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Meteoritics and the origins of atomic nuclei

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Abstract—The science of nucleosynthesis was substantially inspired by chemical analyses of meteorites. As if in repayment, that theory now imbues meteoritics with enlarged meaning. I recount the emergence of four great issues for nucleosynthesis—issues that received decades of my own attention; and I describe unexpected abundance patterns within meteorites that were suggested by the resolution of those issues. The latter have altered the information content of meteoritic science. The issues are:

1. a quantitative *s*-process theory
2. cosmoradiogenic chronology
3. explosive nucleosynthesis and gamma-ray astronomy
4. cosmic chemical memory

Starting from historical origins for each issue, I comment upon both the broad cultural canvas in which they lie and my own work in their establishment. Examples of predicted (or rationalized) meteoritic measurements illustrate our surprised delight at the expansion of the range and power of meteoritic science.

Youk'n hide de fier, but w'at
you gwine do wid de smoke?
Uncle Remus: Plantation Proverbs
—Joel Chandler Harris

INTRODUCTION

The invitation to present this paper is the highest honor of my scientific life. All meteoriticists understand this. We are devoted to our meetings and to our traditions. The Meteoritical Society maintains a strong sense of unity, both scientifically and collegially. Our society has moved into the highest ranks of scientific research. Its research purview has broadened to include questions of deep importance to physical science. The list of previous Leonard Medal recipients is a very distinguished one. Within this setting I experience deep satisfaction that my research is judged to have played a role in the enlarged scope of meteoritic science.

Meteoritics has long influenced the science of nucleosynthesis. Consider two examples. The relative abundances of nonvolatile elements are determined with highest precision from the meteorites. The Suess and Urey (1956) review of meteoritic abundances galvanized the thinking of the pioneers of stellar nucleosynthesis theory—Fred Hoyle, William A. Fowler, and A. G. W. Cameron—by presenting a well defined target for that general theory. The Suess and Urey paper itself described many of the nuclear correlations and mechanisms that found their way into the theory. The xenology that issued forth from John Reynolds' laboratory (Reynolds, 1963) in the 1960s—^{129}Xe*, ^{244}Pu-Xe, and CCF-Xe—turned attention onto the supernova nucleosynthesis that occurred just prior to the formation of our solar system. These meteoritic findings stamped themselves on to nucleosynthetic and astrophysical theory.

But in the 1970s astrophysics began to alter the perception of meteoritic science. This reverse flow from astrophysics into meteoritics was unforeseen and surprising when it emerged, although some of its ideas may be also found in older speculations that had been discounted or forgotten. The consequence of this is that today meteoriticists realize that they are also doing astronomy, that they are finding in these falling stones unique memories of events that predated our solar system formation and that had not been previously regarded as viable objectives of meteoritics. I like the name "cosmic chemical memory" for this new field of astronomy, though some may find the adjective "cosmic" a trifle to much for their taste. I described it as a new field of astronomy in the 1981 George Darwin Lecture, which the RAS had invited me to deliver (Clayton, 1982a) to their 1981 winter meeting in London, and I will continue to employ that name here. Its essence is the idea that meteorites contain chemical structures that already existed in the earlier interstellar medium. Some meteoritic samples could not have emerged from an initially homogeneous mother cloud. Isotopic structures have been, because of their unambiguous visibility, the fingerprint for identifying such structures. Cosmic chemical memory is isotopically grounded on the astrophysical fact that *differing isotopes* of a given element have had *differing chemical histories* through their presolar times. The truth of this stuns us repeatedly as our research laboratories expose one fossil astronomical clue after another. Our chemical training has prepared us to regard distinct isotopes as chemically identical except for their differing mass; but it did not prepare us to anticipate their differing histories. My focus on differences in isotopic chemical history has, in my own view, been my contribution to meteoritics.

I will not even try to review this large and rapidly growing body of knowledge. Rather I will, as seems fitting for this paper, highlight four topics of astrophysics that impact meteoritics:

1. quantitative *s*-process theory
2. cosmoradiogenic chronologies of nucleosynthesis
3. explosive nucleosynthesis and gamma-ray astronomy
4. cosmic chemical memory

By concentrating on major historical developments, I hope to illustrate the enlarged scope of meteoritic science.

QUANTITATIVE *S*-PROCESS THEORY

My research on the *s* process began 34 years ago and has never ceased. William A. Fowler accepted me as his graduate research student in 1957. This was my decisive good fortune. It was the same year that his famous review (Burbidge *et al.*, 1957) appeared, and I became (I believe) the first Caltech graduate student to work primarily on nuclear astrophysics. "Willy" charted my life by entrusting me with the development of a quantitative theory of the *s* process. Their description (Burbidge *et al.*, 1957) had outlined its physics and astrophysics but had contained only qualitative descriptions of the numerical consequences of the process.

The primary question was how the element barium could be so overabundant in red-giant stars. Values of Ba/Fe greater than 100 times solar were commonly observed. So we began with the problem of calculating the results of irradiating Fe with neutrons. Although an exact solution involving long sums of exponentials was known, it could not be evaluated for technical reasons. We therefore invented an approximate technique of high reliability, one that remains useful today because it replaced the long sum of widely varying and canceling magnitudes with but a single term, an exponential multiplied by the neutron fluence raised to a calculable power. The results from my Ph.D thesis (Clayton *et al.*, 1961) are shown again in Fig. 1. Displayed there is the product of abundance times neutron-capture cross section of each isotope lying on the *s*-process path, normalized to a single Fe seed nucleus. Each curve is labeled by the average number of neutron captures n_c per seed nucleus for the specific neutron fluence involved. Table 1 gives our associated result for the relationship of n_c to the neutron fluence τ (in units of neutrons per millibarn (10^{27} n cm^{-2})).

We drew several important physical conclusions from Fig. 1:

(1) The large Ba overabundances in giants could indeed arise from Fe seed, but other less abundant or lower mass seed nuclei were inadequate.
(2) No single τ could account for the solar abundance distribution.
(3) The solar abundances require a distribution of neutron exposures, one characterized by decreasing quantities of Fe seed being exposed to increasing fluences τ.
(4) The astrophysical realization of requirement (3) could be met by either of two scenarios: recycling of smaller fractions of Fe through larger numbers of stellar interiors, or repeated irradiations within a single star of ever smaller fractions of the material. At the time I favored the former, but today we give more importance to the latter during the He-shell thermonuclear flashes in red giants (*e.g.*, Iben, 1985).

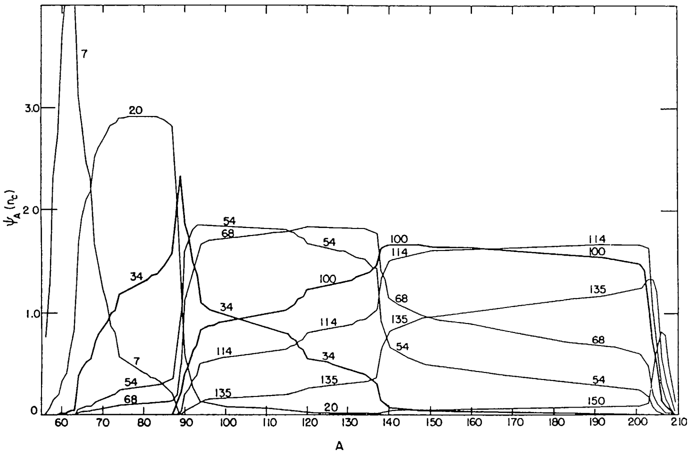

FIG. 1. The distribution $\psi_A = \sigma_A n_A$ per initial seed Fe nucleus. The curves are labeled by n_c, the average number of neutrons captured per initial Fe nucleus for that neutron fluence tau. None resembles the solar abundance distribution. From Clayton *et al.* (1961).

We (Clayton *et al.*, 1961) calculated and displayed the following specific example of an exposure distribution that would give an adequate match to the solar abundances and cross sections as they were then known:

$$\sigma N_s = 2160\psi(\tau = 0.1) + 990\psi(\tau = 0.2) + 45\psi(\tau = 0.6) + 45\psi(\tau = 1.1)$$

where $\psi(\tau)$ is the product σN_s per initial Fe seed nucleus, all on the meteoritic scale Si = 10^6. Our coefficient of the last term was too large owing to inadequate definition at that time of the solar σN_s curve, with its now evident "ledge-precipice" structures to which we called attention. But property (3) above is very evident in this result. This equation is today interpreted as

$$\sigma N_s = N_1\psi(\Delta\tau) + rN_1\psi(2\Delta\tau) + r^2N_1\psi(3\Delta\tau) + r^3N_1\psi(4\Delta\tau) + \dots$$

where $\Delta\tau$ is the neutron fluence during an AGB star He-shell flash acting on N_1 seed nuclei, and r is the fraction remaining, after mixing with the envelope, for subsequent flashes of that fluence, leading to the regular decrease of the seed abundance exposed to ever larger fluences. We believe today that these flashes in the double-burning-shell asymptotic-giant-branch (AGB) stars provide the lion's share of the *s* process. We noted early on (Seeger *et al.*, 1965) that an exponentially declining

TABLE 1. Fluence τ* required for n_c neutron captures per Fe.**

τ	n_c	τ	n_c	τ	n_c
0.1	2.8	0.6	34	1.4	135
0.2	6.9	0.8	54	1.6	145
0.3	12.8	1.0	84	1.8	149
0.4	20.1	1.2	114	2.0	151

* Neutron fluence τ in units 10^{27} cm^{-2}.
** Table from Clayton *et al.* (1961).

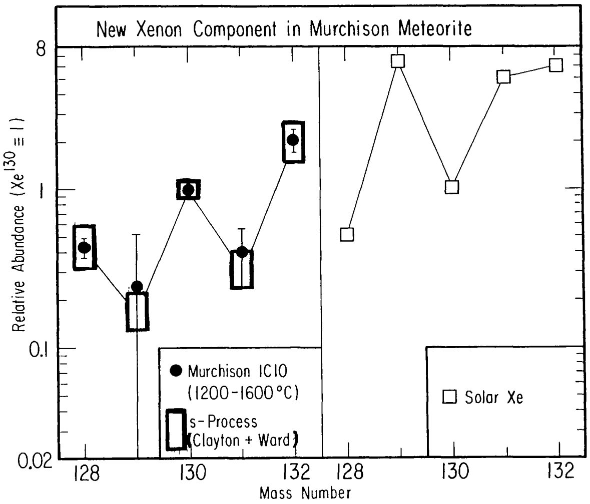

FIG. 2. The pattern of isotopic excesses in the Xe_s. Figure from Srinivasan and Anders (1978). This composition (left panel) is so wildly different from solar Xe (right panel) as to require almost pure *s*-process xenon. The dust carriers were later identified as silicon carbide.

envelope of fluences was easier to calculate and fitted the solar data. Later, Clayton and Ward (1974) showed that even the exact solution could be calculated exactly and easily for an exponential distribution of exposures; therefore the literature is replete with reliance on that approximation to the fluence history of the pulsations (*e.g.*, Käppeler *et al.*, 1982, 1989). We have now reached the time when the exponential distribution is sometimes inadequate, especially for the branches in the capture path, so that return to a model of the pulse sequence is required (Käppeler *et al.*, 1989).

Willy Fowler taught us all that nuclear astrophysics is a laboratory science, and I have felt satisfaction at being able to assist in the development of the laboratory *s* process. My two trips to Oak Ridge in 1962 and 1964 to visit R. L. Macklin and J. H. Gibbons were to help motivate and learn from the first program designed to study the *s* process (Macklin and Gibbons, 1965). During my 7-year period with the Max-Planck-Institute for Nuclear Physics in Heidelberg, I accepted an invitation to collaborate with the Kernforschungszentrum Karlruhe on their new plan of study (Käppeler *et al.*, 1982). They have now assumed the world's leadership on this nucleosynthesis laboratory problem. I here offer public thanks from us all to Dick Macklin, Franz Käppeler and Hermann Beer, who have by diligence and by technical innovation erected a monument of astrophysical data that will be remembered.

But in what way did this interesting development alter meteoritic science? In 1975 I submitted with Richard Ward a paper to *Geochim. Cosmochim. Acta* on *s*-process xenon. In this work we not only calculated the isotopic signature of *s*-process Xe (Xe_s), but we also argued that its signature should be detectable in meteorites. We advanced two arguments based on the trapping of Xe in grains condensing in stellar outflows. The simplest was that red-giant STARDUST would condense and carry Xe_s directly and might, contrary to the prevailing paradigm of the hot gaseous solar system, survive in the meteorites in components garnered from cold accumulation instead. The second, based on what I call *polarization,* is that the fraction of Xe_s and Xe_r condensed at ejection from differing stars cannot accidentally be equal (unless they are both zero), so that Xe_s excess must exist in the interstellar medium either in the gas phase or in the dust phase, which is above all many differing dust phases (STARDUST, SUNOCONS and NEBCONS). These dust acronyms (Clayton, 1978a) seem destined to stick because they are so specific and useful. During solar aggregation the polarization would lead to either excess or deficiency of Xe_s in bulk meteoritic aggregates, probably through surface-correlated size fractions (Clayton, 1980). When the heavy anomalies in FUN inclusions were soon discovered, Clayton (1978b) reinterpreted their meaning by that same polarization principle. On either ground, Clayton and Ward asserted in 1975, Xe_s was a signature to be sought. Interestingly, our paper could not be accepted by GCA, because it was too speculative and seemed to others to be unrelated to meteoritics. I did not agree with this judgment, although I certainly understood it, and reluctantly withdrew the paper. The time was just not ripe.

This changed suddenly in 1977 when Edward Anders telephoned me to ask what had happened to our preprint. He went on to explain that work in his laboratory had actually uncovered *s*-process xenon. The etching oxidation of carbonaceous residues had left one etched residue that released near 1000 °C the unmistakable pattern of Xe_s. Their (Srinivasan and Anders, 1978) result is reproduced in Fig. 2. Note the abundance minima in the left panel at ^{129}Xe and ^{131}Xe, just where the solar abundances shown in the right panel are maxima. It was the first clearly interpretable indication of STARDUST in meteorites, and has been followed by an explosion of similar results. Subsequent work (Tang and Anders 1988) has shown this carrier to be SiC. Its favored site of origin (Lewis *et al.*, 1990; Gallino *et al.*, 1990) is the AGB carbon stars. These SiC carriers also carry *s*-process Kr (Ott *et al.*, 1988) and Ba (Ott and Begemann, 1990) and are anomalous in their structural elements (Zinner *et al.*, 1989).

As for our paper on Xe_s—we quietly resubmitted it (Clayton and Ward, 1978). The reader will, I trust, recognize that my purpose in the recollection is not to throw any stones, but rather to document one of the early examples of astrophysics pointing to a new thrust for meteoritics. That the idea could not be accepted before its demonstrated correctness is not unusual for a scientific innovation. I am grateful to Edward Anders for the scientific correctness of his handling of this prediction.

At the same time meteoritics had placed a new stone in the edifice of natural philosophy. The *s* process and the *r* process actually happen. Prior to this discovery they were but theoretical tools used to interpret the solar mixture. Here was clear evidence that the *s* process occurred alone. Here were samples formed before its yield had been mixed with the interstellar medium. A great and profound theory slipped quietly into the realm of fact. My subsequent reinterpretations, based on that fact, of the FUN anomalies (Clayton, 1978b,c; 1979b) really hooked me on cosmic chemical memory theory, because these were macroscopic solar system rocks! But more of that later.

COSMORADIOGENIC CHRONOLOGIES OF NUCLEOSYNTHESIS

Chronologies of nucleosynthesis are constructed from the only clocks we have for the solar abundances—namely, radioactivity. That class of nuclei offers the hope of determining the age of the elements themselves, rather than the age of the solar system.

Rutherford (1929) began this by following the mass spectrometric determination of the existence and relative abundances of the two naturally occurring isotopes of uranium. Three decades later Fowler and Hoyle (1960) greatly upgraded that idea by: (1) adding the ^{232}Th/^{238}U abundance ratio; (2) using their concept of the *r* process to estimate the relative production rates of those isotopes; (3) outlining a framework of continuous galactic nucleosynthesis to relate the solar abundance ratios of these radioactivities to their presolar age. This was a landmark of astrophysics. Their calculation has been repeated by many over these three decades as new nuclear or astrophysical details have emerged. But the results remain inconclusive, primarily because the *r*-process production ratios cannot be calculated with sufficient assurance but, also, because of uncertainty in galactic history.

Meteoritics played a key role in two events that enlarged the cosmochronology picture. One was the discovery by Reynolds (1960, 1963; Hohenberg *et al.,* 1967) of extinct ^{129}I and extinct ^{244}Pu by their trapped Xe daughters in meteorites. These and other extinct radioactivities discovered since showed that only a small fraction of the nuclear abundances were synthesized shortly before the solar origin, but that the bulk dated back to much earlier times, agreeing with that conclusion from Fowler and Hoyle. But how much earlier? The other discovery which directly addresses that question was the solution of cosmoradiogenic chronologies (Clayton, 1964), which I now recount.

It was in 1961 when meteoritic data and a Swiss scientist named Bernhard Hirt taught me about isochrons. Visiting at Caltech, Hirt showed me his fragmentary Re/Os isochron for iron meteorites. See Luck *et al.* (1980) for a modern version. I learned not only that the slope gave the age of the meteorites but also that the intercept fixed the initial solar ratio (^{187}Os/^{186}Os)$_0$ = 0.80. By calling my attention to initial Os, Hirt set the seeds for one of the fortunate moments in my life. During the next year I was examining the *s*-process correlation between cross sections and abundances in detail, concentrating especially on the "*s*-only isotopes," when I noticed that the ^{187}Os/^{186}Os was too large for the predictable nuclear systematics of neutron capture. The ^{187}Os should be only about 40% of ^{186}Os, and looking back on Hirt's graph, I saw that even initial ^{187}Os was much too abundant. I first feared that the new but convincing *s*-process theory was failing, but rather quickly realized that initial ^{187}Os was so abundant owing to *presolar decay of* ^{187}*Re.* The decay in the interstellar medium between the times of ^{187}Re nucleosynthesis and the formation of the solar system had resulted in a large buildup of radiogenic ^{187}Os. I called this "cosmoradiogenic ^{187}Os" to distinguish it from the geologic radiogenic osmium. For the first time we had the tool for determining how much of the initial ^{187}Os was cosmoradiogenic, and thereby we had a new technique for nuclear cosmochronology. The tool was the *s* process, and by luck I was holding it in my hands.

Figure 3, taken from Clayton (1964), shows the *s*-process path of slow capture and subsequent beta decay through ^{185}Re, ^{186,187,188}Os, and onward. It also shows the isobaric chain of beta decays of the very neutron-rich *r*-process nucleosynthesis, which is at A = 187 arrested at ^{187}Re, giving ^{187}Os its apparent *s*-only status. Based on this simple new decomposition for initial ^{187}Os I could write

$$^{187}\mathrm{Os} = {}^{187}\mathrm{Os}_s + {}^{187}\mathrm{Os}_c,$$

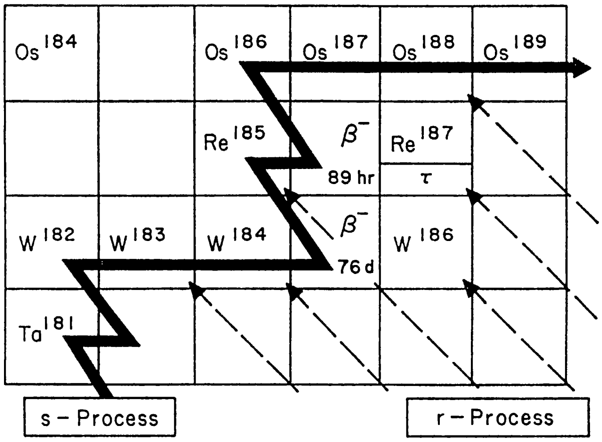

FIG. 3. The *s* process path through the isotopes of Re and Os. The ^{186}Os and ^{187}Os would both be strictly *s*-only isotopes, shielded from *r*-process production, were it not for the slow cosmoradiogenic decay of ^{187}Re. The *s*-process theory allowed the decomposition of initial ^{187}Os into its *s*-process and its radiogenic components (Clayton, 1964).

where ^{187}Os$_s$ is the true *s*-only component and ^{187}Os$_c$ is the cosmoradiogenic component. The theory also required that

$$\sigma(187)\mathrm{N}({}^{187}\mathrm{Os}_s) = \sigma(186)\mathrm{N}({}^{186}\mathrm{Os})$$

and that substitution into the prior equation allowed calculation of the value of ^{187}Os$_c$. The ratio of daughter abundance to parent abundance, ^{187}Os$_c$/^{187}Re, then allowed, by the usual radiogenic relationships, the calculation of the presolar age of the ^{187}Re. In this way meteoritics ideas plus the new *s*-process theory enabled a decomposition that was previously thought to be impossible, if indeed it was thought of at all. Fowler's own surprise was evident on a spring day in 1963 when he called me to his office to ask how I had been able to see a relationship that had escaped others.

The immediate answer was that 12% of all ^{187}Re ever synthesized had already decayed prior to solar formation. The long ^{187}Re half-life then demands that much of the Re was already very old, at least 10 Ga old, when the sun formed. Although the method has uncertainties of its own, this answer is in a sense much more definite than are the transuranic parents. The ^{187}Os decomposition can be done much more accurately than can the calculation of *r*-process abundances of transuranics. Os is like a bucket catching the Re decay, and the contents of the bucket are well measured. It put bedrock under cosmochronology. How much harder it would be, by contrast, to have to use the ^{185}Re/^{187}Re abundance ratio, considering that only 12% has decayed and that their production ratio in the *r* process cannot be calculated that accurately.

The same technique was extended to Rb/Sr, U/Pb and Pb/Pb, establishing those cosmoradiogenic chronologies as well (Clayton, 1964). This increased the techniques of long-lived cosmochronologies, those capable of constraining the *beginning* of nucleosynthesis rather than the rate of late nucleosynthesis, from three in number to eight. During my last sabbatical in Durham, UK in 1987 (chosen in part because it was the site of our Newcastle Meteoritical Society Meeting!), I summarized and extended my work on the cosmochronologies and on the issues of astrophysical history for our Galaxy that intertwine the nu-

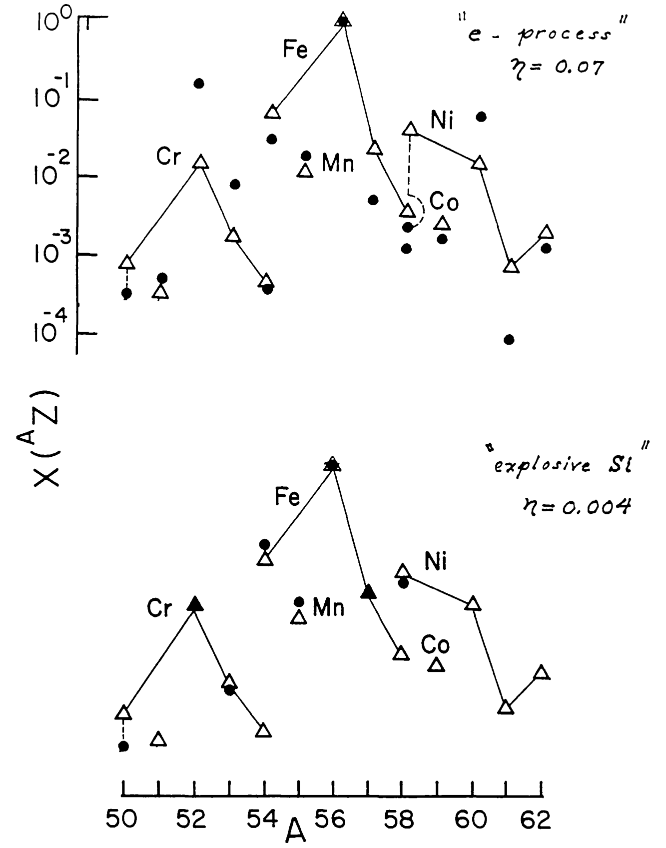

FIG. 4. A comparison of the observed solar abundances in the iron peak (triangles) with the calculations of the two competing theories of the 1960s. Top panel shows the "e process" of Burbidge *et al.* (1957), in which the Fe isotopes are synthesized as themselves under (n,γ) vs. (γ,n) equilibrium. This solution requires $\eta = 0.07$ excess neutrons per nucleon in the equilibrium mixture. Bottom panel shows explosive silicon burning at low neutron excess, requiring explosive ejection, in which ^{56,57}Fe are ejected as ^{56,57}Ni radioactive parents. (Calculations by Hainebach *et al.* (1974)). The better solution and better astrophysical context of the lower panel led to the prediction of the detected gamma-ray lines from supernovae (Clayton *et al.*, 1969).

clear issues (Clayton, 1988a). The analytic solutions (Clayton, 1985) to the differential questions for the chemical evolution of the Galaxy provide much the best framework for interpreting the physical meaning of the cosmochronologies, which measure actually not the history of nucleosynthesis but the age spectrum of solar nuclei, a subtle distinction that has confused many.

What in summary have the nuclear cosmochronologies determined that is directly important for meteoritics? Firstly, that the age spectrum of solar nuclei is continuous and extends back to 8–10 Ga before the sun. This ensures that the Galaxy was already mature when the sun formed. Secondly, that their age spectrum is almost flat (to accommodate both ^{235}U/^{238}U and Re/Os); *i.e.,* presolar nuclei of all ages existed mixed in the presolar cloud. Thirdly, that the fraction of nuclei synthesized within a short time prior to formation of the sun is small, so that the extinct residuals (^{107}Pd, ^{129}I, ^{146}Sm, ^{244}Pu) *from continuous and homogeneous nucleosynthesis* (no spikes or inhomogeneous admixtures) are given by

$$N^*/N_{\text{total}} = (2\text{-}3)\ \text{tau}/T_{\text{Gal}}$$

where tau is the mean lifetime and T_{Gal} the age of the Galaxy at solar birth. The factor 2 to 3 is the factor (1 + k) which results from early growth of the Galactic disk (Clayton, 1985, 1988a), a growth that dilutes the Galactic nucleosynthesis component within the age distribution. This result applies to the mean interstellar medium. I have also outlined a theory for relating that mean to the mean activity within cold cloud cores (Clayton, 1983). This theory may resolve the old problem of the relative numbers of ^{107}Pd, ^{129}I, ^{146}Sm and ^{244}Pu in the solar nebula without need of late spikes or admixtures while also giving meaning to the often invoked "free decay interval" for ^{129}I.

And, finally, for effects of cosmic chemical memory, the residual for the fraction of any nucleus that remains in its *initial chemical carrier* (or state) is given by the same equation, where in that case the lifetime tau is the one appropriate for the rate of interstellar destruction of that carrier. In short we deal here with the history of our stuff, the matter of the meteorites.

EXPLOSIVE NUCLEOSYNTHESIS AND GAMMA-RAY ASTRONOMY

In their framework paper Burbidge *et al.* (1957) described what they called "the *e*-process" for the nucleosynthesis of the iron abundance peak. Hoyle (1946) had introduced that idea—that in nuclear thermal equilibrium, or nuclear statistical equilibrium, ^{56}Fe became the most abundant nucleus because it possesses the largest nuclear binding energy per nucleon. In equilibrium (n,gamma), captures are opposed by equal rates of (gamma,n) photoneutrons, and ^{56}Fe becomes more abundant than other Fe isotopes while Fe becomes more abundant than any other element. The neutron separation energies control these isotopic ratios, and for the Fe they gave a good caricature of the solar abundances.

Nature was leading us astray with a grand joke, however. That successful fit is shown in the top panel of Fig. 4. It was hailed as a triumph of nuclear astrophysics and a proof of its correctness. In that solution each isotope of Fe is synthesized as itself. The calculated dots resemble the solar abundance triangles. Despite a worrisome overcalculation of the ^{52}Cr abundance and a definite underproduction at the ^{58}Ni abundance, shown clearly in the figure, this result swept away doubt. But an incorrect aspect of this argument temporarily hid the best prospect for confirming nucleosynthesis with gamma detectors.

The breakthrough arose ten years later, when nuclear astrophysicists were considering the sequence of events that stellar evolution actually presents. Oxygen burning was shown to create primarily ^{28}Si, and the question that asserted itself was that of how ^{28}Si would transform itself to the iron abundance peak. Fowler and Hoyle (1964) made a good stab at this problem, arguing that photodisintegration rather than fusion would somehow rearrange ^{28}Si into ^{56}Ni. But lacking a convincing description of either that process or the ejection sequence, they concluded that beta decays within the star before its disruption could allow the B^{2}FH *e*-process solution to follow, synthesizing ^{56}Fe as itself with an abundance determined by its own nuclear properties. This argument held sway with most of us, although, interestingly, Suess and Urey (1956) had pointed to the doubly magic nature of ^{56}Ni while asserting, "that ^{56}Ni was the primeval nucleus from which ^{56}Fe has formed"—an idea that they, and Hans Suess privately, have attributed to O. Haxel—"and, hence, that the nuclei of this mass region had formed on the neutrondeficient side of the energy valley. . . . Hence, the process leading to the excessive abundance of mass 56 cannot have taken longer than a few days."

A more convincing astrophysical description arose both from computer integrations of nuclear reaction rates within a reaction network (Truran *et al.,* 1967) and from a theoretical "quasiequilibrium" formulation of that network (Bodansky *et al.,* 1968). These showed explosive silicon "melting and resolidifying" into iron (to misuse time-honored chemical terms) and that also formed a beautiful abundance peak shown in the lower panel of Fig. 4. But in the solution the ^{56,57}Fe abundances area actually those of their radioactive ^{56,57}Ni progenitors. The ejection would have to be rapid, both to avoid fouling up the abundance fit and because the supernova explosive burning and ejection would leave insufficient time for electron captures by ^{56}Ni. Associated consequences for gamma astronomy and for supernova light curves of ejecting such a large mass of radioactivity were not immediately recognized by those teams. But it is immediately evident that the lower panel of Fig. 4 is the superior fit, as it eliminated the large ^{52}Cr overabundance and successfully produced ^{58}Ni. Clayton and Woosley (1969) even emphasized in a separate work that the ^{58}Ni success was a decisive argument in favor of the new picture.

It was not until early 1968 that this writer saw these ejected radioactivities as the best targets for gamma ray astronomy, giving their observation the capability of demonstrating that Fe was indeed explosively fused in supernova ejecta. After all, when one sees atomic lines one has no idea how long their nuclei have existed, but when one sees nuclear-decay lines one knows he is looking at "new nuclei." That idea reappeared naturally because I had already introduced it several years earlier (Clayton and Craddock, 1965). We therein had suggested gamma-ray lines as tests of nucleosynthesis by presenting an evaluation of the visibility of transbismuth radioactivity in the Crab nebula, a supernova that had exploded nearly 938 years ago. Although that earlier paper did provide a rallying point for experimental teams hoping to build and fly gamma telescopes, the mass of ^{56}Ni ejecta was very much greater than the most optimistic estimates of transbismuth activity, rendering the new 1968 prospect much more favorable and exciting. Our paper (Clayton *et al.,* 1969) set an inspiring target for gamma astronomers, a target that was decisively affirmed in supernova 1987A in the Magellanic Cloud when the Gamma Ray Spectrometer on Solar Maximum Mission was able to record the predicted 847keV and 1238keV gamma rays penetrating through its shield into its central detector (Fig. 5, Leising and Share, 1990, and references therein). This "smoking gun" demonstrated unequivocally that ^{56}Ni was created during the explosion, and the 0.075 solar masses of it ejected was very nearly the amount we had predicted two decades earlier as the amount needed per supernova to account for the Galaxy's supply of iron. My only disappointment at this spectacular discovery was that we were not able to do it with Gamma Ray Observatory, a NASA project on which I have been a Co-Investigator for a dozen years, now successfully in orbit since April 1991, but too late because of the shuttle disaster for its hoped-for destiny with SN1987A. That's just Murphy's Law, I suppose. But I take great satisfaction that one of my Rice students (Mark Leising) was one of the SMM discoverers, just as another of them (Gerry Fishman) was a co-discoverer with an early balloon flight (Sandie *et al.,* 1988) as well as co-author 22 years ago of the prediction itself, and that two of my other Rice students (Wade Craddock and Stan Woosley) have played historically important roles in this story. Woosley's thesis (Woosley *et al.,* 1973) became "the book" on explosive nucleosynthesis, a topic in which he has remained the leader.

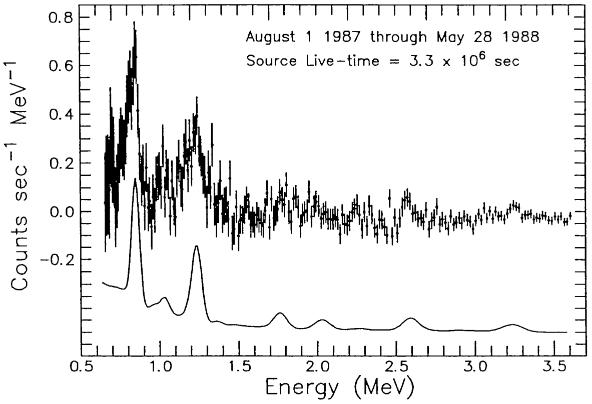

FIG. 5. The mean gamma-ray spectrum observed by the SMM Gamma Ray Spectrometer over the period August 1, 1987 to May 28, 1988. This is the excess flux from the Large Magellanic Cloud. The lower line shows the expected ^{56}Co gamma spectrum, which is clearly seen in the data. Supernova 1987A had ejected 79 Jupiter masses of pure radioactive ^{56}Ni just five months earlier. This was the largest recorded nuclear accident of all time.

But what have this explosive nucleosynthesis and gamma astronomy to do with meteoritics? First, the explosive nucleosynthesis identified the extinct radioactivities that would be carried in the dust that condensed within the supernova interior (SUNOCONS) before mixing with the interstellar matter. SUNOCONS were found to condense in supernova 1987A, and perhaps even in the 938-yr-old Crab (Fesen and Blair, 1990), but not so efficiently as to fulfill predictions that it could dim the 1987A remnant's light (Dwek, 1988). Hoyle and Wickramasinghe (1970) had introduced that mechanism as a preparer of large quantities of interstellar dust, and Clayton (1975a,b) identified those SUNOCONS as bearers of huge isotopic anomalies. Very controversial, however, was the question whether that dust would leave any observable traces within the meteorites. The image of a hot gaseous early solar system had a strong grip on meteoritics, leading to many convictions that remnants of interstellar dust could not be preserved. Nonetheless, the contemporaneous discoveries of isotopic anomalies in meteorites generated much excited speculation. An example is to be seen in Fig. 6, my photograph of most of the participants in the first international workshop on isotopic anomalies. I organized this workshop during 1975, to be hosted by University College, Cardiff, in summer 1976 at Gregynog, the Davies family estate in central Wales that had been deeded to University College. Chandra Wickramasinghe, Fred Hoyle and Willy Fowler, co-organizers are seen there along with many of our Meteoritical Society. The fascination of isotopic anomalies sank its hooks deeply into all of us who participated in that weeklong workshop. Explosive nucleosynthesis and condensation of its products were one of our central themes. Figure 7 reproduces a slide that I presented there in my theoretical introduction. It shows two fossil extinct radioactivities whose daughters were argued (Clayton, 1975b) to be common in interstellar SUNOCONS—excess

FIG. 6. Participants in the 1976 Gregynog Workshop on Isotopic Anomalies, held at Gregynog, Wales, and sponsored by University College, Cardiff. The writer and W. A. Fowler are center front, with Fred Hoyle and Chandra Wichramasinghe, the hosts, at the far right. Many 16-yr-younger meteoriticists are discernable. *Photo by D. D. Clayton.*

^{44}Ca from ^{44}Ti decay and excess ^{41}K from ^{41}Ca decay. The new arguments were that virtually all of these nuclei owe their solar abundance to those radioactive parents, and that most of the superrefractory Ti and Ca should condense within SUNOCONS rather than issue forth as gaseous atoms. These predictions have led to many searches that have only now, at this 1991 meeting, borne fruit (Zinner *et al.,* 1991a). But the primitive drawing in Fig. 7 shows that at that time I had not expected to find the interstellar particles themselves, still intact within the meteorites, but had instead expected the usual correlation of daughter excess with parent element in some class of CAI (see also Clayton, 1977c). So it is that nature's surprises exceed our speculations.

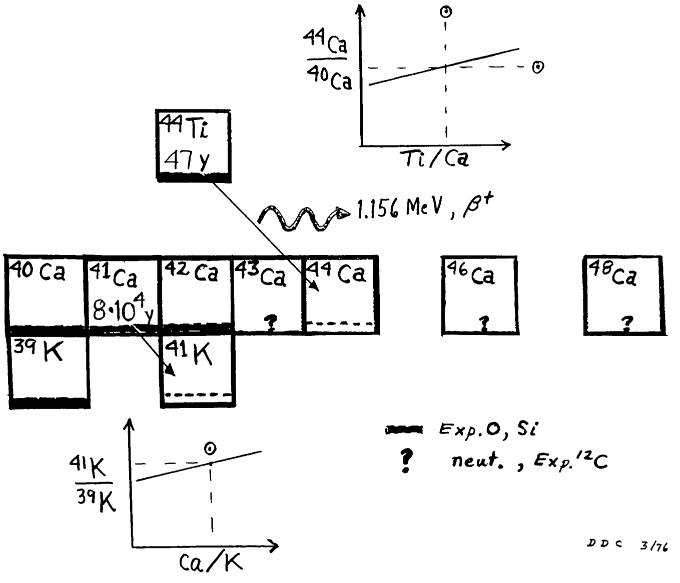

FIG. 7. Extinct radioactive anomalies in SUNOCONS, a prediction slide presented by this writer at the 1976 Gregynog Workshop in his keynote theoretical outline. Stable ^{41}K and ^{44}Ca are synthesized almost totally as radioactive ^{41}Ca and ^{44}Ti progenitors (Bodansky *et al.,* 1968; Woosely *et al.,* 1973). Their condensation thermally within expanding supernova interiors motivated the prediction (Clayton, 1975b) of huge fossil excesses in interstellar dust of the SUNOCON type.

And what of gamma ray astronomy and meteoritics? The best bets for detecting interstellar radioactivity by its gamma radiation were set forth in a series of papers by this writer during the 1965–1975 decade (*e.g.,* Clayton, 1982b). In addition to ^{56}Co they included ^{22}Na, ^{44}Ti, ^{57}Co, and ^{60}Fe. Each of these became a prime suspect also for extinct fossil effects within the meteorites. Then came the next surprise. When the first interstellar radioactivity was finally discovered by the HEAO-C spectrometer (Mahoney *et al.,* 1984), it was, of all things, ^{26}Al. The same activity that Harold Urey and others had predicted as the heat sources for the asteroids but which I had rejected as having too small a yield in stars to be detectable in the interstellar medium, even though Clayton and Hoyle (1976) had argued that novae would make enough of it for important fossil correlations of ^{26}Mg* with Al to exist in refractory interstellar dust. After its discovery, however, Clayton (1984), quickly readjusting as theorists do, showed that novae were the likely sources of the ^{26}Al and also showed why the supernova interpretation by its discoverers was not the correct one (at least not if production ratios in supernovae are $^{26}\mathrm{Al}/^{27}\mathrm{Al} < 0.01$ as calculated). Today the source of ^{26}Al is still not known as we begin our effort to discern something of its distribution with the Gamma Ray Observatory. Compton Observatory also hopes to find several "hot-spot" supernova remnants glowing in the ^{44}Ti lines and perhaps the other predicted radioactivities. We shall see. But it is already clear that gamma-ray astronomy and meteoritics are partners to the core.

COSMIC CHEMICAL MEMORY

As the number of isotopic anomalies in macroscopic chunks of meteorites escalated during the late 1970s, it became necessary to seek a central paradigm for their very presence. The most fruitful one appears to me to be a chemical-memory paradigm (Clayton, 1977a; 1978a,b; 1981a,b; 1982a): *the isotopic anomalies are the natural consequence of the aggregation and chemical transformations of presolar dust that routinely carries chemical and isotopic properties reflecting its own formation and interstellar evolution.* Differing kinds of dust have differing isotopic and chemical structure. The mechanisms for this have been my primary concern with meteoritics. The theory was constructed to deal with endemic anomalies in macroscopic solar-system solids rather than with preserved STARDUST. I regard this cosmic chemical memory as "the cause" of most such isotopic anomalies, which I emphatically distinguish from stellar nucleosynthesis as "the cause" of the abundances of chemical elements. Confusion of these two ideas pervades much early discussion of isotopic anomalies. Far from being self evident, this chemical-memory interpretation was not even the one utilized in most of the brilliant discoveries of isotopic anomalies by nuclear chemists. Those discussions usually utilized alternative paradigms described below (see Brush, 1990, for an historian's account).

I see three major reasons why other discovery papers usually discussed inhomogeneous injection of isotopically anomalous matter into the solar nebular as a preferred framework of interpretation. Firstly, it was the path of least resistance. The chemistry of meteorites was throughout the 1970s interpreted in terms of condensation of first solids within a hot gas as it cooled down. This was viewed so literally that chemical ideas were sometimes rejected in meetings (by some) because they were inconsistent with that sequential condensation. A variation offered to save the hot gaseous picture envisioned injection of anomalous gas into only one portion of that hot gaseous nebula. The second reason was the discovery of ^{26}Al decay in constituents from which the meteorites formed (Gray and Compston, 1974) followed by the demonstration by Lee *et al.* (1977) that in some calcium-aluminum-rich inclusions (CAI) the fractional excess in ^{26}Mg correlated linearly with the Al/Mg abundance ratio, exactly as it would if the mineral separates of those inclusions had solidified from a melt containing live ^{26}Al. Because the inferred ^{26}Al abundance was believed to be too large by a factor of order 10^3 to exist routinely in interstellar matter, these authors reasoned that it must have been freshly synthesized and admixed into the solar nebula. Cameron and Truran (1977) promptly offered an astrophysical scenario for this that was so bold as to include the other known isotopic anomalies and extinct radioactivities under its umbrella. This scenario was an elaboration of Cameron's (1962) arguments. The overpressure from the neighboring supernova that created the inhomogeneously admixed matter in that scenario was thought to have "triggered" the solar nebula collapse, thereby escaping the *ad hoc* character of this paradigm, which was to remain popular for most of the subsequent decade. Wasserburg and Papanastassiou (1982), for example, utilized the imagery of the inhomogeneous supernova injection throughout their lengthy and brilliant review of their contributions to the extinct-radioactivity problem. It was still a few years before the discovery of live ^{26}Al in the interstellar medium today (Mahoney *et al.,* 1984) would motivate a decisive argument (Clayton, 1984; Clayton and Leising, 1987) that supernovae could not be the primary sources of interstellar ^{26}Al. Quantitative evaluation of the rate of ^{26}Al nucleosynthesis required by the gamma-ray data (Clayton, 1984, 1986a), on the other hand, showed its interstellar abundance to be an order of magnitude larger than expected by anyone, which in turn was shown to support the plausibility of large *fossil* ^{26}Mg excesses in aluminum-rich grain assemblages (Clayton, 1986a). These huge predicted excesses have now been found (Zinner *et al.,* 1991b) in surviving STARDUST; however, their relationship if any to Al-correlated mineral suites within CAI or to corundum particles (Anders *et al.,* 1991) remains murky. But nature has now taught us to respect her audaciousness, so that we must admit much still to be learned about ^{26}Mg*, which exists abundantly, and about its consequences within rocks.

Equally influential was the third reason, pervasive doubt that cosmic chemical memory could produce stable-isotope anomalies in macroscopic samples. Interstellar grains in meteorites had not yet been discovered in the 1970s, so that espousal of them appeared irrelevant to the existing problem of isotopic anomalies in CAI, which are mm-sized rocks that have somehow been assembled in the solar system. Because a mm-sized rock has mass of at least 10^9 interstellar grains, it seemed to many that isotopic anomalies could not persist in an average of such a huge number of interstellar particles. Demonstrating how this can plausibly occur has been one of my objectives for this theory from the beginning.

One purpose of this rhetoric is the documentation of *theory* as having been a full partner with observations, and occasionally a leading partner, in the development of this science. In reminding us of many examples of this I am not attempting self service. Theory must play an even stronger role in the future if the presolar record is to be correctly interpreted, and its emphasis will, I believe, be on physical chemistry and on a self consistent chemical history of matter from the stars to the meteorites. Such a description will then become a tool for fingerprinting solar origin and meteorite-parent-body processes. This is an entirely different question than the meaning of surviving STARDUST.

Although I argued as an advocacy strategy against the idea of inhomogeneous injection for 15 years (Clayton, 1977a; 1978b,c; 1979a,b; 1982a), I do not regard the idea of bulk nebular inhomogeneities as dead. I simply prefer to look first at chemical memory. But the bulk composition within any given volume element of the solar accretion disk (or "nebula") may change with time if the mean isotopic composition of infalling matter does so. This variant could be constructed from either a spatially inhomogeneous molecular cloud core or from an injection event (the supernova trigger or a nearby AGB star (Cameron, 1984)). Isotopically distinct solids might have formed at different times, in this view, in a disk of changing isotopic composition. The "apparent age difference" may even differ from the actual time difference. One might also find such reasons for one solid sample to differ from another in trace elements as well. But the plausibility of this has not been explored by physical modelling.

Whatever temporal isotopic variations are attributed to sorting of interstellar dust (fine grained *vs.* coarse grained, *etc.*) should nonetheless be recognized as a variant of cosmic chemical memory rather than as a spatial inhomogeneity, because the resulting temporal sequence would derive from the prior existence of an isotopically fractionated initial chemical state (*e.g.*, fine-grained versus coarse-grained isotopic compositions). Chemical memory consists of those effects that depend in any way on the initial chemical state of the interstellar medium.

If the interstellar medium (strictly, the specific molecular cloud) carries homogeneous bulk abundances—that is to say, if each macroscopic volume element contains identical elemental and isotopic concentrations—then the chemical microstructure of gas and solids is the *only way* to preserve isotopic anomalies. Whatever isotopic anomalies that might exist in dust grains would, moreover, necessarily reflect their individual histories. Each grain has, to some degree of fidelity, a memory of everything that has happened to it from its birth through its interstellar evolution. Even a well mixed interstellar medium of gas and dust is expected to contain dust of vastly different chemical and isotopic signatures, so that if those dust types can be separated by dynamics or by chemistry, the chemical memory can be recovered. Without spatial inhomogeneities, without supernova trigger or special admixture, that molecular cloud might collapse and form a planetary system having isotopically anomalous solids if the chemical paths to the formation of those solids did not partake equally of each type of dust structure. That explanation constitutes cosmic-chemical-memory theory. Isotopic and astrophysical arguments led me with increasing conviction (Clayton, 1977a,b; 1978a,b,c; 1979a,b; 1981a,b; 1982a,b; 1986a,b; 1988b) to recommend adopting it as the only explanation, making exceptions only where demanded by extraordinary situations (perhaps ^{26}Al, for example). Not only is this theory the most plausible and the most successful in dealing with the data, but it is also advantageous to concentrate on seeking a global success with one theory instead of a patchwork of *ad hoc* events. It Copernican flavor in treating the sun's birth as nonspecial was explicitly noted in 1979 in another paper that would not be accepted for two years: "Our conjecture can be dramatized by the following *Gedanken* observation: Consider a low-mass star forming in a cold cloud without benefit of a neighboring supernova and surrounded by a preplanetary accretion disk with temperatures less than 1000K. We argue that Ca-Al-rich aggregates exist there too, and that they also bear isotopic fractionation and isotopic anomalies *i.e.* FUN" (Clayton, 1981a).

The chemical-memory theory has advantages from the point of view of the philosophy of science. It can be continuously enlarged, modified, or refocussed by independent studies of specific details without invalidation of its paradigm. The entire scientific community contributes to its definition. It is a "progressive research program" in the sense defined by Lakatos (1971), a virtue that appears not to be shared by inhomogeneous admixture interpretations, which have the stand-alone character of *ad hoc* constructions. The starting conditions for chemical memory theory are natural: an interstellar medium dominated by precondensed mater (for the refractory elements) bearing large chemical and isotopic fractionations of predictable character. This situation is the one that I (Clayton, 1978a) singled out as the key to the early solar system. In fact, I attribute the several-year lack of enthusiasm for chemical-memory theory more to community failure to recognize the progressive nature of the theory than to a belief that the idea is wrong.

It remains interesting that these competing theories produce quite different results if the local heating in the solar nebula (accretion disk) was great enough to vaporize *all* dust. The possibility of bulk isotopic anomalies in the inhomogeneous admixture theories, either spatial or temporal, was a feature having appeal for many. One requires for that purpose that the gas cool again and nucleate before homogenization. Cosmic chemical memory, on the other hand, is erased by vaporization, and therefore requires survival of at least refractory residues of particle vaporization for retaining isotopic anomalies. Owing to disk transport processes, however, refractory residues need not be prepared in each zone, not even in zones where the isotopically anomalous samples form (*e.g.*, Wood and Morfill, 1988).

The interstellar medium has composition gradients because a considerable time is required to homogenize stellar ejecta in the interstellar medium. Cameron (1973) was, to my knowledge, the first to use that fact as part of a conjecture in meteoritics, namely that large radiogenic age differences among meteorites might not be real. But he found no convincing mechanism for utilizing that large-scale interstellar inhomogeneity. I (Clayton, 1977b) arrived at a similar meteoritic conjecture, and did identify its mechanism as being chemical memory within interstellar matter by arguing that volatility differences between parents and daughters (Al-Mg, Rb-Sr, U-Pb), rather than spatial inhomogeneities, were the driving forces that created separate *chemical* pools of different apparent radiogenic age. That is to say, two different dust types within the uniformly mixed medium have differing radiogenic excesses for quite natural historical reasons. Reeves (1978) readdressed instead a spatial-mixing inhomogeneity, as did Schramm (1985). The question today is not whether interstellar composition gradients exist, because they are known to, but whether those gradients persist on a sufficiently fine scale within molecular clouds to have produced isotopic anomalies in solids. I maintain instead that the isotopic anomalies in those solids reflect endemic aspects of interstellar chemical history. *It is the very core of chemical-memory theory that, on astrophysical grounds, different isotopes of the same element have not had the same chemical history.* The physical reasons for this are what I call the *mechanisms of cosmic chemical memory.* Cosmic chemical memory is the set of physical and historical reasons for isotopic fractionation to exist within the interstellar medium. Its tablets can be read both backwards to the very origin of the chemical elements and forwards to the solar system processes that have produced our parent bodies.

I must here salute the first indications of chemical memory. They are found in speculations surrounding the three great early discoveries in isotopic anomalies, which in chronological order were: (1) isotopically heavy xenon (Reynolds and Turner, 1964) now known as Xe-HL; (2) ^{22}Ne-rich neon (Black and Pepin, 1969; Black, 1972) now known as Ne-E; and (3) the ^{16}O-rich oxygen (R. N. Clayton *et al.*, 1973) discovered first in CAI where its value is largest. Each of these discoveries induced speculation that some presolar dust component had escaped the vaporization that was at that time presumed to have been total (*viz*, Black, 1972). R. N. Clayton *et al.* (1973) went somewhat further in suggesting that ^{16}O-rich dust might form near a massive exploding star that had just produced ^{16}O by nucleosynthesis. Black (1975) appears to have had the same idea in mind for Xe-H. Soon thereafter a subtly different idea appeared—that each isotopic anomaly was in fact condensed not around but *within the interiors of supernovae* as they expanded and cooled, before the prompt mixing with circumstellar matter that unavoidably dilutes each isotopic effect by a large factor: Xe-H (Clayton, 1975a, 1976, 1981b, 1989), Ne-E as its ^{22}Na parent (Clayton 1975b), and ^{16}O (Clayton, 1975a; 1977a; 1981a,b; 1986b). These isotopic anomalies launched chemical-memory theory, which today has a much broader astrophysical fabric. The two noble-gas anomalies now appear to be straight cases of surviving carbon STARDUST (*e.g.,* Lewis *et al.,* 1987; Tang and Anders, 1988), rendering them *ipso facto* chemical memories, but of a specific kind, not of the bulk type (like macroscopic ^{16}O excess) that the theory was advanced to handle. Hoyle and Wickramasinghe's (*e.g.,* 1962, 1970, 1977) emphasis on the likely ubiquity of carbonaceous STARDUST and SUNOCONS in the interstellar medium was another precursor.

In contemporary discussions of the physical mechanisms of cosmic chemical memory within macroscopic samples it is appropriate to be reminded that *interstellar grains have now been found in meteorites.* The most convincing examples are small carbonaceous particles bearing a wide spectrum of large isotopic variations in carbon, noble gases, and in other associated elements. Anders (1988) reviewed those highlights, which now, owing to their glamourous unambiguity, have temporarily obscured the original quest. But they came *after* the great debates of the 1970s over the FUN inclusions. Demonstrations that interstellar grains themselves are abundant in carbonaceous meteorites do indirectly increase the plausibility that interstellar grains also play a major role in the formation of anomalous objects that are themselves too massive and too nearly normal to be regarded as "interstellar marbles." For example, models of interstellar SUNOCON destruction imply that requiring 5% of interstellar aluminum to exist as ^{16}O-pure SUNOCONS from the carbon-burning shells of past supernovae would also require that >50% of of newly synthesized Al condense within the expansions of supernovae as oxides (Clayton, 1981b, 1982a, 1986b; Liffman and Clayton, 1988, 1989). This may even be true. But how efficiently can interstellar Al oxide retain its oxygen while it is being processed within a solar accretion disk to form the CAI themselves? How were the CAI in fact formed? Will exchange with ambient oxygen be faster or slower than the time to evaporate Mg? Lots of questions need answering, not only on this endemic anomaly but on every chemical-memory effect. We stand only at the beginning of reading the cosmochemical record.

The equally rich and varied endemic meteoritic correlation of ^{50}Ti variations with those of ^{48}Ca, ^{54}Cr, ^{58}Fe (*e.g.,* Lee, 1988 and references therein) and ^{62,64}Ni (Birck and Lugmair, 1988) and sometimes with ^{58}Fe (Volkening and Papanastassiou, 1989) and/or ^{66}Zn (Volkening and Papanastassiou, 1990; Loss and Lugmair, 1990) surely originates with a neutron-rich nucleosynthesis process (Hainebach *et al.,* 1974; Hartmann *et al.,* 1985); but how does that ejecta appear still correlated in the mineralized samples of meteorites? This chemical question has received little attention. My argument (Clayton, 1981b) is that because the inner supernova zones carry only Fe-peak metals, their SUNOCONS would necessarily be metallic droplets, rather than oxides or silicates, if indeed they condense at all. Variations (positive or negative) in this droplet component within bulk dust during aggregation in the solar disk would then provide this correlation of either sign, almost symmetrically. This was, I believe, the first plausible chemical-memory interpretation of that correlation in meteorites. I suggested on the same occasion, as a variation on that theme, that these innermost zones may emerge entirely gaseous and thereby be partially separated from the partial condensation of the more abundant isotopes of those metals within those SUNOCONS condensed within overlying zones—*i.e.,* a chemical-memory argument based on *an absence* of ^{50}Ti-bearing SUNOCONS. In that latter case, surface-correlated accretion by the known abundant component of smallest interstellar grains (Clayton, 1980; Liffman and Clayton, 1988) would be the fixer for chemical memory, again providing symmetric pools of opposite signs, this time sorted by particle size. Following the discovery of very large negative ^{50}Ti anomalies, Hinton *et al.* (1987) re-argued the case in favor of inhomogeneous admixture from a nearby supernova; but their argument in terms of the relative numbers of atoms is flawed, and Fahey *et al.* (1987) countered with still other reasons supporting chemical memory.

Some aspects of the presolar record require not just presolar mechanisms for forming anomalous dust but also the evolution of the interstellar medium itself. Both the preservation of SUNOCON and STARDUST anomalies and the creation of anomalies by interstellar evolution require a chemical history for interstellar dust. This is a tall order for both astrophysics and cosmochemistry. Interstellar shock waves (McKee, 1989) are the primary threats to longevity for interstellar dust. It appears that a *mass lifetime* m/(dm/dt) = 100Ma is within a factor 5 or so of the correct answer. The *existence time of a particle core,* on the other hand, is not easily related to an average mass rate of sputtering because individual particles continuously change their size and composition as they alternately sputter and accrete gaseous atoms. But the particle itself lives on. Clarifications are found in the Monte Carlo histories for refractory interstellar dust in a simplified two-phase interstellar medium by Liffman and Clayton (1988, 1989; Clayton *et al.,* 1989). They formulated a computational machinery capable of generating detailed histories for interstellar particles, with however many simplifying assumptions. They dealt with idealized particles. Their formulation maintains a ledger on the changing structures and sizes of the individual particles as the interstellar medium ages, so that many questions concerning survival of dust components can be addressed. The accreted mantles were given no chemical structure in their work, but are treated as amorphous collections of refractory atoms (NEBCONS). Their calculations demonstrate that: SUNOCON cores do indeed live much longer than the average mass lifetime; the size spectrum does indeed evolve as sputtering and reaccretion move atoms from particle to particle; the age structure (Clayton *et al.,* 1989) of the layered particles can indeed be modelled. Figure 8 is my cartoon of the board upon which the chemical-memory game is played.

Old dust would be isotopically anomalous if it had formed from even an average interstellar medium. This comes about because the continuing processes of Galactic evolution and nucleosynthesis monotonically change the isotope ratios in the bulk ISM. In this isotopic-anomaly mechanism one concentrates on the NEBCON component and takes it to inherit the mean isotopic composition of the gas at its time of deposit. I particularly noted that old oxidized dust would appear to be ^{16}O-rich because it is actually ^{17}O-and-^{18}O-poor by equal factors owing to the secondary-nucleosynthesis nature of the two heavier isotopes (Clayton, 1989b). We later modelled the dust layers

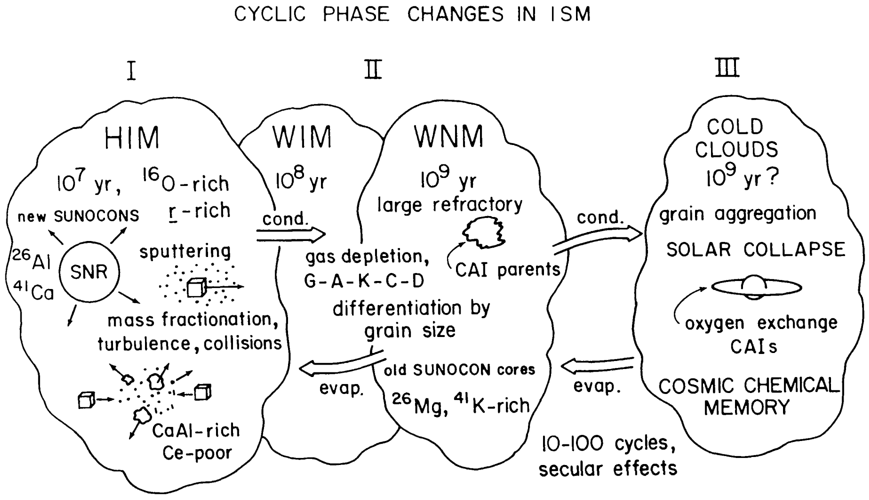

FIG. 8. The evolving Galactic organism, generator of cosmic chemical memory. Matter cycles chemically through three phases of the interstellar medium—hot, warm and cold, New SUNOCONS are placed initially within the hot ionized medium (HIM), whereas new STARDUST initially enters primarily the warm ionized medium (WIM). Sputtering of grain surfaces followed by reaccretion of amorphous cold gas (NEBCONs) in cold clouds occurs repeatedly during the lifetime of each particle (Liffman and Clayton, 1988, 1989). Aggregation of macroscopic bodies and oxygen exchange happens in a warm solar accretion disk within a collapsing cold-cloud core. The initial dust of the solar system was cycled through 10–100 such repetitions before eventually finding itself in the solar disk. (Figure from Clayton, 1981b, 1982a.)

numerically within the framework of the Liffman and Clayton (1988) construction (Clayton *et al.*, 1989). We defined an *average age* of the material in the grains as an average of the times of residence of the spherical layers remaining within the particles at the time the solar system formed. We showed that refractory-oxide dust is on average 3–5 × 10^8 years old when the sun formed, and hence about 5% richer in ^{16}O than is the gas at that time. The reader will be aware that these numerical details are not as significant as the concept of interstellar evolution itself creating isotopic anomalies.

Eventually this subtopic must be generalized beyond the mean-interstellar-composition ideal. The matter of the solar neighborhood underwent random presolar isotopic variations that may have been even larger than its mean evolution. The sun's own composition may be distorted by such a variation (Clayton, 1977a; Reeves, 1978; Schramm and Olive, 1982). Supernovae of both types occur every Ma or so in the solar neighborhood's compositional sphere, and intermediate-mass giants may pollute large portions of the local medium and even portions of the solar molecular cloud (Cameron, 1988) with their peculiar isotopes. Recognizing the potential of grain-size spectra to record surface correlated gaseous anomalies, the temporally layered particles introduced by Clayton *et al.* (1989) may record those fluctuations in a physically recoverable way, just as the monotonic evolution was recoverable in physical ways. The particles need only be size sorted before aggregation. I doubt that these isotopic variations imprinted on dust selectively by the evolution of the ISM can hereafter be omitted from our consideration of the presolar record in meteorites.

So I conclude as I began. We envision an interstellar medium populated by a wide range of differing dust particles, each with its own place of birth, its own physical modifications by a stern interstellar environment, and its own structural and isotopic signatures. We envision processes that can dynamically sort them by size, by age, by thermal filtering, by density or inertia. We envision their aggregation into larger clumps in diverse thermal settings, causing differing macroscopic aggregates to differ isotopically, and to remain different even after closed-system metamorphism. Astrophysics must continue to lead the way to many of these considerations. Cosmic chemical memory can be both an archaeology of presolar history and a fingerprint of solar birth. I am proud to have played even a small role in our visualization of its Galactic workings.

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