Recent Developments on the Problem of the Origin of the Solar System [and Discussion]

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Recent developments on the problem of the origin of the Solar System

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Relics of the molecular cloud origins of the Solar System are found in the deuterated molecules of meteorites. The situation is summarized and discussed in conjunction with the isotopic anomalies of heavier elements, to obtain an overall view of the whole event.

1970: The classical protosolar nebula

It will be convenient to use the year 1970 as a reference date and to compare our present views with those prevailing then. Those were the times of the 'homogeneous, cooling protosolar nebula', here called the 'classical' protosolar nebula. A gaseous cloud, with dimensions of a few tens of astronomical units and a mass of a few hundredths to a few solar masses (according to the various authors), extended in a disk-like fashion from an axis of rotation where was (or was to be) the Sun. The cloud was of standard cosmic composition, thoroughly mixed. The temperature, pressure and density were decreasing functions of the radial distance.

Many of the presently observed characteristics of the Solar System were assumed to have been generated by physicochemical processes, in full thermal equilibrium, during the cooling of the nebula, from temperatures in excess of 2000 K. For an extended review of this, see for example the *Proceedings of the Nice Conference on the Origin of the Solar System, 1972*.

Wetherill has recently pointed out an important difficulty with the thermal luminosity of this hypothetical nebula. Simple calculations, considering on the one hand the gravitational energy released from the collapse of the gaseous mass and on the other hand the luminosity corresponding to the temperature required, run into serious difficulties unless one appeals to very short lifetimes.

Fossil radioactivities

Next I will give a summary of the recent data that cannot easily be explained in the frame of this classical protosolar nebula, and for which some extension of the picture is required.

The most dramatic event of this last decade is certainly the discovery of fossil ^{26}Al in a few meteorites. These nuclei are observed in the form of 'anomalous' ^{26}Mg in certain mineral phases. The strong correlation between the abundance of this anomalous component and the Al/Mg ratio of the phase leave little doubt about the fact that the effect is due to the presence of 'live' ^{26}Al at the period of crystallization, which later decayed (half life 7.6×10^5 a) into this anomalous ^{26}Mg component (Lee *et al.* 1976; Gray & Compston 1974).

A cosmic ray spallation origin for this ^{26}Al is made highly unprobable by absence of other spallation products (Reeves 1979). The only alternative origin known today is stellar thermonuclear reactions, probably (although not certainly) from a supernova. The proper nuclear mechanism is yet to be identified. Heavy-ion reactions (such as carbon burning) and also exploding H, He burning phases, with reactions on ^{14}N have both been proposed (Truran & Cameron 1978; Arnett & Wefel 1978; Arnould *et al.* 1978).

They suggest a supernova explosion in the vicinity, in space and time, of the planetary system in formation. The detection of similar anomalies in ^{107}Ag, clearly related to the decay of ^{107}Pd (half life, $\tau_{\frac{1}{2}} = 6.5 \times 10^6$ a), and some recent data on the ^{129}Xe/^{127}Xe (from ^{129}I decay; $\tau_{\frac{1}{2}} = 25 \times 10^6$ a) also corroborate this picture (Jordan *et al.* 1977; McCulloch *et al.* 1978) It will be the aim of this paper to find, from astronomical observations, 'simple' and 'natural' explanations to this event.

ISOTOPIC ANOMALIES ON STABLE ELEMENTS

The fossil anomalies described in the previous section were restricted to a few grams of meteoritic matter. Another class of tell-tale events came with the discovery of widespread isotopic variations of oxygen (^{16}O, ^{17}O, ^{18}O,) that could not be assigned to physicochemical processes. The interpretation is complex and still incomplete. It appears to involve the presence of several initial reservoirs of oxygen with up to 5% differences of isotopic ratios in the form of gases or grains. The wealth of observational data could then be explained by variable mixtures from these reservoirs. Many other isotopic anomalies of stable elements have been found, albeit on a much smaller scale. Here again the interpretation appears to require the existence of several initial reservoirs with differing isotopic composition (R. N. Clayton, this symposium).

DEUTERATED MOLECULES

A vigorous effort has been made in recent years to study the isotopic abundance ratios of hydrogen-containing molecules in meteorites. These studies can yield important information on the nature of the physicochemical processes taking place during the formation of the Solar System, first because there is some idea of the original D/H ratio in the primitive matter of the planetary system. The estimates obtained indirectly from a study of the helium isotopic ratio in the solar wind (Geiss & Reeves 1972; Bochsler & Geiss 1979), helium in meteorites (Black 1972) and Jupiter's atmosphere (Combes *et al.* 1978), coincide fairly well with the present-day interstellar value (Rogerson & York 1973; Vidal Madjar *et al.* 1977) of $D/H = 2 \times 10^{-5}$ (thus confirming the view that D has not been largely generated or destroyed during the last 5×10^9 a). It is worth recalling here that D is generally believed to be a product of the 'Big Bang', slowly to be destroyed by astration in stars (Reeves 1974).

Secondly advantage is taken of the large isotopic mass ratio (2) of hydrogen. Isotopic effects are thus expected to be the largest here, and hence most easily detectable.

The first substance of interest in this respect is simple tap water. Let the number V_{M} be the ratio of D/H, by number of atoms, in molecule M to the same ratio in primitive matter ($D/H = 2 \times 10^{-5}$). For tap water one has $V_{\mathrm{H_2O}} = 8$ and the question is why? For crystalline water in many meteorites this value does not differ appreciably (Boato 1954). However, recent studies have yielded values of V up to 30 (Javoy *et al.* 1980; Kolodny *et al.* 1980; Robert & Epstein 1980) in organic matter.

Much larger values of V are commonly found in dark molecular clouds: up to 10^2 for HCO^+; up to 5×10^2 for HCN; and up to 2×10^3 for HNC (Jefferts *et al.* 1973; Guelin & Lequeux 1979).

The molecule HDO has been observed and, although no V are reported, its mere detection implies $V_{\mathrm{H_2O}} \gtrsim 50$ (J. Lequeux, private communication). These D enrichments are assigned to ion-exchange reactions at the very low cloud temperature ($T \approx 50$ K). (Physically this corresponds to the higher mass, hence lower vibration frequency, hence lower zero-point energy of the deuterated molecule which, through the partition function, finds itself more populated than its lighter counterpart at low temperature.)

One is naturally tempted to assign to the Solar System V values given above (for water and organic compounds) the same origin, in other words to consider these molecules as *relics* of the dark cloud prehistoric phase of the planetary system. In a recent paper (Geiss & Reeves 1981) a number of alternative possibilities have been considered together with this one. In view of the numerous difficulties met by these alternative solutions the dark cloud relic interpretation is the most likely one.

It is noted that the V values of the Solar System are intermediate between the cloud values (10^2 to 10^3) and the value for no enrichment at all ($V = 1$). Why is this? In the classical protosolar nebula an early heating to large temperature values ($T > 1000$ °C) is assumed. In this case the V would gradually decrease to $V \approx 1$ because of the $HD + H_2O \leftrightharpoons HDO + H_2$ reaction and similar ones for the organics (Reeves & Bottinga 1972), *and all relic D enrichment would have been erased.*

One could of course invoke later processes in the solar nebula to re-establish these large V. One may, for instance, consider the possibility of molecular exchange reactions taking place in the cold counterparts of the Solar System at a temperature of *ca.* 200 K. One would then invoke a migration of terrestrial and meteoritic water from these regions, perhaps in the form of comets, a rather contrived assumption.

It appears strategically advisable to follow a simpler avenue of thinking and to naïvely associate the Solar System V value to molecular cloud processes. But, then, why are they systematically one or two orders of magnitude smaller than the cloud values?

The key point here is that equilibration of the V value to ambient temperature can only take place in the *presence of a large reservoir of hydrogen.* In the dark clouds, the water molecules are observed to be present both in the gas phase (from radio emission) and as an icy component at the surface of the dust grains (from i.r. absorption) (Gillet & Forrest 1973; Papoular & Rouan 1981). It is believed that the exchange reactions take place in the gas phase, mostly by H_3^+ and CH_3^+ reaction (Mitchell *et al.* 1978).

Suppose that at a given moment the solid and gaseous phases are somehow separated. The water on the grains will retain the V value characteristic of this moment (except for a small effect due to absorption). If full equilibrium had been maintained previously, this V would yield the temperature at the moment of the separation. No amount of heating could later alter this value (provided that the dissociation temperature is not reached).

The gas–grain separation could simply result from the gravitational collapse of a dust cloud (Goldreich & Ward 1973), and consequent accumulation of grains in some extended body, from the interior of which the hydrogen gas would naturally be ejected. This scenario, however, requires that the dust grains accumulate *before* their ice coatings are vaporized. The V value observed for water and organics indicate a temperature of 200 K or less, totally consistent with this requirement. (The estimation of such a low temperature is probably still valid even if equilibrium is not always maintained.)

It is not easy to see how these deuterated molecule abundances could be accounted for in the frame of the classical protosolar nebula.

THE ASTRONOMICAL SITUATION

These new data on isotopic anomalies (fossil and stable) and on deuterated molecules suggest that new elements should be introduced to the picture. To avoid arbitrariness, it appears advisable to lean as much as possible on astronomical information about the physical context of stellar birth.

Proceeding in this way is soon rewarding. Young stars are indeed found in close contact with dark molecular clouds, and thus the large V values appear quite natural. Furthermore most stars are born in clusters and associations. Most of these associations are not gravitationally bound. In a period of *ca.* 10^7 a the stars move away from each other and the association is disrupted (Blaauw 1964).

These associations are usually characterized by the presence, in their midst, of a small number of very bright massive stars, called O and B stars (hence the name of OB association). Because of their large luminosity, these stars last only a few million years. Thus some of these massive ($M \geqslant 16\ M_{\odot}$) stars will live and die before the association is dispersed. At their death they explode and develop a supernova remnant which expands and, in *ca.* 10^5 a, covers a large fraction of the whole association. Thus, newly made nuclei are transported and mixed with the gaseous matter of the OB association.

A statistical study of stellar populations indicates that, in an average size association, about ten stars will contaminate the cloud matter before the end of star formation and dispersion (Reeves 1979). Thus we expect all stars and planets formed in an OB association to contain some newly made atoms. The characteristic times involved here are *short enough* to account *naturally* for the short-lived fossils, such as ^{26}Al, in the forming Solar System.

It should be added that the relative amount of contamination will always be small. The exotic ejecta from any exploding star will be mixed with 10^4 to 10^5 $M_{\odot}$ of ordinary interstellar matter in the 10^5 a of the remnant deceleration. Simple calculations show that the 'anomalies' brought by any one supernova (abundance difference of one species between 'before' and 'after') is at most 1 %. The added effect of all the supernova within the lifetime of one association should not be larger than 10–20 %, as observed.

Thus, in the context of an OB association, with its placental molecular cloud, a natural explanation has been found for recent data. This suggests that the picture of the protosolar nebula should be extended to the 'protosolar dark cloud' and 'protosolar OB association'. One should then consider questions such as: 'How much of the physicochemistry of the planetary system took place in the dark cloud phase?' and 'What was the influence of nearby stellar perturbations (expanding H II regions, supernova explosions and remnants) on the Solar System during its earliest phase?'.

A SCENARIO

This section is more speculative. Here I try to imagine the situation in the context of the protosolar OB association and to deduce some useful information. I will choose the Orion region as model and try to remain as close as possible to the observations (Zuckerman 1975; Kutner *et al.* 1977).

The story starts with an extended mass of interstellar matter travelling between two arms of our galaxy. It has the standard chemical composition, inherited from all the nucleosynthetic processes (red giants, planetary nebulae, novae, supernovae) from stars of all masses, since the beginning of the galaxy. This I shall call the 'background composition', against which later injected anomalies will be contrasted.

A fair fraction of the refractory elements is condensed into dust grains.

This matter is presumably well mixed and homogeneous in chemical composition. Some degree of inhomogeneity could already be present as the various grains may have condensed in different situations (expanding novae and supernovae remnants) (Eberhard *et al.* 1979; Greenberg 1978; Clayton 1977; Srinivasan & Anders 1978).

Grains are continually bombarded by galactic cosmic rays. In view of their small average size (*ca.* 0.1 μm) most of the spallation products will be ejected from the grains. However, xenon nuclei will not (Geiss & Reeves 1981). Thus measurements of xenon isotopic ratios may yield an estimate (or an upper limit) to the total fluence received by a meteorite, including both its early dust phase and its later meteoritic phase (if no degassing took place). The values obtained are of the order of 10^{17} cm^{-2}, equivalent to 10^9 a of galactic cosmic rays. As will be discussed later, a fraction of this irradiation could have taken place during the protosolar OB association phase itself.

As this matter approaches a galactic arm, it is strongly decelerated and compressed. It takes the form of a giant molecular cloud with $M \approx 10^5$ $M_\odot$, density (n_H) *ca.* 10^3 cm^{-3} and dimensions of several tens of light years (Kutner *et al.* 1977). It becomes opaque to stellar light and cools to very low temperature. Atoms combine in molecules, and ices are deposited on the grains. The high energy ($E \geqslant 300$ MeV) cosmic ray still penetrate the cloud (Cesarsky & Volk 1978) and keep some degree of ionization. Ion-molecular exchange reactions initiate a fairly active chemistry leading to the formation of interstellar molecules such as HCN, H_2CO and heavier ones, together with the D enrichment reported previously.

Piecewise, this cloud fragments and collapses into smaller units of $M \approx 10^3$ $M_\odot$ and $n_H \geqslant 10^6$ cm^{-3}, such as the KL nebula in Orion. More fragmentation takes place within this object, soon leading to a very close-packed cluster of several tens of infrared objects.

Studies of the i.r. emission pattern show that the members of this cluster are separated by *ca.* 10^{-2} light year at most, roughly one-hundredth of the average interstellar distance in the galaxy. This '*promiscuity*' of newborn stars is an important piece of observational information which will enter in the new picture of the origin of the Solar System. For comparison, the long-period comets have orbits extending to 0,5 light year. Thus, if comets were already in existence during this proto-infrared cluster phase of the Solar System, they were probably cruising between the stars like electrons in a crystal.

Within *ca.* 10^5 a the most massive of the objects warm up to the point of becoming visible as blue supergiant stars (O and B). Their light contains enough H-ionizing radiation to initiate HII regions such as the Orion nebula. The border of this region moves rapidly in space in the form of a shock front and reaches dimensions of several light years. Partial vaporization of the grains takes place throughout this region.

During their main-sequence period these blue stars develop powerful stellar winds accompanied by strong u.v.- and X-radiation fluxes. These stellar winds are presently considered as a potentially important source of cosmic rays (Cassé & Paul 1980).

Within a few million years these stars will expand as Red Giants, and explode, forming a vast supernova remnant extending several tens of light years away. In about 10^5 a, the matter ejected from the dead stars will thoroughly mix with the entire cloud in the form of gas and new grains.

Another piece of important information is obtained by observation. The events described here do not take place simultanelusly in the whole cloud, but rather in several episodes taking place in different parts (Elmegreen & Lada 1977). Star formation spreads like forest fire. At any one time, various regions coexist with different degrees of advancement of the process. Thus, at one light year from the i.r. cluster in Orion, lies the Trapezium cluster with visible stars (Zuckerman 1975). Its age is *ca.* 1 Ma. In the near vicinity three other subgroups exist with ages of about 3, 5 and 8 Ma (Levato & Abt 1976). In this way, processes occurring late in the life of an O star will influence nearby i.r. objects.

The analysis of the deuterated molecules indicates that a certain fraction, at least, of the physicochemistry of the Solar System took place in the dark cloud phase. Other effects could also date from this period. Shock fronts from progressing H II regions or supernova remnants should be expected to have left some traces. Could chondrules be the residues of their passages in dense regions?

How are we to describe the early Solar System with its many companions in close proximity. After other authors, I am presently attracted by the picture of 'accretion disks?'. One nice thing about these disks is that *they are known to exist in Nature*, as witnessed for instance by the X-ray sources.

One imagines a cloud fragment, with $M \approx 10^3\ M_{\odot}$, $n_H \approx 10^6\ cm^{-3}$, in which a certain number of protostars have already started to condense, forming many centres of gravitational attraction. The residual matter is slowly falling into these centres, forming around each one an accretion disk where the gas is kept spiralling towards the axis. During this transit period, part of the grains coalesce and accumulate in the form of larger bodies, on which the gaseous drag becomes less and less important. They are finally left on Keplerian orbits while the gas phase ends up in the sun.

The main difference between this picture and the standard nebula is that matter is added continually from outside. This opens the possibility that the formation of the Solar System took place during an extended period of time, during which matter, variously affected by the nearby supernova remnants, could have been introduced, as suggested for instance from the $^{129}Xe/^{127}Xe-^{129}Xe/^{132}Xe$ data of the Heidelberg group (Jordan *et al.* 1977).

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Discussion

M. M. Woolfson (*Physics Department, University of York, Heslington, York YO1 5DD, U.K.*). I was very pleased to hear that Dr Reeves is now proposing that the origin of the Solar System is somehow associated with the origin of stars in clusters. As he will know the 'capture theory' which my colleagues and I have been developing over the past few years also begins in such an environment. We have examined the outcome of an interaction between a condensed solar-mass star and a diffuse protostar of lesser mass. It has been clearly shown that a tidal filament can be drawn out of the diffuse star and captured by the condensed star. Under suitable conditions, planetary condensations can form in the tidal filament as Jeans (1919) showed many years ago.

In a recent paper, Kobrick & Kaula (1979) have also come to a similar conclusion although they have suggested a mechanism somewhere between that of Dr Reeves and myself. Thus they too have a captured filament but this is also allowed to dissipate to form a captured nebula. In support of my own version of the capture mechanism I must say that it seems an unnecessary complication to take material that has been conveniently concentrated in a collapsing protostar, to allow it to become very diffuse and then to go through the rather complicated, and theoretically very uncertain, process of forming it into planets.

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