

## Origin of Elements in the Solar System

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*“If our inconceivably ancient Universe even had any beginning, the conditions determining that beginning must even now be engraved in the atomic weights.” Theodore W. Richards (1919)*

**Abstract:** The solar system is chemically and isotopically heterogeneous. The earth contains only 0.0003% of the mass of the solar system, but the abundance pattern of non-radiogenic isotopes for each terrestrial element has been defined as “normal”.

The outer planets consist mostly of light elements like H, He and C. The inner planets are rich in heavy elements like Fe and S. Isotopic irregularities are closely linked with these chemical differences in planets, as well as in the primary minerals of chondritic meteorites.

Chondrites are heterogeneous, agglomerate rocks from the asteroid belt that separates the two types of planets. They contain troilite (FeS) inclusions with isotopically “normal” Xe, like that found in the inner planets. Chondrites also contain diamond inclusions (C) with abundant He and “strange” Xe enriched in isotopes from the r- and p-processes. The Galileo probe found similar r-products in the Xe isotopes of Jupiter, a planet rich in He and C. The sun is a mixture of the chemically and isotopically distinct components found in its planetary system. Inter-linked chemical and isotopic irregularities, short-lived radioactivities and other post-1957 observations are used here to evaluate the two most conflicting opinions on the origin of elements in the solar system.

The first of these is that the elements in the solar system originated via remote element synthesis (RES). The RES model is the modern version of the classic nebular model postulated by Kant and Laplace over 200 years

*Proceedings of the 1999 ACS Symposium* (organized by Glenn Seaborg and O. Manuel): *The Origin of Elements in the Solar System: Implications of Post-1957 Observations* (O. Manuel, editor, Kluwer/Plenum Pub., 2000) pp. 589-643.

ago for the origin of the solar system. It is a natural extension of the cosmological view of element synthesis. According to the nebular RES view, products of nuclear reactions collected from multiple stellar sources over vast regions of space and produced a well-mixed protosolar nebula having approximately the elemental composition of the sun's photosphere and isotopic ratios of carbonaceous chondritic meteorites. The sun formed as a fully convective, homogeneous protostar. Elements in the planetary system were subsequently redistributed to produce the solar system's current chemical gradients. This nebular RES model was modified in the late 1970s and early 1980s to try to explain the occurrence of isotopic anomalies and decay products of short-lived nuclides by the addition of very small amounts of exotic nucleogenetic material, which either had been injected from nearby stars or survived as interstellar grains that became embedded in meteorites.

An alternative explanation is that the elements in our solar system were produced by local element synthesis (LES). The LES model is the latest version of the classic catastrophic model postulated by Buffon over 250 years ago. This asserts that the entire solar system formed directly from poorly-mixed debris of a spinning star, concentric with the present sun, which exploded axially as a supernova (SN). The sun formed on the SN core and the chemical gradients in the planetary system were inherited from the parent SN. The outer planets formed mostly from the light elements in the outer SN layers. Iron meteorites and the cores of the terrestrial planets formed in a central, iron-rich region of the SN debris. These planet cores were subsequently overlaid as lighter material from other SN layers fell toward the condensing sun. Diffusion enriched lighter nuclei at the evolved sun's surface making it appear to be composed of light elements such as H and He. Lyttleton, Hoyle, and Brown earlier suggested other versions of LES to explain the distribution of angular momentum in the solar system.

Reynolds' mass spectrometer began generating empirical challenges to the nebular RES model soon after publication of the classical papers by Burbidge *et al.* (1957) and Cameron (1957). Data from space probes and ion-probe mass spectrometers have made the RES model even less attractive. The catastrophic LES model now explains the maximum number of phenomena (chemical and isotopic irregularities, decay products of short-lived radioactivities, and observations on planets, the sun and other stars) with the minimum number of postulates, although this implies that elemental abundances for the sun are similar to those of the inner planets and that nuclear evolution is much more advanced for elements in the sun's interior than for elements in the solar photosphere or in the Jovian planets. The most abundant elements for the bulk sun are the same ones concluded 80+ years ago from early analyses of meteorites (Harkins, 1917). They are: Fe, Ni, O, Si, S, Mg, and Ca. Others have reached somewhat similar conclusions about the sun from efforts to find a unique solution to the solar structure equations (Rouse, 1975), to explain the low flux of solar neutrinos (Hoyle, 1975), and to explain isotopic anomalies in meteorites (Lavrukhina, 1980; Lavrukhina and Kuznetsova, 1982).

## 1. INTRODUCTION

This paper brings together and evaluates the observations that provide meaningful information on the origin of elements in the solar system, with emphasis on new data not available to Burbidge *et al.* (1957) and Cameron (1957) in writing their classical papers on stellar nucleosynthesis. It is not intended that this work will be an exhaustive review of all the earlier research on the subject. The number of authors who have contributed to the knowledge of the origin and abundances of the elements is too great to be included in a review paper of reasonable length. The small book by Kuroda (1982) gives an excellent historical review of scientific developments on the origin of chemical elements, and includes the opening quote by Theodore Richards on receiving the Nobel Prize in Chemistry in 1919.

At the onset it is useful to acknowledge that most of the material in the solar system lies hidden in the sun's interior. For the small fraction of material in the planetary system, the chemical composition varies with radial distance from the sun, and the individual planets themselves consist of layers of different compositions. Thus, (a) only a small fraction of material in the solar system is available for study, and (b) there are steep chemical gradients in the accessible material.

In spite of this difficulty, recent measurements have provided much better experimental data with which to evaluate the models proposed for the origin of elements in the solar system than for those in any other part of the universe. Therefore it is logical to focus on, and to attempt to explain, the system for which one has the most information. There is not enough detailed experimental data available to decide the origin of elements elsewhere in the universe.

Most authors assume that local abundances of elements and isotopes were generally representative of those in the galaxy, and perhaps beyond when the protosolar nebula formed. Thus, "universal" and "cosmic" are frequently substituted for "solar" as the adjective describing these abundances. If the sun and other stars developed from homogeneous material which had been collected from multiple stellar sources over vast regions of space, then "universal" or "cosmic" abundances may be the same as "solar" ones. Indeed, that is one of two models proposed to explain the origin of elements in the solar system. This model is known as remote element synthesis (RES). An alternative model of local element synthesis (LES) was proposed in the 1970s. These are summarized below.

1. *Remote element synthesis (RES)*. According to this popular view (Wood, 1999), products of nuclear reactions gravitated from multiple stellar sources over vast regions of space to produce a dense interstellar cloud of gas and dust such as the Orion Nebula. Simultaneous contraction and

fragmentation of this interstellar cloud occurred because, “As the cloud contracted, successively smaller portions of it became gravitationally unstable and begin to contract independently.” (Wood, 1978, p. 327). Figure 1 is a typical text-book illustration of the formation of the solar system from one of these small, contracting sub-units (Zeilik, 1982, Figure 12.21).

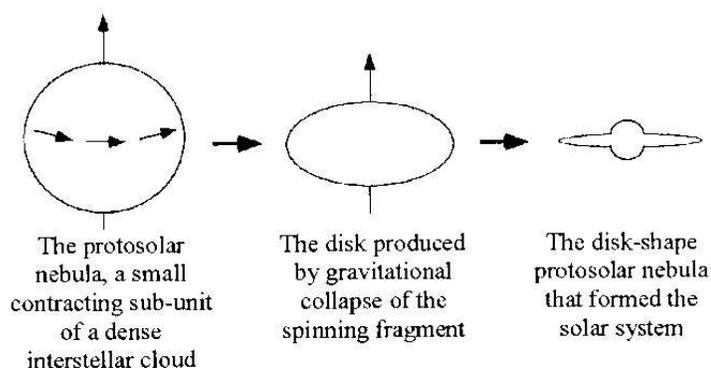


Figure 1. Schematic drawing of events for the formation of the solar system from a contracting fragment of an interstellar cloud with angular momentum. This is the nebular RES model.

On the left is the well-mixed protosolar nebula having approximately the elemental composition of the sun's photosphere and the isotopic composition of carbonaceous chondritic meteorites (*e.g.*, Arnett, 1996). Angular momentum is conserved as this fragment of interstellar cloud contracts, thus causing it to rotate faster and to take on a disk-like shape. The sun forms in the center as a fully convective, homogeneous protostar. Then, elements redistribute to produce the solar system's current chemical gradients. The RES model is an outgrowth of the classic nebular model postulated by Kant and Laplace over 200 years ago for the origin of the solar system (Miyake, 1965). The RES model was recently modified to explain the occurrence of isotopic anomalies and the decay products of short lived nuclides in meteorites by the addition of about 0.0001 parts of exotic nucleogenetic material from a separate stellar source (Fowler, 1984; Wasserburg, 1987; Anders and Zinner, 1993; Cameron, 1995; Zinner, 1997). This may have been injected from a nearby supernova (Manuel *et al.*, 1972; Cameron and Truran, 1977) or survived within interstellar grains of dust that had been in the early protosolar nebula and became embedded in meteorites like microscopic time capsules of exotic material (Black, 1972; R. Clayton *et al.*, 1973; D. Clayton, 1975a,b; Ott, this volume).

2. *Local element synthesis (LES)*. According to this view, the solar system formed from locally-produced stellar debris. The LES model is an outgrowth of the classic catastrophic model postulated by Buffon in 1745

and later refined by Chamberlin and Moulton and by Jeans early in this century (Miyake, 1965). Manuel and Sabu (1975, 1977) asserted that the LES model also explains the occurrence of isotopic anomalies, inter-linked chemical and isotopic irregularities, and the decay products of short-lived nuclides. They suggested that the entire solar system formed directly from chemically and isotopically heterogeneous debris of a spinning star, concentric with the present sun. Figure 2 shows their mechanism for the formation of the solar system.

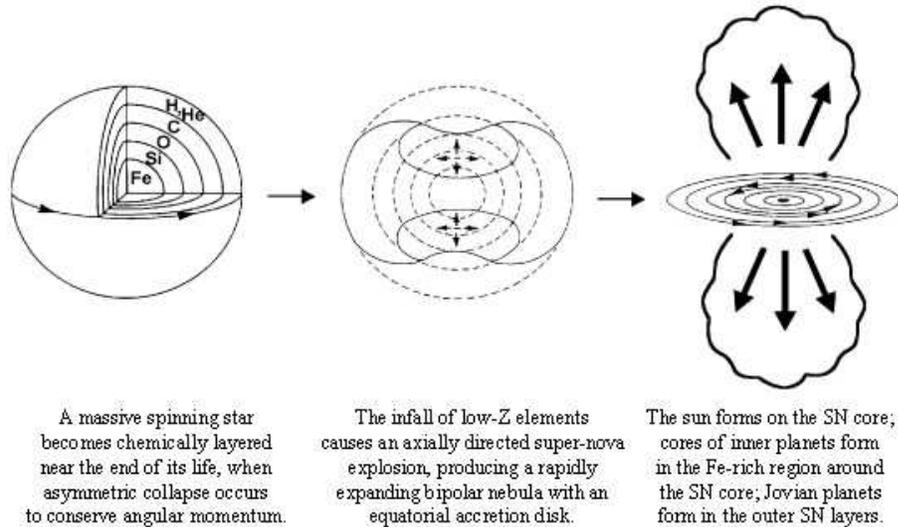


Figure 2. Schematic drawing of events for the formation of the solar system and the LES model (Manuel *et al.*, 1998a).

According to this view, the sun formed on the supernova (SN) core and the outer planets developed mostly from the light elements in the outer SN layers. Iron meteorites and cores of the terrestrial planets formed in a central, Fe-rich region of the SN debris. The sun and the inner planets accreted in layers, as lighter material from other SN layers fell toward the forming sun. Diffusion continued to enrich the lighter elements and the lighter isotopes of individual elements at the evolved sun's surface (Manuel and Hwaung, 1983). According to the LES model, chemical gradients were inherited from the parent SN, and these decreased with time from natural mixing. Three earlier versions of the LES model suggested that a spinning star made the solar system (Lyttleton, 1941), that debris from an explosion of the sun's binary companion formed the planetary system (Hoyle, 1944),

and that the SN shell ejected by an explosion fragmented to form many separate solar systems (Brown, 1970).

Most observations available in 1957 seemed to favor the RES model. Recent reviews on element synthesis (Arnett, 1996; Wallerstein *et al.*, 1997) and almost all the papers presented at a recent St. Louis symposium on isotopic anomalies and short-lived nuclides in meteorites (Bernatowicz and Zinner, 1997) also conclude that the latest observations are consistent with the concept of RES in multiple stellar sources. For example, in the overview, Zinner (1997, p. 3) states that “*It was realized early on that the solar system not only is a very homogeneous mixture of material from many different stellar sources but that these stars themselves incorporated the debris of previous generations of stars (“galactic chemical evolution”).*” This homogeneous mixture of the RES model is illustrated in the left frame of Figure 1. A follow-up news report, begins, “*Amazingly, individual grains of dust from stars that existed before the sun was born have made their way to Earth in meteorites.*” (Bernatowicz and Walker, 1997, p. 26). These illustrate the continued dominance of the RES model in the space sciences community.

However, one point that has troubled scientists for decades (*e.g.*, Lyttleton, 1941; Krat, 1952; Urey, 1956; Huang, 1957) concerns the production of binary, multiple, and planetary systems by the simple condensation of gas and dust with large angular momentum. In spite of this concern, variant ideas about the origin of elements in the solar system have encountered stiff resistance, perhaps because the 1957 papers made such brilliant advancements in noting the connection between abundances of nuclides and their syntheses by reasonable nuclear reactions at each stage of stellar evolution, up to the final supernova shown in Figure 2.

A large amount of new data on the solar system has been reported since 1957. Isotopic ratios in the solar wind and in solar flares, the neutrino flux, and helioseismology have given new insight into the sun’s interior. Analyses on samples of meteorites, the moon, Jupiter, Mars, and material from the Earth’s interior have revealed the decay products of short-lived nuclides and evidence that elements, and even the isotopes of individual elements, were poorly mixed at the birth of the solar system. The Hubble telescope, pulsar planets, and SN1987A have given new insight into the birth and death of stars. These post-1957 observations can be compared with predictions of the RES and LES models to evaluate their merits.

In many cases, the nebular RES model (Figure 1) and the catastrophic LES model (Figure 2) require or predict specific trends that are different from one another. A few examples are below.

(a) According to the RES model, that stable isotope which has less nuclear binding energy than any other,  $^1\text{H}$ , accounts for about 90% of all atoms in the solar system; the LES model claims that most of the solar

system came from the hot interior of a supernova where nuclei with much greater nuclear stability, *e.g.*,  $^{56}\text{Fe}$ , are more abundantly formed.

(b) According to the RES model, chemical heterogeneities in the solar nebula increased with time, whereas for the LES model chemical and isotopic diversity clearly decreased with time.

(c) The RES model requires that major chemical heterogeneities in the planetary system were produced by variations in P, T, oxygen fugacity, etc.; the LES model requires that these heterogeneities were inherited from the parent star.

(d) The RES model predicts no linkage between elemental and isotopic compositions; the LES model predicts that some elemental and isotopic irregularities of the supernova remained coupled, not only in microscopic grains of meteorites, but also in planetary-sized objects.

(e) Excesses and depletions of the same isotope are difficult to explain by the RES model, usually requiring separate stellar sources; excesses and depletions of the same isotope are predicted in the LES model because “normal” isotopic ratios are produced by mixing these.

(f) The RES model predicts no coupling of nucleogenetic isotopic anomalies with the decay products of short-lived radioactivities; the LES model predicts that these will be coupled because natural mixing reduced the levels of nucleogenetic isotopic anomalies while short-lived nuclides in the solar nebula decayed away (Figure 2).

(g) The RES model predicts similar elemental and isotopic compositions for the sun and Jupiter (Figure 1); the LES model predicts that the compositions of these two largest bodies in the solar system will differ because they consist of material from different regions of the supernova that gave birth to the solar system (Figure 2).

In what follows, abundance estimates are reviewed and the literature on the origin of elements is evaluated. An extensive review is given of post-1957 observations, including trends in composition, tracer isotopes, interlinked chemical and isotopic heterogeneities in meteorites and in planets, decay products of short-lived nuclides, isotopic anomaly patterns, heterogeneities in the sun, and pertinent astronomical and geological observations. Although the review of literature on the origin of the elements follows the review of abundance estimates, the abundance and origin of the elements intertwine. Accordingly, the different models of origin, both RES and LES, each have their own abundance counterparts.

## 1.1 ABUNDANCES OF ELEMENTS

A great deal of dedicated labor by a large group of scientists has been expended in collecting elemental and isotopic abundance data. Readers are

referred to reviews on this subject in the books and articles cited below and to the articles by Ebihara *et al.* (this volume) and Grevesse and Sauval (this volume). Readers should also note especially the excellent summaries on the sources of abundance data in Chapters 2 and 3 of Kuroda (1982), Section II of Trimble (1975), Chapter 2 of Arnett (1996), and Trimble (1996).

In their classical papers on the synthesis of elements in stars, both Cameron (1957) and Burbidge *et al.* (1957) relied heavily on the Suess and Urey (1956) compilation of data for abundances of the elements. The data by Suess and Urey data are still widely cited. The scientific community has adopted only minor changes in elemental abundance estimates over the past 40+ years (*e.g.*, Cameron, 1968, 1973, 1982; Palme *et al.*, 1981; Anders and Ebihara, 1982; Anders, 1988; Anders and Grevesse, 1989; Grevesse and Sauval, this volume), in spite of rapid advancements in analytical instrumentation and space exploration that have increased the availability of material from various parts of the solar system.

However, estimates of the abundances of the elements underwent radical changes during the preceding 40 year period, between 1917 and 1957. That change came primarily from assuming that abundances of elements in the solar photosphere are representative of those in the interior of the sun (Goldschmidt, 1938). For reasons given below, there may be reason to question whether some of the changes were improvements.

The pioneer in building a reliable data base for elemental abundance estimates, William Harkins of the University of Chicago, was also a leader in recognizing a possible relationship between elemental abundances and nuclear stability: "...the more stable atoms should be the more abundantly formed..." (Harkins, 1917, p. 859). He warned that elemental abundances in the Earth's crust and the sun's gaseous envelope may not represent the overall composition of these bodies.

After cautioning against use of surface abundances, he pointed out that, "*There is, however, material available of which accurate quantitative analyses can be made, and which falls upon the earth's surface from space. The bodies which fall are called meteorites, and no matter what theory of their origin is adopted, it is evident that this material comes from much more varied sources than the rocks on the surface of the earth. In any event, it seems probable that the meteorites represent more accurately the average composition of material at the stage of evolution corresponding to the earth than does the very limited part of earth's material to which we have access.*" (Harkins, 1917, p. 861).

Harkins therefore used chemical analyses on 318 iron meteorites and 125 stone meteorites to arrive at his conclusion that the first seven elements in order of abundance consist of Fe, O, Ni, Si, Mg, S, and Ca. He stated that, "...not only do all these elements have even atomic numbers, but in addition

they make up 98.6% of the material of the meteorites.” (Harkins 1917, p. 862). Fe alone accounts for 72% of these elements.

Harkins’ abundance estimates clearly reflected the enhanced nuclear stability of elements with even atomic numbers and the occurrence of maximum nuclear stability for Fe (Mayer, 1948), Harkins’ most abundant element. When Harkins (1917) considered only the elements in stone meteorites, he found the same seven most abundant elements, but their order changed slightly to O, Fe, Si, Mg, S, Ca, and Ni.

The positions of Fe, Ni and S relative to those of O, Si, Mg, Ca and Ca depend on the ratio assumed for metal: sulfide: silicate phases. Noddack and Noddack (1930) assumed a ratio of (iron: troilite: stone) = 68: 9.8: 100 and used the chemical analyses of iron meteorites, troilite inclusions (FeS), and stone meteorites to conclude the same seven most abundant elements, in slightly different order, O, Fe, Si, Mg, Ni, S and Ca.

Most later authors (Noddack and Noddack, 1934; Goldschmidt, 1938; Urey, 1952) assumed a lower ratio of (metal : silicate), except Brown (1949). Brown assumed that the Earth’s core and mantle have the compositions of iron and stone meteorites, respectively. He used the location of the seismic discontinuity for the Earth’s mantle/core boundary to obtain a value of (metal : silicate) = 67 : 100 (Brown, 1949).

Goldschmidt (1938, 1958) suggested that chondritic meteorites may best represent the abundances of nonvolatile elements and that stellar spectra may estimate the abundances of volatile elements. This assumes the validity of the RES model, in which an initially homogeneous cloud formed the sun and its planets. If so, then “*The enormous difference in chemical composition of the giant planets, the earth-like planets, and meteorites, is quite natural when examined from the point of view of cosmic evolution.*” (Goldschmidt, 1958, p. 70). He continued: “*Thus the giant planets, the earth-like planets, planetoids and meteorites differ in that only the giant planets have been able to retain much of their original share of hydrogen (and probably helium) while all minor and miniature ‘autonomous’ bodies have lost their hydrogen and helium...*” (Goldschmidt, 1958, p. 71).

The elemental abundance estimates by Urey (1952) were also based on the abundances of the light, volatile elements in stellar spectra and on the abundances of nonvolatile elements in meteorite phases weighed, “*...in such a way as to secure a mixture having the density of the moon.*” (Urey, 1952, p. 230). Suess and Urey (1956) did not accept the (metal : silicate) ratio recommended by Brown (1949), adopting instead the suggestion by Urey (1952) that fractionation occurred during the formation of the terrestrial planets, thus, “*...separating metal from silicate in such a way that the silicate was lost preferentially. Hence, the ratio of core to mantle of the earth cannot serve as a basis for an estimate of the respective cosmic ratios.*”

(Suess and Urey, 1956, p. 56). Table 1 compares estimates by Harkins (1917) and Suess and Urey (1956) for the seven most abundant elements.

Table 1. Examples of pre-1957 estimates of the solar system's most abundant elements

Elements	Harkins (1917)	Suess and Urey (1956)
The Most Abundant	Iron (Fe), element 26	Hydrogen (H), element 1
2nd Most Abundant	Oxygen (O), element 8	Helium (He), element 2
3rd Most Abundant	Nickel (Ni), element 28	Oxygen (O), element 8
4th Most Abundant	Silicon (Si), element 14	Neon (Ne), element 10
5th Most Abundant	Magnesium (Mg), element 12	Nitrogen (N), element 7
6th Most Abundant	Sulphur (S), element 16	Carbon (C), element 6
7th Most Abundant	Calcium (Ca), element 20	Silicon (S), element 14

Iron (Fe) is the most abundant element in Harkins' estimate. This consists mostly of  $^{56}\text{Fe}$ , the decay product of a doubly-magic nuclide,  $^{56}\text{Ni}$ .  $^{56}\text{Fe}$  is the most stable of all nuclides, i.e., it has minimum mass per nucleon. The other heavy element on Harkins' list, nickel (Ni) has two stable isotopes,  $^{62}\text{Ni}$  and  $^{60}\text{Ni}$ , with the second and third lightest mass per nucleon. All seven of Harkins' elements exhibit the enhanced nuclear stability associated with even values of atomic numbers, and the five lightest elements on his list consist mostly of nuclides ( $^{16}\text{O}$ ,  $^{24}\text{Mg}$ ,  $^{28}\text{Si}$ ,  $^{32}\text{S}$  and  $^{40}\text{Ca}$ ) that have the heightened nuclear stability associated with multiples of the  $^4\text{He}$  nuclide.

If the elemental abundances shown in the center column of Table 1 are wrong, then it is a remarkable coincidence that Harkins' mistake in 1917 yielded an abundance pattern of elements that would so closely follow the nuclear properties that were to be discovered years later. Since nuclear evolution is most advanced in the central region of an evolved star (Burbidge *et al.*, 1957), elements that are produced deep in the stellar interior (Figure 2) will display the relationship that Harkins (1917) found between elemental abundances and nuclear stability.

According to the tabulation by Suess and Urey (1956), the first seven elements in order of abundance are H, He, O, Ne, N, C, and Si. Their most abundant element, hydrogen (H), consists mostly of  $^1\text{H}$ . This has the highest mass per nucleon (and lowest nuclear binding energy) of any stable nuclide. The five elements with even atomic numbers, He, O, Ne, C, and Si, account for only 7% of these seven most abundant elements; the two with odd atomic numbers, H and N, account for the other 93%.

The sharp contrast between the abundance data of Suess and Urey (1956) and those that reflect nuclear stability (Harkins, 1917) results directly from the assumption by Suess and Urey that abundances of elements in the solar photosphere are representative of those in the sun's interior. This assumption remains in vogue today, although for such assumption, Arnett (1996, p. 10) notes that the most abundant nuclei, "...are not the most tightly

bound”, and he later asks, “...how can the heavier yet more tightly bound nuclei have remained so rare?” (Arnett, 1996, p. 12).

The solution to this paradox came from signs that internal diffusion in the sun segregates elements and isotopes within it (Manuel and Hwaung, 1983; MacElroy and Manuel, 1986; Bahcall *et al.*, 1995, 1997), as will be illustrated in Table 2 of the next section. It will also be shown that divergent views about the origin of elements in the solar system, whether based on the RES model or the LES model, closely parallel the differing opinions about the internal composition of the sun.

## 1.2 ORIGIN OF ELEMENTS

Most of the early papers about the origin of elements dealt with primordial or cosmological, rather than stellar, synthesis. This concept pre-dates that of stellar synthesis and is by definition remote element synthesis, RES. The possibility of catastrophic local element synthesis, LES, was not considered by Cameron (1957) or Burbidge *et al.* (1957), although one of the authors had earlier suggested that the sun’s planetary system formed directly from SN debris (Hoyle, 1944, 1945, 1946a). Thus, nebular RES was tacitly assumed by default in 1957.

### 1.2.1 1957 Views on Element Synthesis

At the time of publication of the papers by Cameron (1957) and Burbidge *et al.* (1957) on stellar nucleosynthesis, there existed two competing ideas of cosmological element synthesis. The *yelm* theory stated that the universe was created at a particular instant of time and expanded ever since. The other idea, the steady state theory, assumed that the universe had no beginning and that matter is created throughout space at the rate that it disappears at the boundary of the expanding universe (Bondi and Gold, 1948; Hoyle, 1948).

Burbidge *et al.* (1957) criticized primordial theories, “...which demand matter in a particular primordial state for which we have no evidence...” (Burbidge *et al.*, 1957, p. 550), but they did not explicitly endorse the steady state concept. Cameron (1957) and Burbidge *et al.* (1957) instead focused attention on nuclear reactions that convert H into heavier elements during normal stages of stellar evolution and on mechanisms that eject these nucleosynthesis products back into the interstellar medium.

Both Cameron (1957) and Burbidge *et al.* (1957) used abundance estimates based mostly on elements in the solar system (Suess and Urey, 1956), and both referred to Hoyle’s earlier work on thermonuclear reactions in stars (Hoyle, 1946b). But neither mentioned the possibility that elements

in the solar system might have been produced locally, LES, nor the suggestion that our planetary system may have formed from debris of the sun's binary companion (Hoyle, 1944, 1945, 1946a).

Burbidge *et al.* (1957) and Cameron (1957) instead laid the foundation for the currently popular concepts of remote element synthesis, RES (Wood, 1978, 1999; Anders and Zinner, 1993; Cameron, 1995; Zinner, 1997) and chemical evolution of the galaxy (Trimble, this volume and 1988; Timmes *et al.*, 1995; Zinner, 1997) by statements such as, "*It is tempting to believe that our galaxy may have been originally composed entirely of hydrogen.*" (Cameron, 1957, p. 203) and, "*Since stars eject the products of nuclear synthesis into the interstellar gas it seems highly probable that only the 'first' stars can have consisted of pure hydrogen.*" (Burbidge *et al.*, 1957, p. 569).

However, that same year Huang (1957) speculated that binary and multiple stars and those with planetary systems may have formed on "pre-stellar objects"; an idea that had previously been advanced by Krat (1952) and Urey (1956). The catastrophic LES model (Figure 2) is consistent with both i) stellar nucleosynthesis to a final supernova (Burbidge *et al.*, 1957), and ii) the formation of a secondary star and planetary system on the SN core and stellar debris (Huang, 1957).

Burbidge *et al.* (1957) even recognized trends in the abundance data which suggested LES for material in the solar system. Examples are the introductory and concluding statements from Section XII. D. of Burbidge *et al.* (1957, p. 639): "*As mentioned in Sec. VII, the forms of the back sides of the abundance peaks of the r-process isotopes might suggest that the conditions obtaining in a single supernova were responsible for their synthesis.*", and "*It does not appear unreasonable from this point of view, therefore, that a single supernova has been responsible for all of the material built by the r-process currently present in the solar system.*"

Since publication of the classical papers by Burbidge *et al.* (1957) and Cameron (1957), space studies have become popular and important new information has been obtained from analyses of samples from other parts of the solar system and from astronomical observations on the sun and other stars. Results from sample analyses raised questions about the validity of the standard solar model and provided evidence of chemical and isotopic heterogeneities and decay products of short-lived nuclides at the birth of the solar system. Results from astronomical observations raised additional questions about the composition of the sun's interior and revealed asymmetric ejections of poorly-mixed material from dying stars.

The following section will briefly show how a newly developed instrument began finding many apparent exceptions to the nebular RES model for the origin of the solar system soon after publication of the papers by Burbidge *et al.* (1957) and Cameron (1957).

### 1.2.2 Empirical Challenges to the Nebular RES Model for the Solar System

The idea of remote element synthesis (RES) seemed both attractive and natural in 1957 as attention first shifted from cosmological to stellar synthesis. However, the RES concept did not anticipate later findings that the solar system formed from material containing chemical and isotopic irregularities from nucleosynthesis, in addition to short-lived radioactivities.

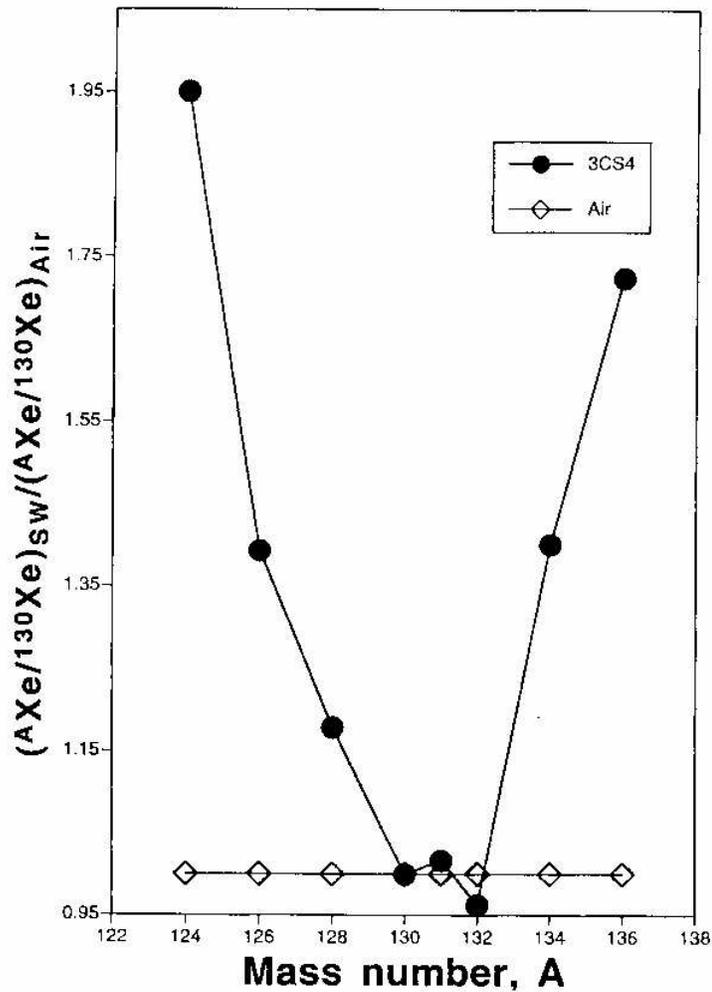


Figure 3. A comparison of isotopically "normal" xenon in air ( $\diamond$ ) with the isotopically "strange" xenon in the 3CS4 mineral separate of the Allende carbonaceous chondrite ( $\bullet$ ).

One year before publication of the 1957 papers on stellar synthesis, Reynolds (1956) reported the development of a stable isotope mass spectrometer for noble gases that uncovered many of these features of the early solar system. The new mass spectrometer first uncovered the presence of radiogenic  $^{129}\text{Xe}$ , the decay product of extinct  $^{129}\text{I}$ , in the Richardton meteorite (Reynolds, 1960a). The instrument also exposed this decay product embedded in xenon with a primordial isotopic anomaly pattern for the other eight isotopes,  $^{124-136}\text{Xe}$  (Reynolds, 1960b).

Reynolds' instrument later showed that xenon in meteorites contains excesses of  $^{134,136}\text{Xe}$  and  $^{124,126}\text{Xe}$  made by the r- and p-processes in a supernova explosion (Manuel *et al.*, 1972). These r- and p-products of xenon occur only in a meteorite phase with abundant primordial He (Sabu and Manuel, 1980), as discovered by a group using the Reynolds' mass spectrometer at the University of Chicago (Lewis *et al.*, 1975). They also found that another meteorite phase trapped a complementary xenon component with excess  $^{128-132}\text{Xe}$  from the s-process of nucleosynthesis, before a star reaches the final supernova stage (Srinivasan and Anders, 1978).

Figure 3 compares isotopic abundances of "strange" xenon in mineral separate 3CS4 of the Allende carbonaceous chondrite (Lewis *et al.*, 1975) with those of Xe in air. The light, neutron-poor isotopes,  $^{124,126}\text{Xe}$ , and the heavy, neutron-rich isotopes,  $^{134,136}\text{Xe}$ , are enriched by factors of  $\approx 40-95\%$ . Other heavy elements trapped with isotopically "strange" xenon also display excesses of isotopes produced in a supernova explosion (Maas *et al.*, this volume; Ballad, *et al.*, 1979; Oliver *et al.*, 1981), but the light elements (He, C, Ne) trapped there are isotopically "normal".

Figure 3 shows one of the unexpected discoveries made possible by the use of Reynolds' (1956) high-sensitivity mass spectrometer. Such large isotopic anomalies from nucleosynthesis, the close association of the "strange" xenon with primordial helium, and the decay products of short-lived nuclides in meteorites first prompted Manuel and Sabu (1975, 1977) to propose local elements synthesis, LES.

### 1.2.3 The Rise of the Catastrophic LES Model for the Solar System

The nebular RES model shown in Figure 1 offers no explanation for the reciprocal isotopic anomalies first reported for xenon in meteorites (excess r- and p-products in some minerals and excess s-products in others) and since found in several other heavy elements (Begemann, 1993). Nor does RES explain the close association of isotopically "normal" light elements with isotopically "strange" heavy elements.

The LES model shown in Figure 2 was developed to explain why essentially all primordial He in meteorites is trapped with isotopically

“strange” Xe, Kr, and Ar, but none with isotopically “normal” Xe, Kr, and Ar (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1980). This feature of noble gases is illustrated in Figure 4 for mineral separates of the Allende carbonaceous chondrite (Lewis *et al.*, 1975).

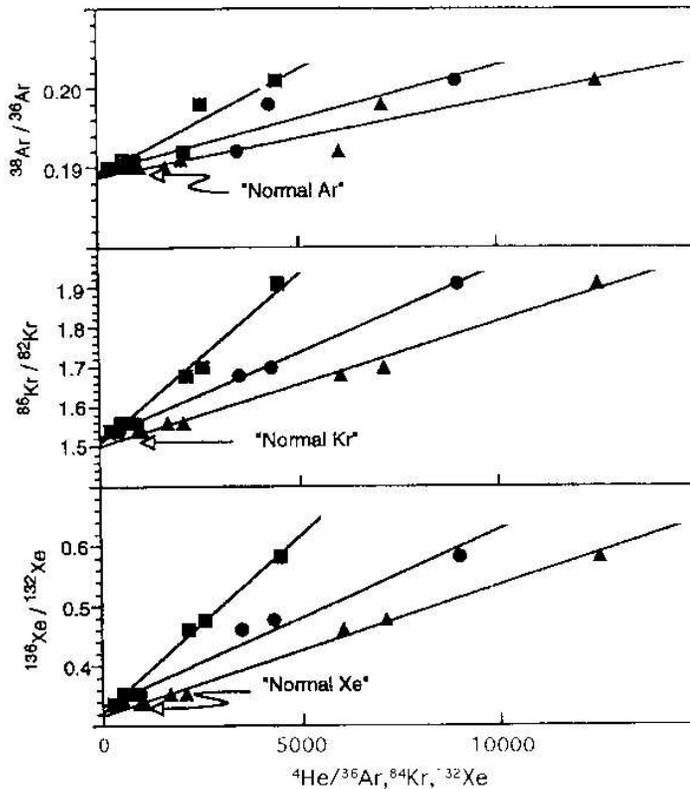


Figure 4. The close coupling of primordial He and isotopically “strange” Ar, Kr and Xe. Isotopically “normal” Ar, Kr and Xe are at the intercepts, where the abundance of primordial He vanishes. (Data from Lewis *et al.*, 1975). ▲ represents values of  $(^4\text{He}/^{132}\text{Xe}) \times 0.15$ ; ● represents values of  $(^4\text{He}/^{84}\text{Kr}) \times 0.08$ ; ■ represents values of  $(^4\text{He}/^{36}\text{Ar}) \times 5$ .

To explain the correlation of elemental and isotopic irregularities shown in Figure 4, Manuel and Sabu (1975, 1977) abandoned earlier suggestions that the “strange” Xe might be a fission product of a superheavy element (Srinivasan *et al.*, 1969) or material added to the solar system from a supernova (Manuel *et al.*, 1972). They proposed that the entire solar system instead formed directly from chemically and isotopically heterogeneous debris of a single supernova, as illustrated in Figure 2.

According to their view, isotopically “strange” Xe, Kr, and Ar are closely associated with abundant He because these elements came from the outer SN layers that also produced the giant Jovian planets. Likewise, isotopically “normal” Xe, Kr, and Ar came from the stellar interior where fusion reactions had consumed light elements such as He to produce heavier elements like those found in iron meteorites and in the rocky, iron-rich, terrestrial planets. Thus, the correlations of isotopic ratios of heavy noble gases with elemental abundances of He (Figure 4) reflect the fact that some minerals formed in the outer layers, and other phases formed in the inner layers, of the SN that produced the solar system (Figure 2).

The possibility of producing the solar system directly from debris of a local star had been proposed earlier to explain its distribution of angular momentum. Lyttleton (1941) imagined that the solar system was produced by the break-up of a single star due to rotational instability. Hoyle (1944, 1945, 1946a) envisioned that the early sun had a larger, binary companion that exploded as a nova or a supernova. A small fraction of the material thrown off by the exploding star became the sun’s planetary system. Brown (this volume; 1970-1991) and Brown and Gritzso (1986) focused on the dynamics of SN shell fragmentation to produce solar systems.

The LES model shown in Figure 2 was developed to explain interlinked chemical and isotopic inhomogeneities and decay products from short-lived radioactivities in meteorites (Oliver *et al.*, 1981). However, it also explains the distribution of angular momentum in the solar system.

Support for the LES model shown in Figure 2 came from who found that the abundances of short-lived nuclides in meteorites are consistent with a single stellar source (Kuroda and Myers, 1996, 1997; Sahijpal *et al.*, 1998; Goswami, this volume) and from the efforts of Rouse in developing equations for the calculation of solar structure without the assumption of a constant mean molecular weight (Rouse, 1964, 1969), presenting calculations showing a higher mean molecular weight in the sun’s core than indicated by the standard solar model (Rouse, 1975, 1983), and demonstrating that new data on the solar neutrino flux (Rouse, this volume; 1995) are consistent with the presence of a high-Z, iron-like core in the sun.

Other support for the occurrence of an event such as that depicted in Figure 2 came from observations of bipolar nebulae with the Hubble telescope (Frank, this volume; 1997). Frank’s (1997, p. 38) idealized drawing for the formation of bipolar nebulae is remarkably similar to the diagram shown by Oliver *et al.* (1981) for the origin of the solar system (Figure 2).

Finally, it should be mentioned that Reynolds’ high sensitivity mass spectrometer (Reynolds, 1956) made possible the detection of fission products from  $^{244}\text{Pu}$  in meteorites (Rowe and Kuroda, 1965). This proved the occurrence of a supernova and provided a way to date the time of the

supernova event. Kuroda and Myers (1996) combined  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  dating with U-Pb dating to show that the SN event occurred 5 Gyr ago. They also showed that the  $^{26}\text{Al}$ - $^{26}\text{Mg}$  dates of SiC in meteorites indicate that the larger grains formed 1-2 Myr after the SN event (Kuroda and Myers, 1997).

Thus many features of the catastrophic LES model were confirmed. However, one obvious problem remained. Since light elements like H and He are totally consumed from the interior of an evolved star, the presence of an H,He-rich star at the center of the solar system seemed inconsistent with the suggestion that the sun formed in the manner illustrated in Figure 2.

Data from high sensitivity mass spectrometers (Reynolds, 1956) also solved this enigma by exposing differences in the isotopic compositions of noble gases in the solar wind (SW) and those in the two major primordial noble gas components in the planetary system.

Component X contains isotopically normal He and Ne and isotopically "strange" Xe, Kr and Ar. It is on the right side of Figure 4. Component Y contains isotopically "normal" Ar, Kr and Xe, with little or no He or Ne. It is on the left side of Figure 4. Mixtures of these two dominant types of primordial noble gases (Sabu and Manuel, 1980) produce the correlations shown in Figure 4 for Allende mineral separates (Lewis *et al.*, 1975).

By assuming that noble gases in the sun are a mixture of these two primordial noble gas components, Manuel and Hwaung (1983) were able to identify a systematic enrichment of lighter mass isotopes in all five noble gases of the solar wind (SW) from diffusion inside the sun that selectively moves lighter mass particles to the solar surface. When solar photospheric abundances were corrected for this diffusive mass-fractionation, the seven most abundant elements in the bulk sun were found to be: Fe, Ni, O, Si, S, Mg, and Ca, in decreasing order (See other paper by Manuel, this volume).

Table 2 compares the seven most abundant elements found by Manuel and Hwaung (1983) with those from the recent estimate by Grevesse and Sauval (this volume). The most noteworthy feature of Table 2 is its remarkable similarity to the two lists of elements in Table 1. Another noteworthy feature is the discord between the list of elements in the middle and the right columns of each table.

Table 2. Examples of post-1957 estimates of the solar system's most abundant elements

Elements	*Manuel and Hwaung (1983)	Grevesse and Sauval (this volume)
The Most Abundant	Iron (Fe), element 26	Hydrogen (H), element 1
2nd Most Abundant	Nickel (Ni), element 28	Helium (He), element 2
3rd Most Abundant	Oxygen (O), element 8	Oxygen (O), element 8
4th Most Abundant	Silicon (Si), element 14	Carbon (C), element 6
5th Most Abundant	Sulphur (S), element 16	Neon (Ne), element 10
6th Most Abundant	Magnesium (Mg), element 12	Nitrogen (N), element 7
7th Most Abundant	Calcium (Ca), element 20	Magnesium (Mg), element 12

\*Photospheric abundances of Ross and Aller (1976) corrected for diffusive mass fractionation.

In terms of nuclear physics, the most abundant elements in the middle and right columns of Tables 1 and 2 are opposites: One claims that the most abundant nuclide is  $^{56}\text{Fe}$ , the ash of thermonuclear reactions at equilibrium. The other claims that the most abundant one is  $^1\text{H}$ , the stable nuclide that releases the greatest energy per nucleon in thermonuclear reactions. Nuclear evolution is highly advanced in the first case; it has hardly begun in the second.

Slight differences in the order of elements in the right columns of Table 1 and Table 2 reflect the small changes in mainstream elemental abundance estimates over the past 43 years (*e.g.*, Suess and Urey, 1956; Grevesse and Sauval, this volume). In addition to a slight change in order, silicon has been replaced with magnesium as the seventh most abundant element.

However, the agreement of the list of elements in the middle columns of Table 1 and Table 2 is even more remarkable. Harkins (1917) and Manuel and Hwaung (1983) considered completely different measurements in concluding that Fe, O, Ni, Si, Mg, S and Ca are the seven most abundant elements. Harkins used analyses of 443 meteorites to arrive at this conclusion. Manuel and Hwaung combined analyses of the photospheric spectrum by Ross and Aller (1976) with isotopic analyses of noble gases in the solar wind (Eberhardt *et al.*, 1972) to conclude the same seven elements, in only slightly different order. The question is whether this agreement might be happenstance.

Eighty-three (83) elements remain in the solar system, two long-lived actinide elements ( $_{90}\text{Th}$  and  $_{92}\text{U}$ ) plus 81 stable ones in the range of  $^1\text{H}$ - $_{83}\text{Bi}$ . If each element has an equal chance of being selected, then the random chance of selecting Harkins' set of seven elements is  $(7!)(83-7)!/(83!)$ , i.e., there is one chance in 4,000,000,000 for meaningless agreement between the compilations of Harkins (1917) and Manuel and Hwaung (1983). Since these are trace elements in the solar photosphere, the chance for a meaningless selection of these elements from the photosphere is even less if atomic abundances in the photosphere determine the selection probability for an element.

Since nuclear evolution is more advanced in the central region of an evolved star (Burbidge *et al.*, 1957), it should come as no surprise that the most abundant elements in the sun are those produced in the deep interior of a star (See Figure 2). In fact, so much  $^{56}\text{Co}$  was produced in SN1987A that the decay of this  $^{56}\text{Fe}$ -precursor dominated the light curve for about 120-900 days after the supernova explosion (Chevalier, this volume).

In Section 2 below, the tracer isotope technique is used to determine the origin of chemical and isotopic diversity in the solar system, from the nanometer scale (nm) of the tiniest meteorite grains to the astronomical unit scale (AU) of interplanetary distances. Some readers may want to skip Section 2 and use the list of conclusions in Section 3 to select portions of Section 2 for further study.

## 2. DETAILS OF OTHER POST-1957 OBSERVATIONS

Even in 1957, scientists knew that the planetary system was heterogeneous on a macroscopic scale (Urey, 1952). Since then, it has been found that meteorites, the oldest known solids in the solar system, display both microscopic- and macroscopic-scale irregularities in isotopic as well as in elemental compositions. These findings do not agree with predictions of the nebular model of Kant and Laplace (Figure 1) because “*The classical picture of the pre-solar nebula is that of a hot, well-mixed cloud of chemically and isotopically uniform composition.*” (Begemann, 1980, p. 1309).

Exactly what information do these heterogeneities contain about the origin of local elements? Can they be explained by reasonable processes acting on a well-mixed cloud of “cosmic” composition (Figure 1), as indicated by the nebular RES model (Wood, 1999)? Or are they remnants of extremely heterogeneous debris from the supernova (Figure 2) that gave birth to the solar system according to the catastrophic LES model (Manuel and Sabu, 1975, 1977)?

Can less drastic starting material explain the data, such as a rather uniform cloud of interstellar gas and dust but for grains of dust that survived conditions in the presolar nebula and became embedded in meteorites (Black, 1972; R. Clayton *et al.*, 1973; D. Clayton, 1975a, b, 1982; Clayton and Hoyle, 1976)? What significance might these observations have for the injection of exotic material from a nearby supernova explosion, *i.e.*, from a blend of RES methodology with a small contribution from LES methodology (Cameron and Truran, 1977; Goswami, this volume)? Regardless of the mechanism, can the observations be explained if 99.99% of the starting material had normal isotopic composition and only 0.01% had exotic nucleogenetic composition (Fowler, 1984; Wasserburg, 1987)?

Differences in the natural abundances of isotopes allow the “tracer isotope technique” to answer these questions. To illustrate the power of tracer isotopes, suppose there are three samples that consist of the same elements but the isotopic abundances of one of the elements is different in each sample. An example might be samples A, B and C of hydrogen bromide (HBr) with  $(^{79}\text{Br}/^{81}\text{Br})_A = 1.0$ ,  $(^{79}\text{Br}/^{81}\text{Br})_B = 2.0$ , and  $(^{79}\text{Br}/^{81}\text{Br})_C = 0.50$ . Each of these three compounds has an isotopic “fingerprint” that allows isotopic analyses to identify possible parent sources and reaction products. Further, tracer isotopes constrain the production of one sample from another. For example, sample A might be a mixture of samples B and C, but obviously sample B could not be a mixture of A and C, nor could sample C be a mixture of A and B.

After a brief review of chemical gradients in the solar system, isotopic irregularities and the tracer isotope technique will be used to decide the roles of RES and LES in producing the elements in the solar system.

## 2.1 TRENDS IN ELEMENTAL COMPOSITION

In addition to new discoveries since 1957, remarkable patterns appear in the abundance distribution of elements in the solar system that may, or may not, have significance. A logical question might be why is H, which is the first element in the periodic table and the lightest of all elements, also the most abundant element in the solar photosphere? Likewise, one might ask why is He, which is the second element in the periodic table and the second lightest of all elements, also the next most abundant element in the solar photosphere? Are these coincidences?

Likewise, one might question the remarkable similarity in the distribution of elements in highly evolved, massive stars, *e.g.*, Figure 46 of Taylor (1972) and Figure 20.44 of Zeilik (1982), as well as in the interior of the Earth, *e.g.*, Figure 9 of Taylor (1972) and Figure 8.2 of Zeilik (1982), and in the planetary system that orbits the sun, for example Figure 1 and Table 1.1 of Miyake (1965). In each case, the central region has abundant even- $Z$  elements with maximum nuclear stability, such as Fe and Ni ( $Z = 26$  and  $28$ ). The outer region contains higher abundances of light elements of low atomic number and relatively low nuclear binding energy, such as H and C ( $Z = 1$  and  $6$ ). The intermediate region contains elements of intermediate atomic number and nuclear binding energy, such as Mg and Si ( $Z = 12$  and  $14$ ).

### 2.1.1 Trends in Composition of the Earth

Terrestrial planets have obviously undergone some metamorphic processing to form the crust and atmosphere, and the chemical boundaries are not sharply defined. Oxygen ( $Z = 8$ ), for example, is abundant at the surface and in the mantle of the Earth, but not in the core where metallic Fe and Ni are dominant. The Earth's inner core is generally believed to consist almost entirely of Fe and Ni, but its outer core may also contain lighter elements such as S ( $Z = 16$ ), in addition to Fe, Ni (J. Lewis, 1974; Wood, 1978; Hou *et al.*, 1993). Chapter III of Miyake (1965) contains a superb review of the early theories proposed to explain the Earth's layered structure.

It is widely assumed that low abundances of light elements in the Earth and other terrestrial planets were caused by heating and loss of volatiles and that their layered internal structures were caused by gravitational sinking of high-density Fe, Ni to the core (Urey, 1952, 1954; Miyake, 1965). Grossman (1972), Grossman and Larimer (1974), and Saxena and Eriksson

(1983) reviewed the early literature, and Yoneda and Grossman (1995) and Larimer (this volume) present more recent work on the possibility of producing meteorites and Earth-like objects from a gas initially having the composition of the solar photosphere if pressure, oxygen fugacity, and composition of the gas phase are considered as variables.

Eucken (1944) also envisioned that the solar system formed from a primitive nebula rich in H and He, but he suggested that the Earth may have developed in layers, beginning with the accretion of Fe that condensed first from a high temperature, high pressure, central region of the nebula. Eucken's proposal generated considerable interest in the possibility of both equilibrium condensation and heterogeneous accretion of the Earth.

Turekian and Clark (1969) and Vinogradov (1975) endorsed the concept of heterogeneous accretion of the Earth. However, these authors assumed that an inner Fe,Ni-rich region of the solar nebula was produced by a combination of condensation and redistribution of material from an initially homogeneous solar nebula. According to their model, "*The iron body that is now the Earth's core formed by accumulation of the condensed iron-nickel in the vicinity of its orbit. It then served as the nucleus upon which the silicate mantle was deposited, and the mantle in turn shielded the core from subsequent reaction with H<sub>2</sub>S and H<sub>2</sub>O to form sulfides and oxides.*" (Turekian and Clark, 1969, p. 347). Vinogradov (1975) suggested that identical processes formed iron meteorites and the Earth's core. Alexander (this volume) shows that some iron meteorites were not produced by planetary differentiation, and Qi-Lu and Masuda (this volume) show that some iron meteorites retain a primary nature, including isotopic anomalies from nucleosynthesis.

### 2.1.2 Trends in Composition of Meteorites

Meteorites are the oldest known solids in the solar system. Thus trends in their chemical constituents may indicate the origin of compositional differences across the solar system and in planetary bodies. Their point of origin is believed to be the asteroid belt, which marks the divide between the smaller, high density, rocky, iron-rich, inner planets and the giant, low density, gaseous, outer planets. According to the nebular RES view of the early solar nebula (Figure 1), the asteroid belt is, "... *evidently a transition region between the hot, inner solar system, where high temperature condensates accreted into small bodies and eventually into rocky planets, and the cold, outer solar system where volatile ices condensed along with high- and low-temperature minerals.*" (Chapman, 1998, p. 16).

According to the catastrophic LES view of the early solar nebula (Figure 2), the asteroid belt is also the boundary that separates the condensation

products of the inner supernova layer, in which the dense, iron-rich, rocky planets were made, and the outer supernova layer, in which the low density, gaseous, giant planets were made. The differences seen in the elemental and isotopic compositions of mineral separates of meteorites (Figures 3 and 4) are consistent with their origin at this major boundary.

Meteorites display many of the same macroscopic differences in composition that are recognized in the Earth, in the planetary system, and in models of highly evolved massive stars. There are three main classes of meteorites: iron, stony iron, and stone. Iron meteorites consist mostly of metallic Fe,Ni, as does the Earth's core. Stony irons contain separate regions of metallic Fe,Ni and ferromagnesium silicates. Stone meteorites consist of two types: chondrites and achondrites. About 90% of the stone meteorites are extremely heterogeneous, agglomerate rocks known as chondrites. The extent of their heterogeneity is well illustrated in Figure 4 of Goswami (this volume), Figures 34-38 of Mason (1962), Figures 11 and 18 of Wood (1978), and in Figures 2.1 and 3.1 of Dodd (1981).

Vinogradov (1975) noted that the blebs of Fe,Ni alloy in stone meteorites exhibit the same polymorphic varieties that are seen in iron meteorites, such as kamacite with up to 6% Ni and taenite with up to 50% Ni. Thus the process that formed the Fe,Ni inclusions of stone meteorites not only formed the iron meteorites but probably even the larger iron cores of the inner planets. The remaining 10% of the stone meteorites are achondrites. They are more highly differentiated than chondrites and contain no chondrules, the aerodynamically-shaped, glassy, rapidly-quenched droplets of silicates, which are designated by the name chondrite.

Currently, the relative abundances of the three types of meteorites in observed falls are 3% irons, 1% stony irons, and 96% stones, with chondrites:achondrites  $\approx$  10:1 (Dodd, 1981). The composition of the Earth's core may indicate that the irons were dominant in the accretion process when the cores of the terrestrial planets formed. (Vinogradov, 1975).

Olbers (1803) suggested that asteroids and meteorites are pieces of a disrupted planet between Mars and Jupiter. Olbers' suggestion is still in vogue, except that the asteroids of different composition (Anders, 1964; Dodd, 1981) are now assumed to be the parent bodies for the meteorites instead of one planetary object. Like the planets, "...the distribution of compositional types among the asteroids is found to vary systematically with heliocentric distance." (Gradie and Tedesco, 1982, p. 1405).

It has generally been assumed that meteorites were derived from material having "cosmic" elemental abundances (Mason, 1962) in accordance with the nebular RES model, and that carbonaceous chondrites represent the most primitive accretion products. However, the largest isotopic anomalies are found in carbonaceous chondrites. Even if the chemical irregularities in

meteorites arose from large differences in temperature, pressure, and oxygen fugacity, this leaves the isotopic irregularities unexplained. Further, it is not easy to understand how planetary layers of various composition formed from material with “cosmic” abundances or by accreting chondritic meteorites. For example, Wood (1978, p. 344) recognized differences in the oxidation state of Fe and in the thermal histories of the tiny grains of material in a carbonaceous chondrite and remarked: “*Thus, even on a millimeter scale, this aggregation, which we believe to be very similar to the raw material the planets are made of, is a disequilibrium mixture of high- and low-temperature components. If the Earth was put together out of material like this, one might logically ask why the metal didn’t react with the ferric iron until one of them was used up, and how did we end up with iron in three states of oxidation in the Earth?*”

Chemical, isotopic, textural and/or mineralogical differences are not limited to primitive chondrites. Some achondrites, as well as chondrites, are breccias. The Erevan meteorite is part of a group of achondrites, which closely resemble the lunar soil in texture (Dodd, 1981). A carbonaceous chondrite clast in this achondrite contains a fragment of phosphorus-rich sulfides that is believed to have condensed from the solar nebula and to be a primary carrier of P and K in carbonaceous chondrites (Nazarov, 1994). Recently, Nazarov *et al.* (1998) showed that this P-rich sulfide fragment is enriched in elements produced by the s-process, with an abundance pattern for refractory elements that is similar to the one reported in “presolar” SiC grains (Amari *et al.*, 1995; Lodders and Fegley, 1995).

As noted earlier, the tracer isotope technique can be used to decide if chemical and isotopic irregularities seen across the planetary system and in individual grains of meteorites are products of condensation and segregation of an interstellar cloud according to the nebular RES model (Figure 1), or that coupled with a small component of exotic nucleogenetic material (Fowler, 1984; Wasserburg, 1987), or residual heterogeneities from the stellar debris that gave birth to the solar system (Figure 2).

## 2.2 TRACER ISOTOPES IN THE SOLAR SYSTEM

The tracer isotope technique can be used to decide the merits of the nebular RES model (Figure 1) versus the catastrophic LES model (Figure 2). One wants to determine whether the bulk solar system (99.99%) was derived from homogeneous and isotopically “normal” ingredients according to the latest RES model with only about 0.01% of exotic nucleogenetic material with “strange” isotopic ratios added (Fowler, 1984; Wasserburg, 1987), or if the entire solar system was derived from chemically and isotopically heterogeneous supernova debris, according to the LES model (Manuel *et al.*,

1998a). If the solar system (Lyttleton, 1941; Brown, 1970; Ramadurai, this volume) or some part of it (Hoyle, 1944; Vahia, this volume) formed from stellar debris by some other mechanism, then elemental and isotopic variations might be somewhat like those expected for the catastrophic LES model, provided that there is a viable mechanism such as that shown in Figure 2 to preserve these stellar-produced gradients as the solar system developed.

A word of caution is in order before proceeding to use the tracer isotope technique to decide the origin of chemical and isotopic heterogeneities in the solar system. In the following discussion of tracer isotopes in the solar system, it is assumed that chemically produced isotopic effects arise solely because of differences in mass. An exception to this general rule has been demonstrated for the production of ozone with an electrical discharge of molecular oxygen (Thiemens and Heidenreich, 1983) and for the production of molecular oxygen with an electrical discharge of carbon dioxide (Heidenreich and Thiemens, 1985). However, it has not been shown that any of the “strange” isotopic ratios observed in meteorites came from electrical discharges, and it is highly unlikely that such a process produced a significant fraction of the isotopic anomalies that match the patterns expected from the accumulation of the decay products of extinct radionuclides and the presence of poorly mixed products of the nucleosynthesis reactions that made the elements (Begemann, 1980).

### **2.2.1 HETEROGENEITIES IN THE PLANETARY SYSTEM**

Systematic gradients in the chemical composition of the sun’s planetary system were considered above in Section 2.1. The composition varies with radial distance from the sun: Light elements with low nuclear binding energy (H, C) are abundant in the outer planets, such as Jupiter; elements with maximum nuclear stability (Fe, Ni) are abundant in the inner planets, such as Mercury; and intermediate weight elements of intermediate nuclear binding energy (Mg, Si) are abundant in intermediate planets, such as Mars. The tracer isotope technique can determine if these chemical gradients in the planetary system are better explained by the catastrophic LES or the nebular RES models, or some hybrid of the two.

#### **2.2.1.1 Inter-linked Chemical and Isotopic Diversities**

In the following three sections, the tracer isotope technique will be used to answer the following questions: 1) Were chemical and isotopic heterogeneities initially linked? 2) Are isotopic variations still linked with chemical heterogeneities, and if so are they coupled over planetary distances? Did isotopic and chemical heterogeneities decrease with time?

### 2.2.1.1.1 Primordial Coupling of Isotopic and Chemical Diversities.

Figure 4 shows the first experimental evidence that elemental abundances of a light element, He, are closely coupled with isotopic abundances of its heavy congeners, Ar, Kr, and Xe, in mineral separates of the Allende carbonaceous chondrite. These data from R. Lewis *et al.* (1975) formed the basis for the original suggestion that the entire solar system formed directly from debris of a single supernova (Manuel and Sabu, 1975; 1977). According to this model, isotopically “strange” Ar, Kr, and Xe had come from the outer layers of a supernova where fusile elements (H, He, C) like those in the outer planets are still abundant. In meteorites these isotopically “strange” heavy noble gases are trapped with abundant He and Ne in nanometer sized diamonds (Lewis and Anders, 1988), which are plausible vapor condensation products from material rich in H, He, and C (Shindo *et al.*, 1985).

Isotopically “normal” Ar, Kr, and Xe, such as seen in the inner part of the solar system, are at the intercepts of the correlations shown in Figure 4, where elemental abundances of He vanish. This noble gas component may be from the star’s hot interior, where He was possibly destroyed by fusion to make Fe, S, and other abundant elements in the inner planets.

Correlations between elemental abundances of primordial He with isotopic excesses of  $^{38}\text{Ar}$ ,  $^{86}\text{Kr}$ , and  $^{136}\text{Xe}$  are exactly those expected if isotopically anomalous Ar, Kr, and Xe were initially associated with an ingredient of the solar nebula that contained all of its He. In other words, these correlations are to be expected if the solar system had been formed from poorly-mixed supernova debris (Figure 2). Because chemical differences between noble gases are minimal, this evidence for a primordial linkage between the elemental abundances of a light, fusile element and isotopic enrichments of heavy elements apparently survived the condensation and chemical reactions which occurred between the time of the nucleosynthesis and the formation of the planetary solids.

The close coupling of primordial He with isotopically “strange” Ar, Kr, and Xe, as shown in Figure 4, is a common property of the noble gases in meteorites (Sabu and Manuel, 1980). This property is consistent with the predictions of the catastrophic LES model for the entire solar system. It is unexplained by the nebular RES model and is generally overlooked by its supporters. Because RES posits that He is the second most abundant element, the results cannot be explained by injecting 0.0001 parts of exotic nucleogenetic material (Fowler, 1984; Wasserburg, 1987).

Chemical and physical methods used to isolate chemically-distinct phases from primitive meteorites with different nucleogenetic components is another obvious, but seemingly overlooked, indication for primordial coupling of chemical and isotopic irregularities in the elements that formed meteorites. Lee *et al.* (1996a,b, 1997) and Manuel *et al.* (1998a) cite other

examples of inter-linked chemical and isotopic irregularities in the early solar nebula, as expected from LES, such as coupling of the chemical classification of meteorites with their levels of excess  $^{16}\text{O}$  (R. Clayton *et al.*, 1976), the linking of the FeS in diverse meteorites with the Xe of terrestrial isotopic composition (Lee *et al.*, 1996a,b), and the connecting of SiC inclusions with the s-products of nucleosynthesis (Huss and Lewis, 1995).

### 2.2.1.1.2 Planetary Coupling of Isotopic and Chemical Diversity.

In 1960 the first hint of planetary-scale isotopic diversity was found in primordial Xe (Reynolds, 1960a,b). This work as well as many later analyses in laboratories around the globe confirmed that the isotopic composition of primordial Xe in the Earth differs from that in carbonaceous chondrites that formed farther away from the sun (*e.g.*, Eugster *et al.*, 1967). These analyses ascertained the residual link of isotopic heterogeneity with the radial chemical gradient of the planetary system.

Oxygen further ascertained the residual coupling of chemical and isotopic heterogeneities over planetary distances when R. Clayton *et al.* (1976) demonstrated that fractional enrichments of monoisotopic  $^{16}\text{O}$  can be used to group meteorites and planets into at least six distinct categories. Meteorites or planets in one category cannot be made by differentiating objects from another category. The fractional level of  $^{16}\text{O}$  in the Earth and the Moon is like that in achondrites, stony-iron meteorites, and enstatite chondrites. Their level of  $^{16}\text{O}$  is unlike that in carbonaceous and ordinary chondrites and in urelites.

In 1972, it was shown that the type of Xe trapped in average carbonaceous chondrites, AVCC Xe, is a mixture of mass fractionated terrestrial Xe and the isotopically “strange” Xe, which is released from carbonaceous chondrites at 600°-1000°C (Manuel *et al.*, 1972). This “strange” Xe was trapped in nanometer-sized diamonds (Lewis and Anders, 1988) with abundant primordial He, but isotopically “normal” Xe was trapped with little or no He, as shown in Figure 4 at the intercept where He vanishes.

Residual linkage of isotopically “strange” Xe with primordial He (Figure 4) was recently confirmed with the release of data from the 1995 Galileo probe, which penetrated the He-rich atmosphere of Jupiter. In spite of large experimental errors, the value of the  $^{136}\text{Xe}/^{134}\text{Xe}$  ratio in Jupiter is distinctly larger than that in the solar wind and approximately equal to the value seen in Xe extracted from the Allende mineral separate 3CS4 (Windler, this volume; Manuel *et al.*, 1998b,c). Xenon from this same mineral separate is shown as an example of isotopically “strange” Xe in Figure 3, and it is represented by the data points with the largest enrichment of  $^{136}\text{Xe}$  in Figure 4. The presence of isotopically “strange” Xe in the He-rich atmosphere of Jupiter is another example that nanometer-scale coupling of chemical and

isotopic components in meteorites has survived as large-scale gradients in the chemical and isotopic compositions of the planetary system.

Primordial Xe of the type found on Earth is also dominant in Mars and in the troilite (FeS) of diverse meteorites, including the troilite separates from the very primitive, heterogeneous, Allende carbonaceous chondrite (Hwaung and Manuel, 1982; Swindle *et al.*, 1995; Lee *et al.*, 1996a,b). The presence today of terrestrial-type Xe in meteorite inclusions of FeS and in planets that are rich in Fe and S further illustrates that planets are composed of material with the elemental and isotopic heterogeneities seen on a much smaller scale in meteorites.

The above examples illustrate that isotopic differences are still linked with residual chemical gradients in the planetary system as expected from the catastrophic LES model (Figure 2). However, they are unexplained by the nebular RES model, even with an injection of 0.0001 parts of exotic nucleogenetic material (Fowler, 1984; Wasserburg, 1987). Nevertheless, the examples may be consistent with other suggestions that the solar system formed from stellar debris (Lyttleton, 1941; Hoyle, 1944; Brown, 1970; Vahia, this volume; Ramadurai, this volume) provided that there is a mechanism to preserve inter-linked chemical and isotopic gradients over planetary distances in forming the sun's planetary system.

#### 2.2.1.1.3 Coupling of Isotopic Anomalies with Short-Lived Nuclides.

If the LES model is used to postulate that the elements in the planetary system came from heterogeneous supernova ejecta, as illustrated in Figure 2, natural mixing would be expected to diminish the isotopic anomalies while natural decay would decrease the abundance of short-lived nuclides. Thus, the amount of extinct radioactivity might be coupled with the magnitude of the isotopic anomalies.

Linkage of isotopic anomalies with extinct radioactivity was first observed when Reynolds (1960a) found the decay product of extinct  $^{129}\text{I}$  embedded in Xe with a general isotopic anomaly pattern across all nine Xe isotopes (Reynolds, 1960b). The decay product of extinct  $^{129}\text{I}$  ( $t_{1/2} = 16$  My) might be used to date the supernova event, except that (a)  $^{129}\text{I}$  can be produced by nuclear reactions other than the r-process of a supernova, and (b) iodine is a volatile element that is unlikely to condense into the solid phase until long after the supernova event.

The decay product of extinct  $^{244}\text{Pu}$  ( $t_{1/2} = 82$  My) is better suited to date the last supernova event because (a)  $^{244}\text{Pu}$  cannot be made by any nuclear reaction other than the r-process, and (b)  $^{244}\text{Pu}$  became part of meteorite minerals that trapped other actinide elements like U. Thus, the  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  and the U-Pb chronometers can be cross-calibrated by using U-Pb dating to determine the age of actinide-rich meteorite minerals and  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  dating to determine how much earlier a supernova produced the  $^{244}\text{Pu}$  (Figure 5).



chondrite. The grains formed within 1-2 Myr of a supernova explosion, over a time period in which the  $^{26}\text{Al}/^{27}\text{Al}$  ratio decayed from a value of 0.60 to 0.10 (Kuroda and Myers, 1997; Manuel *et al.*, 1998a). Amari *et al.* (1992, p. L43) reported that the grains, "... exhibit extremely exotic isotopic compositions, distinct from the majority of the SiC grains, ..." As expected of early condensate from heterogeneous supernova debris, large isotopic anomalies have been found in other elements, including C, N, Si, Ti, and Ca.

Kuroda and Meyers (1997) noted that the levels of extinct radioactivity in these SiC grains decrease with particle size, as has also been found in fallout particles from nuclear weapons testing. Apparently, higher values of the  $^{26}\text{Al}/^{27}\text{Al}$  ratio occur in SiC grains that started to nucleate early and grew larger; lower values of the  $^{26}\text{Al}/^{27}\text{Al}$  ratio occur in smaller grains that started their growth later. Figure 6 (Manuel *et al.*, 1998a) illustrates how the  $^{26}\text{Al}/^{27}\text{Al}$  ratio in these SiC grains varies with the particle size.

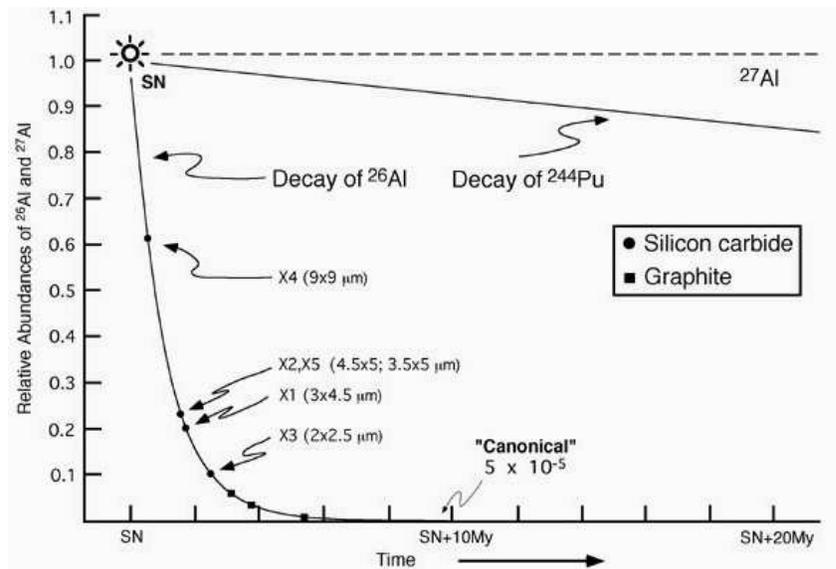


Figure 6. High levels of radioactive  $^{26}\text{Al}$  and large isotopic anomalies were trapped in meteorite grains of silicon carbide (Amari *et al.*, 1992) and graphite (Zinner *et al.*, 1991) that formed within 1-6 Myr of the supernova event. Reprinted from Manuel *et al.* (1998a).

Figure 6 shows that larger grains of SiC formed within 1-2 Myr of the supernova event and graphite grains formed within 3-6 Myr. One SiC grain contains a large excess of  $^{44}\text{Ca}$  (Amari *et al.*, 1992) from the decay of  $^{44}\text{Ti}$ , a supernova-product with a 59-year half-life (Ahmad *et al.*, this volume). This grain may have formed on an even more refractory, Ti-rich particle that condensed even before the complete decay of  $^{44}\text{Ti}$ .

Thus high abundances of short-lived nuclides, such as  $^{26}\text{Al}$ , were initially coupled with large isotopic anomalies in other elements, such as C, N, Si, Ti, and Ca. These anomalies are found in grains with the same physical properties exhibited by other high-temperature condensates. These findings imply that heterogeneities in the solar nebula decreased with time, as expected from application of the catastrophic LES model (Figure 2) but not from that of the nebular RES model (Figure 1).

The RES model, which implies a supply of elements from multiple stellar sources, even with a late injection of exotic material, explains neither the observed linkage of extinct radioactivity with isotopic anomalies nor the coupling of these isotopic properties of the elements with the physical size of the host grains. Further, Figure 6 shows no evidence for a “canonical” value of  $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$  (Podosek and Swindle, 1988), as might be produced from an injection of  $10^{-4}$  parts of exotic nucleogenetic material into an otherwise homogeneous solar nebula (Fowler, 1984; Wasserburg, 1987).

### 2.2.1.2 The Relation of “Strange” and “Normal”

The LES model (Figure 2) requires that there be isotopic excesses as well as depletions in nucleogenetic isotopic anomalies so that elements of “normal” isotopic composition can be made by mixing two or more isotopically “strange” components. This is not expected for the RES model (Figure 1), nor for RES plus an added exotic nucleogenetic component. Different alien sources are required to explain excesses and depletions of the same isotope for the RES model, and the probability of alien stellar sources decreases as their number increases. Thus, the tracer isotope technique can determine whether there is a relationship between the isotopic compositions of “strange” and “normal” components, as expected of LES, or if the “strange” isotopic components are indeed totally alien to those of “normal” material in the solar system, as expected of RES.

Complementary enrichments and depletions in isotopic ratios were first noticed in Xe. One component is enriched in light isotopes,  $^{124,126}\text{Xe}$ , from the p-process and in heavy isotopes,  $^{134,136}\text{Xe}$ , from the r-process (Manuel *et al.*, 1972). A complimentary component was later discovered with an excess of the intermediate mass isotopes,  $^{128-132}\text{Xe}$ , from the s-process of nucleosynthesis (Srinivasan and Anders, 1978).

Oliver *et al.* (1981) noticed positive and negative isotopic anomalies in U, Ba, Ca, Xe, and Te, which are unexpected from the addition of alien nucleogenetic material. On the basis of their observation, they commented that, “*The existence of positive and negative isotopic anomalies are expected, however, if the solar system formed directly from unmixed stellar debris that contained products of the different nucleosynthesis reactions that collectively produced all of the isotopes of each element.*”

Begemann (1993) found the most compelling evidence of complementary enrichment and depletion of isotopes when he compared the elements, Ba, Nd, and Sm in the inclusion EK-1-4-1 of the Allende carbonaceous chondrite with the same elements in the grains of SiC from the Murchison carbonaceous chondrite. In the inclusion EK-1-4-1 of the Allende meteorite, these three elements were enriched in isotopes that were made by the r- and p-processes of nucleosynthesis. In the SiC grains from the Murchison meteorite these same isotopes were depleted. The relative depletions in the SiC grains of Murchison are in the same proportion as the enrichments in the inclusion EK-1-4-1 of Allende. In other words, the isotopic anomaly patterns are “mirror-images,” as illustrated in Figure 7 for any element with seven stable isotopes.

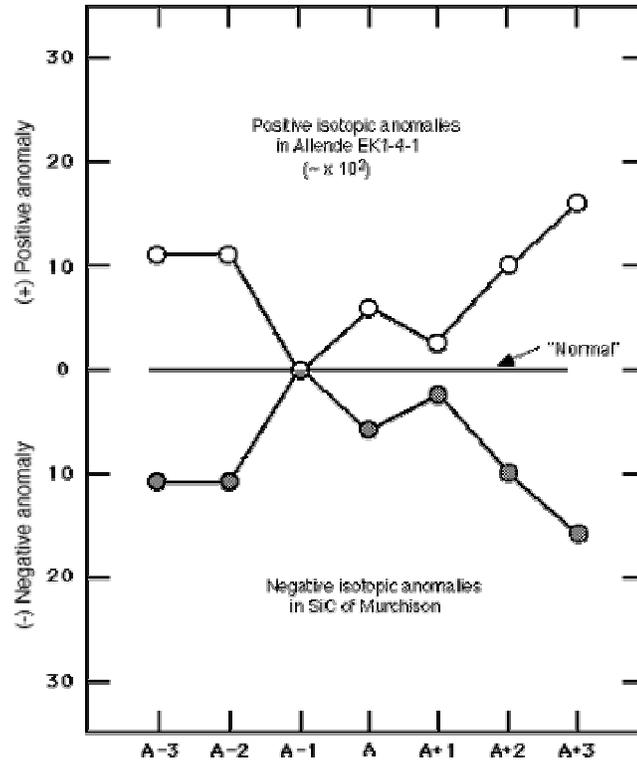


Figure 7. An illustration of “mirror-image” (+ and -) isotopic anomaly patterns seen in Ba, Nd and Sm. These elements are enriched in s-products in SiC inclusions of the Murchison meteorite; these same elements are enriched in r- and p-products in inclusion EK-1-4-1 of the Allende meteorite (Begemann, 1993). This figure is from Manuel *et al.* (1998a).

Individual plots for the enrichments and the depletions of stable isotopes of Ba, Nd, and Sm in inclusions from both of these meteorites are shown in Figure 2 of Begemann (1993) and in Figure 3 of Zinner (1997). In commenting on the pattern displayed in Figure 7, Begemann (1993) stated that, “*For Ba, Nd and Sm the surprisingly good (anti)-match of the anomalies pattern in MuSiC and Allende FUN inclusions appears too good to be entirely serendipitous, the implication being that the s-Ba, Nd, Sm in SiC from Murchison are quantitatively complementary to the excess of r-Ba, Nd and Sm in Allende inclusions.*”

The data in Figure 7 demonstrate a clear relationship between “strange” and “normal” isotopic components, as expected from use of the catastrophic LES model (Figure 2). It is of course also possible that the isotopic anomaly patterns shown in Figure 7 came from multiple injections of exotic nucleogenetic material into a cloud of interstellar material. In that case, it is entirely serendipitous that two extraneous stellar sources would generate “mirror-image” anomaly patterns, which happen to sum to the isotopic composition of “normal” solar system material.

### 2.2.1.3 Scale of Chemical and Isotopic Variations

The scale of chemical and isotopic variations can also be used to decide if the observations fit the nebular RES model (Figure 1) or the catastrophic LES model (Figure 2). If the elements in the solar system were produced by the RES model shown in Figure 1 and the isotopically anomalous material represents only about 0.01% of the bulk (Fowler, 1984; Wasserburg, 1987), then planets or other large objects (*e.g.*, those representing  $\approx 0.1$ -1.0% of the solar system) will not display the same isotopic anomalies that are seen on the small scale represented by individual grains in meteorites.

However, if the elements in the solar system were produced from heterogeneous supernova debris, as suggested by the LES model (Figure 2), then the coupling of chemical and isotopic irregularities will be less dependent on the size of the objects, except for differences in the times required to form large and small objects and in the quantities of material averaged together in large ones. In other words, for the LES model the same linkage between elemental and isotopic abundances might be expected in microscopic grains of meteorites and in planetary-sized objects.

Thus for the solar system, the LES model suggests that the isotopic compositions of the elements, which formed the sun and the planets, may not only differ, but be part of the isotopic irregularities retained in tiny grains of material in the meteorites as well. It has already been shown in Section 2.2.1.1.2. that there are planetary-scale variations in the isotopic ratios of some elements. This was further demonstrated by the recent finding that the  $^{136}\text{Xe}/^{134}\text{Xe}$  ratio in Jupiter (Windler, this volume; Manuel *et al.*, 1998b,c) is

indistinguishable from isotopically “strange” Xe in the Allende mineral separate 3CS4, in which  $^{136}\text{Xe}/^{134}\text{Xe} = 1.04$  (Lewis *et al.*, 1975), but distinctly larger than that in the solar wind, where  $^{136}\text{Xe}/^{134}\text{Xe} = 0.80$  (Kaiser, 1972).

The sun and Jupiter are the two largest bodies in the solar system, yet this disclosure confirms differences in the isotopic abundances of the elements that formed them. This lends further support to the catastrophic LES model for explaining either the presence of all of the elements in the solar system (Lytleton, 1941; Brown, 1970; Manuel and Sabu, 1975, 1977; Ramadurai, this volume) or at least those in the planetary system (Hoyle, 1944; Vahia, this volume). The nebular RES model (Figure 1), even with the addition of a 0.01% of exotic nucleogenetic material, does not explain how the sun and Jupiter might have formed from isotopically distinct reservoirs.

The two heaviest isotopes of Xe,  $^{136}\text{Xe}$  and  $^{134}\text{Xe}$  are generally believed to be produced solely by the r-process of nucleosynthesis (Burbidge *et al.*, 1957). Since the fractional enrichment of  $^{136}\text{Xe}$  is greater than that of  $^{134}\text{Xe}$  in “strange” Xe (Manuel *et al.*, 1972), some have suggested that the “strange” Xe represents an exotic r-process (Heymann and Dziczkaniec, 1979; Clayton, 1989; Howard *et al.*, 1992). However, Ott (1996) has shown that the standard r-process can explain the isotopic ratios in “strange” Xe if there was a separation of the stable Xe isotopes from their radioactive precursors within a few hours of their production. Thus, there is no need for an *exotic* nucleogenetic component in Xe. The anomalously high abundances of  $^{136}\text{Xe}$  in “strange” Xe of meteorites may be the counterpart to large excesses of  $^{132}\text{Xe}$  in “strange” Xe of terrestrial samples (Kuroda, 1960; Bennett and Manuel, 1970).

## 2.2.2 HETEROGENEITIES IN THE SUN

Isotopic ratios in the solar wind and in solar flares can be used to determine the internal composition of the sun. The nebular RES model (Figure 1) and the standard solar model imply that the solar system formed from elements that have the same composition seen on the solar surface. The catastrophic LES model (Figure 2) indicates that the sun grew heterogeneously and that its interior may have a different composition than its surface (Manuel *et al.*, 1998a). Several years ago Hoyle (1975) also proposed an Fe-rich solar core to account for the low flux of solar neutrinos, stating that, “*The exterior of the sun, comprising 50 percent or more of the present solar mass, is taken to have been added 4.7 x 10<sup>9</sup> years ago.*” (Hoyle, 1975, p. L127).

### 2.2.2.1 Elemental Composition

The isotopic compositions of the elements in the solar wind and in solar flares can be used to determine whether diffusion in the sun enriches the

light elements at its surface. If diffusion enriches lighter nuclei at the surface, the effects may be seen in isotopic abundances of elements there.

It has long been known that thermal diffusion can separate particles on the basis of mass. For an un-ionized gas, Chapman and Cowling (1952, p. 255) noticed that, "...the heavier molecules tend to diffuse into the cooler regions..." This may describe matter at the solar radius with an effective temperature of about 5800 K and a mass density of about  $2.7 \times 10^{-7}$  g/cc (Rouse, 1998). Inward the degree of ionization increases and thermal diffusion may enrich lighter nuclei at stellar surfaces. Heavier ions tend to diffuse towards the warmer region of an ionized gas. Chapman and Cowling (1952) noted that, "This must happen in the sun and the stars, where thermal diffusion will assist pressure diffusion in concentrating the heavier nuclei towards the hot central regions." (Chapman and Cowling, 1952, p. 255).

The first report on the isotopic composition of Xe in the solar wind stated that, "...terrestrial atmospheric and solar-type xenon may be related to each other by a strong mass fractionating process ..." (Marti, 1969, p. 1265). Compared to terrestrial Xe, solar wind Xe is enriched in the lighter mass isotopes by approximately 4% per amu (Boulos and Manuel, 1971; Kaiser, 1972), although, as much as 7-8% of  $^{136}\text{Xe}$  in the solar wind may be the isotopically "strange" Xe seen in meteorites (Sabu and Manuel, 1976a; Pepin *et al.*, 1995).

Figure 8 shows the fractionation relationship between solar wind and fission-free terrestrial Xe (Sabu and Manuel, 1976a). Since air contains only about 1/10th of the Earth's total Xe (Canalas *et al.*, 1968; Hennecke and Manuel, 1975), the correction for fission in Figure 8 amounts to only 1.8% at  $^{136}\text{Xe}$ . The fission correction is significantly smaller for  $^{131-134}\text{Xe}$ .

The fission correction to atmospheric xenon in Figure 8 is based on the initial inventory of  $^{244}\text{Pu}$  that would have been associated with the uranium content of the Earth's crust and upper mantle (Becker *et al.*, 1968). Isotopic ratios for solar wind Xe are averages of the three separate analyses of lunar soils cited by Sabu and Manuel (1976a). The effects of mass fractionation (MF), which selectively enriches the lighter mass isotopes by 3.5% per amu, are shown in Figure 8 by the sloping MF-line. Positive deviations from the MF-line at  $^{124,126}\text{Xe}$  and  $^{134,136}\text{Xe}$  suggest the presence of a small component of isotopically "strange" Xe in the sun (Sabu and Manuel, 1976a; Pepin *et al.*, 1995).

As indicated in Section 1.2.3, Manuel and Hwaung (1983) identified a systematic enrichment of lighter mass isotopes across all five of the noble gases in the solar wind. When solar photospheric abundances were corrected for this fractionation, the seven most abundant elements in the bulk sun were found to be: Fe, Ni, O, Si, S, Mg, and Ca.

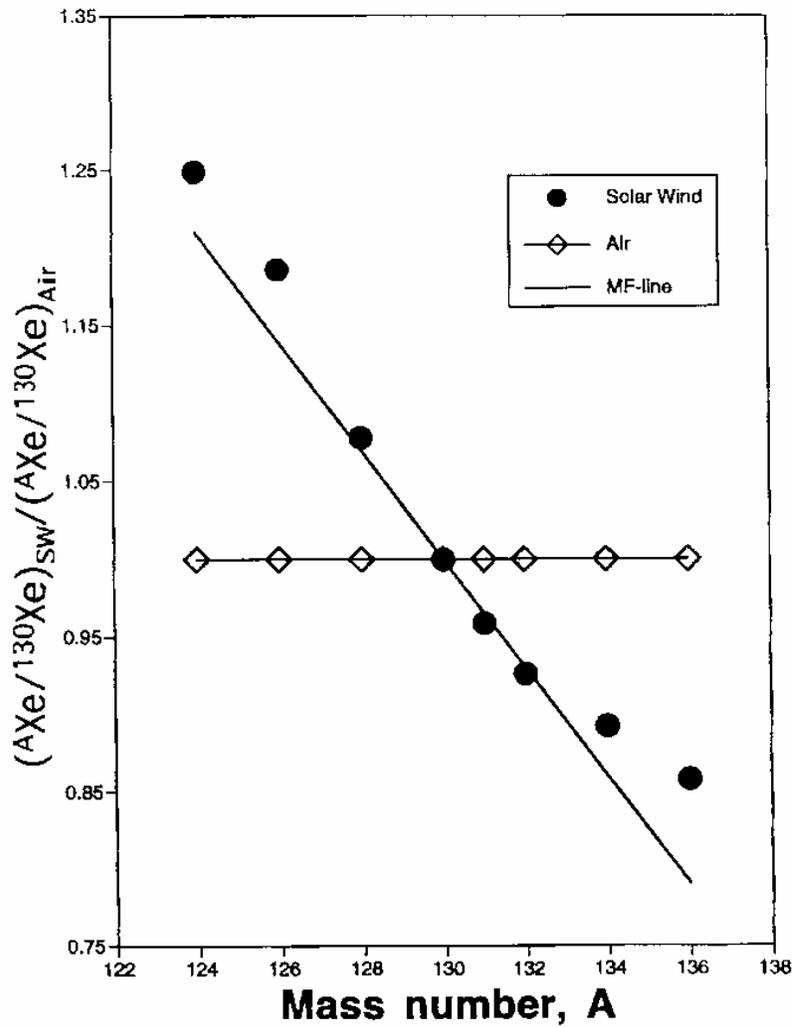


Figure 8. An illustration of the mass fractionation pattern that relates the isotopic composition of SW and terrestrial Xe. The sloping line shows the effects of mass fractionation. Deviations from the fractionation line at  $^{124,126}\text{Xe}$  and  $^{134,136}\text{Xe}$  are due to the presence of a small component of isotopically "strange" Xe in the sun (Sabu and Manuel, 1976a).

Acknowledging that their conclusion about solar abundances might "*seem extreme and controversial*", Manuel and Hwaung (1983, pp. 219-220) proposed three tests for their conclusions based on future measurements of:

1. The isotopic composition of a refractory element like Mg in the solar wind;

2. The solar neutrino flux using detectors other than  $^{37}\text{Cl}$ ;
3. The isotopic composition of Xe in Jupiter.

All three of the measurements have now been made and, although the quality of the data is less than ideal, the results are affirmative for all three tests (Manuel, 1998).

Grevesse and Sauval (this volume) note that solar modelers will have difficulty in computing a shining sun if Fe, Ni, O, etc., are its most abundant elements. Modelers have also been unsuccessful in explaining other observations, *e.g.*, the solar neutrino flux (See papers by Guzik and Neuforge, Ramadurai, and Rouse in this volume and references therein). The standard solar model itself may be changing; compare for example the definition of the standard solar model given by Dar and Shaviv (1996, p. 935) with recent comments about the possibility of diffusion and elemental segregation in the sun (Bahcall *et al.*, 1997; Grevesse and Sauval, this volume).

Thus, the most abundant element in the interior of the sun is probably iron, rather than hydrogen. *I.e.*, the sun's most abundant nuclide is  $^{56}\text{Fe}$ , the one with minimum mass per nucleon, rather than  $^1\text{H}$ , the stable nuclide with the lowest nuclear binding energy and highest mass per nucleon.

There is, however, one observation which seems to favor the standard solar model and the mainstream elemental abundances recommended by Goldschmidt (1938), Suess and Urey (1956) and others. This is the remarkable similarity between the abundances of non-volatile elements in CI-type carbonaceous chondrites and those in the solar photosphere (*e.g.*, Ebihara *et al.*, this volume; Grevesse and Sauval, this volume). This is an unlikely coincidence. If CI carbonaceous chondrites formed from material in the outer part of a supernova, as suggested by the catastrophic LES model (Figure 2), the exceptional likeness between the abundances of non-volatile elements in carbonaceous chondrites and those in the solar photosphere suggests the possibility of chemical layering, not only in the sun, but also in the sun's precursor star (Figure 2) and perhaps in other stars.

#### 2.2.2.2 Isotopic Composition

A companion paper (Manuel, this volume) shows that the energetic events which produce solar flares also disrupt diffusion in the sun and cause shifts in the isotopic abundance ratios of He, Ne, Mg and Ar. Thermonuclear fusion near the sun's surface has increased the  $^{15}\text{N}/^{14}\text{N}$  ratio in the solar wind over geologic time (Kerridge, 1975), *via* the  $^{14}\text{N}(^1\text{H}, \beta^+ \nu)^{15}\text{N}$  reaction suggested by Bethe (1939). Solar flares bring up bubbles of less mass-fractionated He, Ne, Mg and Ar to the solar surface. Flares also dredge up nitrogen with less of the solar proton-capture product,  $^{15}\text{N}$ . These observations are consistent with the catastrophic LES model (Figure 2) for the origin of our elements. For the conventional, nebular RES view and the standard solar model (Figure 1), "*Many explanations have been advanced to*

account for the long term variation in  $^{15}\text{N}/^{14}\text{N}$  ....., but none has yet been accepted as satisfactory.” (Kim *et al.*, 1995, p. 383).

Hwaung and Manuel (1982) identified, and Lee *et al.* (1996a,b; 1997) confirmed, the close association of terrestrial-type Xe with meteorite inclusions and with planets rich in Fe and S. Thus, the presence of terrestrial-type Xe in the solar wind affirms that Fe and S are abundant in the interior of the sun, although this is accompanied by high concentrations of He and other light elements that diffusion has enriched at the sun’s surface. In this regard it is noteworthy that Harkins (1917) and Manuel and Sabu (1983) both concluded that Fe and S are among the more abundant elements in the solar system.

Thus, the experimental observations cited above indicate that the sun itself is heterogeneous, because:

- (a) Diffusion inside the sun enriches the lighter elements and the lighter isotopes of individual elements at the solar surface, but the diffusive mass fractionation process is partially disrupted for particles ejected by solar flares (Manuel, this volume);
- (b) The  $^{14}\text{N}(^1\text{H}, \beta^+)^{15}\text{N}$  reaction suggested by Bethe (1939) has increased the  $^{15}\text{N}/^{14}\text{N}$  ratio in the solar wind, but nitrogen ejected by solar flares contains less excess  $^{15}\text{N}$  from this reaction;
- (c) The presence of terrestrial-type Xe in the solar wind and the close association of this type Xe with Fe and S in meteorites and planets reinforce the claim that Fe and S are major constituents of the bulk sun although they are only trace elements in the photosphere.

## 2.3 ASTRONOMICAL AND GEOLOGICAL OBSERVATIONS

### 2.3.1 SUPERNOVA EXPLOSIONS

In 1976, an illustration of the formation of the solar system from supernova debris (Figure 2) was presented at the Spring AGU meeting in Washington, D. C. (Sabu and Manuel, 1976b). Although it was widely believed at that time that it was impossible to form a planetary system directly from supernova debris, a few years earlier, LeBlanc and Wilson (1970) had in fact calculated that the explosion of a rotating star might produce oppositely-directed, axial jets of material.

Later observations on Cassiopeia A (Chevalier and Kirshner, 1979), on SN1987A (Chevalier, this volume; 1992-1996), and observations on more distant dying stars with the Hubble telescope, *e.g.*, the photographs of bipolar nebulae (Frank, this volume; 1997), clearly demonstrate that supernova

debris can be ejected axially and leave a spatial record of chemical and isotopic inhomogeneities from the parent star. These observations offer an obvious explanation for the origin of inter-linked elemental and isotopic irregularities that are observed in the sun and its planetary system.

### 2.3.2 FORMATION OF PLANETARY SYSTEMS

Despite the widespread belief that the earliest planetary solids formed about 4,550 My ago, in a paper included in this volume Kuroda and Myers have shown many examples of radiogenic/radioactive ratios of nuclides in terrestrial and lunar samples that are only expected in samples that are older than this. Such measurements should not be rejected as necessarily indicating experimental error or the transport of the parent or daughter into/out of the sample. Some refractory grains of meteorites condensed 1-2 My after a supernova (Figure 6), and combined  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  and U-Pb dating indicate that the supernova event itself was 5000 My ago (Figure 5).

Recent astronomical observations show that supernova debris can form planetary systems: Wolszczan and Frail (1992) discovered and Wolszczan (1994) confirmed the first planetary system that lies beyond the Earth's solar system. This system orbits the collapsed supernova core, which produced the millisecond pulsar, PSR 1257 + 12. The planets within the system most likely formed directly from the supernova's debris: Previously formed planets around the parent star would not have survived the explosion.

More interestingly, small Earth-like planets composed of dense material representing elements in an advanced state of nuclear evolution, were reported within 0.5 AU of the pulsar (Wolszczan, 1994). Such material occurs in the four terrestrial planets close to the sun and near the center of highly evolved massive stars (Figure 46 of Taylor, 1972). These findings certainly suggest that planetary systems may form directly from supernova debris and even inherit chemical heterogeneities from the parent star.

Lin *et al.* (1991) had indicated that a planetary system could be produced around the collapsed core of a supernova from a rotationally-supported disk of material that may fall back after a stellar explosion, and Manuel *et al.* (1998a) showed that the planetary system around the pulsar PSR 1257+12, could have been made in this manner. The question is whether the Earth and the rest of the sun's planetary system may have been formed this way.

As noted earlier, Eucken (1944), Turekian and Clark (1969), and Vinogradov (1975) independently suggested that the Earth's iron core formed first and was then layered by a mantle of silicates. The concept of heterogeneous accretion of the Earth is still debated (Palme and O'Neill, 1996), but the tracer isotope technique effectively rules out the possibility of the Earth's internal structure being produced by geochemical differentiation.

Manuel and Sabu (1981) and Allègre *et al.* (1983) independently concluded from isotopic measurements of terrestrial noble gases that the Earth's mantle consists of two basic layers. The upper mantle was exhaustively degassed in forming the Earth's crust and atmosphere, "...within the first 200 My of the Earth's history." (Manuel and Sabu, 1981, p. 260). Regarding the upper depleted mantle and the lower primitive one, Allègre *et al.* (1983, p. 766) stated that "... these two reservoirs must have been separated for at least 4,400 Myr...".

Both of the above research teams concluded that the lower mantle has retained primordial  $^3\text{He}$ . Manuel and Sabu (1981, p. 260) also posited that, "*The primitive nature of the lower mantle rules out the formation of the iron core by partial melting and geochemical differentiation.*" In view of the high mobility of  $^3\text{He}$ , it is difficult to imagine a process that would extract iron, for transport into the Earth's core, and leave  $^3\text{He}$  in the lower mantle surrounding that core.

However, Lee and Halliday (1995, 1996, 1997) and Halliday *et al.* (1996) used the dating method based on  $^{182}\text{Hf}$ - $^{182}\text{W}$  ( $t_{1/2} = 9 \text{ My}$ ) to conclude that the Earth's core formed late in the genesis of the planet, after a delay of about 50 Myr when most of the  $^{182}\text{Hf}$  had decayed away. Their conclusion was based on the fact that Hf is a lithophile element but W is a moderately siderophile element and that the isotopic composition of W in the bulk terrestrial silicates is identical to that of the W in chondritic meteorites. It should be pointed out that their data show equal "deficits" of  $^{182}\text{W}$  in the metal phase of ordinary chondrites and iron meteorites and equal "enrichments" of  $^{182}\text{W}$  in chondrites and bulk terrestrial silicates. It is thus possible that W isotopes provide no details about core formation but give additional evidence of heterogeneous accretion of the Earth.

Analyses of supposedly "differentiated" iron meteorites also indicate that some formed from chemically and isotopically heterogeneous material rather than by geochemical differentiation (See Alexander, this volume; Qi-Lu and Masuda, this volume). Alexander and Manuel (1967) detected a higher concentration of radiogenic  $^{129}\text{Xe}$ , which is the decay product of extinct  $^{129}\text{I}$ , in a graphite inclusion of the Canyon Diablo iron meteorite than had been found previously in all but two stone meteorites. Niemeyer (1979) determined that the  $^{129}\text{I}$ - $^{129}\text{Xe}$  formation times of silicate inclusions in iron meteorites closely parallel those of "primitive" chondritic stone meteorites, but the  $^{129}\text{I}$ - $^{129}\text{Xe}$  formation time of a troilite (FeS) inclusion predates that of both chondrites and silicate inclusions of iron meteorites. He concluded that, "...this troilite formed in a different nebular region from the silicate and metal, and was later mechanically mixed with these other phases." (Niemeyer, 1979, p. 843). Much earlier, Urey (1952) had noted that the spherical shape of troilite nodules in iron meteorites, as

opposed to the flattened shape expected from large overburden pressures, might indicate formation in small bodies.

Downing and Manuel (1982) observed large variations in the ratio of spallation-produced noble gas isotopes,  $^{21}\text{Ne}/^{38}\text{Ar}$ , in the Canyon Diablo iron meteorite. They concluded that these variations could not be explained by differences in depth or target element chemistry within the parent body. Similar variations had been reported earlier in mineral separates of the Odessa, Toluca, and Grant iron meteorites, leading Downing and Manuel (1982) to conclude that some of the different phases of iron meteorites had existed before compaction and been pre-irradiated.

Niemeyer's conclusion about the formation of troilite in a distinctive nebular region was further confirmed by later investigations, which showed that there is a characteristic isotopic composition of primordial Xe in the troilite inclusions of iron and stone meteorites (Hwaung and Manuel, 1982; Lee *et al.*, 1996a,b; 1997; Lee and Manuel, 1996). This same form of primordial Xe occurs not only in the FeS inclusions of diverse meteorites but in the terrestrial planets that are rich in these elements. This observation effectively rules out geochemical differentiation of initially homogeneous material to produce a reservoir in the solar system with abundant Fe and S.

Masuda and Qi-Lu (1998) recently found additional evidence that iron meteorites did not form from the differentiation of isotopically homogeneous solar material. Their measurements on the isotopic composition of Mo in six meteorites revealed an isotopic heterogeneity from nucleosynthesis. They concluded, quite correctly, that, "*It is obvious that the bulk iron meteorite retains a primary nature.*" Of course, isotopic anomalies in iron meteorites are small, when measured relative to terrestrial standards. Much larger isotopic anomalies of Mo are to be found in material that formed in the outer part of the solar system, *e.g.*, Nicolussi *et al.* (1998).

Thus, there is overwhelming geochemical evidence that the solar system formed from chemically and isotopically heterogeneous material and that the major chemical differences within the Earth and across the solar system were inherited. Further, there are astronomical observations which confirm that planetary systems can form directly from supernova debris. Conversely, there is no corroborative evidence that any of the so-called "presolar" grains traversed interstellar distances before becoming embedded in meteorites. In fact, irons constitute the only class of meteorites which contain material that has been exposed to cosmic rays for the long time period needed for a journey across interstellar distances, but iron meteorites display the smallest isotopic irregularities from nucleosynthesis when measured relative to terrestrial standards.

### 2.3.3 OBSERVATIONS OF THE SUN

Several different groups have suggested that modern helioseismic observations may indicate diffusion, limited mixing, and layering in the chemical composition of the sun (Rouse, 1985; Bahcall *et al.*, 1995, 1997; Basu, 1997). Further, a recent paper by Antia and Chitre (1998) suggests that various elemental abundance profiles inside the sun are consistent with modern helioseismic observations.

Many other observations of the sun indicate that the composition of its photosphere does not represent the solar interior. It has been suggested, for example, that the solar neutrino puzzle (Bahcall and Davis, 1976) may indicate chemical layering in the sun, with more high-Z material in the core than at the surface (Rouse, 1975; Wheeler and Cameron, 1975), perhaps even an iron-rich core (Hoyle, 1975; Rouse, 1975, 1983, 1995) or a central black hole (Clayton *et al.*, 1975; Ramadurai, this volume). However, solar neutrinos are only part of a unison of observations indicating that the interior of the sun is unlike its surface. Rather than repeat here information that has already been given, the reader is referred to Table 3, which summarizes the observations.

Table 3. Hints on the composition of the solar interior

Problem	Solution	Ref.
Chemical disequilibrium of iron and high abundances of siderophile elements in Earth's mantle	Accretion of the iron core in a central, Fe-rich region of the protosolar nebula	a,b
The low flux of solar neutrinos	The sun's core is also Fe-rich	c
A unique solution to the equations for solar structure	Requires high mass particles like Fe in the core of the sun	d
Enriched light isotopes of He, Ne, Ar, Kr and Xe in the solar wind	Diffusion in the sun enriches light-weight nuclei at the solar surface	e
Light-weight isotopes are less enriched in solar flare particles	Energetic events disrupt diffusion; bring up less fractionated material	f,g
Terrestrial-type Xe in the solar wind; "strange" Xe in Jupiter	Tracer isotopes indicate abundant Fe & S in the sun; abundant C & He in Jupiter	e,h,i
High photospheric abundances of beryllium	Only superficial mixing occurs in the solar photosphere	j
Strange isotope ratios of N and Li in the solar wind	Thermonuclear reactions occur in the outer part of the sun	k,l

- |                              |                                   |
|------------------------------|-----------------------------------|
| a. Turekian and Clark (1969) | g. Manuel and Ragland (1997)      |
| b. Vinogradov (1975)         | h. Kaiser (1972)                  |
| c. Hoyle (1975)              | i. Manuel <i>et al.</i> (1998a,b) |
| d. Rouse (1975)              | j. Balachandran and Bell (1998)   |
| e. Manuel and Hwaung (1983)  | k. Manuel (1999)                  |
| f. Rao <i>et al.</i> (1991)  | l. Chaussidon and Robert (1999)   |

Of course, no “direct” observations of material in the sun’s interior exist, but close scrutiny of the available measurements, such as those listed in Table 1, offers hints that the standard solar model (Dar and Shaviv, 1996) may have flaws and that the composition of the solar interior differs from the photosphere.

In summary, the information in Table 2 indicates that the standard solar model does not provide a unique solution for the structure of the sun and the solar neutrino flux suggests problems with the model. Observations since 1957 have led several to suggest an iron-rich solar core. This does not require segregation of the sun over the past 4-5 Gyr. The core of the sun probably formed from the same Fe-rich reservoir of elements that produced the iron meteorites and the cores of terrestrial planets in the inner part of the protosolar nebula.

These findings are consistent with predictions of the catastrophic LES model (Figure 2) for the origin of the solar system. The companion paper (Manuel, this volume) provides additional evidence for drastic chemical layering in the sun and for fusion reactions near its surface. These observations are unexplained by the nebular RES model (Figure 1) for the origin of the solar system.

### 3. CONCLUSIONS

The conclusions of this study, in the approximate order of the paper, are below:

1. Ideas about the abundances of elements and their origin intertwine. If Harkins (1917) was correct in using analyses of meteorites to conclude that the seven most abundant elements in the solar system are Fe, O, Ni, Si, Mg, S and Ca, then elemental abundances in the solar system are closely linked with the stability of their nuclei. Such elements are produced in the interior of highly evolved stars. Thus Harkins’ abundance pattern favors the catastrophic LES model shown in Figure 2. Burbidge *et al.* (1957) and Cameron (1957) relied on the abundance table of Suess and Urey (1956), which is based more on abundances in the solar photosphere. For these abundances, nuclear evolution is much less advanced and the most abundant

nuclide,  $^1\text{H}$ , is the one with minimum nuclear binding energy. The Suess-Urey abundance pattern favors the nebular RES model shown in Figure 1. Table 1 compares these two sets of abundances.

A new high-sensitivity mass spectrometer reported the year before the classical papers by Burbidge *et al.* (1957) and Cameron (1957) provided the following empirical challenges to the nebular RES model:

(a) Amounts of the decay products of  $^{129}\text{I}$  and other short-lived nuclides in meteorites meant that there was too little time to produce a well-mixed nebula between nucleosynthesis and the formation of meteorite grains.

(b) By 1960, an anomalous abundance pattern across all nine stable xenon isotopes,  $^{124-136}\text{Xe}$ , in chondritic meteorites hinted that atomic weights in the solar system might vary across planetary distances.

(c) In the 1970s, monoisotopic  $^{16}\text{O}$  and excesses and depletions of the isotopes of heavy elements made by the r-, p-, and s-processes were found in grains of meteorites. This implied that different nucleogenetic components of a given element were not mixed before condensation. Examples are shown in Figure 3 and in Figure 7.

(d) In 1975 it was shown that elemental abundances of He are closely linked with isotopic abundances of Ar, Kr and Xe in meteorites (Figure 4). This linkage between chemical abundances of a light element and isotopic abundances of heavy elements is expected in poorly mixed debris of a supernova (Figure 2).

(e) In the early 1980s, lighter mass isotopes of elements were shown to be systematically enriched in the solar wind. The empirical fractionation pattern is that expected if diffusion in the sun enriches the lighter elements and the lighter isotopes of individual elements at the solar surface.

(f) When solar photospheric abundances were corrected for diffusive mass fractionation, the seven most abundant elements in the bulk sun turned out to be the same ones that Harkins (1917) had concluded from analyses of meteorites. These results are shown in Table 2. The chance of producing this agreement by random selection is about  $\approx 2 \times 10^{-10}$

(g) Across the planetary system, the abundance of Fe increases towards the sun. When corrected for diffusion, the composition of the bulk sun itself fits this elemental abundance trend.

2. The tracer isotope technique was used to determine the origin of microscopic- and macroscopic-scale variations in the chemical and isotopic compositions of meteorites, planets and the sun. The results indicate that:

(a) There was a primordial coupling of isotopic and chemical irregularities in the material that first formed solids in the solar system.

(b) This initial linkage of chemically and isotopically distinct components included trace as well as major elements and compounds, *e.g.*, He, C, O, Ne, Xe, SiC, FeS, and even different chemical classes of meteorites.

(c) The coupling of chemically and isotopically discrete members has been preserved across the planetary system and across nanometer distances in the diverse, agglomerate rocks we call chondritic meteorites.

(d) Combined U-Pb and  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  dating shows that a supernova produced the solar system's  $^{244}\text{Pu}$  about 5000 My ago (Figure 5).

(e)  $^{129}\text{I}$ - $^{129}\text{Xe}$  and  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  dating of bulk meteorites suggested a link between extinct radionuclides and general isotopic anomalies.  $^{26}\text{Al}$ - $^{26}\text{Mg}$  dating of individual meteorite grains confirmed the coupling of larger isotopic anomalies with shorter-lived nuclides in grains of SiC that started to nucleate earlier and grew larger (Figure 6).

(f) The reciprocal isotopic anomaly patterns in meteorite grains fit those expected from poorly-mixed products of the same nuclear reactions that made isotopically "normal" elements in the solar system (Figure 7).

(g) The Galileo probe into Jupiter's helium-rich atmosphere revealed a tracer isotope ratio there,  $^{136}\text{Xe}/^{134}\text{Xe}$ , that is unlike that in the solar wind, but indistinguishable from the isotopically "strange" xenon that is trapped in helium-rich meteorite minerals.

(h) Xenon in the sun appears to be a mixture of the "strange" and "normal" isotopic components found in its planetary system (Figure 8), consisting mostly of the "normal" xenon that occurs in Fe, S-rich planets and meteorite inclusions.

(i) When solar photospheric abundances are corrected for the effects of diffusion in the sun (Figure 8), the sun's most abundant nuclide is the ash of thermonuclear reactions at equilibrium,  $^{56}\text{Fe}$ , instead of  $^1\text{H}$ , the stable nuclide that is the best fuel for these thermonuclear reactions.

(j) The remarkable similarity between the abundances of non-volatile elements in CI-carbonaceous chondrites and those in the solar photosphere may indicate chemical layering, not only in the sun, but also in the sun's presursor star (Figure 2) and probably in other stars.

(k) The isotopic ratios of many elements in the solar wind indicate that diffusion occurs inside the sun, but material ejected in solar flares is less mass-fractionated (See Figure 1 and Table 1 of Manuel, this volume).

(l) The  $^{14}\text{N}(\text{H}, \beta^+ \nu)^{15}\text{N}$  portion of the CNO cycle has increased the  $^{15}\text{N}/^{14}\text{N}$  ratio over geologic time near the surface of the sun, but nitrogen ejected by solar flares contains less  $^{15}\text{N}$  from this proton-capture reaction.

(m) The presence of terrestrial-type Xe as the dominant Xe component in the sun (Figure 8), and its close association with Fe and S in meteorite minerals and planets, reinforces the claim that Fe and S are major, rather than trace, elements in the bulk sun.

(n) Post-1957 observations in astronomy and geology do not support the concept of nebular RES over catastrophic LES.

These facts strongly favor the catastrophic LES model illustrated in Figure 2 over the nebular RES model (Figure 1), even when the injection of exotic nucleogenetic material has been posited (Fowler, 1984; Wasserburg,

1987). The LES model is further supported by Lyttleton's initial proposal that the solar system was produced by a rotating star (Lyttleton, 1941), by the solar models of Rouse (this volume, 1964-1995), by the chronologies determined from the decay products of short-lived nuclides (Kuroda and Meyers, this volume, 1996, 1997; Sahijpal *et al.*, 1998; Goswami, this volume), and by the fact that the different nuclear reactions, which made the elements in the solar system at various stages of stellar evolution (Cameron, 1957; Burbidge *et al.* 1957), did not completely mix and remain engraved as "strange" and "normal" atomic weights of the elements.

The conclusions of this study are consistent with the suggestions by Buffon, Chamberlin and Moulton, and Jeans (Miyake, 1965) that a catastrophic event produced the solar system, rather than the gravitational collapse of a nebula as proposed by Kant and Laplace (Miyake, 1965).

The opposing view, remote element synthesis (RES) and the classic nebular model of Kant and Laplace, has been assumed in most review articles and books (Clayton, 1968; Trimble, 1975, 1982, 1983, 1988, 1991; Kuroda, 1982; Barnes *et al.*, 1982; Cameron, 1984; Tayler, 1988; Pagel, 1988; Wheeler *et al.*, 1989; Arnett, 1996; Wallerstein *et al.*, 1997; Wood, 1999), symposia (Reeves, 1972; Milligan, 1978; Mathews, 1988; Prantos *et al.*, 1993; Bernatowicz and Zinner, 1997; Goswami *et al.*, 1997), and award lectures (Fowler, 1984; Wasserburg, 1987; Cameron, 1995) on the origin of elements. This assumption is implicit in titles like the "Origin of Elements" without any stipulation of the specific batch of elements being considered.

Additional studies of the sun and isotopic analyses of material from other regions of the solar system should resolve these differences of opinion within the next few years and give us a broadly based consensus on the origin of elements in the solar system.

*Postscript* — The words of three distinguished scientists encouraged the author in writing this review. First, the assertion by Edward Anders that, "*It is a well-known maxim underlying all of physical sciences: that one should strive to explain the maximum number of phenomena by the minimum number of arbitrary postulates*" (Anders, 1964, p. 587). Another was Albert Einstein's statement that, "*The right to search for truth implies also a duty. One must not conceal any part of what one has recognized to be true*" (Broad, 1978, p. 951). Finally, sage advice from Sir Fred Hoyle (1982, p. 9), "*As I say, I think we should have persisted, despite all the catcalls and brickbats, the shaking heads and the curled lips that one so frequently encounters when presenting ideas outside the mainstream of the search for knowledge.*"

The abundance pattern of the various atomic species contains a record of their origin (Richards, 1919), but that record could not be deciphered until the composition of the sun was resolved. Although the conclusions reached here are unpopular, I am confident future generations will find that Figure 2

is a reasonable explanation for the initial and present distribution of nuclides in the solar system, including high abundances of light elements like hydrogen and helium at the sun's surface and an iron-rich interior with an abundance peak at  $^{56}\text{Fe}$ .

## ACKNOWLEDGEMENTS

My wife, Caroline, and all my children have shown great patience and kindness as I ignored other responsibilities in order to pursue my lifelong obsession to understand the origin of the solar system. I am also grateful to Professors Paul K. Kuroda and John H. Reynolds for introducing me to this exciting field, to John Koenig, Daniel Armstrong, Carl A. Rouse, Ken Windler, and V. A. Samaranayake for helpful comments on an earlier version of this manuscript, to the undergraduate students, Ken Windler, Adam Nolte, Dan Ragland, Lucie Johannes, Joshua Zirbel and Cara Lietz who helped decipher raw data from the mass spectrometer on the Galileo probe into Jupiter's atmosphere, to Dr. Daniel S. Goldin of NASA for releasing those data, and to Bill James for accepting a heavier teaching responsibility so I would have time to research and write this review.

## DEDICATION

This paper is dedicated to Bo Lozoff, founder of the Human Kindness Foundation of Durham, NC and to Gerry D. Reece (LWP#179321), Robert Driscoll (CP#33), Rufus Ervin (CP#136) and others who spend their lives in prison because society does not yet acknowledge that we are all basically the same, except that the behavior of individuals is determined by cause and effect (Menninger, 1968; Humes, 1999), just as the origin of the elements is engraved in their atomic weights.

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