PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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R. J. Tayler

Phil. Trans. R. Soc. Lond. A 1988 **325**, 391-403
doi: 10.1098/rsta.1988.0056

Phil. Trans. R. Soc. Lond. A **325**, 391–403 (1988)
Printed in Great Britain

Nucleosynthesis and the origin of the elements

By R. J. Tayler
Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, U.K.

Stars obtain their energy from nuclear-fusion reactions and these reactions can produce most elements and isotopes up to the neighbourhood of iron in the periodic table. Most more massive elements are also believed to be produced in stars by reactions involving the addition of neutrons. Mass loss from stars, both castastrophic and gradual, returns processed matter to the interstellar medium and in this way the raw material for the Solar System was assembled.

It was originally believed that the Solar System was formed from a gas cloud that was chemically and isotopically homogeneous, with the variation of composition of objects today being attributed to processes occurring in the solar nebula. This was changed by the discovery of isotopic anomalies in meteorites. It is now clear that there was some departure from fine-scale mixing in the solar nebula. This may have resulted from late irradiation by a supernova or from the survival of interstellar grains with particular nucleosynthetic origins, or both, as well as from incomplete mixing of the interstellar gas.

1. Introduction

Observations of the Solar System and of stars and gas clouds show that all objects in the Universe do not have the same chemical composition. In addition, the only plausible explanation of the source of the energy radiated by the Sun and most other stars is the conversion of light elements into heavier elements by nuclear-fusion reactions, so that the chemical composition of the Universe must be changing with time. Although this change occurs in the central regions of stars, many stars expel processed matter into space, so that the change becomes visible and the material can be incorporated in new generations of stars. It is therefore of interest to try to understand the observed composition of any object in terms of the original composition of the Universe and of processes which have occurred during its history. The oldest known stars in our Galaxy, in globular star clusters, are also the ones with the lowest heavy-element content, which supports the view that the younger stars contain heavy elements formed during the galactic lifetime. Stars form out of the interstellar gas and the chemical composition of the Solar System should therefore be related to that of the region of the interstellar gas of our Galaxy out of which the Sun formed *ca.* 4.6 Ga BP.

It is important to ask in what ways the present composition of the Solar System might differ from its original composition. It is generally, but not universally, believed that all objects in the Solar System were formed together (see, for example, Woolfson (1979) for a contrary viewpoint). If this is not true and if some objects have been captured by the Sun, it is to be expected that there will be chemical composition variations which reflect different origins. If the entire Solar System (other than the Sun) was captured, there is no need for the age of 4.6 Ga quoted above to apply to the Sun. However, the general consensus of opinion is that the Sun and the planets did form together and we shall adopt that view. Even in this case there are good reasons

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why all objects in the system should not have the same composition. There may have been some segregation of chemical composition during the formation phase, particularly if some elements were preferentially incorporated in small solid particles, and the less massive objects have certainly lost most of their volatile gases. The present composition of the Sun differs from its original composition because of nuclear reactions in its interior, but it is not believed that any composition changes produced by these reactions should have been carried to the surface and have become observable. The initial composition of the system will have contained radioactive isotopes; some of the long-lived ones remain in measurable quantities, and others are represented today only by their decay products. Some very minor changes of composition will have been produced by the interaction of cosmic rays with the Solar System.

The main possibility of change as opposed to redistribution arises from the motion of the Sun in the Galaxy. Although the Sun, like other stars and gas clouds, moves in an approximately circular orbit about the galactic centre, the Sun's random motion relative to pure circular motion causes it to move throughout a toroidal volume which is about 1 kpc (3×10^{19} m) wide in the plane of the Galaxy and about 160 pc thick perpendicular to the plane. Other stars and gas clouds possess different random velocities from the Sun. Although it is easy to show that it is very unlikely that the Sun has passed very close to another star during its past history, and this view is strengthened because it is unlikely that the Solar System could have survived such a close passage, it is very probable that the Sun has made a number of passages through gas clouds, including giant molecular clouds, and it may have acquired material from such clouds. It has been suggested that, as a result, the surface composition of the Sun might not be the same as its original composition (Talbot & Newman 1977), although it is generally thought that the constant mass loss through the solar wind is likely to keep the surface of the Sun clean. Even if inflow replaces outflow temporarily during the cloud passage, it is probably not long before the original composition is again exposed.

A passage through a giant molecular cloud would have much greater influence on smaller objects in the Solar System and, in particular, on the reservoir of comets (Oort cloud), which is generally supposed to reside at the outer edge of the system. At the very least each passage through a molecular cloud, which might occur at intervals of a few hundred million years would cause a significant perturbation in the Oort cloud including both a loss of comets to the Solar System and sending an increased number of comets on orbits close to the Sun (see, for example, Napier & Clube 1979; Bailey 1986); at the most, matter captured from the molecular cloud might provide a new source of comets (McCrea 1975). The chemical composition of contemporary molecular clouds should differ at least in detail from that of the interstellar gas out of which the Solar System was formed. This implies that a study of comets might give information about something other than the original composition of the Solar System.

Until relatively recently it was thought that the chemical composition of the Solar System did not have any variations that could not be accounted for by fractionation and the loss of volatile elements. The Solar System abundances that were largely derived from the carbonaceous chondritic meteorites were basically those of Suess & Urey (1956) frequently updated by Cameron (see, for example, Cameron 1982) and they are also frequently referred to as the cosmical abundances.

The evidence of uniformity could not be regarded as wholly secure. For example, elements such as iron and nickel are clearly concentrated in the Earth's core. The observed seismic and magnetic properties of the Earth are not obviously inconsistent with the view that the Earth and the Sun have basically the same composition apart from the Earth's loss of volatiles. It is not, however, easy to change this qualitative agreement into a precise quantitative agreement. There is a further complication. Although isotopic as well as elemental abundances can be studied in terrestrial, lunar and meteoritic samples, for most elements there is no serious possibility of studying isotopic shifts in solar spectral lines, so that the solar isotopic ratios are unknown. It was originally an act of faith that, because terrestrial and meteoritic elemental abundances matched those of the Sun and because terrestrial and meteoritic isotopic ratios appeared to be the same, isotopic ratios would be similar throughout the Solar System.

This view was very clearly expressed by Suess (1965) in an article appropriately titled *Chemical evidence bearing on the origin of the solar system.* He stated:

> Among the very few assumptions which, in the opinion of the writer, can be considered well justified and firmly established, is the notion that the planetary objects, i.e. planets, their satellites, asteroids, meteorites, and other objects of our solar system were formed from a well-mixed primordial nebula of chemically and isotopically uniform composition. At some time between the time of formation of the elements and the beginning of condensation of the less volatile material, this nebula must have been in a state of a homogeneous gas mass of a temperature so high that no solids were present.

All of this was changed when it was discovered that terrestrial and meteoritic isotopic ratios are not always the same. It was found that there are small inclusions in the Allende meteorite which have different isotopic ratios from those of standard Solar System material. The fall of this meteorite on 8 February 1969 at Pueblito de Allende near Hidalgo de Parral in Mexico and its subsequent analysis transformed views of meteoritic composition. Subsequently many further anomalies were found in Allende and other meteorites. These discoveries raise important questions about the source of the material that formed the Solar System, about the initial departures from uniformity in its chemical composition and about the manner in which these microscopic anomalies were preserved during the formation process.

Following this general introduction, I shall discuss in the following section current ideas about the origin of the elements before returning in §3 to questions relating to the Solar System. A general review of the problem of the origin of the elements can be found, for example, in Tayler (1984).

2. Nucleosynthetic processes and sites

In this meeting we are primarily concerned with two questions: why does the Solar System have the chemical composition that it has and what clues does the distribution of composition provide towards an understanding of the system's origin? Before discussing the Solar System it is necessary to discuss present views concerning the evolution of the chemical composition of the Universe as a whole.

At present the hot Big Bang cosmological theory appears to be in at least-good qualitative agreement with observations of the large-scale structure of the Universe (see, for example, Boesgaard & Steigman 1985). For the purpose of this talk we will assume that the theory is valid. An important feature of the theory is that the Universe started by expanding from a very hot dense state in which its constituents were elementary particles and that atomic nuclei (other than the proton) first came into being through nuclear-fusion reactions when the Universe was about one minute old. The only compound nucleus formed in any quantity was ^{4}He but there were also traces of ^{2}H, ^{3}He and ^{7}Li; most of the material continued to be ^{1}H.

The Big Bang theory is not in fact unique and the free parameters in the theory can be chosen so as to give a variety of initial chemical compositions for the Universe. The important factor in the predictions of the theory is the almost complete absence of elements more massive then helium; what the astronomer refers to rather inaccurately as heavy elements. The aim is to determine which values of the free parameters yield the observed initial composition and to decide whether they are consistent with other tests of the theory. Observations of a variety of helium and heavy element contents of gas clouds in our own Galaxy and other galaxies suggest that we can extrapolate back to the time when there were no heavy elements and deduce the primeval helium abundance. The result is $X \approx 0.77$, $Y \approx 0.23$, where X and Y are respectively the mass fractions in the form of ^{1}H and ^{4}He after the initial nuclear reactions. The choice of free parameters in the Big Bang theory which leads to this production of ^{4}He does not appear incompatible with other relevant observations. We shall take this as our starting point. It should be added that it remains the hope of cosmologists and particle physicists that a fuller understanding of the theory will determine the values of the apparently free parameters. If that proves to be so, the unique theory will have to match the observations.

The present composition of the Universe differs from its primeval composition. We believe that this has arisen through nuclear reactions in stars or in more massive objects. What is not clear at the moment is whether any significant production of heavy elements occurred before the formation of our own and other galaxies. This is not important in a general discussion of processes but we will comment briefly on this point later.

Stars form out of interstellar gas, and in a spiral galaxy like our own star formation has been a continuing process ever since the Galaxy itself formed. As protostars contract out of the interstellar gas, their interiors heat up. While the stellar material remains an ideal classical gas, heating is an inevitable consequence of contraction but, once the central density is high enough that the Pauli exclusion principle influences the energy states occupied by electrons, it becomes possible for an increase in pressure, which is required to balance gravity, to be accompanied by a decrease in temperature. If the interior temperature becomes high enough, energy-releasing nuclear-fusion reactions will occur. A succession of nuclear-fusion reactions can, in principle, produce almost all elements and isotopes in the periodic table up to those with the most strongly bound nuclei in the region of iron (the iron peak).

Not all of these nuclear reactions will occur in every star. Some stars attain a maximum central temperature and then cool down after only some of the reactions have taken place; this cooling may be preceded by a substantial loss of mass which implies that final stellar masses may be much less than initial masses and that nuclearly processed material is returned to the interstellar medium. Very-low-mass stars (less than about $0.1 M_{\odot}$, $M_{\odot}$ is the solar mass) have no nuclear reactions at all. In contrast, high-mass stars (greater than about $10 M_{\odot}$) are believed to have the complete set of nuclear reactions and to end their lives as supernovae with a substantial loss of mass once they have run out of nuclear fuel.

The series of nuclear-fusion reactions can be described as follows:

(i) hydrogen-burning, H $\rightarrow$ He;
(ii) helium-burning, He $\rightarrow$ C, O;
(iii) carbon-burning, C $\rightarrow$ Ne, Na, Mg, etc;
(iv) neon-burning, Ne $\rightarrow$ O, Mg, Si;
(v) oxygen-burning, O $\rightarrow$ Si, S, P, etc;
(vi) 'silicon-burning', Na, Mg, Si, S, P $\rightarrow$ Cr, Mn, Fe, Co, Ni.

Hydrogen-burning involves the build up of four protons into helium either directly or using C and N as catalysts, with two β-decays being required. In helium-burning α-particles combine to produce ^{12}C and then ^{16}O. Carbon-burning and oxygen-burning start with fusion reactions between two ^{12}C and two ^{16}O nuclei respectively, whereas neon burning involves the removal of α-particles from ^{20}Ne by photons and their addition to other nuclei. Silicon-burning is a complicated network of fusion reactions and photodisintegrations.

The temperature required for hydrogen-burning is upwards of 10^7 K, helium-burning typically starts at about 10^8 K, and the final reactions leading to the iron peak require temperatures of a few gigakelvins. The majority of nuclear energy is released in hydrogen-burning, which occurs in main sequence stars. Most red giants and supergiants have helium-burning in their central regions. There are very few stars observed in later stages of nuclear evolution both because of the occurrence of neutrino-emitting reactions at high temperatures and densities, which are a much greater energy loss from a star than photon-emission from the surface and which therefore reduce the time taken for these evolutionary stages, and because there are relatively few massive stars. In any star that goes any significant way along this series of nuclear reactions, there may be several zones in which different nuclear processes are occurring at the same time.

The production of heavy elements inside stars would not be of any observational interest if it were not for the mass-loss processes that have already been mentioned, which return to the interstellar medium material which has a different composition from when it was used to form a star. Some of these mass-loss processes are relatively mild, as in the ejection of the outside of a fairly low-mass star to form a planetary nebula. Other processes are violent and catastrophic such as the explosion of a supernova. An important development in the theory of the origin of the elements was the realization that there were both quasi-static nuclear reactions occurring in normal stages of stellar evolution and explosive nuclear reactions occurring, for example, in supernovae.

There is an important distinction between quasi-static and explosive reactions. In quasi-static reactions, an unstable nucleus that may be formed can be expected to decay before it is involved in another reaction. In contrast, in an explosion, unstable nuclei can be involved in a succession of reactions within their normal half-lives. Ultimately unstable nuclei will decay, even if it is after they have been ejected into space, but their decay products are frequently isotopes that cannot be produced readily, if at all, by quasi-static reactions. Although we cannot study the detailed isotopic composition of the Sun and other stars, we do have such information about terrestrial rocks and meteorites and it is clear that some of the Solar System material must have undergone explosive nuclear processing.

Normal nuclear-fusion reactions do not produce the nuclei of elements beyond the iron peak. Their production requires energy rather than yielding energy, so that it is not surprising that the total quantity of them is relatively small. Although massive nuclei could in principle react by charged particle reactions at high enough temperature, the required particle energies are so high that they would be more likely to be broken into smaller fragments than to produce even more massive nuclei. In fact, it is believed that most of the isotopes more massive than nickel have been produced by neutron capture reactions.

As the neutron is an unstable particle there must be processes producing neutrons. Two basic types of neutron-capture reactions have been identified, slow neutron capture (s-process) and rapid neutron capture (r-process). The s-process is believed to occur at a normal stage of stellar evolution when neutrons are produced in an ordinary nuclear-fusion reaction and when there is a high probability that such a neutron will be captured before it decays. A favoured production reaction is

$$^{13}C + ^{4}He \rightarrow ^{16}O + n.$$

There is at the same time little likelihood that any unstable nucleus will capture a further neutron before the nucleus decays. This s-process produces most of the less neutron-rich isotopes of the heavy elements. A strong stimulus to the development of ideas of nucleosynthesis was the discovery of technetium in the atmosphere of an ordinary star (Merrill 1952). Technetium has no isotope that is stable or has a half-life of more than *ca.* 0.2 Ma. As the stars in which it is observed are certainly older than that, it must have been produced in them and it is attributed to the s-process.

The r-process is akin to the other explosive reactions that we have mentioned earlier. Neutrons are added so rapidly that unstable nuclei do not usually decay until ones are produced that will not accept another neutron or until they have been removed from exposure to the neutron flux. One site in which large quantities of neutrons may be produced in appropriate conditions is in the centre of a massive star which is about to become a supernova. As the density of the inner regions increases, neutronization may occur because the capture of electrons by protons becomes energetically favourable. If this is a site of the r-process, the supernova explosion which follows provides a mechanism for putting some of the r-process isotopes into the interstellar medium. In recent years theoretical studies have also identified a modified r-process, the rn-process which occurs with lower neutron fluxes than the standard r-process. It must be stressed that the astronomical sites of the r- and rn-processes remain uncertain (Cameron *et al.* 1985), although it seems likely that the principal site of the r-process involves the expansion of highly neutronized matter from the cores of supernovae.

There are two groups of isotopes which were not produced by any of the processes that have so far been described. These are deuterium, ^{3}He, lithium, beryllium and boron and some of the less neutron-rich isotopes of the heavy elements. Significant amounts, in relation to the observed abundances, of deuterium, ^{3}He and ^{7}Li may have been produced in the Big Bang but this is not true for the other isotopes. It is now generally believed that these light isotopes, which are much less abundant than their neighbours in the periodic table, were produced by break-up of the more abundant nuclei of elements such as C, N and O in interactions between cosmic rays and the interstellar gas. It is not only difficult to produce these light isotopes but it is also difficult to retain them because, if they are incorporated into stars, they are destroyed by nuclear-fusion reactions at temperatures significantly lower than those required for hydrogen-burning. The origin of the proton-rich isotopes of the heavy elements, which are also of extremely low abundance, is still not entirely clear, although proton capture reactions have been discussed. The full range of nucleosynthetic processes was first discussed by Burbidge *et al.* (1957) and by Cameron (1957) and subsequent refinements have been of detail rather than of principle.

The original composition of the Solar System should be to a first approximation the chemical composition of the interstellar gas in the region where the Solar System formed. It is necessary to discuss how this composition was determined by the various processes which we have just described. In principle we should like to determine the chemical composition of the galactic gas disc at any time in terms of its initial composition and of nuclear reactions in stars during the disc's past history. The initial composition of the disc cannot be determined directly from observation. It is thought to have been close to that produced in the Big Bang. The stars in the halo of our Galaxy, such as those in the globular star clusters, are older than the disc stars. They also have a heavy-element content which is significantly smaller relative to H than that of the Sun (by a factor of between 10 and 10^3) and it is possible that the disc started with a composition similar to that observed in the halo. The origin of the halo heavy elements is uncertain. They may have been produced in hypothetical Population III stars whose formation may have preceded that of galaxies. Alternatively the presently observed halo stars may have inherited their heavy elements from the very first halo stars.

It is believed that most of the heavy elements in the disc must have been produced in the disc itself and also that the present chemical composition of the disc gas, and indeed the composition at the time of formation of the Solar System, would not have been significantly different if the disc had started with no heavy elements. A discussion of the evolution of the disc composition requires study of the following:

(i) star-formation, the rate at which gas is turned into stars and the distribution of masses of the stars formed;

(ii) stellar-evolution, the degree of nuclear evolution occurring in stars of different initial masses including the distribution of chemical composition inside stars;

(iii) mass loss from stars, stage(s) of stellar evolution at which different types of star lose mass, the amount of mass lost, its composition taking account of possible explosive nuclear reactions during the mass loss process and its ejection speed;

(iv) mixing of gas expelled from stars with the ambient interstellar medium.

Clearly (ii) and (iii) are not really distinct as mass-loss from a star may terminate its nuclear evolution, whereas this would have continued if no mass was lost. It should perhaps be remarked that, as some isotopes are produced in massive stars which evolve very rapidly while others are produced in longer-lived stars of lower mass, the average elemental and isotopic composition of the interstellar gas will have changed with time. As the Solar System was formed up to 10 Ga after the galactic disc, an approximately steady state should have been reached by then.

It is certainly not possible to determine the original composition of the Solar System by going through the above chain of processes; there are far too many uncertainties. Instead the observed composition of the Solar System is to be regarded as one piece of observational information to be used in trying to obtain a self-consistent account of the chemical evolution of the solar neighbourhood. In such discussions it is usually assumed that the chemical composition of the interstellar gas is a smooth continuous function in space and time, although observations of the composition of stars of similar ages and of the present interstellar gas have sufficient uncertainties that fluctuations of 50 % or more at any given time cannot be ruled out. Perhaps the most important question which we have to consider is whether uniformity of composition is to be expected on the scales with which we are concerned inside the Solar System. In particular, what do observed departures from uniformity inside the Solar System tell us about the formation and evolution of the system?

It is generally believed that the most important input of heavy elements into the interstellar medium is through the explosions of supernovae. They expel matter at a very high speed (more than about 10^4 km s^{-1}). The matter out of which stars are formed has, in contrast, a random thermal speed of only a few kilometres per second. Supernova ejecta must be slowed down before they can enter stars and this slowing down must be as a result of collisions with existing interstellar gas. If it is simply assumed that the momentum of the supernova ejecta is shared with the interstellar gas until it is moving approximately like the gas, it is clear that each solar mass of processed material must share its momentum with several thousand solar masses of interstellar gas. This implies that, provided the supernova ejecta is mixed in with the interstellar gas, a single supernova has little effect on the gas composition. To put it another way, the observed composition must result from the operation of a large number of supernovae so that an overall smoothness is not implausible. The assumption of momentum-conservation is extreme; in the early stages of a supernova explosion, energy-conservation is a better approximation and momentum-conservation only becomes appropriate when the ejected gas is able to cool, but usually much of the momentum remains at this stage.

Some useful production of less heavy elements occurs in planetary nebulae, stars which eject matter at little above their escape velocity. It is clear that the argument given above does not then hold. The material will soon merge into the interstellar medium producing a local change in element abundances. There are also novae that expel some processed matter at a speed between that of planetary nebulae and supernovae. However, the first mixing of matter into the interstellar medium is not the end of the process. Even for a supernova the initial mixing with the interstellar medium is likely to take less than 10 Ma. The time can only be substantially greater if the matter bursts out of the galactic disc with less than escape velocity and subsequently falls back. However, the fact that the galaxy still contains interstellar gas when it is of order 15 Ga old indicates that, unless the gas has all passed through many generations of stars, which is not supported by detailed study, the timescale for star formation is much longer than that for initial mixing. This means that the gas which goes into stars at any given time has had ample time to pass through many interstellar clouds where further stirring will occur.

Two possibilities remain. The first is that stars are formed in regions which have recently experienced a new input of processed matter. This could imply both that at a given time star-forming regions have a higher than average heavy element abundance and that the processed matter has not yet experienced fine-scale mixing. It is frequently suggested that explosions of supernovae stimulate the formation of further stars and in particular it has been proposed that the formation of the Solar System was immediately preceded by the explosion of a supernova (Cameron & Truran 1977). This idea has since been questioned (Clayton 1978) but we shall return to it in the next section. The other possibility is that, although processed matter is generally well mixed into the ambient gas, this is not equally true on all lengthscales. If this is so, there might be small pockets of anomalous composition in a gas cloud. One point to which we will return later relates to the possibility that small solid particles might form out of the products of nucleosynthesis and might survive the mixing process.

Once a star (and planets and smaller objects) is formed, it must continue from time to time to be exposed to the effects of supernova explosions. It now presents a very small cross section compared with when it was spread out as interstellar gas and the resulting change of chemical composition should be unimportant except in the very rare case of explosion of a very close star. The interaction with giant molecular clouds, which has already been mentioned in the previous section, is potentially much more significant. I shall therefore assume that once the planets and other smaller objects in the Solar System have formed they are not subjected to any further direct irradiation by products of nucleosynthesis.

3. Considerations particularly relevant to the Solar System

Although the process of star-formation is still only imperfectly understood, we believe that a subunit of an interstellar gas cloud of mass greater than the present mass of the Solar System has contracted and formed the Solar System. The present distribution of chemical elements throughout the system must reflect any original irregularities and also any segregation processes which have occurred during the formation of the system. It is with the initial composition of the material that I am concerned and I shall leave the later stages of the Solar System formation to other authors. Early observations of the composition of the Solar System were consistent with its having formed out of a pool of gas of uniform composition and the arguments given in the previous section have suggested that there is nothing unreasonable in such an assumption. However, as has also been explained, there must be some modification in this view as a result of the discovery of microscopic abundance anomalies in meteorites; see Wasserburg & Papanastassiou (1982) for a review of the meteoritic evidence. We are concerned with what this implies about the uniformity of composition of the gas cloud that formed the Solar System.

The crucial point in our previous discussion was that the overall composition of the Solar System has received nucleosynthetic contributions from many stars of different types. Some stars preferentially produce one group of elements and other stars another group. In particular, some isotopes of individual elements are most easily produced in quasi-static stages of stellar evolution and others are produced in explosive processes in supernovae. So many contributions are required to produce the final mix of elements and isotopes that we are, in principle, prepared to believe that the composition of the interstellar medium varies smoothly in space and time. The composition of Allende suggests that this cannot be true in fine detail; we would not be surprised at segregation of elements during the formation of the Solar System but separation of isotopes of one element is more difficult. This suggests the possibility that part or all of the proto-solar system might have contained some nucleosynthetic products which have not mixed thoroughly with the remainder of the gas, possibly because there has not been enough time for the mixing to be effective.

This possibility led to the idea that the Solar System material may have been exposed to material from a nearby supernova very shortly before the Solar System formed (Cameron & Truran 1977). Indeed it was suggested that the formation of the Solar System was a particular instance of supernova-induced star formation. It has previously been suggested that the Solar System material was exposed to a final spike of nucleosynthesis to account for the manner in which the heavy, radioactive elements acquired their present abundances (see, for example, Schramm 1974), but the real stimulus was the discovery that ^{26}Al must have been present when the Solar System formed (Lee *et al.* 1977); this is required to explain the observed abundance of ^{26}Mg. ^{26}Al has a half-life of only 0.7 Ma and this suggests that it must have been produced just before the Solar System; this is a much shorter time delay after the first nucleosynthetic event than had been previously estimated. Although the total amount of matter from a single supernova, which would be added to the Solar System material, would not have a significant influence on the overall composition of the material, unless the supernova was extremely close, it might provide inclusions of material with anomalous abundances as a result of incomplete mixing. Reeves (1978) put forward a modified suggestion that involved a number of supernovae. He argued that most stars are formed in OB associations in which a significant number of massive stars are likely to evolve and become supernovae before many low-mass stars have formed. His suggestion was that the Solar System might have been exposed to about ten supernovae, with different abundance anomalies being produced by different supernovae.

Clayton (1978, 1986) has proposed a different way of explaining the abundance anomalies in meteorites without requiring a supernova explosion just before the formation of the Solar System. His idea is that small solid particles (sunocons) can condense out in supernova ejecta in a similar manner to the observed condensation of grains in the expanding atmospheres of novae. The grains would then possess isotopic abundances which were typical of the supernova or at least of that part of the supernova envelope in which they condensed. The grains would be mixed into the interstellar gas and they would then survive until they were placed in an environment which favoured grain destruction. The Solar System material could have included grains which has been formed in the envelopes of a number of supernovae and some of these grains may have survived the formation of the Solar System and have been incorporated in some of the smaller solid objects. In this picture, just as in the suggestion by Reeves, there is no reason why the different abundance anomalies in meteorites should be explicable in terms of the mix of isotopes manufactured in a single supernova. Clayton has argued that some correlated abundance anomalies in meteorites, such as those involving O and Al, are understandable because the elements would be associated in the exploding supernova. Grain-formation would keep them together, whereas this might be much more difficult in a gas phase. Following Clayton's suggestion, Consolmagno & Cameron (1980) agreed that a supernova trigger was not necessary for the production of anomalies. Wasserburg (1985), however, still argues that the meteorite evidence requires late injection of *ca.* $10^{-4}\ M_{\odot}$ of freshly synthesized material.

Clayton's proposal raises the question of the survival of grains which have formed in other environments; indeed he did also (Clayton 1978) mention grains formed in stellar winds and in cool gas clouds. The formation of grains in novae has already been mentioned; novae do play a role in nucleosynthesis (Truran 1985) and their grains might therefore also contribute to abundance anomalies. Grains are also believed to form in the atmospheres of cool stars. The suggestion that grains might, in effect, remember their place of origin has another implication. When abundances are obtained for the interstellar gas by observations of absorption lines superimposed on stellar spectra (Morton 1974), some elements are found to be depleted compared to normal cosmic abundances and it is assumed that these depletions indicate what elements are contained in interstellar grains in the same region. If grains are not mainly formed in the interstellar gas this could alter this conclusion at least in detail.

Lee *et al.* (1977) argued very strongly that ^{26}Al must have been present in the inclusions in Allende when the meteorite was formed. They stated that the evidence was strongly against ^{26}Mg arriving in interstellar marbles. If that is correct the ^{26}Al cannot have been produced in sunocons except in the supernova trigger which Clayton wishes to exclude. The original argument that there could not be a steady-state abundance of ^{26}Al in the interstellar medium comparable with that deduced for the meteorite has since been considerably weakened by the discovery of a γ-ray line which can be attributed to the decay of ^{26}Al (Mahoney *et al.* 1982, 1984). If this identification is correct, it suggests that the current abundance of ^{26}Al in the interstellar medium may well be comparable with that deduced for the forming Solar System. Truran (1985) has suggested that novae may be the main source of the radioactive elements ^{22}Ne and ^{26}Al and Clayton (1984) also favours novae for the production of ^{26}Al.

The view expressed by Suess (1965) that the Solar System material was at one time homogeneous and gaseous is no longer the accepted view today. Whether or not Clayton's explanation of the meteoritic anomalies is correct, it seems clear that the protosolar nebula contained dust grains and that some of these will have entered solid bodies in the Solar System without being completely vaporized. This means that it is necessary to consider the extent to which solid particles survive destruction in the interstellar medium. Barlow (1978) considered the destruction of interstellar grains by sputtering in H II regions, in the intercloud medium and in shock waves produced by cloud–cloud collisions and by supernova remnants. He found supernova shock waves to be the most important (see also Seab & Shull 1983) and estimated ages between 0.2 and 2 Ga depending on the composition of the grain. A discussion by Draine & Salpeter (1979) suggests that a destruction timescale at the lower end of Barlow's estimate might be appropriate.

If this is correct, it could raise a problem for Clayton's idea that grains from supernovae are incorporated directly into the Solar System but not of course for the general idea that small solid particles avoided dissolution as the system formed; the formation and destruction rates of grains must be approximately equal but, if grains are destroyed rapidly, most of the grains in the Solar System must have been young. Clayton (1986) has agreed that it is unlikely that the sunocons would escape destruction from sputtering unless they acquired mantles that protected the inner regions and he has further argued that adequate mantle formation would be likely. Clayton (1983) has also suggested that the observation of ^{142}Nd in meteorites indicates that the meteorites contain grains which were produced in the atmospheres of cool stars and which contained s-process elements including ^{146}Sm which decays to ^{142}Nd. For another view that meteorites do contain grains from a variety of astrophysical environments see Kerridge & Chang (1985).

There is a further line of evidence concerning the incorporation of interstellar grains of any type in Solar System objects. If a grain is in the ordinary interstellar medium as opposed to being deep inside a dense cloud, it is exposed to a flux of cosmic rays and these cosmic rays will from time to time damage the grain. If the grain is not melted but becomes part of a meteorite or another solid body, the damage caused by the cosmic rays will be frozen and will be able to be studied. Obviously the average extent of cosmic ray damage will depend on the age of the grain unless it has spent most of its existence in a highly shielded environment. Wasson (1978) argued that grains would spend most of their life in a region exposed to cosmic rays and that the observed cosmic ray exposure ages of chondritic meteorites were too low for them to be composed of interstellar grains. In addition he argued that most interstellar grains would not survive in the solar nebula. It is clear that the interstellar origin of inclusions in meteorites is a complicated and controversial topic, which will, I hope, be clarified later in this symposium.

Although small solid particles are almost certainly the most efficient manner of introducing abundance irregularities into the solar nebula, unless these irregularities are due to a late supernova, there remains the possibility that the interstellar gas itself is less well mixed than we have been implicitly assuming. The argument relating to supernova ejecta was that each solar mass would have to interact with several thousand solar masses of interstellar gas before it was moving sufficiently slowly to be incorporated in the general interstellar medium. This argument does not, however, say that the supernova ejecta must be smoothly mixed into the swept-up gas. The role of magnetic fields is crucial in the behaviour of supernova remnants. If there were no magnetic field, the mass lost by a typical supernova would escape freely from the Galaxy without colliding with the interstellar gas because the collision mean free path for energetic supernova particles is greater than the thickness of the gas disc (Spitzer 1978). It is the magnetic field that enables hydrodynamic behaviour to occur because the gyration radii of the particles are very much smaller than the disc thickness. The essence of this is that the ejected material and the ambient interstellar medium only interpenetrate a few gyration radii at most. In these early stages after the explosion, efficient mixing of the two components will only occur if instabilities at the interface lead to such small scale irregularities that the particles are no longer effectively tied to the magnetic field lines.

Once the supernova material is effectively part of the general interstellar medium, the most effective mixing process may well be ambipolar diffusion, whereby the neutral component of the interstellar gas can slip relative to the ionized component. If the material spends a sufficient time in clouds which are essentially neutral, the assumption of fine-scale mixing may be realistic. It would, however, require a very detailed discussion to demonstrate that this mixing would be effective right down to the scale in the interstellar gas which could lead to microscopic inclusions in meteorites.

If the solar nebula formed with abundance irregularities due to the presence of small grains and possibly due to irregularities in the gas component, these would be effectively erased in the Sun, if it had a fully convective Hayashi phase, but they would survive in the rest of the nebula provided that it was never both at a high temperature and thoroughly well mixed. Although it appears that high temperatures did occur in the solar nebula even quite far from the Sun (Wasson 1978, Boynton 1985), it is also believed that irregularities did survive the formation process.

Reference was made earlier to the possibility that the passage of the Solar System through a giant molecular cloud might lead to the capture of new comets. This is one reason why an accurate composition of a comet sample would be of great interest, although even if new abundance anomalies were found it would probably prove very difficult to associate them with a capture event rather than with the formation phase of the Solar System.

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