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Introduction to Panel Discussion: Chemistry and Cosmos

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Introduction to panel discussion: chemistry and cosmos

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These remarks are intended to recall the general character of the models referred to in the title of the panel discussion, and to call attention to some of the particular features in which chemistry appears to be specially concerned.

Introduction

At any given epoch in the history of a galaxy, chemistry proceeds – so far as astronomers can ascertain – in only a very small fraction of all the matter present. The sites concerned are:

circumstellar material near cool stars;
supernova ejecta, or interstellar material encountered by such ejecta;
interstellar 'molecular' clouds;
planetary systems.

Astronomers still know only the one planetary system, the Solar System. It is chemistry that makes this system, and any others like it, different from anything else in the cosmos; in fact that makes their existence possible. Chemistry should provide the vital clues to the origin and formation of planetary systems. These rather obvious considerations were the motivation for the holding of this Discussion Meeting.

Planet formation

For the moment we restrict attention to the formation of the planets of the Solar System, without considering the formation of the Sun except in so far as this may be part of the same process.

It seems fairly certain that Earth and Moon as individual bodies of matter were formed about $4\frac{1}{2}$ Ga BP. Available evidence supports the inference that all the terrestrial planets are of the same age. There is little direct evidence about the ages of the giant planets but there is nothing known to contradict the proposition that they are at least as old as the terrestrial planets. So it is generally taken as a good working hypothesis that all the planets were formed about $4\frac{1}{2}$ Ga BP, in what can be regarded as a single 'operation'. Actually Professor Cole, in this Discussion, advances a somewhat modified opinion on this last point.

At that epoch the Galaxy would have been in essentially the same state as it is now. In particular the raw material available for planet-formation would have been like present interstellar matter (ISM); effectively so, even if Professor Woolfson's 'capture theory' is accepted, because it uses material taken from a protostar formed from such material. This ISM has approximate composition by mass, in the form of gas hydrogen, 73 %, helium 25 %, heavier elements 1 %, and in the form of dust-grains 1 %. Apart from inert gases, some of the gaseous material is in molecular form; the dust grains are made of solids, most of the mass of which is contributed by the 'heavier' elements.

Models of planet-formation from this material are based upon one or other of the following hypotheses.

(*a*) A body of the raw material came to form a nebula revolving around the Sun. Each existing planet was formed from this nebula by accretion processes that, when complete, left this planet with the mass and overall composition which it has retained ever since.

(*b*) Proto-planets were all simply comparable bodies of the given raw material. A proto-planet by contraction and sedimentation, possibly accompanied by loss of material and/or rotational fission, evolved to yield one, or possibly two, of the present planets.

We briefly discuss each hypothesis in turn.

(*a*) *Solar nebula hypothesis*

Many variants have been studied: here we try to concentrate upon what appear to be the essential features common to all models that may be treated under this heading.

The Sun is assumed to acquire the nebula composed of the given raw material and occupying a region of radius of the order of that of the orbit of Neptune. The total amount of material is usually supposed to be not a lot more than that of the present planetary system so that its motion as a whole is controlled effectively by the gravitation of the Sun alone. This motion is essentially that of a body of gas under this gravitation; initially it is supposed to be steady circulation about a central axis through the Sun. In the rotating frame appropriate to any particular distance from the axis there is a gravitational attraction of the nebular material towards the equatorial plane of the system. This tends to cause dust grains suspended in the gas to fall towards that plane, and to accumulate close to the plane. If this happens the dust component of the nebula would form a thin layer of this heavier material in differential rotation in the plane about the axis. Such a layer would be gravitationally unstable in the sense that it would tend to break into fragments exceeding some minimum size, any one of which would tend to contract upon itself under its self-gravitation. If such a fragment has some means of dissipating the kinetic energy of the relative motions of its parts it would tend to form a permanent condensation of its constituent matter. This seems to be the simplest way of forming the condensed bodies called *planetesimals* which are mentioned so frequently in the course of the discussion.

Planetesimals, by virtue of the way in which they come into existence, must tend to go into approximately circular orbits about the Sun at about the distance from the Sun at which they are formed. But there must be stochastic features in the happenings resulting in stochastic features in the assembly of initial orbits. So there must ensue very many collisions between the planetesimals.

If it be assumed that whenever a planetesimal or a merger of planetesimals collides with another such body the two bodies form a single new merger, then such mergers will form and large ones will swallow up smaller ones. As the processes continue the effective cross section of a larger merger for accreting smaller ones is enhanced by its growing gravitational field. A stage must come when in this manner a comparatively small number N of comparatively large bodies will have accreted all the planetesimals, and there is negligible chance of a collision between any of the N. The symmetry of the system about its equatorial plane requires all the N orbits to be in that plane. The formation process requires all the orbits to be described in the same sense. The requirement of no further collisions favours almost circular orbits. The value of N must depend upon all the parameters of the system, particularly those that determine how the planetesimals had been distributed over the plane in which they were formed.

The bodies would have been formed from the condensed material of planetesimals in ways that should ensure that the bodies themselves are composed of such material. If all the contemplated processes have performed efficiently the N bodies would be composed of effectively all the dust material originally present in the postulated solar nebula. The generally inferred composition of the dust would, as regards element abundances, result in these bodies having just about the composition of actual terrestrial planets.

The envisaged production of the N bodies would thus have used up only about 1% of the mass of the nebula. So far as the discussion goes the remaining 99% would still be present as gas. If any of the N bodies had become sufficiently massive, it would start accreting this gas and, of course, the more it adds to its mass in this way the more effectively it can accrete until it has gathered up all such material within its range of influence.

On this model those of the N bodies that accrete little gas would be its 'terrestrial' planets, such as Mercury, Venus, Earth, Mars, which have total mass *ca.* 2 Earth masses. Those that accrete most gas would be 'giant' planets, such as Jupiter and Saturn, which have total mass *ca.* 413 Earth masses: those that accrete an intermediate amount would be other 'giants', such as Uranus and Neptune, total mass *ca.* 32 Earth masses. If we take $N = 8$ we should expect on the model the four 'terrestrial' planets to have no more than 0.5% of the total mass. In the actual Solar System they have about $200 \div 445 \approx 0.45\%$. This may appear to be a good overall check on the model. But it need be no more than a check on the general correctness of ideas about the raw material of the planets.

All that has been said here about this type of model is only a simplified qualitative description intended to indicate the sort of concepts involved. Workers in the subject have carried out extensive computer simulations based upon precise quantitative statements of the postulates used.

Such work shows that with (*a*) suitably chosen initial conditions and (*b*) well-formulated assumptions about processes of merging, accretion, etc., the model does reproduce a set of bodies quantitatively similar to the planets of the actual Solar System as regards orbits, masses and element-composition.

This type of model seems to have difficulties in estimating the time intervals required for the various processes.

It seems also to have little to say about the axial spins of the planets or about the occurrence of satellite systems. Without further eleboration such a model does not predict the internal structure of the planets, in particular that of the terrestrial planets.

In practice such models seem to throw little light upon the formation of the Sun: they seem mostly to suppose simply that the Sun has been in its present state at all relevant epochs.

Questions about the chemistry of the solar nebula model

These are the questions at the basis of this discussion; here we mention a few quite briefly.

Within the postulated solar nebula does the Sun cause any relevant variation of the chemical properties of the ISM with distance from the Sun? Such variation seemed to be an essential feature of early models in this category, but it now seems to have come to receive less attention.

The occurrence and outcome of sedimentation of grain material into the equatorial plane of the nebula must be determined by the chemical nature of the grains; are the grains expected to adhere to each other after encounters? If so, do they adhere selectively, say, metal to metal?

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

What is the expected chemical composition of the sedimentary layer? Would it indeed condense into planetesimals? If it would, what would be the masses and chemical composition of these bodies? Or is there some fate of the material more probable than the formation of planetesimals?

If in some model the production of some form of planetesimals is the most probable outcome at the stage concerned, is the most probable next stage the merging together of these bodies into bodies of ultimately the masses of terrestrial planets? What chemistry must proceed during and after such accretion? Would it produce the inferred core–mantle structure of terrestrial planets?

Then there are questions arising from the presumed next stage, the accretion of large amounts of mainly 'light' gas by some of the bodies just mentioned. For instance is the difference between Jupiter and Saturn, on the one hand, and Uranus and Neptune, on the other, an understandable consequence?

Interested planetary scientists are naturally well aware of such questions. But they may not usually consider the extent to which these might lead to 'diagnostic tests' in the sense of the title of the present discussion. Also part of the motivation for the discussion is to interest chemists in such questions in the hope that they will identify questions that are truly 'diagnostic', and that they may perform the diagnosis.

In practice, diagnoses are not always specific, but probably more often comparative. For instance, a chemist may not care to say that the merging of planetesimals is impossible, but he may wish to say that a model which avoids an appeal to merging is that much more likely to be valid. Consequently we must proceed to consider, as an alternative to the solar nebula model, the proto-planet type of model.

(*b*) *Proto-planet approach*

We start with the same raw material as before and we take as a typical temperature for a 'cool' region of interstellar space 50 K. We ask that it be brought to a state in which the 'Jeans mass' shall be 10^{30} g. That is to say, if a more or less spherical body of the material having this mass were isolated in space it would tend to contract upon itself under its self-gravitation. Call this a *proto-planet*. Provided that it can radiate away energy released by contraction, that contraction will go on until it is stopped by what have come to be called in the context 'degeneracy forces'. We should then have a body of about the density of Jupiter or Saturn and with nearly the inferred chemical composition of those planets. Note that the mass of Jupiter is about 2×10^{30} g and that of Saturn about 0.6×10^{30} g. Were the grain material to settle to the centre of a proto-planet, it would give a core of this material of mass about 1 % of the whole, i.e. about 10^{28} g. If then all the gaseous material were removed there would be left a 'terrestrial' planet like Earth or Venus. Note that the Earth mass is about 0.6×10^{28} g and the Venus mass is about 0.5×10^{28} g. If about 90 % of the gaseous material were removed there would be left bodies of mass about 10^{29} g, i.e. such as Uranus and Neptune which have masses of about 0.9×10^{29} g and 10^{29} g.

Were a planet like Earth to undergo rotational fission the mass ratio of the components would have to be at least 8:1 to satisfy energy and angular momentum requirements. This was long ago demonstrated by Lyttleton (1960) who proceeded to suggest that Earth–Mars with mass ratio about 9:1 and Venus–Mercury with mass ratio about 15:1 could be such systems. There is chemical evidence that may be claimed to support the suggestion.

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

In this approach to planet formation there appears to be a possible natural connection with the formation of the Sun. If there exists a mechanism for forming proto-planets, might not the Sun – and other stars – result simply by a coalescence of proto-planets?

It is tempting to base upon this concept a modern version of the famous Laplace hypothesis. Laplace started with a rotating solar nebula but one from which the Sun, as well as the planets, was to be formed. Also, unlike the solar nebula earlier in this paper, the whole was assumed to be contracting upon itself under its self-gravitation. The material was treated as *continuous*. As the contraction proceeded, it was thought to leave behind rings of the material revolving in the gravitational field of the rest, until a central residue finally contracted upon itself to form the Sun. Each ring of material was thought then to gather itself together to form a planet in about the same orbit.

Such a process is probably mechanically possible, but it could not produce a system like the actual Solar System. As the model is specified any portion of its continuous material would throughout retain its angular momentum about the mass centre of the whole. (Any realistic ordinary viscosity would make little difference.) In the actual Solar System the central Sun contains nearly 750 times the mass of all the rest of it. On the Laplace model it would have to carry about the same proportion of the angular momentum. Instead the rest of the system carries nearly 200 times the angular momentum of the Sun. That is the Sun's angular momentum is about a factor of 150000 smaller than the Laplace model would require!

Now suppose we start instead with about a thousand 'jupiters' moving at random in a region of space of about the extent of the Solar System. Let their total kinetic energy be numerically less than half the absolute value of their total mutual gravitational potential energy. Then, according to the virial theorem, the system must tend to contract upon itself. This would be accomplished by the bodies piling up at the mass centre; were a large number to do this their combined material would become a 'sun' at that position.

There is the problem of angular momentum to be taken into account. The original random motion yields a probable resultant angular momentum, given by a 'random walk' formula, which must of course be conserved. The random arrival of bodies into the central accumulation gives it a resultant angular momentum at any stage in the process. But for one of the jupiters to lodge in that accumulation it has to hit it; i.e. hit a target no bigger than the Sun. This requirement limits the angular momentum that can accumulate at the centre. In fact if R is the radius of the region originally occupied by the bodies and if r is the radus of the central sun, the ratio of the angular momentum of the final sun to that of the original system can be shown to be about $(r/R)^{\frac{1}{2}}$, so that most of the original angular momentum remains to be accounted for. It can then be seen that this angular momentum can be carried by a very few jupiters in approximately circular orbits in a common plane described in the same sense.

Thus, whereas in the Laplace-type treatment of continuous matter the angular momentum has effectively to stay always with the same material, if the material is broken into fragments moving independently under the gravitational interaction of the system, the angular momentum can be, and will be, filtered out from most of the mass and entrusted to a small fraction of it. A numerical example that seems satisfactorily to match the actual Solar System is discussed elsewhere (McCrea 1988).

To form a 'sun' in this fashion it is necessary to have a grouping of 'jupiters' that satisfies the virial requirement. Incidentally, this seems to offer a solution to the long-standing, but infrequently recalled, problem as to why the mass-function for stars gives no indication of continuing smoothly into planetary masses. As to the requirement itself the situation is simply that, if it is satisfied, a star will be formed, otherwise not.

Maybe the requirement fails to be satisfied much more generally than otherwise. As is well known it is commonly inferred that many galaxies have 'dark halos' with masses of order ten times those of the visible regions. The simplest explanation seems to be that the halos may be composed of jupiters.

Questions about the chemistry of a proto-planet approach

From the topics touched upon in the preceding section it is evident that the validity of the proto-planet approach would have far-reaching astrophysical consequences. So it is a matter of great moment to test this validity by any available means.

Chemistry may be the answer because it is clear that the chemical histories of the planets of the Solar System would have been very different in the two ways of forming them that have been outlined here.

The general difference is that the evolution of a largely self-contained protoplanet starting as a diffuse cloud of cold interstellar gas and dust presumably treats the matter far more gently than would, say, the crashing of planetesimals on to a half-accreted Earth. In particular, the proto-planet model seems to allow the chemical *molecular* content of the raw material much more possibility of influencing the evolution.

A set of crucial questions concerns the segregation of materials in planetary interiors, particularly in terrestrial planets. If such a body results from the sedimentation of dust-grain material in an initially diffuse body then is differentiation of substances – say, iron in the centre, followed by silicates – an inevitable natural consequence? If differentiation is not achieved in this way, can it be achieved in the ways commonly postulated for a planet formed alternatively by homogeneous accretion?

Such remarks are here intended only to indicate possible fields for chemical investigation. It would be for chemists themselves to ask the correct questions.

Chemical questions in planetary science not arising as diagnostic tests

Looking at the planetary system as we find it and then trying to look back into its origins many questions of its chemistry arise on their own merits. They are not suggested by particular models of the origin but any solutions could provide highly valuable clues. Here is a rather arbitrary selection.

What is the source of the *water* in the Solar System? Is it made by chemical processes within the system, or is it mainly part of the original interstellar raw material?

Is *methane* (CH_4) an important constituent of planets? Is it readily produced at any stage in the evolution of the Solar System. Was it a significant constituent of the raw material?

Has *radioactive heating* been significant in the evolution of bodies in the system? What was the chief source of radioactive materials?

From time to time there are speculations about there having been in the system a planetary body that *exploded*. Is this chemically plausible?

Planetary bodies have interesting *magnetic properties*; do these have any chemical relevance?

There are many questions relating to the galactic environment. It is usually supposed that the raw material of the Solar System came from a '*giant molecular cloud*'. How is such a cloud formed? What chemical processes take place in such a cloud, particularly ones that might affect the formation of stars and planets. Is the molecular content the controlling factor for the temperature of the material?

How common are planetary systems in the Galaxy? This is perhaps the most important question of all, for many obvious reasons, but it is not obvious how chemistry can help to give an answer at present.

The formation of stars, and presumably planets, clearly depends upon the behaviour of molecular clouds and, probably, their interaction with the spiral structure of the Galaxy. What feature triggers the formation process? Do *supernova outbursts* play an essential part? If so is this *physical*, say in producing shocked material, or is it *chemical*, say in producing local abundance of particular elements, e.g. iron or nickel?

Bibliography

Extensive reviews of this material are given in the following.

Dermott, S. F. (ed.) 1978 *The origin of the Solar System.* New York: John Wiley.
Black, D. C. & Shapley, M. (eds) 1985 *Protostars and planets.* University of Arizona Press.
Runcorn, S. K. (ed.) 1988 *The physics of the planets.* New York: John Wiley.

References

Lyttleton, R. A. 1960 *Mon. Not. R. astr. Soc.* **121**, 551–569.
McCrea, Sir William 1988 *The physics of the planets* (ed. S. K. Runcorn), pp. 421–439. New York: John Wiley.

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