have survived to Cameron (1973b) who argued 'that carbonaceous chondrites, particularly of type I, are probably collections of interstellar grains which have been mildly transformed through exposure to higher than normal temperatures, resulting in a loss of volatile materials.'

Clayton *et al.* (1973) adopted this position, that ^{16}O-rich grains were present in the early solar system and that they occur in varying degrees in the different anhydrous minerals of C2 and C3 meteorites. They speculated that these presolar ^{16}O-rich grains might have served as condensation nuclei for the further hot growth of the mineral inclusions. They further speculated that these ^{16}O-rich carrier grains were initially grown near a stellar object that had recently synthesized ^{16}O, because stellar burning processes ranging from He burning to explosive carbon burning would eject isotopically pure ^{16}O from that burning zone. The grains would only have to have condensed before the ejected gases were mixed and homogenized with those of the interstellar medium; but Clayton *et al.* did not sugget how that could be achieved. It was not until four years later that Cameron and Truran (1977) suggested a quite different model, one not based on dust carriers at all . . . that a supernova adjacent to our forming solar system inhomogeneously admixed its ejected ^{16}O-rich gas with the normal solar system gases. But more of that picture later.

Clayton *et al.* (1973) suggested no specific astrophysical model for the condensation of the interstellar grains enriched in newly synthesized ^{16}O. A major obstacle not addressed by them is the dilution of the new ^{16}O with interstellar gas. Reeves (1972a) had analyzed this problem previously and concluded that supernova ejecta, at their typical high speeds, would sweep up almost 10^5 $M_\odot$ of interstellar gas before slowing down to become part of the interstellar medium. This might correspond to 1 $M_\odot$ of ejected ^{16}O mixing with 10^3 $M_\odot$ of interstellar oxygen, resulting in only a 0.1% ($\delta = 1$) enrichment of ^{16}O in those grains. This anomaly is 50 times too small for enriched minerals of CaAl-rich inclusions. Something much more specific is needed.

A promising solution was advanced by Clayton (1975a, b), who argued that ^{16}O-rich minerals (and many other anomalies) would be chemically trapped in grains condensing within the supernova interior while it was expanding and cooling by the work of the expansion. In the paper restricted primarily to a controversial interpretation of xenon anomalies, Clayton (1975a) said, 'Nor can one lightly dismiss the possibility of grain formation within the denser and deeper supernova envelope when the adiabatic expansion has cooled it to the vicinity of 10^3 K, because expansion of the hot and dense interior is a very efficient cooler that converts the thermal content to bulk cold streaming matter. The ^{16}O anomaly proves that it is possible to form grains before extensive dilution with interstellar matter.' In the companion paper Clayton (1975b) argued that the 10^3 K temperature would be reached when the explosive supernova interior had expanded to a density of

10^{-14} g cm^{-3}, corresponding to about 10^8 atoms of ^{16}O bathing about 10^7 atoms of Mg and other heavy nucleosynthesis products. This density implies a size about 100 AU for the expanding interior, much too small to have been diluted by interstellar matter. This argument reconstructed dynamic ideas first advanced by Cernushi *et al.* (1967) and by Hoyle and Wickramasinghe (1970), who suggested that supernovae could be a significant source of interstellar dust. Unfortunately, the astrophysical-dust literature shows that their ideas were either forgotten or overlooked by other workers (including this reviewer before Clayton (1976a)) concerned with interstellar dust. Aanestad and Purcell (1973) mentioned it only in passing, but Field (1974, 1975), Spitzer and Jenkins (1975), Cameron (1975), Salpeter (1977), and Spitzer (1978) all overlooked it. The idea only reappeared with the later realization that this dust should be isotopically anomalous (Clayton, 1975a, b). In a section entitled 'Explosive Carbon Dust' of a remotely published but widely circulated paper, Clayton (1976a) again addressed the origin of the ^{16}O-rich dust during the expansion of the interior itself:

"Consider then the case of explosive carbon burning, where ^{12}C and ^{14}N or ^{18}O fuel is converted primarily to ^{20}Ne, $^{24,25,26}Mg$, Na, Al, and $^{28,29}Si$, while the initial oxygen is purified to ^{16}O. One of the more refractory condensates to be expected from the ejecta is spinel, $MgAl_2O_4$ (Grossman and Larimer, 1974). Explosive-carbon ejecta should be an ideal factory for spinel shrapnel, and the oxygen of those spinels should be isotopically pure, whereas the Mg should be relatively normal isotopically . . . Clearly, many new approaches to solar system chemistry are suggested by such a line of thought. Forsterite, Mg_2SiO_4, should also be prominent in the ejecta, which leads to a new prediction. Since $^{29}Si/^{28}Si$ is considerably higher in explosive carbon ejecta, these ^{16}O-pure forsterites are accompanied by ^{28}Si-deficient silicon . . . Melilites, especially soda-melilite, $CaNaAlSi_2O_7$, may also condense here, but in less abundance because the Mg/Ca ratio is about 10^2 times greater than the solar value . . . Condensation chemistry should take account of the special composition of the supernova ejecta."

Clayton (1977e, 1978d) suggested naming such supernova condensates *SUNOCONS*, to easily distinguish them from the many other forms of interstellar dust, a simplification that will be used in this review.

Clayton and Hoyle (1976) followed with a discussion of the connection between isotopic anomalies in explosively-formed dust in the case of nova explosions also. An especially interesting point is that the observed rapid condensation of dust in nova expansions provides strong experimental justification for the conclusion that supernova explosions should also condense and eject dust. The supernova has about a year to condense its dust, whereas Nova Serpentis achieved this in two weeks! Clayton and Wickramasinghe (1976) made detailed numerical models of the growth of this nova dust and showed that a good fit to infrared observations was compatible with the time scale and environment. Gallagher (1977) has reviewed the systematic comparison of this theory with a wide class of nova explosions. The common nova therefore seems to offer promise of providing a frequent and varying cosmic experiment in explosive dust formation. This surprise has moved study of the nova into the forefront of astrochemical research.

Key features of the reviewer's (Clayton, 1976a, 1977a, b, c, d, e, 1978d) arguments on ^{16}O-bearing supernova condensates (SUNOCONS) are: (1) The most refractory chemical elements (Ca, Al, Ti) cannot escape from the supernova interior where they are first created because they are bathed in much more abundant Mg, Si, and O; (2) This accounts for the great depletion of Ca, Al, and Ti from interstellar gas when compared to Mg and Si, which are *not* bathed in elements abundant enough to condense them, except perhaps as pure oxides; (3) The oxygen in carbon and oxygen burning is isotopically almost pure ^{16}O, so that the oxygen associated with Ca, Al, and Ti in interstellar dust is, because of this SUNOCON component, more ^{16}O-rich than oxygen associated with the bulk of the Mg and Si; (4) This explains why the CaAl-rich fusions of interstellar grains are more ^{16}O-rich than the bulk of the oxygen in carbonaceous meteorites; (5) The ^{16}O-anomaly is expected to be much larger than the anomalies in the refractory elements because Ca, as an example, is totally condensed and therefore itself normal by definition, whereas the refractory minerals can condense no more than 0.1% of the total oxygen, but that 0.1% is very ^{16}O-rich.

Another step in this line of reasoning was made by Lattimer *et. al.* (1978), who used the theory in an attempt to understand why the separate minerals of the CaAl-rich inclusions have separate ^{16}O anomalies. This idea built on the discussion of R. N. Clayton *et al.* (1977), who made a thorough experimental study of the distribution of the ^{16}O anomaly among separate minerals of CaAl-rich inclusions. The latter authors showed that spinel ($MgAl_2O_4$) is always greatly enriched in ^{16}O, that Ti-rich pyroxene is almost invariably enriched by a large amount, but that melilite is always the least enriched. It is fascinating that spinel crystals imbedded in pyroxene or melilite crystals have the same isotopic composition, although the surrounding hosts are quite different isotopically. R. N. Clayton *et al.* (1977) considered the possibility that there were carrier SUNOCONS that are not observed today but that were preferentially incorporated into spinel and pyroxene when they formed, but much less so in melilite and anorthite. These carriers could be, for example, tiny grains of corundum, spinel or perovskite. What Lattimer *et al.* (1978) added was the observation that melilite and anorthite melt at lower temperatures than the more heavily enriched minerals spinel and pyroxene. It is therefore conceivable that if the inclusions were partly molten at temperatures above the melting points of melilite and anorthite but below the melting points of spinel and pyroxene, the two molten fields might exchange oxygen with a normal oxygen reservoir more easily than the two solids could. Both sets of ideas are interesting, but it is too early to know which, if either, are correct. But unquestionably, a correct theory must explain naturally why different inclusions tend to have the same anomalies in the same minerals and why different minerals of those inclusions have differing ^{16}O-richness. There is also no apparent correlation of ^{16}O-richness with other isotopic anomalies. The paper of R. N. Clayton *et al.* (1977) contains a rich harvest of facts and ideas relevant to this problem.

There is another interesting fact in the work of R. N. Clayton *et al.* (1977) that has received little attention; namely, that the exotic admixed component is not pure ^{16}O. The slope of $^{17}\delta$ vs $^{18}\delta$ is not pure ^{16}O. The slope of $^{17}\delta$ is quoted by them as 0.94 ± 0.01. What this means, simply expressed, is that although the exotic component is very deficient in both ^{17}O and ^{18}O, it is more deficient in ^{18}O than in ^{17}O. The most extreme end member for the mixing line would consist of ^{16}O and ^{17}O only, and in the ratio $(^{17}O/^{16}O)^* = 0.006\ (^{17}O/^{16}O)_{SMOW}$, where the asterisk denotes the ^{18}O-free end member of the mixing line. What we can here suggest is that this is perhaps what one should expect, rather than pure ^{16}O, in SUNOCONS from explosive-carbon-burning shells. Chance and Harris (1979) have argued that the ^{17}O produced by $^{16}O\ (n, \gamma)\ ^{17}O$ in explosive carbon burning cannot be totally destroyed by $^{17}O\ (\alpha, n)\ ^{20}Ne$ during the expansion. They argue that the ^{16}O must capture more of the burst of neutrons than previously believed because the heavy elements become neutron saturated, further captures being opposed by (γ, n) ejection (Howard *et al.*, 1972). They find a ratio $^{17}O/^{16}O$ of the same order as the solar ratio. This reviewer has had insufficient time to attempt reproduction of this exciting result, which requires very careful attention to small nucleosynthesis details; however, it offers hope that spinel SUNOCONS may carry the observed $(^{17}O/^{16}O)^*$.

There is yet another far-reaching application of the oxygen anomalies. Although different classes of meteorites show internal fractionation lines of slope 1/2 connecting distinct phases that have chemically evolved one from another, these so-called fractionation lines of separate objects do not overlap (Clayton *et al.*, 1976). For example, the somewhat different fractionation lines for chondrites of varying types lie slightly above the terrestrial line, whereas that of the C2 matrix is shown originating in the box of Figure 1 slightly below the terrestrial line. These differences mean that different solar-system objects did not share a common oxygen pool. The simplest interpretation is that the presolar ^{16}O-bearing component has different concentration at different parts of the solar system, as the discoverers proposed. In that case, the C2 matrix lying below the Earth would have more of the exotic ^{16}O bearing component, whereas the ordinary chondrites would have less of it than does the Earth. Other solutions to the meteorite families have been noticed, but they seem an extra complication in light of the known existence of the ^{16}O-rich component. But, for the record, D. Clayton *et al.* (1977) observed that the differences could be due to different energetic particle irradiations at the differing locations, resulting in ^{17}O enrichments from $^{20}Ne\ (p, \alpha)\ ^{17}F$, or from an inhomogenous distribution of ^{17}O- and ^{18}O-rich nova grains (Clayton and Hoyle, 1976). It seems likely that the problem of the meteorite families will not succumb to understanding until the CaAl-rich inclusions have first done so. But all are ultimately relevant to the topic of this review.

3.2. Excess ^{22}Ne

The oxygen anomaly was not the first to be discovered nor the first to be explained as having been carried into the solar system by grains that never evaporated. Isotopic anomalies in the noble gases had been known at least a decade prior to the discovery of the oxygen anomaly (Podosek, 1978). The noble gases can be studied by incremental heating of the sample in a mass spectrometer, analyzing the isotopic composition of the gas given off as a function of the temperature of the sample. The different temperature fractions have revealed fascinating differences in isotopic composition.

Specifically, the $^{20}Ne/^{22}Ne$ ratio in the carbonaceous chondrite Ivuna decreased precipitously in the 1000 °C temperature fraction from a value near ten to a value near three! This factor of three change in isotopic ratio was unprecedented. The discoverer (Black, 1972) suggested that this ratio is so bizarre that it cannot be accounted for by conventional means in an initially homogeneous solar system. Black suggested that interstellar grains that had formed somewhere else where the $^{20}Ne/^{22}Ne$ ratio had been much smaller had survived the origin of the solar system and impregnated specific temperature fractions with its isotopic signature. He called this exotic neon component Ne–E. This was a far-reaching conclusion, perhaps the first of its kind based on good data soundly analyzed rather than on pure speculation. Nonetheless, the argument had little impact on astrophysics or on solar system science at the time. It was really after the ^{16}O-anomaly that Black's discovery was well remembered, and is now regarded as being of fundamental importance.

The question was especially pursued by Eberhardt (1974, 1978), Niederer and Eberhardt (1977), who not only improved measurements in the carbonaceous meteorites but also succeeded in showing that ordinary chondrites also contain a Ne–E component. The gas-rich H3 chrondrite Dimmitt revealed very low $^{20}Ne/^{22}Ne/^{22}Ne$ ratios near 1.2, with $^{21}Ne/^{22}Ne$ ratios near 0.02. These numbers are regarded as indicating that Ne–E contains some ^{21}Ne, but it cannot be ascertained whether ^{20}Ne was within the Ne–E carrier or not, because the outgassed samples may contain some admixture of normal trapped gas. Nor are the chemical circumstances clear. The Ne–E in Dimmitt is found in association with graphite, so that it could be either graphite itself or material chemically associated with the graphite. The relationship to the clay-like carrier in Orgueil is very uncertain. Eberhardt (1978) has studied all known aspects of the data and inferred the following *best estimates* for the isotopic composition of Ne–E: $0.45 \leq {}^{20}Ne/^{22}Ne \leq 1.30$; $^{21}Ne/^{22}Ne \leq 0.015$; $^{21}Ne/^{20}Ne \leq 0.012$ with the extra relation $^{21}Ne/^{20}Ne = 0.02–0.009\ (^{22}Ne/^{20}Ne)$.

As stated earlier, astrophysical considerations of Ne–E commenced after the discovery of the oxygen anomalies gave new respectability to such efforts. Arnould and Beelen (1974) remarked that the neon gas ejected from explosive He-burning shells could resemble Ne–E, but they gave no physical scenario for forming carriers or otherwise getting such gas into the early solar system. Clayton (1975b) made a very concrete connection with supernovae. He argued that supernova condensates (SUNOCONS) would condense before ejecta could mix with surrounding matter, roughly within a year, and that ^{22}Na (2.6 yr) produced in the explosion would be able to condense as sodium and change to ^{22}Ne only after the grain had grown. By this chemical fractionation mechanism within the site of nucleosynthesis itself, carriers of almost pure ^{22}Ne could be generated. Clayton (1975c) had earlier argued that supernovae should reasonably be expected to eject a ^{22}Na yield from explosive He shells comparable to the ^{21}Ne abundance, although his purpose had been to develop the prospects for nuclear gamma ray astronomy as a means of confirming explosive nucleosynthesis. The dust forming in such ejecta would contain a mixture of ^{22}Ne from ^{22}Na decay, of neon gas trapped in the growing grains, and of spallation neon induced by cosmic-ray interaction during their residence in the interstellar medium. Arnould and Norgaard (1978) have recomputed the first of these two processes in considerable detail and conclude that suitable carriers of Ne–E are likely to form, although they could not predict from the first principles the relative importance of ^{22}Na condensation and neon entrapment.

Clayton and Hoyle (1976) showed that ^{22}Na condensation in nova explosions provides another adequate source of Ne–E. They had also been previously (Clayton and Hoyle, 1974) concerned with developing a way to test nova theory via the gamma-ray astronomy of ^{22}Na. They had calculated that a typical nova explosion might be expected to eject about 10^{-7} $M_\odot$ of ^{22}Na, a large and detectable yield, also more than adequate to provide Ne–E carriers in sufficient abundance. One search without success for the ^{22}Na gamma-ray lines for Nova Cygni 1975, Nova Serpentis 1970, and the Crab nebula has been made by Leventhal *et al.* (1977); however, their negative result does not negatively impact the theory because their upper limit to the flux is near the predicted level. With the advent of gamma-ray satellites, particularly HEAO-C next year, we may confidently hope for a confirmation of this potential source of Ne–E.

Perhaps a personal note about the beginnings of my own involvement would be of interest here. I had been working since 1964 on the prospects of measuring radioactivity in interstellar space, which seemed the best way of observationally confirming the correctness of the theories of explosive nucleosynthesis (e.g. Clayton, 1973). It was this preoccupation that facilitated the idea that isotopic anomalies could be implanted by radioactive decay in SUNOCONS (Clayton, 1975a, b), with ^{22}Na being one of the most important cases. Should that in fact be the correct explanation of Ne–E, it would itself experimentally demonstrate explosive production and ejection, because the 2.6 yr halflife of ^{22}Na is too short for more sedate production, ejection and condensation. In this way isotopic anomalies in meteorites may offer the first direct proof of the explosive nucleosynthesis of the chemical elements.

An interesting aspect of the nova origin of Ne–E carriers is that they could be associated with graphite, which Clayton and Hoyle (1976) took to be the major nova condensate. The existence of carbon-rich white dwarfs on whose mixed skin the thermonuclear runaway is argued to occur is quite plausible. Enhancements of the C/He ratio by a factor thirty in novae are common (e.g. Ferland and Shields, 1978). The association of Ne–E with graphite in the Dimmitt meteorite (Niederer and Eberhardt, 1977) suggests an association of the two. In the carbonaceous meteorite Orgueil, Eberhardt (1978) showed dramatically that the very distinct Ne–E carrier is not in the silicate phases, but whether it could also be associated with graphite is uncertain. Arnett and Wefel (1978) have recently shown that a ^{22}Na concentration of about 10^{-8} g g^{-1} is anticipated in the ejected carbon shell of a massive star, thereby providing another potential site for the condensation of Ne–E bearing SUNOCONS. In this case oxygen is more abundant than carbon, which will therefore emerge as CO molecules if thermodynamic equilibrium is maintained. One cannot but wonder, however, if the abundant carbon in this shell cannot conspire to form some carbon-rich compounds even in the face of the CO trap, as Hoyle and Wickramasinghe (1977) have already suggested. They argue that the two-body radiative cross section for $C + O \rightarrow CO + h\nu$ is too small (10^{-22} cm^2) for C to be incorporated into CO during the roughly 10^7 s available during an explosive expansion. Clearly chemistry has much to learn about explosive condensation.

Even if Black's argument for presolar carriers is correct, the explosive condensation of ^{22}Na may not be the correct origin of the carriers. Audouze *et al.* (1976) observed heavy irradiation by energetic particles in large grains of the Ne–E-rich fraction of the Orgueil meteorite. They argued that few MeV protons can produce Ne–E by interactions with Mg (see also D. Clayton *et al.*, 1977). This explanation is rendered implausible by two considerations: (1) the very special energy spectrum required for the protons; (2) the clear identity of Ne–E as a special phase existing in different temperature fractions (Eberhardt, 1978). A second alternate model advanced by Heymann and Dzickzaniec (1976) is ^{22}Na production in solar system gases while minerals are condensing (see also D. Clayton *et al.*, 1977). This model suffers from general astrophysical implausibility. But even the existence of these alternatives means that a clear connection between Ne–E and condensates during explosive nucleosynthesis has not been established.

The leading alternative for Ne–E carriers among interstellar-grain candidates would seem to be dust condensation in the ^{22}Ne-rich atmosphere of a red giant star, probably while it was losing its atmosphere. This comes about naturally in thermonuclear evolution when ^{14}N, the most abundant species except He after H exhaustion, captures two successive alpha particles following heating of the He gas. Arnould and Norgaard (1978) have discussed this possible origin for Ne–E and find it very difficult to achieve within the framework of calculations of stellar evolution. But large *s*-process enrichments of some giant atmospheres perhaps suggest that comparable ^{22}Ne enrichments should also exist there. This association has been very much strengthened by the recent discovery that a carrier of *s*-process xenon in the Murchison meteorite is also associated with Ne–E (Srinivasan and Anders, 1978). The wish for simplicity causes one to seek a single source of Ne–E in these various samples where it has been found, but it may become necessary to recognize several Ne–E-like components and carriers.

The Ne–E anomaly, like the ^{16}O anomaly, clearly brings some important message about the origin of the solar system. Both may also bring a message about supernovae and about nucleosynthesis. Unquestionably these two experimental discoveries suggested an important role for surviving presolar grains as carriers of isotopic anomalies. The author (Clayton, 1977a, 1978d) has tried to use this concept plus new ideas about interstellar chemical and isotopic fractionation as a means for constructing a unified explanation of anomalies. But before examining this approach we must turn to the experimental discovery of extinct ^{26}Al, which abruptly turned the thinking of the scientific community around once again.

4. A Supernova Neighbor to the Early Solar System

One of the beautiful topics in astrophysics and in cosmic chemistry is the radioactive chronologies that can be constructed from relative abundances and halflives. These are used to measure the ages of terrestrial and lunar rocks, the ages of earth, moon and meteorites, and even the ages of the chemical elements themselves (Fowler and Hoyle, 1960; Fowler, 1972; Schramm, 1974; Kirsten, 1978). Of particular interest are the so-called *extinct radioactivities*, radioactive species of vanishingly small abundance that can be inferred to once have existed from the abundance anomalies they left behind in their daughter isobars. The most famous and first example is ^{129}I, which Reynolds (1960) discovered first in the Richardton meteorite by virtue of the excess ^{129}Xe there. A large excess at this single (out of nine) xenon isotope could only be due to the decay of this radioactive parent, whose halflife of 17 million years is too short for any to remain today, but was long enough to expect that some ^{129}I would have been incorporated into the meteorites when they formed 4.56×10^9 years ago. In fact one easily sees that if iodine was synthesized continuously over a 5-to-10-billion-year duration before the formation of the solar system, the ratio at that time to stable ^{127}I should have been

$$\langle {}^{129}\mathrm{I}/{}^{127}\mathrm{I}\rangle_{\mathrm{interstellar}} \simeq (\lambda_{129}/\lambda_{127})(\tau_{129}/\Delta) \simeq 5\pm4\times10^{-3},$$

where the production ratio $^{129}\mathrm{I}/^{127}\mathrm{I}$ is estimable as

$$\lambda_{129}/\lambda_{127} = 1.5\pm0.5 \text{ (Fowler, 1972).}$$

The ratio actually determined in Reynolds' laboratory was found (Podosek, 1970) to lie near $^{129}\mathrm{I}/^{127}\mathrm{I} = 1\times10^{-4}$ for a large variety of meteorites, judging from the ratio of excess ^{129}Xe to stable ^{127}I found there. Jeffery and Reynolds (1961) had perfected for this purpose a beautiful scheme of outgassing in temperature steps following neutron irradiation in a reactor. The isotopic composition of the released gases showed unambiguously that excess Δ^{129}Xe correlated linearly with excess Δ^{128}Xe produced by neutron capture by ^{127}I in the reactor. This proved a correlation of Δ^{129}Xe with iodine not only in bulk but even in separate mineral phases that are successively focused upon by the stepwise heating. A particularly good correlation found by Hohenberg (1967) in the shallowater achondritic meteorite is shown in Figure 3 as an example.

The fact that the observed ratio was 50 times smaller than continuous nucleosynthesis would be expected to maintain was a problem: on the one hand it was far too much to have survived from synthesis near the beginning of Galactic history, and on the other hand it suggested that nucleosynthesis was not continuous up to the time of formation of the meteorites. A 'free-decay interval' of almost 100 M yr was required between the end of Galactic nucleosynthesis (of those nuclei destined for the solar

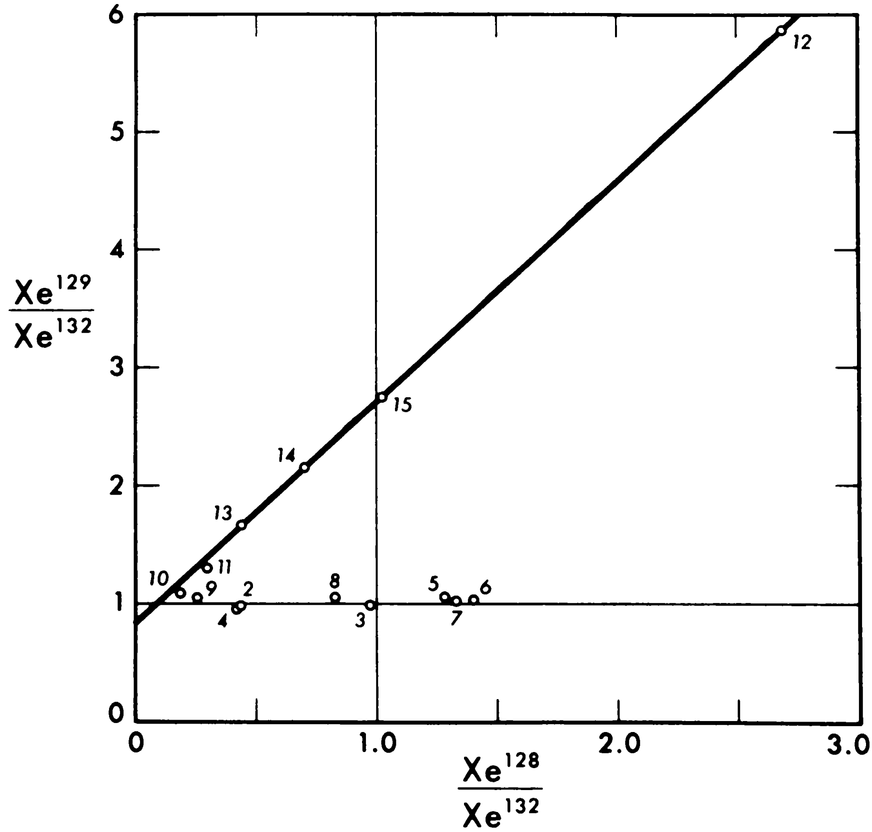

Fig. 3. The correlation of excess ^{129}Xe with ^{127}I is illustrated by the straight-line fit to this data from the Shallowater enstatite chondrite (Hohenberg, 1967). The numerals labeling the points are the temperatures (in hundreds of degrees Centigrade) at which that gas was released from the heated sample. Intentional neutron captures in a reactor have converted a portion of ^{127}I to ^{128}Xe, so that the observed correlation strongly suggests that the excess ^{129}Xe was also derived from ^{129}I in this sample. The slope of the line plus the neutron fluence indicates that the ratio $^{129}\text{I}/^{127}\text{I}$ had the value 1.1×10^{-4} when Shallowater formed if the correlation actually indicates *in situ* decay. This sample was chosen as the best linear correlation known; in many meteorites one must choose the best fit to only a few noncolinear points. Differing slopes are conventionally taken to indicate differing meteorite ages, although puzzles with this interpretation exist.

system) and the existence of the meteorites in order to allow the ratio 5×10^{-3} to decay to 1×10^{-4}. This interval could be envisioned as a quiescent phase in the interstellar medium before collapse of the solar cloud (an astrophysical perspective) or as a lengthy waiting time before the meteorites were cool enough to be able to solidify and retain xenon (a chemical perspective). Reeves (1972b; see also Trivedi, 1977b) gave credence to the former view by pointing out how natural it is from a spiral-density-wave-model of Galactic star formation. The interval 10^8 yr is roughly what passes between the shock-induced formation and subsequent evolution of a massive star to a supernova explosion and the later passage of that same gas through the next spiral compression that can have initiated the birth of the solar system. Figure 4, taken from Reeves (1972b), illustrates this important chronometric effect. His own discussion of this figure follows:

The model is based on the spiral density wave theory of galactic arms. In this model, gas and stars are not attached to the arms, but move from one arm to another (with a transit period of about 2×10^8 yr at the

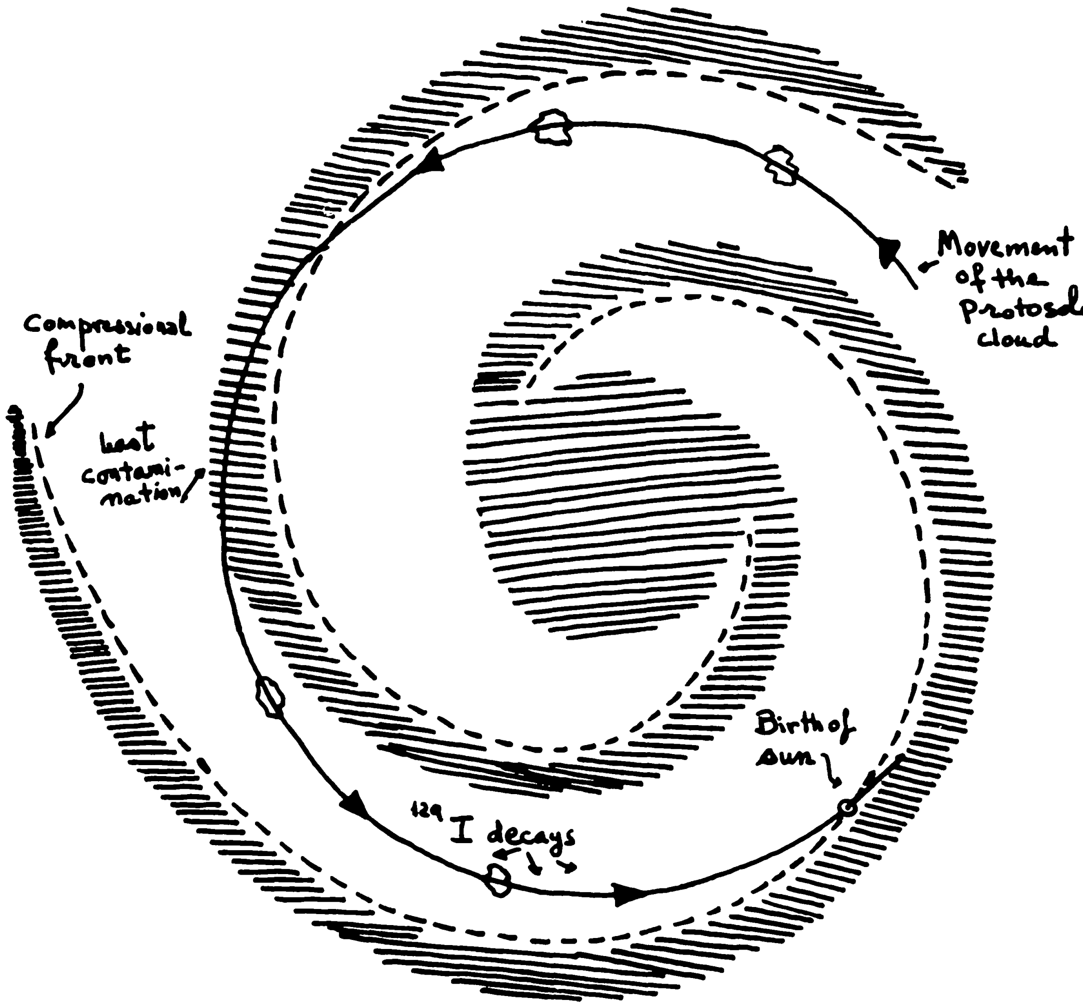

Fig. 4. A scenario for periodic nucleosynthesis. Orbiting galactic gas overtakes and passes through a standing shock wave generated by the galactic density distribution. This figure was presented by Reeves (1972b) as a way to explain why so little ^{129}I exists in the meteorites. He argued that 10^8 years passes between solar formation in a spiral arm and the last previous passage of presolar matter through a spiral arm, when the ^{129}I was explosively synthesized and added to the solar matter by massive stars that evolve in much less than 10^8 yr.

solar distance from the galactic center). Star formation occurs at the inner ridge of each arms, mostly due to the fact that, upon reaching this region, the gas, coming from the previous interarm, experiences a shock deceleration and hence a density increase, favoring gravitational contraction. A given mass of gas has only a rather small probability of reaching the stage of gravitational contraction at each passage across this ridge. Chances are that it will emerge from the ridge and expand back to its initial form.

New stars and surviving clouds then move slowly across the arm. The largest stars evolve rapidly, explode and enrich the spiral arm in newly formed elements (all this in appreciably less than 10^8 yr). A given surviving cloud will get contaminated by the tidal wave of nucleosynthesis from nearby supernova. As this cloud enters the next interarm region, it receives gradually less and less new elements: for approximately 10^8 yr its radioactive elements freely decay and essentially no replenishment takes place until it reaches the next arm where the whole story starts once again.

The (waiting) period obtained from analysis of radioactivity data would correspond to the transit time in the interarm region between the arm where the sun was born and the last arm traversed by the future presolar cloud. It is in this last arm that the sun received most of the ^{129}I responsible for the excess ^{129}I in meteorites.

The chemical view of a lengthy cooling time for the primitive meteorites seems to this reviewer to have been discredited, on the other hand. For one thing, the chemical nature of those meteorites shows that they were never very hot, since they are a mechanical mixture (breccia) of many different phases, some of which could not survive heating to temperatures even smaller than those that outgas the xenon. For another thing, a slow cooling history that waits 10^8 yr should perhaps show an earlier age for the highest temperature releases (~1500 °C) than the lower ones (~1000 °C). An astrophysical waiting period of about 10^8 yr therefore seems more plausible.

This entire conclusion is based on Jeffery and Reynolds' (1961) argument that a linear correlation of the excess ^{129}Xe with excess ^{128}Xe generated by ^{127}I (n, γ) in the reactor 'proves' that the ^{129}I was *alive* at the time the various meteoritic minerals formed from a solar gas containing ^{129}I mixed uniformly with stable ^{127}I. Clayton (1975a) found astrophysical arguments to question that conclusion. He reasoned that both isotopes of iodine would have partially condensed as trace elements in high-T minerals formed during the expansion of the supernovae in which the iodine isotopes were synthesized. He proposed that these grains remained unvaporized in the early solar system, mixed like salt and pepper through the remainder of the gaseous iodine and the iodine condensed in volatile compounds. This mixture could in principle generate a linear correlation between the excess ^{129}Xe liberated at high temperatures and the ^{127}I trapped in high-T minerals. This proposal jolted the cosmochemical community, which treated it more rudely and less scientifically than was warranted.* Trivedi (1977a) criticized the idea with arguments in the open literature, allowing Clayton (1977f) a response of his own view. The exchange was indecisive. It is this review's present opinion that the major shortcoming of this picture is that it requires the following coincidence: any iodine in volatile sites in the early solar system *that later becomes incorporated into high-T minerals* must be in the same high-T minerals that the carriers of the correlation are within, for otherwise the Δ^{128}Xe from ^{127}I (n, γ) would not be expected to have the same high-T release profile. Lewis and Anders (1975) suggested that counterargument. Suspicions continue mounting, on the other hand, that these 'relative ages' may not have exactly the meaning that was ascribed to them previously. Drozd and Podosek's (1976) conclusion that a substantial fraction (about half) of the initial ^{129}Xe was indeed separated in grains strengthens these suspicions.

These points have been recounted not so much because of this reviewer's involvement in this controversy as because their understanding is central to the issues of this review. By one means or the other excess Δ^{129}Xe correlated chemically with ^{127}I made its way from supernova events into the early solar system. New experimental studies of the anomaly are now being made, so that we may hope for early clarifications.

* This paper was twice in 1975 adamantly rejected by referees for *Science* before it was submitted to *Astrophys. J.* Valid scientific objections were slim to nonexistent, whereas emotions like shock, dismay, and even envy are very evident in the reviews.

4.1. Xenon-X

Somewhat earlier, a very significant crisis had arisen in an altogether different isotopic anomaly in xenon, which, as in the case of Black's (1972) postulate of presolar Ne–E, was to have little effect until after other anomalies had been established, thereby changing the scientific mood. It involved ubiquitous excesses of the four heaviest xenon isotopes, a phenomenon known since Reynolds and Turner (1964) and which came to be called 'carbonaceous-chondrite fission xenon' (Pepin, 1968), or 'CCF' for short. This name reflected the common belief that these four isotopic excesses were fission fragments of some heavy or superheavy nucleus having a sufficiently long lifetime to have once existed in the solar system. Its decay in meteoritic samples was speculated to have caused this common excess in the unshielded isotopes, in much the same way that ^{244}Pu fission has been demonstrated within meteoritic samples by a similar pattern of excesses occurring in relative amounts characterizing the fission of ^{244}Pu (Alexander *et al.*, 1971). The major difficulty was commonly thought to be that no fissioning parent was known that could produce fission fragments in the desired relative amounts (Anders and Larimer, 1972). Then Manuel *et al.* (1972) changed the tenor of the discussion by pointing out that the excesses in the four heaviest isotopes were correlated with excesses in the two lightest isotopes of xenon's stable of nine. For example, in stepwise heating experiments, the ratio ^{124}Xe/^{130}Xe correlated linearly with the ratio ^{136}Xe/^{130}Xe. These same correlations remained when Lewis *et al.* (1975) first successfully chemically separated carriers rich in this xenon component, which Manuel *et al.* (1972) had called 'xenon-X'. This was a stunning change, because fission does not produce an enrichment of the two lightest isotopes of Xe. Lewis *et al.* (1975) continued to interpret Xe–X as fission (see also Anders *et al.*, 1975) plus severe fractionation, but their argument continues to lose ground.

On the basis of their observation, Manuel *et al.* (1972) suggested that a supernova explosion was associated with the formation of the solar system. They argued that the *p*-process created an excess of the light isotopes, and that an *r*-process created an excess of the heaviest isotopes, and that these were mixed intimately into creation of xenon-X before the meteorites were formed. In later elaborations of that argument Manuel and Sabu (1975) argued that the entire solar system grew from the residue of a prior supernova in such a way that spatial correlations within the solar system correspond to spatial correlation within the supernova. Sabu and Manuel (1976) added a new suggestion, that the sun was the remaining dwarf from a pair of binary stars in which the other more massive member had exploded as the planetary system was forming. These were probably the first arguments, based on experimental facts, that a neighboring supernova had injected isotopically anomalous matter into the forming planetary system; however, the astrophysical scenarios advanced by these authors have not been found acceptable by the astrophysical community – other than the idea of a supernova injection.

Nonetheless, Black (1975), Clayton (1975a), and Clayton (1976b) sought improved forms of the arguments of Manuel and coworkers. Black (1975) reasoned that a non-normal *r*-process, rather than fission, was the nuclear origin of the excess heavy isotopes, and he suggested a scenario involving the survival of presolar carriers of Xe–X rather than supernova injection. Clayton (1975a, 1976b) made a similar suggestion independently, but he introduced two new wrinkles to the idea that the heavy excesses may also be fission derived: Clayton (1975a) emphasized that a fissioning parent need live no longer than several months in order to be incorporated into grains condensing in the expanding supernova interior; whereas, Clayton (1976b) showed that if the light-isotope excesses were the result of *p*-process xenon being trapped within these SUNOCONS, then the relative fission yields inferred could differ quite significantly from those of Lewis *et al.* (1975). These ideas suggested that special fission components at the source may have contributed to interstellar Xe–X carriers. Howard *et al.* (1975) evaluated specific fissiogenic parents within this scheme. The correct interpretation of xenon-X remains unclear, but the arguments generated from its existence provided a strong early connection of some sort between nucleosynthesis in supernovae and the origin of the solar system.

This reviewer feels that the evidence favors Xe–X as being a presolar component generated in many past supernovae but carried in specific presolar dust grains that did not outgas until after their partial accumulation into small bodies, which would then be characterized by a Xe-X-rich internal atmosphere. The present meteorite carriers could have been chemically formed within these accumulates, trapping Xe–X, so that they need not themselves be presolar. Such a chemical explanation of Xe–X has been consistently pursued by this reviewer (Clayton, 1975a, 1976b, 1978d; Clayton and Ward, 1978). If it is correct, the existence of Xe–X is not evidence for a supernova trigger and injection. It would instead reflect the fractionation of trapped *s* and *r* process Xe in different interstellar carriers, first predicted in 1975 in a widely circulated paper that was not published until three years later (Clayton and Ward, 1978). The discovery of what appears to be *s*-process xenon in high-T minerals of the Murchison carbonaceous chondrite (Srinivasan and Anders, 1978) seems to strengthen this interpretation, confirming the predicted existence of *s*-process-rich grains from red giant stars (Clayton and Ward, 1978).

A correlation of Xe–X with isotopically strange krypton renders it even more mysterious. Figure 5 shows the enhancement factors *w* between sample and trapped gas in successively enriched carbon-rich residues of the Allende meteorite, and corresponding values for Kr in the same residue (Lewis *et al.*, 1977). The persistent nature of the anomaly is evident, although some small changes occur with change in carbon content. Both Kr and Xe are enriched in their heaviest isotopes, but Xe is enriched in the lightest as well. A similar pattern was found in the C2 meteorite Murchison by Srinivasan *et al.* (1977), showing that this exotic anomaly is not confined to the C3 meteorites. Similar discoveries using this technique have been made in Reynolds' lab in Berkeley (e.g. Frick and Moniot, 1977; Frick and Reynolds, 1977). Careful reading of these papers reveals not only differences of interpretation of the probable cause of these anomalies along alternate lines described previously, but also disputes over the chemical nature of the carriers being isolated – 'carbon',

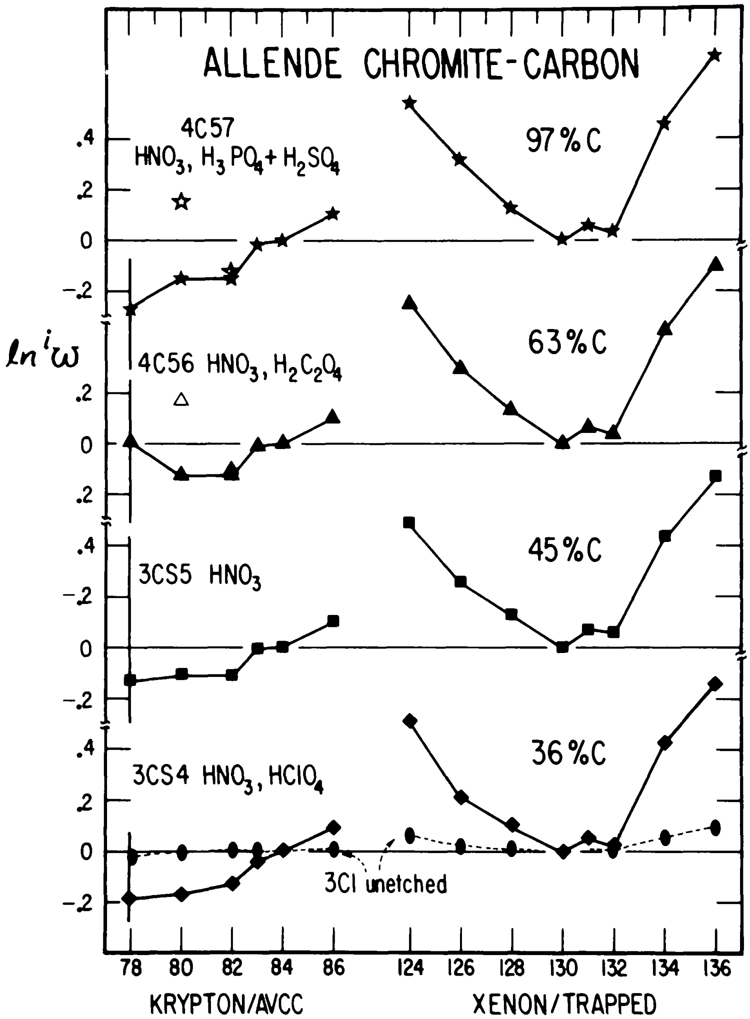

Fig. 5. Isotopic deviations of Kr and Xe in a chemically prepared residue of the Allende meteorite (Lewis *et al.*, 1977). The enhancement factor ${}^{i}\omega \equiv ({}^{i}\mathrm{Xe}/{}^{130}\mathrm{Xe})_{\mathrm{sample}}\ ({}^{i}\mathrm{Xe}/{}^{130}\mathrm{Xe})^{-1}{}_{\mathrm{standard}}$, and analogously for Kr. These anomalies are very large, amounting to approximately a factor of two for ^{136}Xe enrichments. These very dramatic patterns have been interpreted as (1) fractionated gas plus fission fragments in meteorites, (2) an exotic component carried in interstellar grains, or (3) an exotic component injected into the solar system from a nearby supernova. No satisfactory quantitative explanation exists.

'chromite', 'Q', etc. It is a tumultous wonderland of chemical questions, and the answers will ultimately impact the topics of this review in significant, and probably unexpected, ways. The anomalies shown in Figure 5 are very large, and the ubiquitous presence of these carriers in carbonaceous meteorites attests to some very exotic chemistry in the outer reaches of the early solar systen.

4.2. Te–X

Ballad *et al.* (1979) have found that the tellurium in leached residues of Allende is isotopically anomalous. The pattern is very similar to that of the Xe anomalies resulting from the same mineral-separation processes. Because that Xe pattern, shown in Figure 5, was called Xe–X, I propose calling the associated Te anomalies Te–X. The similarity extends also to the shape, having a large excess at the heaviest

(^{130}Te and ^{136}Xe) and at the lightest (^{120}Te and ^{124}Xe) isotopes. Ballad *et al.* propose explaining this in terms of the explanation that they advanced for Xe–X: namely, *r*-process and *p*-process excesses from a supernova that not only caused the origin of the solar system, but from whose debris the solar system primarily formed. The less extreme proposal advanced by Manuel *et al.* (1972) would be that a neighboring supernova injected *r* and *p* excesses into the solar system, and this scenario would be viewed more favorably by most astrophysicists at the present time.

On the other hand, Te–X may have nothing to do with supernova injection, being instead a special collection of presolar carriers in the way discussed earlier for Xe–X. Perhaps even Te_s is also visible, as it was for Xe, in the difference between the spinel and carbon samples reported by Ballad *et al.*

4.3. Extinct ^{26}Al

The bulk of scientific opinion swung behind the idea that a supernova had indeed injected freshly synthesized elements into the forming solar system following the discovery of ^{26}Mg-rich magnesium in Al-rich minerals within the inclusions of C3 meteorites. Because $\tau_{1/2}$ (^{26}Al) = 0.72 M yr is a cosmically short time, the concentration that can be expected on the average in the interstellar medium is small:

$$\left\langle\frac{^{26}\mathrm{Al}}{^{27}\mathrm{Al}}\right\rangle = \frac{\lambda_{26}}{\lambda_{27}}\frac{\tau_{26}}{\Delta} \simeq (10^{-3})\,(10^{-4}) \simeq 10^{-7},$$

where the production ratio $\lambda_{26}/\lambda_{27} \simeq 10^{-3}$ was first estimated by Arnett (1969) from explosive carbon burning. Even a very Al-rich mineral, say Al/Mg = 10^2, would with this concentration contain excess Δ^{26}Mg $\simeq 10^{-5}$ Mg, which is too small for measurement. The excesses actually found in such Al-rich minerals are much larger, up to Δ^{26}Mg $\simeq 10^{-2}$ Mg (Lee *et al.*, 1977). Those authors concluded that 'the existence of ^{26}Al at the observed abundance requires a nucleosynthetic event immediately before or during solar system formation'.

The grounds for this conclusion had been well ploughed in advance, because discussions of ^{26}Al far predated discovery of excess ^{26}Mg. Urey (1955) had suggested that the heat released from the ^{26}Al positron decay was the source of internal heat required to melt and differentiate planetary objects. Wasserburg's laboratory pursued this problem, publishing an exacting negative search in 1970 (Schramm *et al.*, 1970). The first measured anomalies were by Gray and Compston (1974), who tentatively concluded that their results were due to extinct ^{26}Al, and by Lee and Papanastassiou (1974), who tentatively concluded that their Mg anomalies were not due to extinct ^{26}Al. Continuing efforts by the latter group (Lee *et al.*, 1976) successfully showed an unequivocal correlation of the ratio ^{26}Mg/^{24}Mg with the Al/Mg chemical abundance ratio in minerals from Allende inclusions. The long awaited evidence in favor of extinct ^{26}Al has now also been confirmed in at least two other laboratories, in Chicago and in Paris; but more of that later.

The first thorough discussion of the importance of this discovery in the present context was by Cameron (1962) in an influential paper predating the experimental discovery by 14 yr. Taking Urey's (1955) argument concerning the concentration of ^{26}Al needed to melt the meteorite parent bodies, Cameron (1962) wrote:

"... from the time of cessation of nucleogensis until the collection and thermal insulation of the meteorite parent bodies, less than 3.4×10^6 yrs must elapse. The mean life for ^{26}Al is considerably shorter than the time interval expected between supernova explosions within the same immediate volume of the galaxy. Therefore, one would expect that the amount of ^{26}Al available for heating would be considerably increased if the formation of the solar system is associated with any events that follow in the wake of a supernova explosion that contributes short-lived radioactivity to the gases that are to form the solar system ...

A possibility is that a recently formed massive star will undergo a supernova explosion and the ejected gases will accelerate some mass in the interstellar medium; when these gases collide with and accelerate the dense cloud, this has the effect of an overall surface pressure, which may be able to precipitate the general collapse of the cloud. This mechanism would be particularly important for mixing fresh radioactivities produced in supernova explosions into dense clouds at the start of their contraction phase."

This quotation presages clearly the basis of the paper by Cameron and Truran (1977), which was published after the discovery of extinct ^{26}Al and which galvanized extensive discussion of this model. Another interesting aspect of their model is their simultaneous argument that ^{16}O-rich gases leading to the oxygen anomalies were also injected by the neighboring supernova triggering the solar collapse. This provided a model for their origin similar to that suggested by Manuel *et al.* (1972) for Xe–X. Cameron and Truran (1977) attempted, in fact, to ascribe all isotopic anomalies and all extinct radioactivities to this same event. This bold idea has enlivened controversies to which we will return. But first, a look at the evidence for extinct ^{26}Al.

Figure 6 shows a meaningful correlation of abundance ratios taken from four different minerals of the same CaAl-rich inclusion from Allende (Lee *et al.*, 1977). Two different anorthite ($CaAl_2Si_2O_8$) crystals carrying trace magnesium at the low levels $^{27}Al/^{24}Mg = 245$ and 128, a melilite (Ca_2 (Mg, Al, $Si)_3O_7$) characterized by $^{27}Al/^{24}Mg = 9.1$, spinel ($MgAl_2O_4$) and fassaite at lower Al/Mg ratios. Bear in mind that these are all very Al-rich minerals, since the average chondrite ratio is $^{27}Al/^{24}Mg \simeq 0.08$, and that they were removed from the same inclusion, in close proximity to one another. The ordinate shows the $^{26}Mg/^{24}Mg$ ratio found by Lee *et al.* (1977) in those same minerals. These variations are so large that they can be plotted directly, rather than the usual δ notation for small isotopic excess. Furthermore, the most Al-rich minerals contain the largest ^{26}Mg excesses. These are genuine ^{26}Mg excesses, because the measured $^{25}Mg/^{24}Mg$ ratio falls within 0.7% of normal in all of the data taken by this group on that inclusion, whereas that ratio would have also differed if the $^{26}Mg/^{24}Mg$ ratio had been enhanced by simple mass-dependent chemical fractionation. The points plotted in Figure 6 have been corrected for these small fractionation effects by assuming that $^{25}Mg/^{24}Mg$ is exactly normal, thereby introducing small changes into the measured $^{26}Mg/^{24}Mg$ ratio.

The remarkable thing about Figure 6 is that the data defines a quite good straight line. The only sensible way for excess ^{26}Mg to be proportional to the Al concentration is for it to be the daughter product of now extinct ^{26}Al. The slope of the line

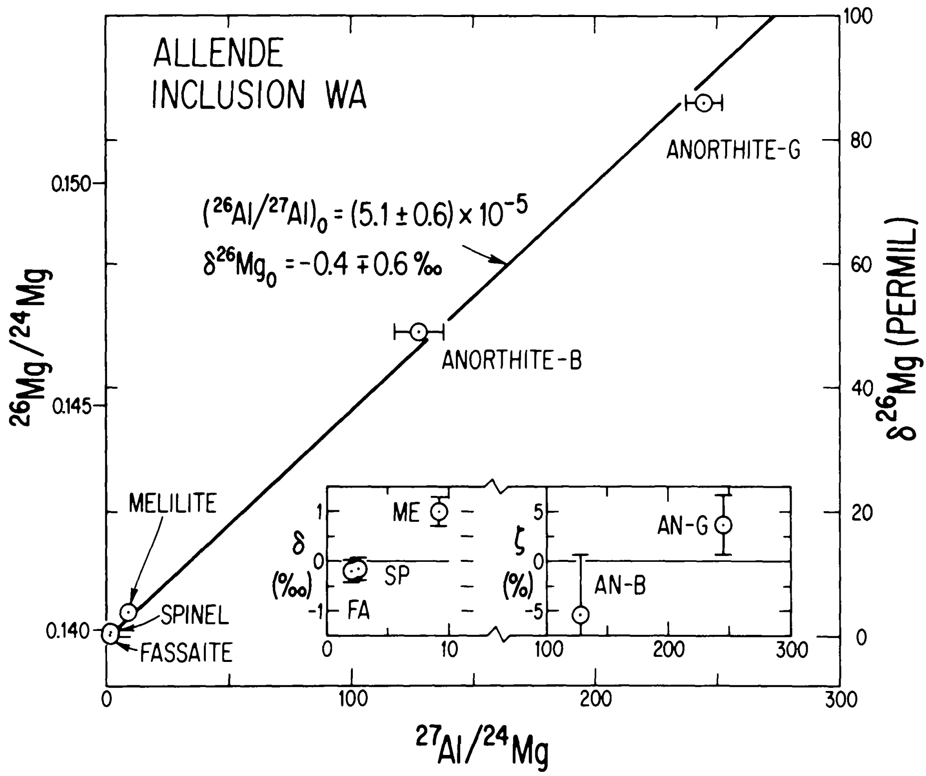

Fig. 6. In several different mineral separates of the inclusion WA from the Allende meteorite, the isotopic ratio $^{26}Mg/^{24}Mg$ correlates linearly with the Al/Mg chemical abundance ratio (Lee *et al.*, 1977). This correlation is most easily explained if radioactive ^{26}Al existed in the Al when these minerals formed from a common isotopically homogenized pool, and in the initial ratio $(^{26}Al/^{27}Al)_0 = 5 \times 10^{-5}$. Even this low concentration of live ^{26}Al would not exist if it had not been injected by a supernova adjacent to the forming solar system. The goodness of fit is shown also in the inset, which shows the deviation with respect to the best-fit straight line. On the other hand, the correlation might perhaps have been generated if the precondensed Al carries a ^{26}Mg spike which is diluted by normal Mg in those minerals containing larger Mg concentrations. The latter alternative requires nonequilibrated chemistry.

defines the relative initial concentration of ^{26}Al needed to produce this linear correlation, namely $(^{26}Al/^{27}Al) = 5 \times 10^{-5}$. This result assumes that both Al and Mg were isotopically homogenized at the instant the minerals formed, so that the only later event is the appearance of ^{26}Mg where the ^{26}Al once was. Such isotopic equilibration would be expected if the inclusions solidified from a common melt, but it might be a suspect assumption otherwise. Nonetheless, in concluding that the ^{26}Al was present live in the solar system, Lee *et al.* (1977) stated as a crucial assumption that the crystallization of the inclusion occurred

"most plausibly from a molten stage. It follows from these arguments that ^{26}Al must have been present in the inclusions at the time of the formation of the crystals now observed and thus in the solar system itself ... In any case, the data *require* isotopic homogenization of Al and Mg in the inclusions at a time when ^{26}Al was still present."

They thought to have proved the last conclusion; but actually their argument is circular. It uses the assumption that Mg was isotopically equilibrated to prove that the ^{26}Al was live, whereupon it can conclude that the Mg had been previously equilibrated. This argument is sufficient but not necessary. This point is stressed here, because it is a loophole in their conclusion, which must nonetheless be admitted as being the most easily believable explanation of their data.

It is of interest, however, that a ^{26}Mg excess in primordial Al-rich solids had been predicted for other reasons before these data demonstrating its existence. Discussing his discovery of short-lived extinct radioactivities that should be expected in supernova condensates, Clayton (1975b) initially said, 'the traditional interpretation of the inability (Schramm *et al.*, 1970) to detect ^{26}Al should be changed. It is refractory and easily lives long enough for grain formation in supernovae. Its absence reflects only the fact that it is synthesized in negligible amounts rather than its inability to survive until meteorite formation.' This widely circulated preprint was altered when referees pointed out the existing evidence (Gray and Compton, 1974; Lee and Papanastassion, 1974) of some unknown type of Mg anomalies, so the published version read simply, 'Anomalies due to ^{26}Al should also be interpreted in terms of presolar grains rather than a primordial concentration.' The author offered that warning in case subsequent evidence should suggest ^{26}Al-derived anomalies, as it ultimately did, because it seemed at the time physically implausible to have very much ^{26}Al in the solar system. This model of presolar SUNOCON carriers of already extinct ^{26}Al was then further developed by Clayton (1977a, b), who advocated an unequilibrated chemistry involving daughter ^{26}Mg trapped within interstellar Al-oxides. This model will not be further reviewed here because the model is in disfavor with the majority of cosmochemists. Instead, four major challenges to the live-^{26}Al interpretation can be laid down: (1) How and when does the abundant $\Delta^{26}\text{Mg} \simeq 10^{-3}$ Al in interstellar Al grains equilibrate with the vast bulk of the Mg, which is not in the same grains? (2) How does one account for slopes (Lorin and Michel-Levy, 1978a) in different inclusions as different as $(^{26}\text{Al}/^{27}\text{Al}) = 5 \times 10^{-5}$ to 10^{-3}, the latter pratically as great as the production ratio? (3) If the ^{26}Al is admixed live from an explosive supernova, why are not the other chemical elements isotopically anomalous due to an accompanying admixture? (4) If daughter ^{26}Mg has in fact totally equilibrated with the bulk of Mg, why is not the Mg concentration uniform within single anorthite crystals (Steele *et al.*, 1978; El Goresy, 1978; Lorin and Michel-Levy, 1978b)? These challenges are important to astrophysical science, because the live-^{26}Al interpretation is the one that demands a supernova associated with the formation of the solar system. If this postulated event has not actually occurred, it would be very counter-productive to assume that it is required by the data.

Cameron and Truran (1977) took the conclusion of Lee *et al.* (1976) as given, and therefore reasoned that the explosion admixed ^{26}Al into the gases that were to form the Allende inclusions. Taking $(^{26}\text{Al}/^{27}\text{Al}) = 6 \times 10^{-5}$ and a production ratio $\lambda_{26}/\lambda_{27} = 2 \times 10^{-3}$ (Arnett, 1969; Truran and Cameron, 1978; Arnett and Wefel, 1978), they concluded that about 3% of the total Al came from that final event of explosive nucleosynthesis. They were heartened by the observation of oxygen anomalies up to 5% of extra ^{16}O to conclude that its admixture from the neighboring supernova is also indicated. By shifting attention on the oxygen anomalies away from interstellar grains and toward injection by this neighboring event, Cameron and Truran (1977) were clearly trying to kill two birds with one stone. They even pressed this quite good idea to the limit of assuming that other anomalies and extinct radioactivities were also injected from the same event; however, in so doing they generated some difficulties. They speculated that a $^{20}Ne/^{22}Ne$ ratio as low as 0.1 in the He-burning shell could have been admixed at the 7% level into normal neon to produce the Ne–E. Their assumption that ^{26}Al came from explosive carbon burning ran into the trouble that that gas is ^{20}Ne rich, so they speculated that either ^{26}Al came from an explosive He shell, or that Ne–E could be carried in grains that had condensed ^{22}Na, as discussed earlier in another context. They continued to discuss their speculation that ^{40}K, ^{129}I, Kr and Xe anomalies, ^{202}Pb and ^{244}Pu were all injected into and inhomogeneously mixed with the presolar gases. Perhaps they pressed these ideas too far in light of subsequent questions, but their attempt at simplification by ascribing many diverse phenomena to a single cause stimulated wide scientific admiration.

Their ink was hardly dry before Clayton (1977a) and Lattimer *et al.* (1977) presented discussions that both enlarged and criticized the Cameron-Truran scenario. Both papers emphasized that 'the collapsing solar nebula must be thought of as a four-component system: interstellar gas, interstellar dust, gas injected by the neighboring supernova, and dust injected by the neighboring supernova. Fluctuation in the relative mixture may account for some anomalies, once the subsequent accumulation chemistry is deciphered, but some of the anomalies may result from a homogeneous distribution of special carriers or of live radioactivities' (Clayton, 1977a). In the words of Lattimer *et al.* (1977):

> Interstellar gas and dust have been enriched by supernova and nova debris (gas and possibly dust) and stellar winds, among other processes, throughout galactic history. The average composition of the dust may be chemically and isotopically different from the gas. The "last event" supernova gas and dust may be mixed into the protosolar cloud when the shock wave from the supernova collides with the cloud and initiates its collapse. We note here, in reference to the problem of producing observable isotopic anomalies, that it may be easier for the "shrapnel-like" grains from the supernova to penetrate to the interior of the cloud than for supernova gas. This gas, part of which mixes by Raleigh–Taylor interfingering at the interface between the expanding supernova shock front and the protosolar cloud, may mostly just pass around the exterior of the collapsing presolar nebula.

Figure 7, taken from Lattimer *et al.* (1978), illustrates roughly three successive stages of this scenario. The expanding supernova components expand outward until they surround a dense cloud whose collapse will result in the solar system. The mixing of gas and dust occurs at this interface and in instabilities it generates.

The question of mixing and instabilities has been discussed by Margolis (1979) in considerably more detail than in the papers that initiated this scenario. His conclusions, casting some doubt on the mechanisms of proposed mixing, were enumerated as follows:

(1) Grains injected into a nebula cannot traverse more column density of gas than given by a few times the grains' mass/area ratio.

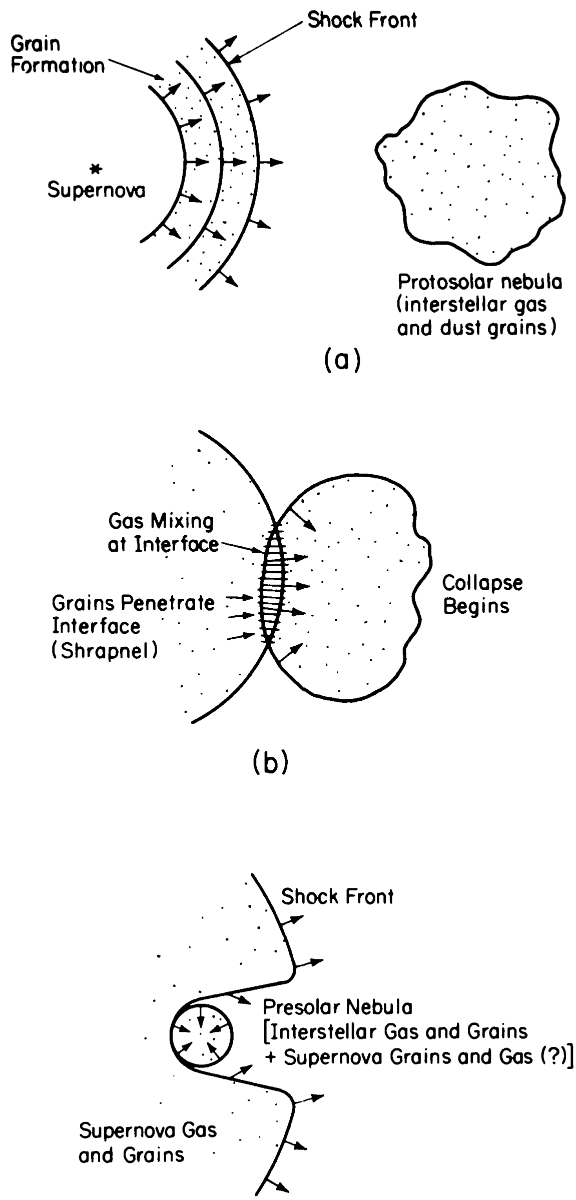

Fig. 7. The supernova trigger scenario for the formation of the solar system. The high pressure in the supernova remnant surrounds the solar cloud, and begins its collapse by squeezing on it. Isotopically anomalous material from this supernova trigger may be admixed into certain portions of the solar-system matter. Figure from Lattimer *et al.* (1978).

(2) Raleigh–Taylor instabilities are not expected to be effective at mixing the anomalous matter into the nebula during a cloud/shell interaction.

(3) Injection of anomalous matter using grains from an impinging shell virtually requires meteorite formation to occur at the edge of the nebula.

(4) Shock heating of the gas can generate the gas temperatures indicated by the condensation calculations (Grossman, 1972). (However, this reviewer would add that this conclusion does not show that existing grains could get hot enough to

evaporate, because grains are much cooler than gas owing to their infrared emissivity.)

(5) A distribution of sizes in the impinging grains can naturally explain the small scale heterogeneity seen in meteorites if the gas at the edge of the nebula is not fully mixed at scales near 10^{11} cm (densities near 100 cm^{-3}) and if the meteorites can have formed there.

The pivotal dynamic aspect of the scenario was identified by Cameron and Truran (1977) as a major motivation for their construction of it. If the pressure wave from the supernova *causes* the collapse of the presolar cloud, it is then not an improbable coincidence that a supernova would have exploded nearby just when the solar system was forming. The two then become related. They imagined that the supernova ejecta, which maintains for a few million years a significant overpressure with respect to average interstellar medium, would surround a cold cloud as in Figure 7, squeezing on it from outside and starting its compression. They characterized this phase by an initial radial velocity. Eventually gravity takes over. From the average dilution of the ejecta with the solar cloud (assuming 2% of the heavy elements arose in the trigger) they were able to roughly argue that the supernova was about five cloud radii from its center, a not unreasonable configuration for star formation. The hardest challenges for this scenario remain those related to the mixing at the interface and the actual generation of the samples in which the isotopic anomalies are found.

In his analysis Clayton (1977a) concentrated on several nuclear problems with acceptance of the entire Cameron–Truran scenario. He pointed out that large amounts of fission xenon from ^{248}Cm ($\tau_{1/2} = 3.7 \times 10^5$ yr) would be expected in meteoritic samples if a major fraction of extinct ^{244}Pu had been injected by the trigger; however, an experiment of Leich *et al.* (1977) rules this out. Therefore the initial solar concentration of ^{244}Pu seems more likely to have been the steady-state residue of continuous galactic nucleosynthesis, which is capable of the task (Fowler, 1972). Similarly, the production of the solar abundance of ^{40}K by the trigger is incompatible with both a lack of excess ^{36}Ar from extinct ^{36}Cl ($\tau_{1/2} = 3.1 \times 10^5$ yr) and from an apparent isotopic homogeneity of solar-system K (Begemann and Stegmann, 1976). He argued it unreasonable that ^{16}O be inhomogeneously admixed, while ^{40}K was homogeneously admixed. Clayton (1977a) concluded that if one seeks a best single explanation for all anomalies, the chemical and isotopic fractionations expected within routine interstellar dust offers greatest promise. Clayton (1978d) summarized his development of that model. Only the Al-correlated ^{26}Mg speaks clearly in favor of a supernova injection, so, in an attempt to save the picture, Clayton (1977a, b) devised an extinct carrier chemistry that may accomplish that correlation. He also argued that if a plethora of other predicted anomalies from injection of an explosive carbon shell is not found, a preferable scenario of the Cameron-Truran type is one involving only an explosive He shell, ejecting ^{16}O, ^{12}C, ^{22}Na, and ^{26}Al, but eschewing heavy element nucleosynthesis. This more modest alternative is supported also by Arnould *et al.* (1978) and by Chance and Harris (1979). The main experimental problem is that ^{16}O and ^{26}Mg seem to be the only anomalies in most

CaAl-rich inclusions, whereas other anomalous elements (all!) are expected if these inclusions contain 2% by mass of ejecta from an explosive carbon-burning shell. There are only two known inclusions that have anomalies in other elements as well. They will be reviewed later.

In their analysis, on the other hand, Lattimer *et al.* (1977, 1978) concentrated on the grains that might be injected into the solar nebula by the supernova trigger. They used the assumption of chemical equilibrium within the interior of that supernova to identify specific mineral carriers that they thought had the best chance of surviving any subsequent high temperatures. They seem to have taken no position on whether the 'live ^{26}Al' was injected in gaseous form or dust form, but their discussion of the ^{16}O anomalies clearly shows that for it they have adopted the SUNOCON-carrier picture, in which case all prior supernovae suffice equally well. Only three ways occur to this reviewer to chemically decide if the ^{16}O-bearing SUNOCONS originated in prior galactic supernovae or in the supernova trigger, or whether the excess is an inhomogeneously admixed gaseous injection:

(1) inhomogeneous admixing of an injected gaseous supernova shell or of the injected SUNOCONS from that trigger could logically cause the most ^{16}O-rich minerals and/or matter to also have contained the highest ^{26}Al/^{27}Al ratios. This reviewer knows of no indication of such a correlation; to the contrary, the evidence is against it. Continuing measurements may clarify this.

(2) SUNOCONS from a single supernova should be isotopically anomalous in all major elements, whereas a mixture of SUNOCONS from all supernovae could be average except for oxygen. Clayton (1977a, b) who devised this argument in support of his thesis that a normal interstellar medium is sufficient to generate isotopic anomalies, concentrated especially on Mg. Consider a common condensate, $MgAl_2O_4$ say, from an expanding carbon shell. If carbon shells are the nucleosynthesis site of all three Mg isotopes, then the interstellar mix of these spinels contains ^{16}O and isotopically normal Mg (except for some extra ^{26}Mg owing to ^{26}Al decay), whereas spinels from the supernova trigger would contain Mg characteristic *of that one particular star and zone* (plus live ^{26}Al). Stellar evolution calculations, though extremely complicated and unsettled on this point, indicate that stars of different mass and initial composition in different stages of carbon exhaustion in their carbon-burning shells will not accidentally have identical Mg isotopic compositions. Since only two out of about fifty Allende inclusions show isotopic anomalies in elements other than ^{16}O and ^{26}Mg, this argument suggests that the ^{16}O-bearing SUNOCONS came from a large number of prior supernovae.

(3) Ancient interstellar grains should have received a long period of interstellar cosmic-ray bombardment. Two interesting effects are produced. Nuclear spallation reactions create rare nuclear species, but whether these remain in the grain or not depends upon the size of the grain. The average interstellar grain (by number) seems too small (10^{-6} cm to 10^{-4} cm) to trap a nucleus recoiling with 10 MeV of kinetic energy, but the energy spectrum of the nuclear recoil will vary widely from reaction to reaction. Audouze *et al.* (1976), who reported heavily irradiated grains in a

Ne–E-rich fraction of the Orgueil meteorite speculated that the irradiation could have produced the anomalous neon. Secondly, the grains are structurally damaged and sputtered by more massive cosmic-ray ions (especially Fe). This is actually what Audouze *et al.* detected, linear trails of radiation damaged material. It is difficult to confidently assess the extent to which radiation damage should be cured by heating in the meteorite assembly itself. This reviewer is unaware of a major study limiting in a rigorous way the extent to which carbonaceous chondrite grains could have pre-existed in the interstellar environment before accumulation. The problem seems to warrant study. The point in the present discussion, of course, is that such damage could in principle distinguish interstellar SUNOCONS from injected SUNOCONS. It is perhaps relevant that the abundance of Be and B in carbonaceous chondrites has been attributed to interstellar irradiation of graphite grains (Ramadurai and Wickramasinghe 1975; Dwek 1978). Interstellar irradiation may also provide the origin of the $^{17}O^*$ in the otherwise-pure-^{16}O SUNOCONS, as reflected in the correlation slope 0.94 ± 0.01 for $^{17}\delta$ vs $^{18}\delta$ (R. N. Clayton *et al.*, 1977).

4.4. Extinct ^{107}Pd

A very important discovery that seems, on the face of things, to corroborate a last-minute injection of fresh products of nucleosynthesis is the excess ^{107}Ag found by Kelly and Wasserburg (1978) in the Santa Clara iron meteorite. Ag has only two stable isotopes, $A = 107$ and $A = 109$, so Kelly and Wasserburg paid special attention to fractionation effects. A large increase of 4% in the $^{107}Ag/^{109}Ag$ ratio was found in only one iron meteorite, Santa Clara, where, significantly, the Pd/Ag elemental abundance ratio has variable values as great as 10^4, about a factor 10^2 larger than in most iron meteorites. Silver is just exceedingly rare in Santa Clara, occurring in concentrations of order $10^{-9}\ g\ g^{-1}$. It is the smallness of this silver concentration that allows the excess ^{107}Ag to be visible, and the fact that it is detectable only in the largest Pd/Ag-ratio samples suggests that it is the daughter of now-extinct ^{107}Pd ($\tau_{1/2} = 6.5$ my). Kelly and Wasserburg express hope of eventually finding a linear relationship between $^{107}Ag/^{109}Ag$ and Pd/Ag that would strengthen this conclusion; but for the moment, the significant ^{107}Ag excess exists only in the high-Pd/Ag sample of Santa Clara.

The ratio of $^{107}Pd/^{109}Ag$ inferred by Kelly and Wasserburg (1978) to have been present when Santa Clara formed is 2×10^{-5}. This ratio is interestingly close to the value $^{129}I/^{127}I = 1 \times 10^{-4}$ known (Podosek, 1970) to characterize the silicates of undifferential meteorites. But the shorter halflife of ^{107}Pd renders impossible an interpretation similar to the one that has traditionally been applied to ^{129}I. A period of continuous nucleosynthesis in the galaxy, followed by a free-decay interval to allow $^{129}I/^{127}I$ to fall to the value 1.0×10^{-4}, generates a $^{107}Pd/^{110}Pd \simeq 10^{-7}$ (with sensible choices for production ratios.) This residual amount is a factor of 10^2 less than the ratio inferred from the excess ^{107}Ag. Therefore a more complex explanation of these extinct radioactivities is needed. Three possibilities seem to exist:

(i) *Supernova injection.* Cameron and Truran (1977) suggested that the supernova trigger injected both ^{26}Al and ^{129}I, and they would certainly add ^{107}Pd to that list. If the injection occurs about one million years before the meteorites form, the relative halflives of ^{129}I and ^{107}Pd are irrelevant, and only their production ratio in the last event matters. One immediate problem is the variability of the values of $^{129}I/^{127}I \simeq (1 \pm 0.4) \times 10^{-4}$ found in very different meteorites, seeming to require variable admixing of that supernova debris. On the other hand, uniformity is called for by the common constancy of isotopic ratios in stable elements, except for oxygen, which varies by 5% in C3 inclusions. Although the ejecta seems to be stopped in a skin depth of the presolar cloud (Margolis 1979), it is premature to doubt that the trigger debris could be scattered uniformly by later convection or turbulence through the meteorite-forming region. Perhaps *the variations* in $^{129}I/^{127}I$ could be injected into a uniform sea of residual galactic ^{129}I without upsetting isotopic constancy in other elements. Clayton (1977a) emphasized the apparent constancy of $^{40}K/^{41}K$ as a special problem with having even 40% variations in the $^{129}I/^{127}I$ ratio, but this conclusion depends upon the ^{40}K yield of the supernova trigger. Perhaps what is now needed are very high resolution measurements of the isotopic compositions of stable heavy elements in meteorites having very different amounts of ^{129}I. Such a search rests on the implausibility of a single supernova synthesizing the heavy elements in just the average solar-system ratio, enabling the injected part to remain invisible.

(ii) *Extinct presolar carriers.* Most of ^{107}Ag has been synthesized in the *r*-process, with ^{107}Pd as its radioactive progenitor. Pd is a rather refractory siderophile element, with a predicted condensation temperature in a solar gas at 10^{-3} atmosphere pressure equal to T_{cond} (Pd) = 1105 K (Grossman and Larimer, 1974). Thus a large fraction of Pd will be expected to condense during the early expansion of the supernova *r*-process zone, leading to the standard situation for an extinct anomaly carried in the interstellar grains (Clayton, 1975a, b). Silver is, on the other hand, a well-known volatile heavy element, depleted in C2 meteorites by an average factor of four compared to C1 meteorites (Krähenbuhl *et al.*, 1973). Thus Pd should be much more condensed in SUNOCON carriers. The effect expected in the SUNOCONS themselves is enormous – $^{107}Pd/^{109}Ag$ ratios an order of magnitude larger than normal $^{107}Ag/^{109}Ag$ ratios. Thus a collection of condensed interstellar Pd will be characterized by large ^{107}Ag enhancements. Searches for this SUNOCON-carried extinct anomaly were called for specifically by Clayton (1978b).

In light of this expectation, it is natural to ask whether an iron meteorite with a very high Pd/Ag ratio, such as Santa Clara, can be so because its parent body condensed with a higher ratio of precondensed Pd to volatile Ag than did the parents of other iron meteorites. This possibility is strengthened by the known occurrence of refractory siderophile *Fremdlinge* nuggets in primitive carbonaceous meteorites (El Goresy *et al.*, 1978). Thier existence as a separate primitive component affords the conceptual possibility of preferential accumulation. It would then follow that the silver would be ^{107}Ag-rich, without any need whatsoever for a last-second nucleosynthesis injection. Clearly one must hope for high resolution isotopic analysis of collected siderophile *Fremdlinge* to ascertain whether they may be SUNOCON-rich accumulates, as described by Clayton (1978d).

(iii) *Local production.* Fowler *et al.* (1962) presented a general scenario for the production of ^{129}I and ^{107}Pd within the early solar system. A large flux of high-energy solar particles was assumed generated by the initial solar adjustments. These particles, and associated secondary neutrons, induce a wide variety of nuclear reactions in both gaseous and solid particles in the solar accumulation disk. Many details of their argument have changed owing to changing facts, but some such process remains a limited possibility. Objections hinge mainly on the large amount of energy required to irradiate all of planetary matter, and on anomalies that seem not to exist even though they might be anticipated on that picture (e.g. D. Clayton *et al.*, 1977). Heymann *et al.* (1978) have discussed in detail the revived interest in this process as a generator of anomalies in Ne and Mg.

4.5. Other anomalies

There are a few other cases of reported isotopic anomalies in general meteorite samples (not the two special Allende inclusions to be discussed later) that may be relevant to the controversy over roots. These anomalies are not totally believed by chemists, in part because they have not been reproduced in other laboratories (a prerequisite based on historical cases) and in part because they are so fantastic as to stretch credulity. But if they stand future reinspections, the following four will assume great importance:

(i) *Uranium.* Arden (1977) has found widely varying and large enrichments of ^{235}U with respect to ^{238}U in differing chemically prepared meteoritic samples. If true, these are most likely (1) gas/dust fractionation with the two phases having different average ages (Clayton, 1975a, 1977c), (2) direct supernova injection of young ^{235}U *a la* Cameron and Truran (1977), or (3) chemical fractionation of *r*-process progenitors, especially ^{247}Cm($\tau_{1/2} = 15.6$ my) during dust formation (Blake and Schramm, 1973).

(ii) *Mercury.* Jovanovich and Reed (1976) found very large enhancements of ^{202}Ha relative to ^{196}Hg in specific meteoritic samples, which, if true, has many possible explanations, all of importance ... *s* or *r*-process enhancements, or chemical fractionation of a ^{202}Pb ($\tau_{1/2} = 3 \times 10^5$ yr) progenitor (Yanagita, 1977). Mercury is very volatile and hard to handle chemically.

(iii) *Sulphur.* Rees and Thode (1977) found a roughly 0.1% excess in ^{33}S in a bulk chemical leach of Allende samples. They regarded their results as needing further confirmation before they could be thought of as definite, however. This discovery could be very important because interstellar sulfides of varying compositions isotopically are expected on astrophysical grounds (Clayton and Ramadurai, 1977). An interpretation of this ^{33}S excess in terms of explosive-carbon-burning SUNOCONS was made by Clayton (1978d).

(iv) *Excess* ^{40}*Ar.* Jessberger and Dominik (1979) have confirmed their earlier discovery that some white coarse-grained inclusions contain more ^{40}Ar than can be accounted for by the decay of ^{40}K over the lifetime of the solar system. This excess could be the result of excess ^{40}K injected by a supernova trigger, in which case these inclusions are ^{40}K-rich, or it could be excess ^{40}Ar carried in presolar grains owing to ^{40}K decay during their interstellar residence (Clayton, 1975b, 1977c).

5. Supernova Induced Star Formation

It would be doubly hard to believe that the formation of the solar system was triggered by a neighboring supernova if the Sun is regarded as the only star that formed due to such a cause. Even though chemical evidence can be interpreted in terms of a supernova injection, it would not be in the spirit of post-Copernican science to accept a cause that has selected only our solar system. Only if the same event also provided the cause of human life could such bad odds be invalidated *a posteori*. Star formation is a common thing in the Galaxy. Several new stars per year are evidenced by the millions of stars having ages of less than 10^6 yr. If compression of cold clouds by supernova shock waves is a common cause of star formation, astronomical evidence should be obtainable.

In actual fact, the problem has been difficult because of the fundamental difficulty in obtaining optical observations of star formation. Because stars are born in dense opaque clouds, the events themselves have been optically invisible, so that traditional astronomy was able to do little directly other than find circumstantial evidence on young pre-main-sequence stars (*e.g.* Strom *et al.*, 1975). The newer astronomies, especially infrared and microwave spectroscopy, have provided many extra bits to this age-old puzzle. They have mapped the physical state of the interstellar medium (*e.g.* Spitzer, 1978) and shown that star formation is occurring primarily in cold ($\sim$20 K) dense (10^3–10^6 cm^{-3}) molecular clouds. The origin and lifetimes of these clouds are not known, but it is now commonly believed that these dense clouds have resulted from contraction of the so-called diffuse clouds, which are typically somewhat warmer ($\sim$80 K) and less dense, having neutral hydrogen densities near $n(\text{H I}) \sim 20$ cm^{-3} (Burton, 1976). The 21 cm line of H I is instrumental in mapping these diffuse clouds, but that line becomes weak in the dense molecular clouds where H changes to molecular H_2.

Although it is easy to see that stellar masses can gravitationally collapse in the dense molecular clouds, it is not so easy to see what causes the diffuse clouds to collapse into dense clouds. The characteristic temperature (80 K) and density (20 cm^{-3}) provide a sufficient pressure to resist collapse unless the clouds are more massive than about $M = 10^3 M_\odot$. This is easily seen by asking how large M must be before the negative gravitational energy ($\frac{3}{5}GM^2/R$ for a uniform sphere of radius R) exceeds twice the internal energy ($3MkT/\mu$, where μ is the average mass of a free particle). If $10^3 M_\odot$ is to collapse into stars, a very rich association of about 10^3 new stars must be expected, whereas most young stellar associations have an order of magnitude fewer stars.

The trend of astrophysical thinking in recent years has been toward causing less massive diffuse clouds to collapse by first compressing them with external pressure. Woodward (1978) has reviewed his and other calculations of this astrophysics problem. A small diffuse cloud is imagined in pressure equilibrium with a surrounding medium, which is traversed by an interstellar shock wave. This shock wave strikes and surrounds the diffuse cloud, and Woodward's calculations reveal knots that will subsequently collapse gravitationally. Several means of providing the suddenly increased external pressure have been discussed: large scale galactic shock waves of the density-wave type (Roberts, 1969; Woodward, 1978); cloud-cloud collisions (Loren, 1976); ionization-front shocks (Elmgreen and Lada, 1977); and supernova-ejecta shock compression of the H I cloud. The advantage of the galactic density wave is its potential for providing the long range spiral-arm order so often mapped out by young objects such as H II regions. The advantage of the ionization fronts is that it is both observed and physically expected to occur. The advantage of the supernova shocks is that they naturally occur and have a big effect on the interstellar medium (Cox and Smith, 1974), perhaps even becoming themselves the major phase by volume of the interstellar medium (McKee and Ostriker, 1977).

The overall problem of star formation is too large and too unclear to be reviewed here. Spitzer (1978) contains a good description of most of the known physical ideas. More to the point here is existing evidence that supernova shocks do cause stars to form. Öpik (1953) appears to be the first to have discussed this idea, which he advanced on the basis of already known astronomical facts plus his own intuition. Bird (1964) developed these ideas further, so that although supernovae are not known to definitely cause star formation, the idea is nonetheless a rather old one. It was a topic in its own right before Cameron and Truran's (1977) argument that this very cause for the solar system's collapse also provides the origin of isotopic anomalies in the solar system.

Herbst and Assousa (1977) have prepared the most convincing case for supernova-induced star formation. They studied carefully the stellar R association, Canis Major R1, which contains two classical Herbig emission stars (Z CMa and HD 53367) and several other extremely young stellar objects. These young objects lie on the edge of a large-scale ring of emission nebulosity that they argue to be the shock front of a supernova remnant. They advanced supporting radio evidence consisting of an expanding H I shell coincident with the optical feature. They also argued that the runaway star HD 54662 in CMa OB1 may have been the binary companion of the supernova. The following items summarize the key argument on this Canis association.

(a) *The young stars.* Two stars in CMa R1 (Z CMa and HD 53367) are early-type emission line stars in reflection nebulae catalogued by Herbig (1960). These 'Herbig emission stars' are probably the youngest known stars, being pre-upper-main-sequence objects with likely ages between 10^5 and 10^6 yr. Herbst *et al.* (1978) have made additional optical and radio studies of stars in this association and shown that many are 1 to 2 mag above the main sequence and surrounded still by circumstellar material. Clearly some cause of recent associated star birth was at work about 3×10^5 yr ago, according to their age estimate.

(b) *The emission ring.* There exists a large scale hot ring of optical emission that can be attributed to an outward moving shock front through the interstellar medium. Chevalier's (1974) modeling of the snowplow phase of the expansion showed that the age and size of a supernova remnant are related in astronomical units by

$$E_0 = 2.62 \times 10^{-6} n^{1.12} t^{-1.4} R^{4.52},$$

where the explosive kinetic energy E_0 is in units of 10^{50} ergs, the age t in units of 10^5 yr, the hydrogen density n is in cm^{-3}, and the size R is in parsecs. Using the observed $R = 30$ pc and plausible choices for the supernova energy and interstellar density (3×10^{50} ergs and 1 cm^{-3}) leads to an age 3×10^5 yr, in agreement with the young stellar ages around the ring.

(c) *The expanding neutral shell.* An expanding shell of neutral hydrogen is expected in supernova remnants and is found in CMa R1 (Weaver and Williams, 1974). The central feature appears to be expanding at 32 km s^{-1}. Herbst and Assousa (1978) have argued that the apparent difference between these two expansion velocities is not contradictory. The remnant age is inferred to be about 10^6 yr from these considerations.

(d) *The runaway star.* The runaway O star HD 54662 was argued by Herbst and Assousa (1977) to have once been at the remnant center, where it had been the binary companion of the supernova. It moves at +30 km s^{-1} with respect to the association, but its velocity components and position are not well enough known to ascertain whether it was in fact previously at the remnant center. Reynolds and Ogden (1978) were able to show that the enhanced O III emission near this star has the velocity of the back part of the shell, which is where it should be at present if it has moved at +30 km s^{-1} from the center for 10^6 yr. Blaauw (1961) discussed runaway O stars and argued that they were usually the remaining member of a once massive binary pair, having inherited their large velocity from the orbital velocity when the other more massive member exploded.

Herbst and Assousa (1977) described several other less compelling examples suggesting supernova-induced star formation. They also discussed the frequency of supernova events in relation to the frequency of birth of O associations, and concluded that their rough equality argues that supernovae may well produce O associations. This argument seems a bit unconvincing, considering that if O associations produce supernovae (the traditional connection) one arrives at this equality. Doubts aside, this paper and its sequel, Herbst and Assousa (1978), have marked a major advance in considerations of this important astrophysical question.

These same authors have also acknowledged the main objection to their conclusions – namely that the expanding shell need not be a supernova at all. Two other causes, both believed to be astrophysically frequent, may perhaps have produced this same morphology. The first is sudden over-pressure due to an advancing ionization front surrounding an O star. Because the ionized gas is hotter and has roughly twice as many free particles per gram as the neutral gas, the ionized pressure may exceed that which previously had been in hydrostatic equilibrium by an order of magnitude (Mathews and O'Dell, 1969). Lasker (1966, 1967) has modeled numerically the evolution of such H II regions, and finds that the ionized core will push outward a compressed neutral surrounding region at velocities comparable to the sound speed in the ionized core (about 10 km s^{-1}). Something similar to Canis Major R1 could result. A second and somewhat similar possibility is an energetic wind from the O star. This wind can push out a stellar bubble around the O star. If the wind is supersonic, as is likely, its shock degradation with the interstellar medium can produce a hot shell with many similarities to that of a supernova remnant. This theory was developed by Weaver *et al.* (1977). Herbst and Assousa (1978) have described their reasons for preferring the supernova theory of CMa R1 in preference to these other two; but, clearly, the definitive conclusion awaits the systematic assembling of several highly developed astrophysical lines of reasoning. It does appear that the expanding shell, whatever its cause, is in turn causing star formation. Herbst and Assousa emphasize that 'the strongest argument for a causal connection between the expanding shell and star formation comes from the location of the newly-formed stars with respect to the shell. Recent star formation has occurred over a projected linear extent of 30 pc at or close to the ionization edge which forms the western boundary of the main emission ring.' Each of four linear groups of young stars lie right at the ionization boundary, along the concave edge of the cloud facing the direction of the shock. Woodward's (1976) calculations of a shocked cloud showed, not really surprisingly, that this is where star formation could be expected.

The relationship of star formation by locally produced shocks (supernovae, ionization fronts, winds) to that produced by galaxy-wide density-wave shocks is very unclear. The latter has been supported by spatially coherent star formation over distances as long as spiral arms, but even this conclusion may be premature. Mueller and Arnett (1976) and Gerola and Seiden (1978) have numerically modeled locally induced star-formation propagation in differentially rotating galaxies. The resulting spiral patterns are sobering to advocates of galactic density waves. Because the density-wave model has nagging problems of its own (e.g. Toomre, 1977) we can expect only a long and tortuous path to a clearly correct understanding of star formation.

The paper of Gerola and Seiden (1978) is noteworthy because of the extreme numerical detail of their calculations and because of their comparisons to actual galaxies. They improved on Mueller and Arnett's (1976) groundbreaking study in two significant ways. Firstly, they made the model stochastic instead of completely deterministic by introducing a probability for star formation adjacent to a supernova explosion. Secondly, they chose a sufficiently fine array of cells across the galactic surface to ensure that size effects could not dominate their results. The disk is divided into N rings, each of which orbits the center according to the rotation curve assumed for each model. Each ring is then divided azimuthally into cells of equal area. The nearest neighbors are defined as the contiguous cells, varying between five and seven and changing identity owing to the differential rotation. If a cell has a supernova neighbor, a massive star will be created within that cell in the next time step with probability $P = P_{st}t_a/t_r$ if the age t_a of the youngest star in the cell is less than a time-scale parameter t_r and $P = P_{st}$ otherwise. The aging factor t_a/t_r allows a shocked cell to recuperate over a time t_r and become again ripe for star formation.

Gerola and Seiden compare their results to both M101 and M81 by choosing rotation curves like those of those two galaxies. The form of the rotation curve dominates their results, and the two contrasting galaxies show exciting similarity to their computed counterparts. The curvature of the long arms is reproduced over 10^{10} yr, furthermore suggesting that a locally-induced mode of star formation could indeed be a generator of spiral structure over such times.

What this new burst of ideas on star formation has done (within the field of this review) is to show that it is not unreasonable to suppose that the solar collapse may have been initiated by a supernova shock wave. Not yet giving clear answers, astronomical knowledge nonetheless assures us that such a mechanism need not be considered *ad hoc, special,* or *anti-Copernican.* Although meteoritic science can therefore use such a picture, it is no *panacea* for isotopic anomalies. A detailed model of how, where and when meteoritic solids formed must stand on its own feet, since the grave problems there involve specifically the chemical ontology of laboratory samples. What is still missing is an understanding of how isotopically anomalous meteoritic samples could have arisen as a result of the compression of a cold cloud by a surrounding supernova remnant.

If supernova-induced star formation is a dominant cause of star formation, the evidence from radioactive nuclear cosmochronology is affected. On the galactic-density-wave model for periodic generation of radioactive isotopes (Reeves, 1972b), the time-dependent ratios can be idealized as a periodic injection (see also Trivedi, 1977b). This concept leads to at least one natural explanation of the 10^8 yr waiting period of free ^{129}I decay described in Section IV. In the model galaxies described by Gerola and Seiden (1978), on the other hand, this particular 10^8 yr waiting period plays no role. In a self-propagating-star-formation model, the production history of solar-system nuclei will presumably be a stochastically generated sum of epochs of high enrichment, but it is not yet clear what the average waiting period between fresh admixtures should be. Over long times, differential rotation plus even small radial motions will mix nucleosynthesis products relatively uniformly, in the manner traditionally envisioned for the generation of smoothly monotonic nucleosynthesis rates (Fowler, 1972).

6. Supernova Nucleosynthesis

The thermonuclear evolution of a massive star is a prolific synthesizer of new nuclei, and its terminal central instabilities seem likely to lead to the supernova phenomenon. This certainly will occur if core collapse generates a sufficiently strong outgoing shock wave ($\sim 10^{51}$ erg) to eject mantle and envelope. The core boundary is envisioned as a piston which first falls in as its electron-pressure support is destroyed by electron capture, bounces off a neutron core (e.g. Van Riper and Arnett, 1978; Van Riper, 1978) and generates an outward-moving shock, whose dissipation in the still stationary mantle generates sufficiently high temperatures to ignite nuclear burning in explosive nuclear fuels, Si, Ne, O, and C. This last nuclear processing adds the final changes to the nuclear evolution that had begun when the newly formed star had first become hot enough at its core for hydrogen burning to commence. The resulting overpressure from the thermal release in the supernova mantle accelerates the material outward following its initial jarring in that direction by the passing shock wave. Compressions of 3 to 4 by shocks near Mach 2 are probably typical. Tens of solar masses of highly evolved fuel may be ejected, which, at the observed supernova rate, makes supernova the major source of nucleosynthesis.

The supernova is but the most productive and spectacular vehicle of nucleosynthesis in stars, a general scientific theory that erupted into full vogue following the very influential exposition of it by Burbidge *et al.* (1957). Summarizing the advantages of stellar nucleosynthesis over other theories they said:

"The basic reason why a theory of stellar origin appears to offer a promising method of synthesizing the elements is that the changing structure of stars during their evolution offers a succession of conditions under which many differing types of nuclear processes can occur. Thus the internal temperature can range from a few million degrees, at which the pp chain first operates, to temperatures between 10^{10} degrees when supernova explosions occur. The central density can also range over factors of about a million. Also the time scales range between billions of years, which are the normal lifetimes of stars of solar mass or less on the main sequence, and times of the order days, minutes, and seconds, which are characteristic of the rise to explosion."

The thermonuclear evolution of matter naturally arranges itself into successive epochs selected by the chemical composition and by the Coulomb barrier that dominates charged-particle nuclear reactions – hydrogen burning, helium burning, carbon burning, neon burning, oxygen burning and silicon burning (*e.g.* Clayton, 1968). This temporal sequence is transformed into a radial sequence in the evolved star by the combined effects of radial temperature gradient and the decrease in lifetime with increasing temperature. The evolved core adopts an onion-skin structure, studies of which include a notable series by Arnett (1969, 1972a, b, c, 1973, 1974a, b, 1977, 1978). Figure 8 shows a particularly nice structural profile of such a $25M_\odot$ star by Weaver *et al.* (1978). The radial abscissa is the mass interior to that point, and the ordinate divides the elemental composition at that point into its several fractions by mass (so that the sum remains unity). The logarithmic scale allows relatively small abundances to be displayed along with the dominant ones. This configuration is achieved in about 10^7 years after birth of a $25M_\odot$ star, and would be considerably younger or older if the star were respectively more or less massive. The nuclear evolution of the core is so rapid owing to neutrino losses in core carbon burning and later epochs leading up to Figure 8 that the outward appearance of the star can no longer change. It remains a (probably red) supergiant from the end of helium burning until the time when the shock wave reaches the stellar surface. The

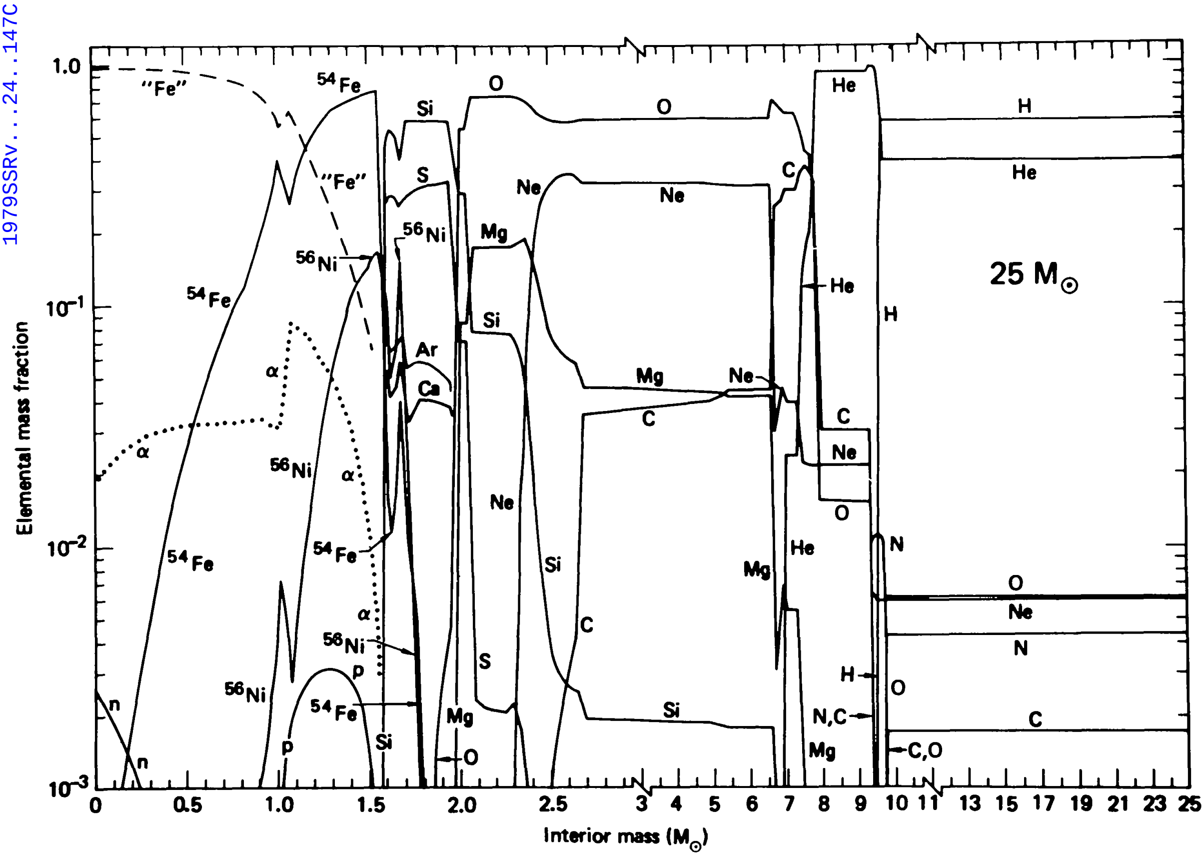

Fig. 8. The chemical composition of a $25M_\odot$ at the beginning of core collapse as computed by Weaver *et al.* (1978). The radial abscissa is the mass contained within that coordinate. The abundances are fractions by mass, so they sum to unity. The several burning shells are evident by composition precipices. This is a sample 'presupernova structure', and one considers the abundance yields when an outward moving shock wave initiates the explosion.

effects in the envelope seem to lead naturally to the observed supernova light curves (Falk and Arnett, 1977).

The changes in composition in Figure 8 occur in the burning shells. For example, near $7M_\odot$ radial coordinate, one sees C disappearing while Ne and Mg rise. Clearly this is the location of the carbon-burning shell, where $^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha$ and to $^{23}Na + p$, followed by partial fusion into ^{24}Mg. Near $2.6M_\odot$, as another example, the Ne is converting to ^{16}O and ^{24}Mg by the neon-burning reactions, which are initiated by the photoejection process $^{20}Ne + \gamma \rightarrow O^{16} + \alpha$ accompanied by $^{20}Ne + \alpha \rightarrow {}^{24}Mg + \gamma$. With a practiced eye one can read the complete thermonuclear evolution of this model star from those composition changes shown in Figure 8. However, these are only the major isotopes of the most abundant elements. The total nucleosynthesis pattern requires a much more complete description.

This description can be aided by the schematic diagram shown in Figure 9. The left half shows the major zones of the presupernova structure, with burning shells indicated. This figure, taken from Clayton and Woosley's (1974) analysis of the nuclear cross-section data of importance to this interpretation, is seen from Figure 8 to have been incomplete in its neglect of the large Ne zone lying between the

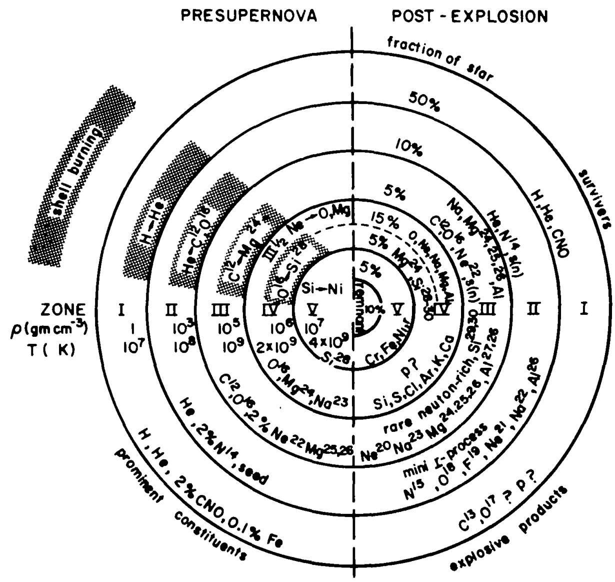

Fig. 9. A schematic onion-skin structure indicating the relationship of the ejected abundances, either previously synthesized survivors of the explosion or explosively created nuclei, to the presupernova structure. Nucleosynthesis highlights of the various zones are described in the text. Adapted from Clayton and Woosley (1974).

carbon-burning shell (III) and the neon-burning shell (III $\frac{1}{2}$). At that time neon-burning seemed likely to be a small portion of an oxygen-burning shell (IV), which in fact extends only between $2.0M_\odot$ and $2.5M_\odot$ in Figure 8. Thus a Zone III$\frac{1}{2}$ characterized by the $2\mathrm{Ne} \rightarrow \mathrm{O} + \mathrm{Mg}$ burning at its base has been added to Figure 9. Figure 9 is useful in its display of the relationship of the presupernova shells to the post-supernova shells. This relationship has assumed greater importance following the discoveries of isotopic anomalies, because they are now being interpreted in terms of the injection of specific supernova shells into the forming solar system or, alternatively, the condensation of SUNOCONS during the expansion of the supernova shells.

The right half, or post explosive half, of Figure 9 attempts to display the major nuclear products ejected from each zone in the explosion. These divide (not always cleanly) into those species that were created in the prior thermonuclear evolution of the stars and those that are created during the explosion itself. Here too some shifts in emphasis have occurred since this figure was published. Arnett (1978) has given a recent estimate of the average bulk yields from these zones. To try to give a clearer picture of the schematic situation, the following subsections contain clarifying remarks about each zone and its likely products:

Zone I. Hydrogen fuses to helium at the base of this zone by the CNO cycles (e.g. Clayton, 1968) in massive stars. Of order half of the mass of massive stars lies outside this burning shell. The CNO isotopes are converted to ^{14}N. The survival of that ^{14}N is its major natural source. Whether radiative proton captures can occur when the shock wave passes through this zone is unclear; if so, it might account for some ^{13}C, ^{17}O, and ^{21}Ne and even some p-nuclei (e.g. Arnould and Norgaard, 1978).

Zone II. At its base, He fuses to ^{12}C by the 3α reaction (e.g. Clayton, 1968). As the ^{12}C grows, it competes increasingly for the α particles, so that $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$ leads to ^{16}O being the major final product after He exhaustion. In the burning shell itself, however, ^{12}C may exceed ^{16}O at the time of the shock, offering the interesting possibility of a carbon-rich zone of ejecta, which could be an important cosmochemical site for condensation of carbonaceous carriers. The ^{14}N left after H-burning is destroyed in the He-burning shell by capturing alpha particles. $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ first creates 2% by mass of ^{18}O, a possible significant source of ^{18}O if the star disrupts at that time or if this matter is mixed to the surface where it is lost. In the hot burning shells of massive stars, however, the ^{18}O is itself destroyed, by $^{18}O\ (\alpha, \gamma)^{22}Ne$. This is presumably the major nucleosynthesis source of abundant ^{22}Ne, and may have something to do with Ne–E carriers (Arnould and Norgaard, 1978). In massive stars the ^{22}Ne is itself also destroyed near helium exhaustion, creating as much as 2% by mass fraction $^{25,26}Mg$ by the reactions $^{22}Ne\ (\alpha, n)^{25}Mg$ and $^{25}Mg\ (n, \gamma)^{26}Mg$, as well as providing a good general *s*-process environment (Lamb *et al.*, 1977).

When the supernova shock passes through this zone, a great variety of interesting things can happen depending upon the state of prior evolution of the thermonuclear burning. A key circumstance concerns whether the ^{14}N has already been destroyed, as it is in the He-burning shell itself, or whether the shocked He can still react with ^{14}N, as above the He-burning shell but below the H-exhausted boundary. If He can be shocked to 5 to 7×10^8 K its reactions with ^{14}N can produce much of the rare isotopes ^{15}N, ^{18}O, ^{19}F, and ^{21}Ne (Howard *et al.*, 1971; Arnould and Beelen, 1974; Arnould and Norgaard, 1978) as well as significant concentrations of the proton-rich radioactive nuclei ^{22}Na (see also Clayton, 1975c) and ^{26}Al (Clayton, 1977a; Arnould and Norgaard, 1978; Chance and Harris, 1979). Arnould *et al.* (1978) have studied another variant for ^{26}Al production in this zone – namely an admixing (not really understood) of a modest density of free protons from the hydrogen-burning shell into the hydrogen-exhausted material underneath. Free protons already in existence there can be utilized well in ^{26}Al production. If the ^{14}N has not already burned, free protons are liberated by (α, p) reactions in the shocked matter, leading to ^{22}Na and possible ^{26}Al production. But if the $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O$ reaction has already occurred, the remaining 2 to 3% of the non-He matter is already neutron-rich, so that proton-rich nuclei will not be produced. But that situation is also exciting, because the (α, n), reactions of the shocked He with either ^{18}O or ^{22}Ne offer the possibility of an intense burst of free neutrons, driving heavy nuclei to neutron-rich isotopes of their respective elements. Cameron (1962) seems to have first described that scenario. This process was first calculated (with postulated shock conditions, however) by Truran *et al.* (1978), and by Thielemann *et al.* (1978), who hoped to use this particular rapid neutron-capture process to generate *r*-process isotopic excesses in heavy elements within two special Allende inclusions (to be discussed in the next section). Whether this process has anything to do with observed isotopic anomalies or not, it certainly will, if it occurs at all, be an interesting contributor to the bulk nucleosynthesis of the *r*-process nuclei. This is an especially interesting question in astrophysics, because the true origin of these neutron-rich isotopes has never been fixed. For a good introductory treatment of both *s*- and *r*-processes of heavy element nucleosynthesis, the reader is referred to Chapter 7 of Clayton (1968). Hillebrandt (1978) has authoritatively reviewed *r*-process scenarios. Truran *et al.* (1978) and Thielemann *et al.* (1978) both emphasized that the Mg emerging from such an explosive neutron burst should be much enriched in ^{25,26}Mg, which are manufactured directly to roughly 2% concentration by mass from ^{22}Ne(α, n)^{25}Mg. Figure 2 of Thielemann *et al.* (1978) shows this particularly vividly. This yield is designated in the explosive-products segment of Figure 9 as a *mini r-process*, but it has not been established by these papers that real supernovae must actually do this inasmuch as it depends on the total prior evolution of the star and on the strength of the outward-moving shock in the supernova. If this *r*-process does exist, it is also clear that SUNOCONS condensing within this zone will be enriched in ^{25,26}Mg and in heavy neutron-rich isotopes.

Zone III. Because the He-burning shell in massive stars has a high temperature, it is likely that ^{25,26}Mg are already enhanced throughout Zone III as remnants of ^{22}Ne (α, n) destruction during the He exhaustion (Lamb *et al.*, 1977; Arnett and Wefel, 1978). In that case the carbon burning at the base of the shell, which is likely to be convectively mixed throughout, produces primarily ^{20}Ne, ^{23}Na, ^{24}Mg, and ^{27}Al (Arnett and Wefel, 1978). The other two Mg isotopes are already there. This is a change in thinking that was previously based on experience in core burning in low-mass stars, where it seemed reasonable that ^{22}Ne would still be in existence at the onset of carbon burning, whose initiating reactions are $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ and $\rightarrow ^{23}Na + p$. The new ^{24}Mg can result from ^{20}Ne(α, γ) or from ^{23}Na (p, γ)^{24}Mg. If ^{22}Ne were still there, the ^{25,26}Mg would also be produced in carbon burning by the ^{22}Ne (α, n) reaction using the alpha particles liberated by the carbon burning. But if Arnett and Wefel (1978) are correct, the carbon burning begins with a huge ^{25,26}Mg excess which is continuously made less conspicuous by the production of large amounts of ^{24}Mg, so that, by the time C is exhausted, the isotopic composition of Mg is almost normal (but probably still somewhat ^{25,26}Mg-rich).

Arnett and Wefel (1978) now argue that the explosive burning when the shock hits will not burn very much more carbon, which is mostly burned already. As a result, the explosive burning does not create the major nuclear species, but rather adjusts their abundances and makes important contributions only to minor nuclei. For example, the three Mg isotopes are only little altered by the explosive burning, which creates perhaps 10% more ^{24}Mg but reduces ^{25,26}Mg by a few percent, which in turn reappears as significantly increased concentrations of the two heavy isotopes of Si. This is a change from previous thinking about parameterized nuclear explosions, wherein the carbon explosion was thought to create all three isotopes of Mg (Arnett, 1969; Arnett and Clayton, 1970). The borderline between 'survivers' and 'explosive products' in this zone of Figure 9 is therefore somewhat ambiguous. This is characteristic of today's nucleosynthesis views, which now attempt to build on the advanced evolution of massive stars rather than somewhat arbitrary explosions of carbon and oxygen. Therefore the systematic reappraisal of nucleosynthesis by Arnett and Clayton (1970) needs interpreting with some understanding. Basically the sites of origin are much as they described in their attempt at reformulating details unclarified by the general B^2FH picture (Burbidge *et al.*, 1957), but the products are not so much explosive (in many cases) as they are explosively adjusted survivers of prior hydrostatic evolution.

Neutron-capture reactions during carbon burning happen on both long (*s*-process) and short (*r*-process) time scales. During hydrostatic carbon burning (Reeves and Salpeter, 1959; Cameron, 1959; Arnett and Truran, 1969) neutrons can be liberated by the weak branch $^{12}C + ^{12}C \rightarrow ^{23}Mg + n$, by $^{13}C(\alpha, n)^{16}O$ reactions following $^{12}C(p, \gamma)\, ^{13}N(\beta^+\nu)^{13}C$, and by $^{18}O(\alpha, n)^{21}Ne$ and $^{22}Ne(\alpha, n)^{25}Mg$ on the residues of helium burning. All happen to some degree, but the number of neutrons captured per ^{56}Fe seed nuclei is no more than about ten (Arnett and Truran, 1969) even if ^{22}Ne still remains at the onset of carbon burning. This is not enough to be the major source of *s*-process nucleosynthesis, but it is more than enough to eradicate the *r*-process isotopes of the heavy elements, leaving only a somewhat enhanced *s*-process distribution at the conclusion of hydrostatic carbon burning.

The same neutron sources can occur in explosive carbon burning. Following Arnett's (1969) dramatic demonstration that explosively burned carbon provided a good match to abundances of ^{20}Ne, ^{23}Na, $^{24,25,26}Mg$, ^{27}Al, $^{29,30}Si$, and perhaps ^{31}P, Howard *et al.* (1972) calculated the fate of heavy isotopes of the elements in the free-neutron burst that accompanies the burning. They found that many rare neutron-rich isotopes of low stability (e.g. ^{36}S, ^{46}Ca etc.) may trace their natural origins to such shells. They made a very important finding in the heavier elements (Fe to Bi) – namely, that (γ, n) photoejection limits the neutron captures after roughly 6 captures, depending on the element. This is another type of mini *r*-process, capable of converting the *s*-enhanced isotopes to *r*-process isotopes of slightly higher atomic weight. This could be of importance to the isotopic anomaly problem, either due to injection of the explosive-carbon-burning shell or owing to SUNOCON condensation during the expansion of that shell. In either case one sees the possibility of finding *r*-enhanced isotopes associated with other products of the shell. However, the results of Howard *et al.* (1972), which were not discussed for elements heavier than Ni owing to a belief that they were not significant contributors to bulk nucleosynthetic yields, need to be recalculated. They assumed that the neutron excess resided in ^{22}Ne, which was at that time 2% by mass of the composition. Therefore the neutron burst from $^{22}Ne(\alpha, n)^{25}Mg$ was intense. In the shells of massive stars, as discussed above, the neutron excess probably resides primarily in $^{25,26}Mg$ owing to ^{22}Ne consumption during prior He exhaustion. Because the explosive burning probably burns only a small mass fraction of the carbon (Arnett and Wefel, 1978), neutron liberation by $^{25}Mg(\alpha, n)^{28}Si$ is not nearly as large as it was in Howard *et al.* (1972) calculations. Therefore, the fate of the heavy elements seriously needs reattention in a calculation coupled correctly (as best as one can) to stellar evolution. Another point of interest is that the limitation on heavy-element captures by (γ, n) resistance discovered by Howard *et al.* has not always been appreciated by other calculations of explosive-carbon burning. Chance and Harris (1979) have recently reemphasized that because of it the heavy elements cannot capture neutrons freely, requiring that the light elements absorb more of them. They have argued that nonnegligible ^{17}O will be ejected for this reason.

Summarizing, ^{20}Ne, ^{23}Na, $^{24,25,26}Mg$, ^{27}Al, $^{29,30}Si$, and ^{31}P are ejected in substantial amounts from Zone III, along with *s*-nuclei from the hydrostatic burning and *r*-nuclei from the portion where carbon burns explosively. In first approximation, Zone III can be thought of as the origin of these nuclei. We await a more definitive treatment of these coupled problems.

Zone III $\frac{1}{2}$. Of the major nuclear species left by the exhaustion of carbon, ^{20}Ne is not particularly tightly bound. Its alpha-particle separation energy of only 4.73 MeV allows the thermal photodisintegration $^{20}Ne + \gamma \rightarrow {}^{16}O + \alpha$ to occur before the gas becomes hot enough for fusion of oxygen with itself to occur. The resulting reactions are called neon burning. Figure 8 shows that the ^{20}Ne-rich zone between carbon-burning and neon-burning shells is quite massive in that $25 M_{\odot}$ model. This large mass contains primarily the major products of carbon burning – ^{20}Ne, ^{23}Na, $^{24,25,26}Mg$, ^{27}Al. Their survival during ejection of this zone is certainly a major contributor to their natural abundances, probably much greater than can be created by the explosive burning of carbon during the ejection process.

The burning of ^{20}Ne at the base of this zone is a significant epoch in stellar evolution (Arnett, 1974a). Among the most abundant species the effective nuclear change is $2\,^{20}Ne \rightarrow {}^{16}O + {}^{24}Mg$, because half of the abundant ^{20}Ne is destroyed by capturing the free alphas liberated by the (γ, α) destruction of the other half. Beneath that shell, therefore, O^{16} and ^{24}Mg dominate the composition. Other reactions with the free alphas are of cosmochemical significance, however. The heavy Mg isotopes are transferred by (α, n) reactions to heavy Si isotopes, and some ^{28}Si is created by alpha capture on the growing ^{24}Mg. But the Si remains heavy-isotope-rich, as the bulk of the ^{28}Si awaits synthesis in oxygen burning itself. Interestingly, therefore, the ashes of this burning shell are characterized by light (^{24}Mg-rich) magnesium and heavy ($^{29,30}Si$-rich) silicon. This circumstance could lead to interesting SUNOCONS trapping this correlation, probably Mg_2SiO_4 (Clayton, 1978d).

Perhaps the most important heavy-element attribute of this zone is that it provides a reasonable site for the *p*-process (Woosley and Howard, 1978). There exists here a large mass mostly devoid of neutron-liberating thermonuclear reactions. The heavy elements find themselves in a photon bath hot enough to drive the isotopes to the proton-rich end by (γ, n) reactions without the usual competing bath of free neutrons. The quantitative investigation of this *p*-process site has marked a significant recent advance in heavy-element nucleosynthesis, largely because the older (e.g. B^2FH; Audouze and Truran, 1975) idea of (p, γ) sites have proved so difficult to locate. Clayton (1978c) has argued that the three proton-rich isotopes of

Sn offer the best opportunity to determine which type of *p*-process has been adopted by nature. He was able to show that the odd-A ^{115}Sn yield has been very small in the *p*-process in comparison with ^{112}Sn and ^{114}Sn, definitely favoring a photodisintegration model over a radiative-capture model. On the other hand, both Trivedi (1978) and Clayton (1979) have pointed out that meteoritic evidence for prior existence of extinct ^{146}Sm seems to point to a (p, γ) process. This reviewer feels that a resolution of this conflicting evidence will be forthcoming from more thorough dynamic studies of a superposition of sites. An incomplete photo-strip-down of Sm could terminate still having excesses at ^{146}Sm, for example; or, on the other hand, a brief photoejection period following a (p, γ) process could conceivably deplete odd-A progenitors of ^{115}Sn. This impasse is an important question for study, because the *p*-process can become a significant diagnostic tool for nucleosynthesis. Heymann (1979) and Heymann and Dziczkaniec (1979) have attempted to utilize Woosley and Howard's (1978) photodisintegration version of this process to get at the origins of *p*-isotope anomalies in meteorites, but the chemical connections remain unclear. We will return to this particular problem in connection with the two special Allende inclusions EK1–4 and C1.

Zone IV. The fusion of ^{16}O with itself via the three exit channels ^{28}Si + α, ^{31}P + p and ^{31}Si + n occurs at the base of Zone IV, which may also be convectively mixed out to near the neon-burning shell. The burning process is well described in the literature. Arnett (1974b) described stars in oxygen core burning, whereas Woosley *et al.* (1972) evaluated the details of the nuclear reaction networks on the fairly realistic assumption that the thermonuclear power balances the energy losses from local neutrino production. The explosive burning was first calculated by Truran and Arnett (1970) and subsequently clarified in almost all details by Woosley *et al.* (1973). This burning shell prior to shock-wave passage is evident in Figure 8 by the sudden exhaustion of oxygen $2.0 M_\odot$ from the center, where it is being converted to ^{28}Si and ^{32}S. At the same time the heavy Si isotopes are being converted by (α, n) reactions to ^{33,34}S. The ^{28}Si is growing at the expense of Mg, which is isotopically pure ^{24}Mg at this stage, via the ^{24}Mg (α, γ)^{28}Si (or equivalent) reactions. The first stage of oxygen burning may be regarded as completed when enough alpha particles have been liberated by $^{16}O + ^{16}O \rightarrow ^{28}Si + \alpha$ reactions to have consumed the residual ^{24}Mg. This stage requires burning of a significant fraction of the ^{16}O fuel and establishes ^{28}Si (isotopically almost pure) as overwhelmingly the most abundant heavier nucleus. Significant ^{32}S has been synthesized, but not enough to have eliminated the isotopic heaviness of sulfur.

During the remainder of oxygen burning, ^{32}S and ^{36}Ar and, to some extent, ^{40}Ca are produced by the (α, γ) reactions. In the explosive burning, the (α, γ) reactions easily penetrate to ^{40}Ca. They are in fact inhibited by (γ, α) photoreactions that establish an equilibrium with respect to alpha-particle exchange among the alpha-nucleus group ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca (Woosley *et al.*, 1973). This restricted equilibrium had been studied by Bodansky *et al.* (1968; see also Clayton, 1968), who named it *quasiequilibrium*. This very useful concept enables a quick realistic calculation of the abundances of species between ^{28}Si and ^{42}Ca during explosive burning. The non-alpha nuclei in this mass range participate by sharing an equilibrium under exchange of free nucleons. The quasiequilibrium becomes increasingly more exact as oxygen is exhausted and merges into silicon burning. Generally speaking, the nuclei ^{28}Si, $^{32,33,34}S$, $^{35,37}Cl$, $^{36,38}Ar$, $^{39,41}K$, $^{40,42}Ca$, and ^{46}Ti and perhaps ^{50}Cr are expected to have emerged predominantly from this burning zone. A substantial amount of surviving ^{24}Mg may be an important part of the total Mg budget.

Zone V. As the silicon slowly 'melts', the quasiequilibrium during silicon burning shifts the abundance from the Si–Ca region to the iron-group abundance peak (Cr, Mn, Fe, Co, Ni). Bodansky *et al.* (1968) and Woosley *et al.* (1973) have studied the details of this. The quasiequilibrium slowly becomes a complete nuclear equilibrium during this transition. An interesting historical point is that the explanation of the natural abundance peak at Fe as a result of this nuclear equilibrium was an early building block to the whole theoretical idea of nucleosynthesis in stars (Hoyle, 1946).

The hydrostatic evolution of the star builds up a Si core of about $1.4M_\odot$ almost independently of the total mass of the star; however, it is not at all clear how much of this matter ever escapes the star when supernova-time rolls around, and the implosion begins at some time during the Si burning itself, as electrons are being removed from the gas by capture, primarily by ^{56}Ni (Fowler and Hoyle, 1964). Part or all of the core may be left as a remnant-neutron-star or black-hole. The fact that the matter is made very neutron-rich offers the possibility of having heavy neutron-rich nuclei (*r*-process) synthesized in the ejected matter near this mass cut (Truran *et al.*, 1968). The dynamics of the core are just not well enough solved to judge the reasonableness of this. The *r*-process has in fact been very difficult to locate in stars, but the reader can find a very nice review of this problem by Hillebrandt (1978).

6.1. Sunocons

Within the framework of this discussion one can quickly reexamine the argument (Cernushi *et al.*, 1967; Hoyle and Wickramasinghe, 1970) that dust will condense in the expansion of the supernova interior. The overheated matter left by the dissipation of the shock wave is mechanically dominated by radiation pressure. A typical condition may be $T = 2 \times 10^9$ K and $\rho = 10^5$ g cm, where the radiation and gas pressure respectively

$$P_r = (\tfrac{1}{3})aT^4, \qquad P_g = \frac{N_0 k}{\mu}\rho T$$

stand in the ratio $P_r/P_g \approx 10^2$. The entropy of the photon gas also dominates that of the particles, so that in an *adiabatic* expansion of this shocked material the entropy of the photon gas remains roughly constant, giving T^3/ρ as a constant of the expansion (e.g. Clayton, 1968, p. 121). For the sample zone chosen in c.g.s. units

$$\rho = CT^3 = \tfrac{1}{8} \times 10^{-22} T^3$$

Expecting condensation to begin when T falls to 2×10^3 K leads to a condensation density $\rho = 10^{-13}$ g cm^{-3}. This density is, furthermore, devoid of H and He, unlike a solar gas would be. The elements O, Mg, Na, Si, Al dominate the composition, so that refractory minerals are to be expected. Figure 10 shows such adiabats for three internal zones as calculated hydrodynamically by Weaver and Woosley (1978). Each zone is first compressed by a factor near three and heated by the passing shock wave.

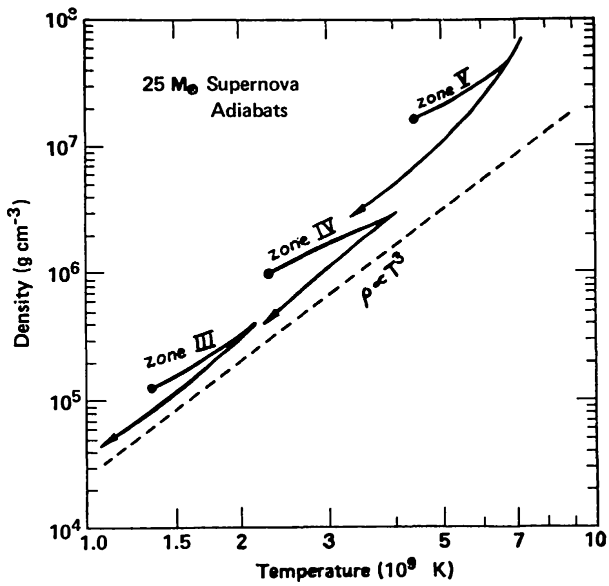

Fig. 10. The trajectory in the ρ, T plane of characteristic points in zones III, IV, and V during the explosion, as computed by Weaver and Woosley (1978). The shock wave first compresses and heats each zone, which then expands along a line approximately $\rho \sim T^3$. Supernova condensates (SUNOCONS) will precipitate when the temperature has fallen to below 2×10^3 K. Each zone expands along almost the same track.

Its overpressure produces an expansion which proceeds in the general direction $\rho \sim T^3$. In fact, each zone moves along a very similar adiabat, so that a density 10^{-13} g cm^{-3} should correspond to an approximate onset of very refractory SUNOCONS from each zone. This domination by radiation pressure will not continue indefinitely during the expansion, but it lasts a very long time as seen by the following: for homologous expansion, $\rho \sim R^{-3}$, so that $T \sim 1/R$. Thus the ratio

$$\frac{P_r}{P_g} \propto \frac{T^4}{\rho T} \propto \frac{T^3}{R^{-3}} \simeq \text{constant}$$

so that P_r exceeds P_g for a very long time. The approximate relation $T \sim 1/R$ sets the required time for grain growth. The radius $R = vt$ increases with the expansion speed, which is unknown for interior supernova zones, but which is expected to be of the order $v \approx 10^8$ cm s^{-1}. Thus a decrease in T from 2×10^9 K to 2×10^3 K corresponds roughly to an increase in R by the factor 10^6. Because nucleosynthesis occurs in shells near 10^9 cm or less, the remnant is 10 to 100 AU in size when grain condensation occurs. At a speed $v = 10^8$ cm s^{-1} this would require a few months of expansion.

Clayton (1975a, b) pointed out that this process should populate the interstellar medium with isotopically anomalous SUNOCONS from the separate zones. The extent of mixing of these zones during these few months remains an unsolved problem, but is seems to this reviewer only likely to occur along the interface of any instabilities, rather than throughout their volume. Clayton (1978d) has taken his estimates of the yields from these separate zones and calculated the abundance and isotopic composition of SUNOCONS expected without mixing. The reader is referred to his paper for those estimates. Lattimer *et al.* (1978) considered the same problem, placing emphasis on the chemical sequence but giving neither SUNOCON abundances nor isotopic compositions. Both of these attempts have highly idealized the problem, each in its own way. Nonetheless, important new possibilities for interstellar chemistry and for solar system science have been focused upon.

Some have doubted that grains can nucleate and grow so quickly. Positive evidence comes from the common nova, which has been studied as a laboratory in this regard (Clayton and Hoyle, 1976; Gallagher, 1977).

As irony would have it, many have estimated that supernova shock waves also destroy dust in the interstellar medium (e.g. Salpeter, 1977; Cowie, 1978 and refs.). For clarity it should be remarked that this is a different problem and *does not* argue against dust formation in the comoving fluid expansion of the supernova interior. The fate of these dust grains as they first encounter the interstellar medium and begin to slow down needs further study.

6.2. Shell admixture from a supernova neighbor

Cameron and Truran (1977) suggested that one or more of these shells was admixed with the solar-system gases while initiating its collapse. The key ^{26}Al seems likely to arise from Zones II, III, or III $\frac{1}{2}$. Such mixing is difficult (Margolis, 1979). Most discussions have selected Zone III, the explosive-carbon-burning shell, but the total problem is so difficult that its study has really only just begun (see earlier discussions in this review). Nor is it necessary, or even likely, to assume that the supernova trigger was a star of the type shown in Figure 8, because such stars *are not* typical supernovae.

6.3. Typical supernovae

It has been argued for some years by Arnett that a 25 to $30 M_\odot$ star is probably the typical supernova insofar as mass-weighted yield is concerned (e.g. Arnett, 1978). Such stars are an important part of the mass spectrum of newly forming stars because they eject such a large mass of nucleosynthesis products. More common lower-mass stars do not synthesize enough, whereas more massive stars are too rare. On the other hand, these objects so important for nucleosynthesis are *not* the average supernova. Ostriker *et al.* (1974) found the death rate of O stars ($M \geqslant 26 M_\odot$) to be 1.2×10^{-12} pc^{-2} yr^{-1}, giving one such event every 10^3 yr for our galaxy. The observed supernova rate for our galaxy (Tammann, 1977) is about (30 yr)$^{-1}$, a factor of 30 greater than the death rate of O stars. Thus the *a priori* expectation would be that any given supernova is unlikely to have been an O star. To argue that the supernova trigger for the solar system was an O star, therefore, one would have to appeal to stellar geneology – that in an association of stars of equal age, the O stars will make the first supernovae and are therefore most likely to induce other star formation. One may hope for continuing improvement in arguments based on stellar statistics such as these. Arnett (1978) has identified the following problems for needed study: (1) evolution of stars of mass $M \leqslant 10 M_\odot$ (which, being numerous, could be important sources), (2) H and He burning stages of massive stars (particularly with tests of theory by observation; investigation of mass-loss and binary effects), (3) the mechanism of the explosion, (4) the initial-mass function and M to M_α transformation for $M \leqslant 15 M_\odot$ and $M_\alpha \leqslant 4 M_\odot$ (where M_α is the He-core mass generated), and (5) abundances in supernovae and young supernova remnants, especially massive ones.

6.4. The Fly-Catcher and the Bing-Bang

Two other interesting variants on the idea that supernova generate the isotopic anomalies merit explicit remarks, although they can not be justly developed here.

T. Gold suggested at the 1976 Gregynog workshop that the solar accretion disk (already formed) was like flypaper for an accidental neighboring supernova. He did not publish this, but it is in the literature (Clayton, 1977a) as follows:

> Finally, one must reconsider whether the supernova need be considered the cause of the solar condensation. It is easy to see that if 100 stars, say, form during the collapse of a 1000-$M_\odot$ molecular cloud, one of them may have exploded and dirtied the solar nebula, especially if the latter has lagged somewhat in its own collapse. One should consider that the debris may have been caught by the planetary disk around the early Sun, an idea advanced by T. Gold as a flypaper model.

Starting with the molecular cloud, Reeves (1978) has argued that abundance variations will be established in an otherwise homogeneous molecular cloud by stellar evolution and nucleosynthesis within that cloud. Small solid objects forming at differing locations would be, in first approximation, chemically identical and therefore appear to be solar; however, small variations would exist owing to the self generated gradients in a sequence of supernova induced star formation (the 'Bing-Bang') within the cloud. Small objects would drift from one star to another, like electrons in a metal, until a few were trapped in the collapsing solar system.

7. Strange Inclusions

Atop the exciting issues described in previous sections comes the strangest surprise of all. From the almost 100 inclusions from C3 meteorites that have been studied, some 5 or 6 have proven to be much more bizarre than the majority. They exhibit isotopic anomalies in many elements. One of these, called EK-1 (for historical reasons), has revealed isotopic anomalies in every element that has been examined with high resolution! These discoveries have loosed the gates of speculation still further. Researchers now advance not only their pet model for producing isotopic anomalies in the solar system, but why it is that that pet model has produced ^{16}O anomalies in all inclusions, excess ^{26}Mg in Al-rich minerals in many inclusions, but a wide range of isotopic anomalies in only a few inclusions. This rich data base seems likely to lead a few pet models to the grave! Nonetheless, recent papers hold four classes of models up to this data to see how they shape up. The four are, as described previously, (1) injection of fresh supernova debris, (2) chemical and isotopic differences among differing condensed phases of an otherwise uniform solar nebula, (3) residual spatial inhomogeneities within a solar nebula, and (4) exotic 'marbles' captured by the solar system after formation elsewhere in a larger chemically inhomogeneous region. For brevity these will be abbreviated by (1) *trigger*, (2) *precondensates*, (3) *inhomogeneities*, and (4) *marbles*. The 'fly-catcher' model can be regarded as a variant of (1), and the 'bing-bang' model as a plausible version of (4).

The strange isotopic compositions themselves are of two apparently different patterns. Often the isotopic composition would be almost normal except for what is interpreted as a systematic mass-dependent fractionation, usually in the sense of progressively enriching the heavier isotopes. After a correction for this fractionation, smaller isotopic derivations at specific isotopes are apparent. These are ascribed to nuclear effects, most likely to a different nucleosynthetic mix. Unfortunately, this decomposition is not unique. There is as yet no independent way of ascertaining the isotopic mass fractionation of the sample, and if a slightly different fractionation is assumed, the residual nuclear effects also differ. A simple relevant example is found in magnesium (Wasserburg *et al.*, 1977), wherein the heavier two isotopes are enriched in the sense that $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ exceed their common meteoritic ratios, with the excesses standing approximately in the ratio 1:2 as expected for mass-dependent isotopic fractionation. Because the ratio of excesses is actually not quite that steep, however, one faces three (*e pluribus*) equally valid interpretations of the residual nuclear effect: (1) $^{25}Mg/^{24}Mg$ is normal and there is a slight deficiency of ^{26}Mg; (2) $^{26}Mg/^{24}Mg$ is normal and there is a slight excess of ^{25}Mg; (3) $^{26}Mg/^{25}Mg$ is normal and there is a slight deficiency of ^{24}Mg. These, plus a whole continuum of choices in which no pair stands in the normal ratio, are equally valid interpretations. This freedom has inspired theoretic arguments to identify the most plausible interpretations, especially by the discoverers of the anomalies and by this reviewer. There is also no baseline for these corrections, so what is usually done for the sake of simplicity is to assume that the fractionated (but otherwise isotopically normal) portion contains all of one of the isotopes, so that the isotopically abnormal portion has no contribution at that isotope. Understandably, attempts to ascertain what has happened are compromised by the arbitrariness of this procedure.

7.1. Oxygen

Not surprisingly, it is the oxygen isotopic anomalies that again play the key role, not because they were the first discovered but rather because they fall relatively intelligibly within a larger system of precisely determined variations. A schematic representation of this oxygen data is shown in Figure 11. The line *AD* of unit slope ($m \simeq 1$) is the identical line to that in Figure 2 that first established the oxygen nuclear anomalies. It is interpreted as a mixing line between ^{16}O-rich oxygen (either *A* itself

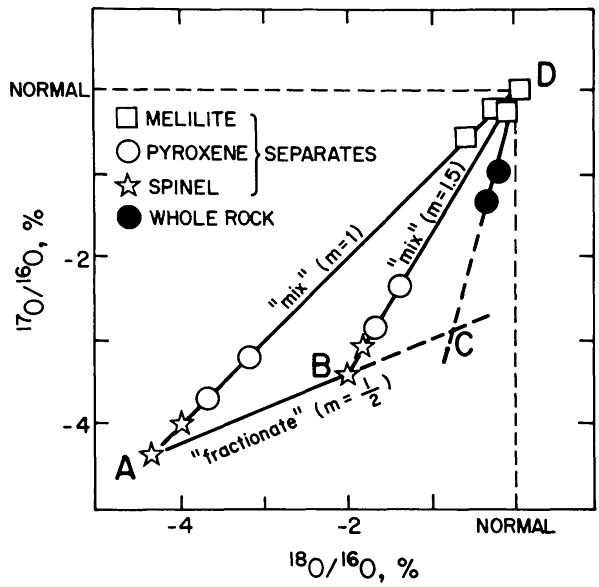

Fig. 11. The three-isotope oxygen plot locates the minerals within the strange inclusions EK1–4 and C1 along different lines than the usual mixing line *AD* for carbonaceous meteorites. This figure from Clayton and Mayeda (1977) is similar to Figure 2, but with emphasis on the relationships within these inclusions. The EK1–4 mixing line *BD* has slope $m = 1.5$, but the mineral sequence, spinel, pyroxene, melilite, is similar to that on *AD*. The point *B* lies, however, on an isotopic fractionation line ($m = \frac{1}{2}$) passing through *A*. Whole-rock analyses of C1 lie along *CD*, as would be expected if C1 also contains a mixing line *CD* as the locus of its mineral separates. This figure is schematic in its replacement of actual separated-mineral data points by a few characteristic examples showing the trend of those minerals along the mixing lines. The line *ABC* could also be a mixing line, but why accidentally of slope $\frac{1}{2}$?

or a more ^{16}O-rich point on the line extension beyond it) and normal oxygen near composition *D*. This line *AD* is shared by the vast majority of inclusions within C3 meteorites, with spinel mineral separates being the most ^{16}O-rich minerals in the inclusions, pyroxene separates being almost as ^{16}O-rich and perhaps a bit more variable, and melilite separates being almost normal. The nature of this mixing process is not well defined but is commonly thought of as either (1) the uptake of decreasing concentrations of ^{16}O-rich presolar carriers during the formation of the spinel, pyroxene and melilite minerals, or (2) an increasing efficiency of exchange of oxygen with a normal oxygen gas reservoir along the mineral sequence spinel, pyroxene melilite.

The oxygen data (Clayton and Mayeda, 1977) for the incusion EK1–4 falls instead along the line *BD*. Once again the spinels are the most ^{16}O-rich in the same mineral sequence, indicating a similar formation process, but the line has a slope $m = 1.5$ rather than $m = 1$. If the line *BD* is a mixing line just as the line *AD* is, the exotic component cannot be thought of as simply ^{16}O-rich, but rich in ^{16}O and ($\frac{1}{3}$ as rich) in ^{18}O. [Note that if the line *AD* is extrapolated downward it passes near the origin to $^{17}O/^{16}O = {^{18}O}/^{16}O = O$ and can be thought of as pure ^{16}O; whereas, if *BD* is extrapolated downward to $^{17}O/^{16}O = O$, the intercept $^{18}O/^{16}O$ is roughly one third of its normal value.] Each of the four different pictures for nuclear anomalies could devise a way of generating a different nucleosynthetic mixture for mixing into normal

(D) oxygen. Whatever the relative plausibilities or implausibilities of such arguments, however, all suffer a great implausibility in the special relationship of point B to point A, which we now consider.

The line AB has a slope $m = \frac{1}{2}$. This means that B could be generated from A by simple mass-dependent isotopic fractionation, or conversely. Or both A and B could have been generated by isotopic fractionation from a common ancestor lying somewhere along the line AB or its extensions. There is no convenient way to see how the limiting spinels at A and those at B could have accidentally fallen along this line of slope $\frac{1}{2}$. It seems safe to assume therefore that A and B were once part of a common pool (Clayton and Mayeda, 1977). This conclusion could take a somewhat different form if the ^{16}O-rich component of AD lies below A on the AD extension, in which case its fractionated counterpart could lie equally far below B on the BD extension. Clayton and Mayeda (1977) have argued against this alternative on the basis that no minerals are found below the AB line, as if it is an ultimate boundary.

The entire suite of minerals along BD was not generated from those along AD by fractionation, however. Had they been equally fractionated in such a scheme, they would have generated a line BD parallel to AD, rather than the line intersecting at D. Even worse, the different mineral separates along AD would probably have experienced unequal fractionation, leading to scatter rather than an observed line. Therefore BD is a mixing line between a composition at B or on the BD extension and the normal composition D. The inclusion EK1–4 looks physically like those that defined the line AD, moreover. So it seems clear that the minerals along BD were formed by the same mixing process as those along AD. Only the ^{16}O-rich end members differ, A or B, and these end members were generated by isotopic fractionation of a common pool before the mixing process with D began (Clayton and Mayeda, 1977).

The nature of the mixing process with D is not very well ascertained. Clayton and Mayeda (1977) reasoned that it is likely that both inclusions formed with uniform isotopic compositions, at A and B respectively. They were then transported to a region containing normal solar gas, where they began an oxygen-exchange process. The spinels and pyroxenes exchanged very little oxygen with D, whereas the melilites and anorthites exchanged so completely that they were moved almost to D along the mixing lines. This explanation is admittedly *ad hoc*, because the actual diffusion constants for these different minerals are unknown. Lattimer *et al.* (1978) added the interesting idea that the temperature could have been raised to the point that melilite and anorthite would melt, whereas spinel and pyroxene would not. They reasoned that the molten minerals would understandably exchange oxygen much more readily than the solid minerals.

There are in Figure 11 two other points for yet another strange inclusion (called C1). These lie along a line CD, and represent the isotopic composition of the bulk inclusion rather than its mineral separates. Clayton and Mayeda (1977) speculate that a similar scenario has led to this inclusion. If they could have examined separated spinels from C1 they would have been guessed to fall near C, along the extension of the *AB* fractionation line. Production of the actual suite of minerals in C1 would be guessed to define a *CD* mixing line. The two whole-rock measurements lie, of course, somewhere along such a line, as observed. The argument is by analogy, but it is an important one considering that both EK1–4 and C1 contain isotopic anomalies in a wide class of other elements as well.

What has all of this to do with supernova and the origin of the solar system? Each of the four classes of models (and any others to come) must find an astrophysically natural way to, first, form the inclusions from different ^{16}O-rich pools that have been produced by isotopic fractionation from a common parent pool and, secondly, a natural way to transport these inclusions to the normal solar gas *D*, with which they must be mixed. Thus this oxygen data schematized in Figure 11 serves as a grid of understanding into which a successful model must naturally fall. It also provides a basis for considering the isotopic anomalies in other elements, to which we now turn.

7.2. Magnesium

The most important other element is Mg. Wasserburg *et al.* (1977) showed that Mg in both EK1–4 and C1 is heavily enriched in heavy isotopes, and approximately in the ratio 2 : 1 which would seem to indicate isotopic fractionation. In EK1–4 the excesses in the ^{25}Mg/^{24}Mg ratio and the ^{26}Mg/^{24}Mg ratio are about 2% and 4% respectively. In C1 the excesses are even larger, being respectively 3% and 6%. These are huge variations compared to previous experience. The approximately 2 : 1 ratio suggests strongly that the Mg in normal inclusions, in EK1–4, and in C1 was derived by isotopic fractionation from a common source. The significance of this cannot be appreciated without awareness of these three dramatic facts: (1) In a given inclusion, the Mg is isotopically identical in the various mineral separates. This is a bizarre contrast to the oxygen data, which has a different value in each separate mineral as discussed above. The implication would seem to be that the process that exchanged anomalous oxygen with the normal reservoir *D* did not simultaneously exchange magnesium. Either the Mg is too fixed chemically to exchange, or else the normal reservoir contains no Mg to exchange with – as if the Mg were entirely condensed and *D* is a gaseous reservoir. (2) The degree of fractionation of Mg from normal Allende inclusions stands for EK1–4 and C1 in the ratio 6%/4% $=\frac{3}{2}$. This ratio is the same as that of the oxygen chords $AC/AB=\frac{3}{2}$ in Figure 11. The self consistent implication is that the same events fractionated O and Mg, and that C1 was subjected to 50% more of that torture than was EK1–4. This coincidence strengthens the confidence with which one ascribes these differences to fractionation. It is worthy of note in this regard that the common $\frac{3}{2}$ ratio could be attributed to a mixture. The chord *ABC* in Figure 11 would then be interpreted as a mixing line rather than a fractionation line. This, in effect, has been suggested by Truran *et al.* (1978), who advanced their trigger model as injecting Mg rich in its heavier isotopes. The implausible part of that would be the coincidences required in order that the mixing lines accidentally assume a slope $m=\frac{1}{2}$ in the three-isotope plots, thereby masquerading beautifully as isotopic fractionation. The reader should form his own judgment, but it is only just to say that virtually all workers take the evidence to be strong in favor of isotopic fractionation. The fact that other heavy elements also show isotopic fractionation between these samples only strengthens the case.

(3) Because the ratio of the excesses in the ratios $^{26}Mg/^{24}Mg$ and $^{25}Mg/^{24}Mg$ ratio is slightly less than 2:1, at least one of the isotopes reflects an intrinsic nuclear anomaly. Wasserburg *et al.* (1977) discuss this as if that anomaly is in ^{26}Mg. If the $^{25}Mg/^{24}Mg$ ratio is restored to normal by isotopic fractionation, there remains a *deficiency* in ^{26}Mg given by $\delta^{26}Mg = -3.6$ parts per thousand (‰) in EK1–4 and $= -1.6$‰ in C1. These values have no correlation with Al/Mg chemical abundance ratio in mineral separates, being the same in each mineral examined within these two inclusions. Wasserburg *et al.* (1977) give emphasis to the potential importance of these negative anomalies and also to the fact that they have been somewhat arbitrary in attributing it to ^{26}Mg. They explained that it could equally well be an excess of ^{25}Mg (if $^{24}Mg/^{26}Mg$ is fractionated to normal) or a deficiency in ^{24}Mg (if $^{25}Mg/^{26}Mg$ is fractionated to normal). With that caveat we follow their inclination in calling this a ^{26}Mg deficiency because a source of ^{26}Mg anomalies is already known ... namely, ^{26}Al decay. Wasserburg *et al.* (1977) envisioned only positive anomalies from ^{26}Al decay because their working scenario utilizes ^{26}Al injection from the trigger into homogeneous solar Mg. However, Clayton (1977b) showed that the SUNOCON theory of precondensates naturally predicts a negative $\delta^{26}Mg$ in a large pool in the following way. The Mg freshly emerging from supernovae is divided into two pools: (1) the Mg condensed in Al-rich SUNOCONS and (2) the rest of the Mg. Because $1\text{–}2 \times 10^{-3}$ of the ultimate ^{26}Mg pool is initially tied up as ^{26}Al in Al-rich SUNOCONS, the second Mg pool has a negative $\delta^{26}Mg \simeq 1\text{–}2$(‰). Clayton (1977b) suggested calling anomalies of this type 'ghosts'. They result frequently in a SUNOCON picture, whenever a specific isotope of an element is chemically fractionated as a radioactive parent in the condensation process. Heymann and Dziczkaniec (1976) advanced the only other proposed explanation known to this reviewer; namely, that ^{26}Mg was depleted by (p, n) reactions in the early solar system by the same process that produced the ^{26}Al. This model currently finds few supporters, however, owing to several other difficulties associated with it.

So both the general heaviness of Mg and a negative $\delta^{26}Mg$ after fractionation have already been attributed to supernovae by intrepid theorists. One feels confident in predicting a host of future explanations of supernova-related Mg. But the fiercest constraints for disciplinarians would seem to be these: (1) Why should this fractionated-like Mg be associated with fractionated-like O if, in fact, is it not a common fractionation process? (2) Why should the unknown nuclear anomalies ($-\delta^{26}Mg$ and heavy elements to follow) occur only in the presence of fractionated O and Mg?

Other strange inclusions have been identified by strongly fractionated Mg, but less is known of other heavy elements in those inclusions. One of the most interesting (called B29) has strongly fractionated Mg that is *depleted* in the heavier isotopes (Wasserburg *et al.* 1977) and in which $\delta^{26}Mg$ is positive (*re* normal $^{25}Mg/^{24}Mg$). This pattern is the complement of those of C1 and EK1–4, but no specific proposal for generating it as a complementary part of a process that made C1 and EK1–4 has been advanced. Nor is it likely to be, because the oxygen from this same sample was found to lie on the usual mixing line (*AD* of Figure 11). This fact presents a knotty problem to assembly of a unified picture of these inclusions.

This B29 inclusion had an entertaining prior history. Gray *et al.* (1973) had identified it as an inclusion having a noticeably small initial $^{87}Sr/^{86}Sr$ ratio. They used this fact to argue that it was one of the oldest known samples. Then Clayton (1978b) interpreted it instead as an isotopic anomaly resulting from gas/dust fractionation in the accumulation processes in the solar system. He argued that because Rb is more volatile than Sr, Sr will be more highly depleted from interstellar gas. The portion of the ^{87}Sr that is generated from ^{87}Rb decay in the interstellar medium will then be more gaseous than will the remainder of Sr. The ^{87}Sr deficiency is then a ghost characteristic of dust-rich accumulates. These interesting ideas may yet find relevance to the problem of B29 in particular and of strange inclusions in general.

Lorin *et al.* (1978) have found two more inclusions having strongly fractionated Mg, but it is not yet clear how they fit into the overall picture of the strange inclusions. One hopes that it will be possible to isotopically analyze still heavier elements in these inclusions.

Several important strange inclusions with different Mg properties have been found recently. Lee *et al.* (1979) have studied an Allende inclusion in which the Mg is isotopically normal despite the fact that this CaAl-rich inclusion is composed primarily of very Al-rich hibronite minerals ($Al/Mg \simeq 10^3$) that should show very large ^{26}Mg excesses owing to ^{26}Al decay (assuming that it were live in the solar system). This inclusion is definitely a strange one, because its Ca is anomalous (see below). The discoverers, who named this inclusion HAL (hibonite Allende), conclude that ^{26}Al was not uniformly admixed into the solar system from the trigger, so that this inclusion formed in a portion of the star that did not receive ^{26}Al. They argued that if one considers instead a longer waiting time until the injected ^{26}Al had decayed ($>6\times10^6$ yr), the primitiveness of the inclusion in a condensation sequence in a hot solar system makes no sense. That argument may itself be physically irrelevant, however. This reviewer has already indicated that in his opinion, such a hot gaseous solar system probably never existed except perhaps for vaporizing volatile accumulates. The possibility that Lee *et al.* (1979) do not address is that the ^{26}Mg excesses, where found, represent instead nonequilibrated chemistry (Clayton, 1977a, b) after the ^{26}Mg was carried into the solar system in Al-oxides. The Al-rich hibonites without excess ^{26}Mg would then be ones that were solidified from a true melt, in which case the carrier spike of ^{26}Mg would have had time to diffusely join the remainder of the Mg being separated into surrounding minerals. This possibility depends on the reasonableness of Clayton's (1977a, b) picture for generating ^{26}Mg anomalies via nonequilibrium chemistry. Experimental evidence, such as, but not only, experiments proposed by Clayton (1977a), does not yet exist or is not commonly known.

Hibonites in inclusions have been studied by other groups, with very puzzling implications for this problem. Lorin and Michel-Levy (1978a) have attempted to clarify this problem by studying hibonites from a type B inclusion of another C3 meteorite, Leoville. No correlation of $^{26}Mg/^{24}Mg$ with Al/Mg was found, although large ^{26}Mg excesses were found. The largest, corresponding to $\Delta^{26}Mg/^{27}Al = 1.0 \times 10^{-3}$, is of the same order as the expected ratio within SUNOCONS (Clayton, 1977a, b, 1978d). MacDougall and Phinney (1979) have examined about fifteen small (~1 mm) hibonite inclusions from carbonaceous meteorites of the C2 class, especially Murchison. They discovered one inclusion with the largest known fractionation excesses (~10% for ^{25}Mg, ~20% for ^{26}Mg), but their experimental precision was not adequate to detect any small nuclear variation – such as the few parts per thousand deficiency of ^{26}Mg within C1 and EK1–4. A few of those hibonite samples, on the other hand, show large excesses in the $^{26}Mg/^{24}Mg$ ratio. These do not correlate with the Al/Mg ratio, however, as one expects from homogeneous live ^{26}Al.

For whichever supernova-related model proves to be correct, the existence of these strange hibonites is an important fact. Within the framework of the trigger and live ^{26}Al, one needs inhomogeneous admixture or late formation of hibonites. From the precondensate picture one needs variable degrees of ^{26}Mg extraction from interstellar Al oxides when they fuse to form the hibonite crystals. From the precondensate picture the following features may be relevant (Clayton, 1978d): hibonites are *not* expected to be abundant SUNOCONS, because Al and Ca emerge from distinctly different shells of nucleosynthesis (III and III $\frac{1}{2}$ of Figure 9 vs IV and V, respectively). The expected ratio *where Al is synthesized* is Mg:Al Ca $\simeq$ $10:1:10^{-2}$. The ^{26}Al production in explosive oxygen burning, where Ca is synthesized, is a problem warranting examination. Hibonites *are* expected in STARDUST, however, but without ^{26}Al.

7.3. Silicon

Isotopic fractionation of silicon at a modest level ($\simeq$1‰) is well known in meteorites (Epstein and Yeh, 1977), ranging to 2.6‰ for $\delta^{30}Si$ in normal Allende inclusions. In the sample C1 (see Figure 11), however, there exists a much larger fractionation of 12‰ per amu (Clayton *et al.*, 1978). This large value is similar to those for oxygen (15‰/amu) and for magnesium (30‰/amu) in the inclusion C1, confirming again that highly fractionated material is involved in its formation. Clayton *et al.* (1978) contain a three-isotope plot showing that $\delta^{29}Si$ lies somewhat above the fractionation line (but with marginal statistical significance), suggesting rather weakly a nuclear excess in ^{29}Si in C1 (or a deficiency in ^{28}Si or ^{30}Si). Such a nuclear anomaly could be accommodated in a variety of ways by any of the four types of supernova-related models.

7.4. Calcium

Isotopic measurements in Ca offer totally new possibilities for preciseness, because it has six stable isotopes. That O, Mg and Si have only three each means that any nonlinearities in the fractionation pattern can be attributed to a nuclear anomaly in any of the three isotopes. With six isotopes, both the fractionation and the nuclear anomalies have a better chance of clear definition. This is not to say that the fundamental interplay between the fractionation uncertainty and the nuclear anomalies does not exist, for it does. But if a nuclear anomaly existed at just one (or even two) of the six isotopes, it would be fairly easy to say which isotope is anomalous. This is not possible in the three previous elements. This optimistic expectation is befuddled by a vexing reality, however. The isotopes of Ca are synthesized in differing ratios by such a large number of different nucleosynthetic sites that a sample of a different nucleosynthetic mix is likely to have isotopic anomalies at *all* Ca isotopes. Only two processes have been discovered that seem likely to result in a spike at only a single isotope of Ca, and these involve the two most abundant isotopes: (1) Because ^{44}Ca is synthesized as its 47 yr radioactive progenitor, ^{44}Ti, it will condense in Ti-bearing SUNOCONS (Clayton, 1975b); (2) Only ^{40}Ca exists in high abundance during Si burning in stars (Bodansky *et al.*, 1968), accompanied however by ^{44}Ti, so that Ca SUNOCONS forming during its expansion may carry a spike of pure ^{40}Ca (Clayton, 1978d). Even these SUNOCON spikes will be diluted by recollapse of the interstellar medium into stars, followed by STARDUST condensation during atmospheric loss (Clayton, 1978d), and STARDUST Ca is expected to be relatively normal. Injection of SUNOCONS by the trigger might be thought a possibility, but the Ca isotopic production varies through the zones of Figure 9 in a complicated way, and the injection of only a single shell seems unlikely. All in all, then, nuclear anomalies in Ca should be a messy spectrum in which one could hope at best for landmarks to point the way.

In the face of this expectation, it would be difficult to define a mass-dependent isotopic fractionation in a highly anomalous sample. In practice, however, the nuclear anomalies are sufficiently small, whatever they are, that the correct order of magnitude for the fractionation is not seriously in doubt. Wasserburg's laboratory has chosen the convention of restoring the ^{44}Ca/^{40}Ca ratio to normal as a way of defining the mass fractionation. The fact that these two isotopes are the ones where spikes might be expected is offset by the higher abundance of these two isotopes. They found (Lee *et al.*, 1978) the fractionation slope to be +0.3‰/amu in C1, −1.8‰/amu in EK1–4, and +7.5‰/amu in HAL (Lee *et al.*, 1979). The negative fractionation (favoring light isotopes) found in EK1–4 looks especially suspicious, since it is in the opposite direction to fractionation normally found in the strange inclusions. In extracting nuclear anomalies for this sample, therefore, one should be sceptical of the assumption that ^{40}Ca/^{44}Ca is normal.

Table III shows the values reported by this team for the nuclear anomalies in Ca, subject to the interpretation that ^{40}Ca/^{44}Ca has been restored to normal by a correction for mass fractionation. The numbers $^{i}\delta$ tabulated are the deviations in parts per thousand of the ratio ^{i}Ca/^{44}Ca when compared to a standard. By construction $^{40}\delta \equiv {}^{44}\delta \equiv$ O, and the reader can modify the entries by relaxing that

TABLE III

Ca anomalies in strange inclusions[a]

Inclusion	Fractionation	$^{40}\delta$	$^{42}\delta$	$^{43}\delta$	$^{44}\delta$	$^{46}\delta$	$^{48}\delta$
EK1–4	−1.8‰/amu	0±0.1	1.7±0.3	0.8±0.6	≡0	−22±13	13.7±0.5
C1	+0.3‰/amu	0±0.2	0.2±0.2	−0.3±0.6	≡0	−14±7	−2.9±0.4
HAL	+7.5‰/amu	0±0.3	−1.9±0.3	−1.2±0.5	≡0	—	−3.0±0.7

[a] Data simplified from Lee *et al.* (1978, 1979). Deviation δ(‰) = parts per thousand.

constraint if he chooses. These two papers actually list more data, giving the Ca isotopic composition for different mineral separates or different physical parts of the inclusions in question. However, within statistical error, the Ca composition is identical for all parts of the same inclusion. This is an important finding similar to that for Mg, but unlike O. It suggests that each inclusion formed from a uniform Ca pool, albeit different pools for different inclusions. Whatever mixing process altered O among the suite of minerals within a given inclusion did not alter the Ca composition. One sensible interpretation is that there was no Ca in the gas that exchanged the O because the Ca was 100% condensed at that time.

Each of these three inclusions reveal nuclear Ca anomalies, but no obvious pattern exists: EK1–4 has excess ^{42}Ca and ^{48}Ca, and perhaps excess ^{43}Ca and deficient ^{46}Ca; C1 has deficient ^{48}Ca and perhaps deficient ^{46}Ca; HAL has deficient ^{42}Ca, ^{43}Ca and ^{48}Ca. Unfortunately, the rarest isotope, ^{46}Ca, is unusually difficult to measure and cannot be regarded as more than a hint of an anomaly. These entire patterns can be altered by arbitrary renormalization *not* setting δ^{44}Ca ≡ O and *not* requiring ^{40}Ca/^{44}Ca to be normal, but no one has yet seen the emergence of a simpler pattern from such a procedure. This is unlike the heavier elements, to which we now turn, for which meaningful simplifications have been found.

7.5. Elements heavier than Fe: Neodymium

Even though the elements heavier than iron have even more isotopes (up to 10 for Sn), a certain simplicity surrounds their nucleosynthesis. They are not made in stars by charged particle reactions, for to do so would require such high temperatures simply to overcome the Coulomb barrier that the nuclei would be instead photodisintegrated. The neutron capture processes have operated on slow time scales (the *s*-process), such that ($\beta^- \bar{\nu}$) decays almost always have time to occur before another neutron can be captured, and on rapid time scale (the *r*-process), such that there is no time for beta decays in a series of rapid (explosive) neutron captures leading to neutron-rich nuclei that decay back to stable isobars after the explosion. These two processes were defined by Burbidge *et al.* (1957). For concise pedagogic exposition the reader may prefer Clayton (1968, Chap. 7). The light isotopes that cannot be synthesized in this way because they are bypassed in such chains are called *p*-nuclei. The *p*-process itself is either (p, γ) reactions on preexisting heavy nuclei

(Burbidge *et al.*, 1957; Audouze and Truran, 1975) or (γ, n) reactions on preexisting nuclei (Woosley and Howard, 1978). It operates less efficiently, as attested to by the fact that the p-nuclei are much less abundant than the s- and r-nuclei. A simplifying corollary is that the p-yields to the s- and r-nuclei can be virtually neglected for most purposes. The s- and r-nuclei are, in first approximation, a two-component system. One of these, the s-process, is quantitatively very successful. This success allows a decomposition of heavy abundances into s- and r-abundances. Clayton and Fowler (1961) did this, but for modern applications it is advisable to repeat the calculations to take advantage of increased knowledge.

The element Nd was one of the first heavy elements to reveal itself as being isotopically anomalous (McCulloch and Wasserburg, 1978a). It was also the first for which the principles of nucleosynthesis dictated a more convincing representation than did the chemistry itself (Clayton, 1978b). Figure 12 shows a portion of the chart of nuclides in the Nd region, and it illustrates the nucleosynthesis decomposition graphically. The seven stable isotopes of Nd begin with s-only ^{142}Nd (because it is shielded by ^{142}Ce from r-production), with the first five isotopes on the s-path. The heaviest isotopes are r-only. The first line of Table IV shows the deviation $\bar{\varepsilon}(A)$ of the ratio ^{A}Nd/^{144}Nd from normal in parts per 10^4 for an average of three measurements of EK1–4 reported by McCulloch and Wasserburg (1978a). The values

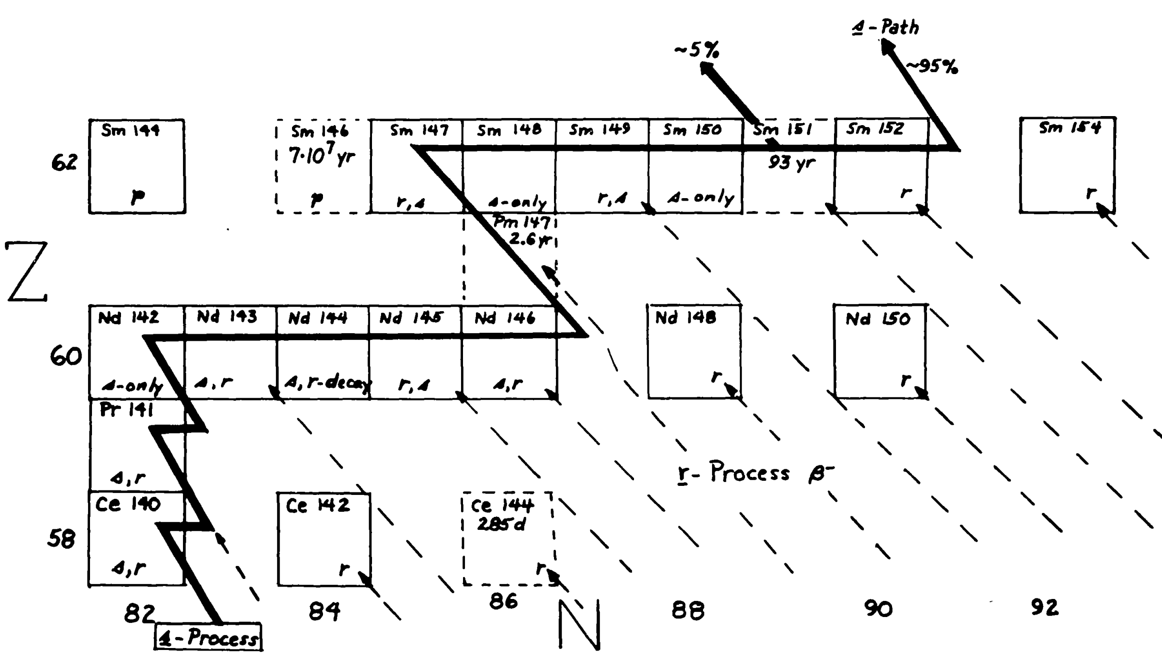

Fig. 12. A portion of the chart of nuclides in the region of Nd and Sm, which are isotopically anomalous in the strange inclusions. The s-process path generated by a slow rate of neutron captures is shown as the heavy line. The beta decays from neutron-rich nuclei generated in the r-process are the dashed lines terminating at the most-neutron-rich stable isobar. The p-isotopes are bypassed by these processes. Using the quantitatively successful s-process theory and neglecting p-yields except at p isotopes, it is possible to decompose the solar abundances of these nuclei into their average s, r, and p contributions. A neighboring supernova does many of the same things, but its yields are not so predictable and are not expected to be the same as the average yields over galactic history.

TABLE IV

Nd isotopic anomalies and s/r decomposition

	^{142}Nd	^{143}Nd	^{144}Nd	^{145}Nd	^{146}Nd	^{148}Nd	^{150}Nd
$\bar{\varepsilon}(A)$[a]	−9.57	−0.17	0	2.47	−12.6	−1.17	−9.57
$\bar{\bar{\varepsilon}}(A)$[b]	0	28.9	0	−2.1	−22.0	−20.7	−38.4
$\varepsilon'(A)$[c]	0	13.6	18.0	24.6	13.8	33.6	33.6
$N(A)$[d]	0.211	0.0949	0.186	0.0647	0.134	0.0447	0.0438
$\sigma(A)$[e]	40	175	67.3	485	105		
N_s[f]	≡0.211	0.0482	0.125	0.0173	0.080	≡0	≡0
N_r[g]	≡0	0.0467	0.061	0.0474	0.054	0.0447	0.0438
N_r/N	0	0.492	0.328	0.733	0.403	1	1
$\varepsilon_r(A)$[h]	0	16.5	11.0	24.6	13.5	33.6	33.6

[a] Isotopic deviation in parts per 10^4 from McCulloch and Wasserburg (1978). Fractionation is chosen so that $\bar{\varepsilon}(142) = \bar{\varepsilon}(150)$. Average of three measures of EK1–4.
[b] From McCulloch and Wasserburg. Fractionation chosen such that $\bar{\bar{\varepsilon}}(142) = \bar{\bar{\varepsilon}}(144)$.
[c] From Clayton (1978b). Fractionation chosen so that $\varepsilon'(148) = \varepsilon'(150)$, and normalization chosen so that $\varepsilon'(142) = 0$.
[d] Abundance per 10^6 Si from Cameron (1973a), based on meteoritic averages. More precise values not needed in lowest order, because anomaly $\Delta^A\text{Nd} = 10^{-4}\ \varepsilon'(A)\ N(A)$.
[e] In mb from Clayton (1978b). See his reasoning and *note added in proof.*
[f] Calculated from $\sigma(A)N_s(A) = \sigma(142)N(142)$. See Clayton (1968).
[g] Calculated from $N_r(A) = N(A) - N_s(A)$.
[h] Defined as average-r anomaly, N_r/N, normalized to $\varepsilon_r(150) = 33.6$ per 10^4.

$\bar{\varepsilon}(142) = \bar{\varepsilon}(150) = -9.57$ have been set equal by construction, coming from a choice of mass fractionation that restores that ratio, ^{142}Nd/^{150}Nd, to normal. Line 2 of Table IV shows an alternative fractionation choice displayed by McCulloch and Wasserburg, in this case by reducing the fractionation so the ^{142}Nd/^{144}Nd is normal. This fractionation clearly is $9.57 \times 10^{-4}/2$ amu smaller than the fractionation assumed for line 1. Neither choice yields an especially meaningful anomaly pattern. McCulloch and Wasserburg then added a very curious observation; namely, that all Nd anomalies can be made positive, and of the same order of magnitude, if one restores ^{144}Nd/^{142}Nd not to normal by the fractionation correction but instead to a value 20 parts in 10^4 above normal (labeled $f^* = 20$ in their Table 2). Their motivation was to arbitrarily generate a pattern looking like an r-process addition to normal solar matter.

Clayton (1978b) made the less arbitrary suggestion that if one wishes to examine the possibility of regarding the data as a fractionation between the solar-system s-process pattern and the solar system r-process pattern, one should choose a fractionation such that the deviations for the r-only isotopes are equal to each other. The fractionation causing $\varepsilon(150)$ to equal $\varepsilon(148)$ is 4.2×10^{-4}/amu greater than that chosen by McCulloch and Wasserburg for line 1. Then because ^{142}Nd is s-only, its anomaly can be set to zero by adding a constant to each $\bar{\varepsilon}$. This renormalization, suggested entirely by a theoretical *Ansatz*, leads to the values $\varepsilon'(A)$ in line 3. The anomalies for every isotope except s-only ^{142}Nd are now positive, and Clayton

(1978b) went on to show as follows that this anomaly pattern is indeed very close to the average r-process abundance pattern in the solar system: (1) the s-process abundances in the range $142 \leqslant A \leqslant 146$ are generated by a superposition of monotonically decreasing s-exposures (Clayton *et al.*, 1961; Seeger *et al.*, 1965), in which case $\sigma(A)N_s(A) \simeq \sigma(142)N(142)$ and $N_s(A)$ can be calculated from the neutron-capture cross sections; (2) The r-process abundances are generated by subtraction (Seeger *et al.*, 1965), ignoring smaller p-contributions, as $N_r(A) \simeq N(A) - N_s(A)$; the pattern $\varepsilon_r \equiv N_r/N$, normalized to 33.6×10^{-4} at $A = 150$, shows remarkable resemblance to the experimental pattern $\varepsilon'(A)$. These steps are shown explicitly in Table IV, and the results are graphically compared in Figure 13. The points and error bars show the experimental pattern $\varepsilon'(A)$ on the right-hand ordinate, whereas the rectangles show an estimated error in the calculated N_r/N ratio on the left-hand ordinate. Of special technical interest are Clayton's (1978b) arguments about the neutron-capture cross sections, which need a definitive and unambiguous resolution, both for this problem and for s-process theory generally.

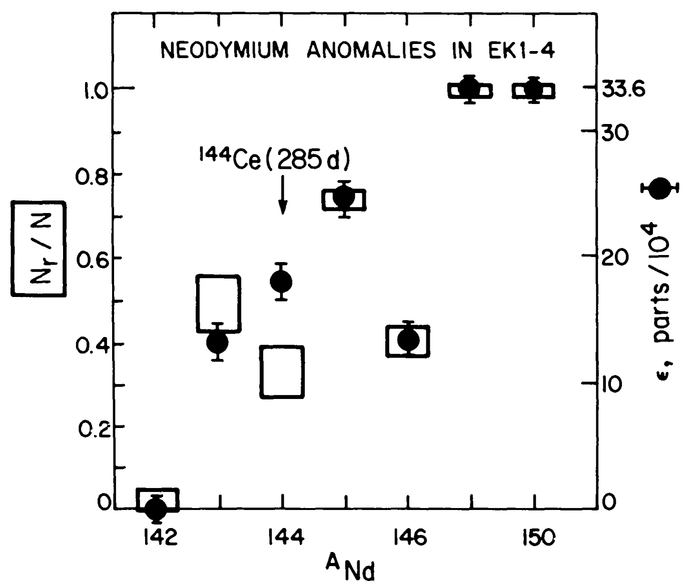

Fig. 13. The decomposition of Nd into s and r components is shown on the left-hand ordinate as the fraction of that isotope due to the r-process. Rectangle size is a subjective estimate of uncertainty owing to uncertainties in the neutron-capture cross sections. The isotopic anomalies measured in EK1–4 by McCulloch and Wasserburg (1978a) are shown with error bars on the right-hand ordinate *after* a choice of mass-dependent isotopic fractionation. The impressive agreement, except for ^{144}Nd, suggests a separation of average s from average r abundances. The ^{144}Nd is not contradictory to this conclusion *if* SUNOCON condensation has chemically fractionated r-process Nd isotopes from ^{144}Ce, the r-process progenitor of ^{144}Nd. Figure taken from Table 1 of Clayton (1978b).

Clayton (1978b) argued that the good agreement shown in Figure 13 is too good to be accidental. He argued that this confirmed the chemical fractionation (in part) of s-isotopes from r-isotopes in the interstellar medium, an idea circulated in 1975 as a preprint of Clayton and Ward (1978). He argued that an arbitrary injection from an explosive shell of a trigger should not so closely resemble the average solar r-process abundances, which are a superposition of countless nucleosynthesis events of variable yields far predating the solar system. Specifically Clayton (1978b) said:

The close agreement of the general Nd anomaly with ε_r would indicate that this sample accumulated with a uniform excess of the solar *r*-process abundances. This appears to be not an 'exotic' *r*-process, but rather a fluctuation owing to physical separation of normal *r* and *s* components. Cameron (1973c) argued that such fluctuations could happen in interstellar gas, whereas Clayton (1977b) argued that fractionation owing to different chemical sites of residence in the interstellar medium is a more likely process. After all, the physical surroundings of *s* and *r* nuclei differ when they are ejected from their different sites of nucleosynthesis. The key to the fractionation seems to be partial condensation of the supernova ejecta before mixing with the interstellar medium, followed by lack of vaporization in the solar nebula. It also does not seem that such a normal ε_r would have been injected from a single supernova triggering the formation of the solar system. Cameron and Truran (1977) specifically suggested that such an event, if it occurred, was not a typical *r*-process event or it would have injected too much ^{129}I. Of course, one could argue that the close agreement to ε_r is fortuitous. No agreement can be decisive until the theoretical estimates of Nd neutron-capture cross sections are replaced by accurate measurements. Nonetheless, my quantitative decomposition of Nd sheds new light on the McCulloch and Wasserburg measurements. A philosophical point is the demonstration by these measurements that the decomposition into *s* and *r* isotopes is not just a theorist's toy.

This argument was to be repeated with even more convincing data in the element samarium (see below). It is also noteworthy that Lugmair *et al.* (1978) were also able to find Nd anomalies in EK1–4, and their measurements confirm those of McCulloch and Wasserburg.

The disagreement in Figure 13 falls at ^{144}Nd, where the observed anomaly is 7 parts in 10^4 ($\varepsilon' - \varepsilon_r = 18 - 11$) greater than the calculated pattern. Clayton (1978b) attributed this discrepancy not to incorrectness of the ideas underlying the calculation but rather to a special anomaly at ^{14}Nd. As Figure 12 demonstrates, the *r*-process yield at $A = 144$ is arrested for 285d halflife at ^{144}Ce. A substantial fraction of the SUNOCONS will have formed before that time, and any that are enriched in the Ce/Nd ratio will therefore carry a large ^{144}Nd excess. Clayton (1978d) speculated that the precursor to the minerals in EK1–4 was enriched in such Ce-rich SUNOCONS. Such a special anomaly would represent the enlarged class of extinct radioactivities predicted initially by Clayton (1975b). It will be very significant if such anomalies can be established, because, better than any other evidence, they could prove that nucleosynthesis happened during explosive ejection and was followed by SUNOCON formation. Table V lists other *r*-process products for which extinct radioactivities in SUNOCONS may be expected. One sees there that *special* (in the sense of being concentrated at that single isotope) anomalies have been detected for five of the daughter nuclei listed there; however, there is no general concurrence that these may yet be taken as evidence for extinct *r*-process radioactivities in SUNOCONS.

7.6. Samarium

It is convenient to discuss this element next because it lends itself convincingly to the same type of analysis and interpretation that was applied to Nd. Anomalous Sm in their sample of inclusion EK1–4 was first reported by Lugmair *et al.* (1978). This

TABLE V

Extinct *r*-process radioactivities in SUNOCONS[a]

r-product	$\tau_{1/2}$	Daughter	*r*-product	$\tau_{1/2}$	Daughter
^{60}Fe	10^5 yr	^{60}Ni	^{129}I	1.6×10^7 yr	^{129}Xe [b]
^{63}Ni	100 yr	^{63}Cu	^{135}Cs	2×10^6 yr	^{135}Ba [b]
^{79}Se	6.5×10^4 yr	^{79}Br	^{137}Cs	30.1 yr	^{137}Ba [b]
^{85}Kr	10.76 yr	^{85}Rb	^{144}Ce	285d	^{144}Nd [b]
^{90}Sr	28.5 yr	^{90}Zr	^{147}Pm	2.62 yr	^{147}Sm
^{99}Tc	2.1×10^5 yr	^{99}Ru	^{151}Sm	93 yr	^{151}Eu
^{106}Ru	368d	^{106}Pd	^{155}Eu	4.96 yr	^{155}Gd
^{107}Pd	6.5×10^6 yr	^{107}Ag [b]	^{171}Tm	1.92 yr	^{171}Yb
^{125}Sb	2.77 yr	^{125}Te	^{182}Hf	9×10^6 yr	^{182}W
^{126}Sn	10^5 yr	^{126}Te	^{194}Os	6.0 yr	^{194}Pt

[a] From Clayton (1978b).
[b] Special isotopic anomalies of these daughters have already been detected (see text), although the proposed cause is controversial.

measurement was also made by McCulloch and Wasserburg (1978b) on their sample of EK1–4, and the results agree within experimental errors. This element is particularly interesting because, as Figure 12 shows, it has two *s*-only isotopes, which Nd does not, and a *p*-isotope, which Nd also does not. It also has the possibility of an extinct-radioactive anomaly due to ^{147}Pm decay in SUNOCONS. The element is also historically interesting for the *s*-process theory, because its two *s*-only isotopes were the first such pair in which the σN equality expected from the *s*-process was experimentally confirmed (Macklin *et al.*, 1963). The excitement of those years was keenly felt by this reviewer, who was working with W. A. Fowler and with the Oak Ridge group on the development of the *s*-process theory (Clayton *et al.*, 1961). The care with which these Sm cross sections were measured at ORNL for this purpose not only validated the *s*-process, but it also now proves quite handy in separating the solar Sm abundance into its average *r* and *s* components. This was done by Clayton (1979) in an analysis of the data of Lugmair *et al.* (1978).

Lugmair *et al.* had chosen their fractionation correction in such a way as to make the deviations of the two *s*-only isotopes vanish; $\varepsilon(148) = \varepsilon(150) = 0$. The remaining pattern resembled an *r*-process excess, with the *p*-isotopes being of comparable excess. Clayton (1979) showed, however, that their pattern of *r*-excesses was not constructed of the same ratios as the average *r*-abundances in the solar system, at least if one retains the mass fractionation chosen by Lugmair *et al.* Clayton argued, however, that ^{148}Sm and ^{150}Sm are too low in abundance and have a 'lever arm' that is too small (2 amu) to determine the optimum fractionation with accuracy. He suggested that a fractionation correction that placed the *r*-process excesses of the two odd-A isotopes (147 and 149) in the average *r*-process ratio to *r*-only ^{154}Sm would allow a more precise test of the possibility of average-*r*/average-*s* separation. Clayton's results are illustrated in Figure 14, where, as in Figure 13, the anomaly in

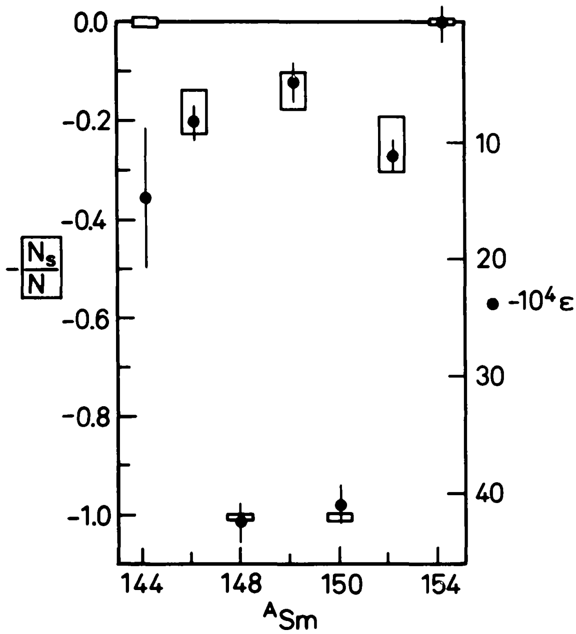

Fig. 14. The decomposition of Sm is shown as an s-process deficiency, $(-N_s/N)$, on the left-hand ordinate with rectangle size reflecting uncertainty. The measured anomalies of Lugmair *et al.* (1978) are plotted on the right-hand ordinate *after* a choice of isotopic fractionation. The impressive agreement (escept at the p-isotope ^{144}Sm, which is independent) argues that the inclusion formed from chemical constituents that had a slight separation of the average s from the average r. Taken from Clayton (1979).

parts per 10^4 is the right-hand ordinate whereas the computed separation between s and r is the left-hand ordinate. Clayton displayed this calculation as an s-process deficiency, since those are the abundance ratios that are directly calculable from the neutron-capture cross sections. The agreement shown in Figure 14 for the six heaviest isotopes is remarkable! The pattern is almost exactly describable as an s-deficiency among those isotopes. This very much confirms the similar success found for Nd in Figures 13. Because the excess is of the *average* r-abundances in the solar system rather than of a *peculiar pattern* of r-abundances, it argues strongly that this is not the result of a special r-process injection from a shell of the trigger. In the same spirit it argues against a locally produced irregularity in the interstellar medium, as one would expect from point to point in the Bing-Bang model of the parent molecular cloud. Any single shell or r-process event would just not be expected to produce the same relative r-abundances as the entire spectrum of r-events has done. These two results, Figures 13 and 14, support instead this reviewer's model of *chemical separation* of s-process nuclei from r-process nuclei throughout the interstellar medium. This separation, which could take the form of gas from dust or of one type of dust from another, is expected *a-priori*, because these two classes of nuclei have been ejected from different classes of stellar objects. There is no way that the condensed fraction of r-process Sm could be expected to be identical to the condensed fraction of s-process Sm in the interstellar medium. In this way, the accumulation processes that occur later and the subsequent chemistry within such accumulates offer many chances for an average-s/average-r separation.

Lugmair *et al.* (1978) concluded that there was no evidence for separation of *p* from *r* nuclei in EK1–4. Figure 14 shows that if one is willing to accept that good fit is a line of evidence, the *p*-process nucleus ^{144}Sm is depleted relative to the *r*-nuclei. McCulloch and Wasserburg (1978b) also found some evidence that this *p*-isotope in EK1–4 is somewhat depleted relative to the *r*-isotopes; but they also examined strange inclusion C1 and found that in it ^{144}Sm is the only isotope clearly in excess. This finding confirms that the *p*-component is independent of the *s* and *r* components to some degree in the events leading up to the strange inclusions.

The point of view motivating the construction of Figures 13 and 14 and the conclusions drawn from it are controversial. The question that is difficult to treat quantitatively is whether it is valid statistically to seek that fractionation correction which results in an anomaly pattern that most closely resembles the average pattern. This reviewer has contended that this procedure is more sensible than the even more arbitrary choices of fractionation made by the experimental discoverers. But the basic question is this: can Figure 13 and Figure 14 be accidents in which an exotic *r*-process injection is made to look like an enhancement of the average *r*-isotopes by a judicious choice of fractionation? To the eye these figures look too good to be accidents, but several points are made to agree by construction so that the independent data being fit is admittedly not as great as it appears to the eye. An exotic *r*-process injection would be expected to involve the same isotopes for enrichment, and even if the relative abundances differed from the average ones, a special choice of fractionation (plus the definition of a normal isotope, $\varepsilon \equiv 0$) could perhaps be made to resemble the average abundances. This reservation is strengthened by the fact that the Ba anomalies (see below) do not separate in such a pretty and simple way. The following statements in the discovery papers are at odds with the emphasis placed in this review:

(1) "No fractionation of *p*- and *r*-products can be inferred from our Sm data." (Lugmair *et al.*, 1978)

(2) "The excess at ^{144}Nd also agrees within the limits of uncertainty with solar-system *r*-abundances. This fact precludes the necessity for supernova condensates of ^{144}Ce, as postulated by Clayton (1978b)." (Lugmair *et al.*, 1978)

(3) "The number of excess atoms are in general *similar* to the cosmic *r*-process distribution. However, significant deviations at ^{149}Sm, ^{147}Sm and ^{135}Ba show that the exotic material was not identical to the average solar-system *r*-process." (McCulloch and Wasserburg, 1978b)

(4) "The deficiency (of ^{135}Ba) in C1 is particularly important, as it implies that the average solar-system value must be made up by an addition of at least 2 parts in 10^4 of exotic ^{135}Ba." (McCulloch and Wasserburg, 1978a).

The reader himself must make his own judgments about these issues, which come very close to the relationship of supernova nucleosynthesis to the origin of the strange inclusions. The data do not tell us what the actual mass fractionation was in the formation of the samples; nor do they identify which isotope (if any) should be regarded as normal ($\varepsilon = 0$) in a decomposition into a normal pattern plus a deviation pattern. These are judgment decisions at our present level of knowledge, and it is precisely because of this situation that contradictory interpretations of the same data can both have a certain validity. The point of view developed by this reviewer has certainly been strengthened, however, by the discovery (Srinivasan and Anders, 1978) of the separated *s*-process xenon component that had been predicted more than two years earlier by that point of view.

Regardless of one's interpretation of the data, there is one additional aspect of it that is very important from any point of view. This point of view was identified and emphasized clearly by McCulloch and Wasserburg (1978a, b). Their analyses have included different mineral separates and splits of the strange inclusions. The heavy cations have substantially the same isotopic composition within different samples of the same inclusion. McCulloch and Wasserburg (1978b) stated, "The melilite and pyroxene mineral phases from EK1–4 have an identical enrichment (in anomalous isotopic deviations) although these phases contain different proportions of Sr, Ba, Nd, and Sm. This ... implies that these minerals formed from an isotopically homogeneous liquid or gas phase or were subsequently isotopically reequilibrated." In other words, the inclusions are not, in their present form, a diverse assemblage of unequilibrated components.

7.7. Barium

McCulloch and Wasserburg (1978a) studied the relative abundances of the six stable isotopes of Ba in strange inclusions EK1–4 and C1. They concluded that Ba was normal except for (1) clear excesses in EK1–4 of the two odd-A isotopes, $\varepsilon(^{135}\mathrm{Ba}) = 13.4 \pm 1.0$ and $\varepsilon(^{137}\mathrm{Ba}) = 12.3 \pm 0.4$, and (2) a clear deficiency in C1, $\varepsilon(^{135}\mathrm{Ba}) = -1.8 \pm 0.7$, plus a possible deficiency, $\varepsilon(^{137}\mathrm{Ba}) = -0.6 \pm 0.4$. In particular, the two *p*-isotopes, ^{130}Ba and ^{132}Ba, appear normal, although a significant deficiency of them in C1 may exist but cannot be claimed owing to the larger statistical errors attendant to their smaller abundances. Relevant quantities are listed in Table VI.

The clear significance of these anomalies is related to the fact that ^{135}Ba and ^{137}Ba are the only two isotopes for which the *r*-process has been a significant parent. Thus the EK1–4 excesses can be regarded as an *r*-process injection from the trigger. In that scenario, the deficiency of 2 parts in 10^4 of ^{135}Ba in C1 would imply that the trigger injected at least that much of all *r*-nuclei, as reflected by quotation (4) of the previous section. Our disagreement with that conclusion is that it rests on the supposition that the anomalies have resulted from an *r*-injection into a homogeneous solar system. In the picture involving differential accumulation of isotopically different chemical phases (Clayton, 1978d) favored by this reviewer, no such sweeping conclusion can be attached to negative anomalies, which bear in general no more significance than positive anomalies. In this case, however, a negative ^{135}Ba anomaly could also indicate an inclusion that formed before the ^{135}Cs *r*-process progenitor ($\tau_{1/2} = 2.3 \times 10^6$ yr) decayed (McCulloch and Wasserburg, 1978a). This would represent a special significance of a quite different kind ... a 'ghost' (Clayton, 1977b).

TABLE VI

Ba anomalies and isotopic decomposition

	^{130}Ba	^{132}Ba	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba
$\bar{\varepsilon}$(EK1–4)[a]	2 ± 7	-1 ± 14	$\equiv 0$	13.4 ± 1.0	-0.8 ± 0.6	12.3 ± 0.4	$\equiv 0$
$\bar{\varepsilon}$(C1)[a]	-7 ± 14	-7 ± 7	$\equiv 0$	-1.8 ± 0.7	0.6 ± 0.6	-0.6 ± 0.4	$\equiv 0$
process	*p*	*p*	*s*-only	*r, s*	*s*-only	*s, r*	*s, r*
N_s[b]	0	0	0.116	0.063	0.375	0.370	3.24
N_r/N[c]	0	0	0	0.80	0	0.32	0.06

[a] From McCulloch and Wasserburg (1978a). Deviations from isotopic normality in parts per 10^4 after defining the ^{134}Ba/^{138}Ba ratio as normal by mass fractionation.
[b] Computed by Clayton (1978b) for continuous *s*-process with exponential distribution of exposures characterizing average solar *s* abundances.
[c] $N_r/N = 1 - N_s/N$ for non-*p* nuclei is the expected shape of an average *r*-process excess, which does not resemble lines 1 and 2 *except* in the sense of expected excess only at the odd-A nuclei.

Clayton (1978b) provided a canonical decomposition of Ba into *s*- and *r*-components. He showed that the pattern of the solar system ratios N_r/N does not in this case have the same shape as the observed anomaly pattern. Unlike Nd and Sm, the pattern cannot be regarded as a separation of average-*s* from average-*r*. The most straightforward implication is that here, at last, is evidence of an exotic *r*-component injected from the trigger. Proponents of that model therefore find comfort in Ba. Clayton (1978b) issued warning against that conclusion when it so differs from the other heavy elements. He pointed out that the fraction of the *r*-process yield that condensed in SUNOCONS will have condensed as Cs progenitors, since both lifetimes, $\tau(135) = 2.3$ m yr and $\tau(137) = 30.1$ yr, exceed the expansion and condensation timescales. However, any subsequent chemical process fractionating Cs from Ba and happening between 10 and 10^7 yr after the explosion will fractionate ^{135}Ba from ^{137}Ba. Another complication is that a significantly greater fraction of ^{135}Ba could be the result of the *s*-process if it has operated in the pulsed-mode studied by Ward and Newman (1978) rather than the continuous mode assumed by Clayton (1978b). Ward and Newman (1978) point out that a significant fraction of ^{134}Ba could actually be the result of ^{134}Cs progenitor in the pulsed *s*-process. Inasmuch as ^{134}Cs has a halflife (2.1 yr) comparable to the pulse duration and has a large cross section for his mass range, a significant pulsed-*s* flow to ^{135}Cs may also occur. This would have the effect, because of the inversion of the odd-even ratio of cross sections in odd-Z nuclei, of substantially increasing the ratio of $^{135}Ba_s/^{134}Bs_s$ above that computed by Clayton (1978b). For all of these complications, it is difficult to conclude much from the Ba anomalies except that a nucleosynthetic separation has occurred somehow, somewhere. Evidence for *live* ^{135}Cs injection from the trigger could, on the other hand, be demonstrated from ^{135}Ba excesses correlating with Cs/Ba chemical abundance ratios. That has not been achieved.

7.8. Strontium

Isotopic anomalies in both EK1–4 and C1 inclusions of Allende have been reported by Papanastassiou and Wasserburg (1978). The simplest interpretation of both samples is that the *p*-isotope, ^{84}Sr, is deficient and the other three, ^{86,87,88}Sr, are normal. Because the latter three are dominated by the *s*-process (Clayton, 1978c), this would imply a separation of *p*-isotopes from *s*-isotopes, at least for Sr. However, the mass fractionation is not known, so Papanastassiou and Wasserburg point out that the data could also be interpreted as a deficit of ^{88}Sr, in which case it would imply a deficit of *r*-isotopes relative to *s*-isotopes. This latter *r*/*s* separation is in the opposite direction from the separation in Nd, Sm, and Ba, where *r* is enhanced relative to *s*. This difference probably represents more of a problem to an injection model than it does to a chemical separation model, but it is too early to tell.

In any case, Sr is surprisingly normal to contain an exotic admixture from a trigger. Clayton (1978c) interpreted the observed anomaly as an *s*-process excess rather than a *p*-process deficiency, but he showed that the excess -*s* is equal to average solar *s* abundances. These in turn fit the theory of average solar abundances very well. Because Sr is on a very sensitive part of the *s*-process abundance curves (Clayton *et al.*, 1961), an admixture from any single *s*-process event would surely differ in composition from average. These data therefore seem to lend marginal support to an interpretation in terms of chemical effects that have sited *p*-process Sr differently from *s*-process Sr in the interstellar medium.

8. Some Final Thoughts – Shot from the Hip

This is a lot of material to have exploded into the scientific scene over a brief five-year period. What, in summary, has emerged as the crucial questions and the prospects for future clarification? A short list of such highlights, as viewed by this reviewer, conclude this work.

(1) The single most important question is whether ^{26}Al was really alive in the solar system, or whether the variable degrees of correlation of ^{26}Mg/^{24}Mg with Al/Mg can have resulted from differing degrees of equilibration of the ^{26}Mg spike carried in interstellar Al oxides with the ambient Mg field when the inclusions were fused. This reviewer sees no prospect of settling this question without greater effort from chemists, perhaps in the form of actual experiments for producing such minerals with isotopic tracers, or perhaps in the form of more convincing petrological studies of the inclusions. This question has to date been addressed by isotopic cosmochemists, more knowledgeable in the techniques of nuclear spectroscopy than in the nonequilibrium chemistry of space petrology, so it is understandable that the isotopic data far exceeds in quality the chemical scenarios for formation of the inclusions.

(2) Can we hope for carefully measured isotopic anomalies in even more elements in the strange inclusions? The answer seems to be affirmative, because ion microprobe techniques are now able to quickly identify inclusions with large isotopic

fractionation of Mg. Additional elements will eventually settle the controversy over exotic *r*-process injection or separation of average *s* from average *r*. Can we hope for isotopic studies of noble-metal *Fremdlinge*? These would help a lot in identifying possible origins for the microinclusions within the inclusions. The rapid technical advances of the past decade encourage the hope for further sensitivity to the world of microsamples.

(3) Detailed knowledge of the chemistry of the interstellar medium can be expected to improve. Both ultraviolet and microwave studies of the ISM are continuing to benefit from new techniques and new observatories and satellites. It may not be too much to hope that we will one day have good grounds for understanding the chemical state of a molecular cloud that is ready to form a planetary system. There is a new wave of openmindedness emerging in the cosmochemical world concerning the possible relationships of this chemical state to the chemical state of certain meteorites. If we may be allowed to wish for free, we might wish for not only a cometary rendezvous, but a sample return mission as well. A laboratory sample of a comet would seem at the moment to be the single most significant sample for clarifying the state of the early solar system.

(4) Was there in fact ever an epoch in the early solar system during which the material that would appear in meteorites was so heated that the dust was vaporized? This reviewer has repeatedly argued that this 'event' is probably a fiction invented by chemists to explain meteoritic abundance groupings according to volatility, but he will be among the first to recant when astrophysical arguments show how that hot state may be achieved. Asked another way, is the parent of meteoritic matter the interstellar medium or an extension of hot solar gases? This controversy is one of major physical importance, representing widely divergent branch points in a consistent theory for the emergence of the planetary system.

(5) The studies of supernovae and their remnants are in a rapidly advancing phase. It seems likely that our knowledge of them ten years from now will vastly exceed our current knowledge. Whether supernovae are a major effect in star formation is probably an answerable question.

(6) Whether a single supernova was actively involved in the origin of the solar system depends more strongly on the correct interpretation of extinct ^{26}Al than on any other data now known.

(7) The theory of nucleosynthesis has benefited enormously from the discovery of isotopic anomalies, whatever the correct connection between supernovae and the origin of those samples. The anomalies have shown that the elaborate superstructure of nucleosynthesis is not just a theoretical toy. They may even yet show, via short-lived extinct radioactivities, that the elements were explosively ejected and condensed into dust in the expansion.

(8) We await understanding of the differences in origin (if any) of the strange inclusions and the common inclusions within carbonaceous meteorites. Perhaps the decisive clue lies in the severe mass-dependent isotopic fractionation of the O, Mg, and Si within them. Each model for producing isotopic anomalies must ultimately

offer a natural reason for associating the isotopic anomalies only with highly fractionated O, Mg, and Si. What is meant is that this O, Mg, and Si should be derivable from normal solar matter by some process that progressively favors retaining the heaviest isotopes; e.g. a thermal residue after evaporation, different velocities after electrostatic acceleration, chemical equilibria governed by vibrational or rotational reduced masses, differential diffusion, differential recoil during sputtering, etc. Illustrative shots from the hip are:

Trigger. Isotopic anomalies result when the trigger shell is admixed into condensing solar gas, but the shock waves and turbulence associated with this mixing process fractionate the ambient O, Mg, and Si. The fractionation physics might be sought in the dissipative hydromagnetic effects that mix the surfaces of these fluids in relative motion. Complicated kinetics.

Precondensates. Isotopic anomalies result from accumulates of differing proportions of gas and different chemical forms of interstellar dust. The dust has been fractionated by a long history of sputtering by ions having a wide range of energies. Differential recoil knocks out light ions more easily. It may even be that the gaseous interstellar element phase is for this reason or another a fractionated version of the condensed-element phase, in which case a variable gas/dust physical mixture generates what looks like a fractionation line. If the isotopic anomalies represent a enhancement or deficiency of one phase, the correlation of anomalies with apparent fractionation follows.

Interstellar inhomogeneities. Isotopic anomalies occur from place to place in the ISM because of variable admixtures of specific supernova events. The hot snowplow as the expanding debris is degraded and stopped by the ISM is fronted by a strong thermal layer, accompanied by a strong pseudo gravity from the acceleration field. Perhaps these may fractionate the normal ISM being ploughed.

(9) Why are the inclusions with anomalous heavy elements the ones showing no evidence of extinct ^{26}Al? Each model also has ways of getting rid of ^{26}Mg excesses caused by ^{26}Al, but do those ways make sense in terms of the different models for producing anomalous heavy elements within the inclusions?

(10) Research papers frequently state that the isotopic anomalies show that the early solar system was not homogeneous. They envision different spatial regions with slightly differing compositions. May not these same variations be generated within a solar system having bulk homogeneity by having somewhat different isotopic compositions in different chemical phases? May this not even be the standard expectation in the interstellar medium?

None of the models for producing isotopic anomalies via supernovae has yet emerged a clear victor. Perhaps we shall find that each has played a role and that our efforts to single out a cause are misguided. Perhaps a supernova has triggered the collapse of the solar system, admixing ^{26}Al and other anomalies into an already spatially inhomogeneous molecular cloud in which different chemical phases and precondensates already have different isotopic compositions and which also contains already large 'marbles' accumulated earlier in the mother cloud. If so, the laborious task ahead is to assemble enough data to discern which effect has caused which anomaly. But what a wealth of data is waiting to be gathered! We are as blind men who have suddenly had their sight restored. New laboratory data breeds new ideas, so that the prospect for scientific understanding of the early solar system is now infinitely brighter than it was just a few short years ago. Perhaps this bright hope accounts for the hostile controversy so evident at scientific meetings on this subject. This reviewer admits to the subjective feeling of witnessing a genuine revolution in solar-system science. The concept a hot homogeneous gaseous origin of solid particles is being replaced, in the minds of some but not in the minds of others, with the concept of accumulation in a cold and swirling disk around a growing central blob. The feeling that all prehistory was erased during a hot gaseous state, except for its remaining radioactivity, is being replaced by the thought that chemical objects accumulated instead directly from the interstellar medium, subject to the slings and arrows of its outrageous fortune. Many kinds of chemical history may be there in different chunks of matter, all a part of the chemical evolution of what I like to call *the galactic organism*. The hope of knowing was wrestled with long ago, by the biblical prophet who spoke for all men by asking (*Job 38*, pp. 31–38):

> Canst thou bind the sweet influences of Pleiades,
> or loose the bands of Orion?
> Knowest thou the ordinances of heaven?
> Canst thou set the dominion thereof in the Earth?
> Who can number the clouds in wisdom?
> Or who can stay the bottles of heaven
> When the dust groweth into hardness
> And the clods cleave fast together?

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