PART I

ORIGIN AND GENERAL PHYSICS OF THE PLANETARY SYSTEM

PLANETARY FORMATION

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Abstract. Existing theories of planetary formation (based on a continuous solar nebula or on discrete objects) are briefly reviewed.

1. Introduction

The formation of the planetary system has been a problem which has stimulated the thought of man since time immemorial and the number of different theories cannot be far short of the number of human beings that have existed. From time to time reviews of the most promising of these theories have been published (for example, Williams and Cremin, 1968; Woolfson, 1969; ter Haar and Cameron, 1963; McCrea, 1972). Even though a number of theories have been formulated since the last of these reviews were published I do not propose to give here another review which simply brings these other reviews up to date. Instead, I wish to discuss the current ideas regarding possible formation of planets and try to follow the pattern in the development of such ideas. In this way, I hope that most recent work will be mentioned while at the same time the development towards possible complete theories will become more evident than by giving a chronological summary of recent papers. References are by no means complete and are intended only as a guide to the principal work that has been carried out.

2. General Outline of the Problem

In its simplest form, the problem we are discussing is 'how can a planetary system like our own form from some acceptable initial state.' Even in this simple statement of the problem there are at least two points on which theorists can argue, even before a theory has been formed. Starting from the wrong end, the first concerns the 'acceptable starting conditions'. To any theorist his own initial conditions are obviously acceptable. I shall to some extent avoid this issue stating simply that any situation where the material is less organized than in the present system and where such a state might reasonably be expected to have existed is acceptable. In practice the argument centres around the question of the existence or non existence of the Sun and possibly other stars when the planets started to form. The second is the statement 'a system like our own'. How much like our own is meant, is it taken to imply that we are trying to form a theory to explain our own solar system, or a theory for forming a system which has the major characteristics of our system. Most theorists, including myself, mean the latter, we are looking for a general mechanism for forming planets which is capable of generating both our own systems and systems similar to it. In compiling a list of the properties to be explained one should therefore take account of all known planetary systems. Since our system is the only one known in any detail, the list in-

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evitably consists only of the properties of our solar system and the question therefore is whether all the properties of our system are general properties of any system. There are at least five stars that have companions of planetary mass and Barnard's star appears to have a number of such companions (see Williams, 1973; van de Kamp, 1971; for more information), but the only possible property that can be deduced is that the companions of Barnard's star appear to be non-coplanar (Black and Suffolk, 1973) though recently doubts have been cast onto Barnard's star observations. A list of properties which a general planetary system should have is therefore:

(1) There should be many planets. (Solar System 9, Barnard's 2+, no information on any of the others.)

(2) These planets should, in general, move on coplanar prograde orbits, though there may be exceptions. (Solar System very well aligned, Barnard's star has angle of 50° between companions.)

(3) There is a central star, much more massive than the sum of the planets, which nevertheless possesses little angular momentum.

(4) There appear to be three groups of planets distinct from one another in mass, chemical composition and position, the terrestrial, major and outer planets, the relevant information being (Allen, 1963; Ramsey, 1967).

TABLE I

Main characteristics of planetary groups

Type	Mass (g)	Basic composition	Interstellar (by mass)
Terrestrial	5–6 × 10^{27}	Refractory, i.e. Si, Fe, Mg + compounds	0.3%
Major	1–2 × 10^{30}	H, He + impurities	100%
Outer	9 × 10^{28}	C, N, O + compounds Some H, He	5%

(Solar System, no information on the others.)

(5) There are a number of other miscellaneous objects, notably satellites, asteroids and comets in the system. (Solar system.)

These properties have to be produced by a mechanism to be described in our theories. Point (3) may or may not need an explanation as it is presumably allowable for a theorist to attempt to form a planetary system about an already formed star. It has also been demonstrated that the solar wind is capable of removing angular momentum from the Sun so that the slow rotation of the Sun need not have anything to do with the formation of the planets. However, it is clear that, irrespective of the type of theory that is postulated, the following general stages must have occurred in order to form a planetary system.

(a) Sufficient material (at least 10^{31} g) must be acquired from which to form the planets and sufficient angular momentum given to it.

(b) This material must be arranged, so that in general the final outcome is a near coplanar system.

(c) There must be a redistribution (either by accumulation or fragmentation) into about 10 objects.

(d) There must have occurred a stage of chemical segregation so that the terrestrial planets are composed of refractory material and so on.

Note that the listing given above need not be in chronological order and that in fact it is quite likely that some stages can occur simultaneously.

There are, of course, more restrictions one can place on the theories, some arising from the cosmochemical work of Anders (1972) and others. However, as I see it, we should first find what types of theories have been generate to account for stages (a) to (d) above, thus satisfying the crude requirements of the system. We should then investigate whether any of them can be rejected when it comes to accounting for the finer points in our knowledge.

3. Possible Theories

The first process to consider is the acquiring of the material for the planets. In practice this can either occur after the Sun has formed or as the tail end of the process of the formation of the Sun. In many reviews in the past this point has been one of crucial division between theories (see for example Williams and Cremin, 1968), possibly because at the time the slow rotation of the Sun was thought to be of crucial importance. I do not propose to make such a division here but rather concentrate on a division between the different forms which the captured material can have, or to be more precise the form in which the material first plays a part in the evolution of the system. Here the division is obvious, the material can either appear in the form of a continuous distribution of dust and gas, the traditional solar nebula, as has been postulated by Hoyle (1946, 1960), ter Haar (1950), Cameron (1962), Schatzman (1967), Pendred and Williams (1967), and Alfvén and Arrhenius (1970a, b) amongst others, or alternatively the matter appears as a collection of discrete objects. These discrete objects can be proto-planets themselves, as is the case in the tidal theories, made famous by Jeans (1916), the most modern theory of this type being due to Woolfson (1964), and modified by Dormond and Woolfson (1971). Alternatively they can appear as smaller objects but nevertheless distinct, as has been suggested by McCrea (1960) and Urey (1966).

Of course, there are many differences between theories, in either of the two classes mentioned, for example Cameron's nebula is much more massive than that postulated by Hoyle. There are also considerable variations in the way the planetary material acquires its angular momentum. In the theories of Cameron (1962) and Schatzman (1967) for example, the angular momentum is that originally in the gas cloud from which the Sun formed and this planetary material does not fall into the Sun because of its high angular momentum, the same being true of the theories of McCrea (1960) and Urey (1966), theories in the other category. In Hoyle's (1960) theory the angular

Programs to compute the equilibrium in the gaseous phase alone – i.e., the chemistry, see, e.g., Figure 3, – have been available for some time. Only very limited efforts have been made to include the condensed phase of matter in the equilibrium (Duff, 1962; Tsuji, 1966).

The collective absorption and scattering by particles (grains as well as liquid drops) also requires knowledge of the particle size distributions. Usually Gaussian or power-law distributions with cutoffs are adopted.

The physics for commencement of condensation in the microscopic realm is insufficiently understood. It is not clear whether a better understanding of this process would shed more light on particle distributions. The absorption and scattering of radiation by 'grains' is well developed in the Mie theory. Programs to compute the cross sections for 2-component refractory core-ice mantle spheres using complex and wavelength-dependent refractive indices are available (e.g., see Figure 1). Similar programs for spheroidal particles could be developed. Some parameters for the geometric asymmetry could be obtained, e.g., from observed polarization of zodiacal light (Greenberg, 1970).

Data for microwave transitions and infrared rotation-vibration absorption is available, but more data will be needed. Data for electronic transitions involving highly excited states of molecules are considerably more sparse and unreliable. There are no difficulties with the atomic-ionic cross sections of astrophysical interest that could not be resolved with presently available methods and programs.

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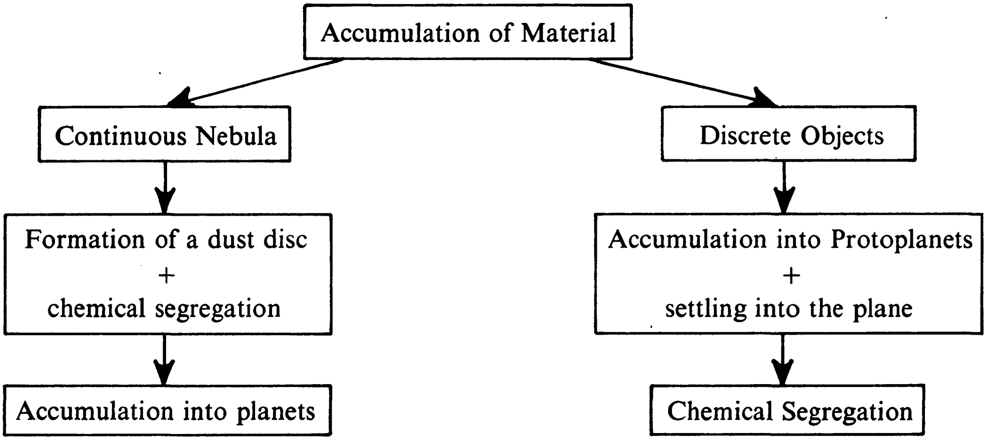
Recently, however, a new idea has been introduced, following a suggestion first made by Lyttleton (1968). This is that the dust grains of refractory material, instead of directly accumulating into planets, first settle into the invariable plane of the rotation and form a disc of no more than a few centimetres thickness. Accumulation into planets in this disc becomes much easier since the density is now higher which means that the disruptive tidal effect of the Sun is much less important. Such ideas have been discussed more fully by Cameron (1972) and Lyttleton (1972), while a variation in which the grains grow as they settle as suggested by McCrea and Williams (1965) has been investigated by Schatzman (1971) and Williams and Handbury (1973). The conclusion of all these investigations is that it is possible to form such a thin disc in a comparatively short period of time and that fairly large objects are easily formed. So far, however, it has not been shown that the correct number of planets will be formed at the correct distances inside this disc.

The major planets form by accumulating hydrogen and helium which give the higher mass while in the region of the outer planets the disc also contains CNO grains but evaporation of hydrogen and helium has occurred. Most of the basic features have therefore been explained by this type of theory.

3.2. DISCRETE ACCUMULATION

In theories of this nature, such as suggested by McCrea (1960) and Urey (1966) the first problem is to generate a coplanar prograde system. (Note that in the tidal theories (e.g. Woolfson, 1964) this is automatic but it is then coincident that the Sun rotates about a near parallel axis.) It is suggested that the random collisions between the globules (for lack of a better word) will achieve both these ends. This contention has been subject to a number of investigations, primarily by Williams and Galley (1971), Aust and Woolfson (1971), and Williams and Donnison (1973). The conclusion of the latest of these, being a computer simulation of the process by Williams and Donnison (1973), shows that there is certainly a tendency for a settling and for removing retrograde orbits but that very many collisions are required to generate a system that is as coplanar as the existing planetary system, but it is not clear whether or not there will be sufficient collisions occurring in practice. As a result of these collisions and accumulations a system of basic object is built up. In the case of McCrea's theory and the tidal theories, these basic objects are of mass similar to the major planets while in Urey's theory they are somewhat smaller. It is now required to segregate the chemical elements and the obvious mechanism is by the settling of the grains to the centre of these objects, as first suggested by McCrea and Williams (1965). A detailed investigation by Williams and Crampin (1971) shows that a heavy core can form in a relatively short period of time, providing the falling grains accumulate all other grains that they collide with. The terrestrial planets then lose their outer hydrogen envelopes because of the proximity of the Sun while the major planets do not. There exists more of a problem with the outer planets. However, I make a suggestion which as far as I know has not been investigated anywhere. The outer protoplanets will be cooler and so the CNO compounds will also be falling as grains. Now Williams and Crampin (1971) showed that the normal refractory material on settling to the centre released potential energy sufficient only to disperse about 7% of the protoplanets. If, however, the CNO compounds also fall then much more energy is released which may well disperse the gaseous (HHe) envelope of the outer planets.

Urey with smaller original globules forms moons rather than planets from the core of his globes and so has a second accumulation process for planets. Again, however, the main features are explained. The difference between the two types of theories are shown in the following



This then gives some indication of most of the general ideas currently prevalent amongst cosmogonists.

We can, as we have indicated already, see a few substreams amongst the two main streams and a very crude summary is given below.

3.2.1. *Continuous Nebula*

3.2.1.1. *Large nebula as part of star formation.* The solar nebula is formed because of the excess angular momentum in the gas cloud from which the Sun forms, the nebula is never part of the star but is left behind by the contracting star. The solar wind, magnetic fields etc. slows the Sun down to an acceptable level. Dust settles in the plane and near the Sun the terrestrial planets form from an accumulation of this nonvolatile material. Further away hydrogen and helium are also accumulated. Some of the names associated with this kind of theory are Cameron (1973), Schatzmann (1967), and Pendred and Williams (1967).

3.2.1.2. *Small nebula as part of star formation.* Here a protostar is formed from the interstellar gas but because of angular momentum difficulties, during the contraction of a star material is left behind in the equatorial plane as a solar nebula, this nebula is much smaller than that in case 3.2.1.1 and transfer of angular momentum is necessary between star and nebula. Again, the terrestrial planets form in a dust disc close to the Sun while further out gases are also accumulated. Typical names associated with work on this type of nebula are Hoyle (1960) and Lyttleton (1972).

3.2.1.3. *Nebula resulting from the accretion of material.* A nebula is acquired by the passage of the already formed Sun through an interstellar cloud and, following Schmidt (1944), the development is then similar in general to that in case 3.2.1.1. Alfvén (1954) suggested that condensation of the infalling matter would occur resulting in the magnetic fields segregating grains (close to the Sun) from the gas. Another new idea introduced by Alfvén is the concept of jet streaming leading more easily to the formation of planets.

3.2.2. *Discrete Objects*

3.2.2.1. *Tidal theories.* In the tidal theories material is drawn out of a passing star and captured by the Sun. A computer simulation by Woolfson (1964) shows that this is possible. Break up of this filament forms protoplanets and the terrestrial planets are formed by the settling of grains to form a core.

3.2.2.2. *Others.* The two main authors are McCrea (1960) and Urey (1966). Material is captured in random orbits. Subsequent collision and amalgamation leads to a degree of settling in the plane for the protoplanets. The terrestrial planets are formed by settling of solid grains and the subsequent loss of gas.

We now discuss some of the differences and possible developments.

4. General Differences and Difficulties

In the continuous nebula type of theory the alignment into the plane of the material is very efficient and one would therefore expect almost complete alignment. In the discreet object type of theory the alignment comes about as a statistical effect and one would not expect the end effect to be perfectly aligned. One can therefore ask whether the existing solar system is too well aligned for the discrete object theory or not well enough aligned for the continuous nebula type of theory. Unfortunately the solar system itself is not clear cut either way and is within the 'error bars' of both types of theory. It is here that Barnard's star and other similar stars may be important. If the analysis of Black and Suffolk (1973) is correct that of the planets detected, moves at a considerable (50°) angle to the other then the continuous nebula theory has difficulties in explaining it. Whipple *et al.* (1972) has also drawn attention to the problem of the alignment (or lack of it) of Pallas and underlined the problem of explaining it in the context of the continuous nebula theory. Observations of Barnard's star (and others) from an extra terrestrial environment offering a longer base line for parallax work may be of use here.

Another possible strange result arising from the study of other solar systems is that all the planets so far discovered are all very close in mass to the major planets of the solar system. In a continuous nebula theory one would expect there to be some dependence on the mass of the parent star in the mass of the planet while the mass in the discreet object theory is more likely to be dependent on outside influences only. Of course, there is a very considerable selectional effect in the data in that planets much smaller than Jupiter cannot be detected while any found much more massive are dismissed as possible stellar companions. Nevertheless, in theory this could prove an interesting test. Though this point has been introduced as a possible strength of the discreet object theories, in fact it also contains their main weakness. It is the question of the origin of the discreet globules which accumulate, they virtually arrive on the scene as thinly disguised postulates, though it could be mentioned that Walker (1972) believes that young stars do show evidence of accreting matter in a discrete form.

One other problem with the discrete theories is the well known under abundance of xenon (Suess, 1949) and other rare gases, the problem basically being that evaporation is probably the main way in which the terrestrial planets lost their hydrogen and helium, but xenon is too heavy to evaporate and so it should be over abundant. The only obvious solution is to assume that in some way the xenon succeeded in finding its way into the interior of the planets.

The major difficulty in the continuous nebula type of theory is to explain why, from the original dust carpet, planets grew to their existing sizes and existing positions. In particular why are all the planets (after compensating for composition) all of very similar mass and why is the spacing of the planets as found, with the peculiar gap where the asteroids are. There are many other difficulties, primarily found by cosmochemists concerning the abundancies of elements and isotopes. Unfortunately, in general these have been couched in the framework of particular theories and some problems vanish with a simple change of model. I will not go into any details here since my main concern was to give a general account of the state of theories today as I see it. In conclusion, we are not at present able to decide which of the main streams of thought are likely to be correct, however, I believe that in the near future this may become more likely for the following reasons.

(1) More observations of Barnard's star and similar systems may give an answer to the question of how well aligned planetary systems should be.

(2) Exploration of other planets may lead to useful information regarding the abundance of xenon and other elements there.

(3) More use of computer models will lead to a better understanding of some of the more complex physical problems involved, for example the collision and accumulation of discreet objects or the growth of planets in a dust carpet.

(4) Laboratory experiments on the adhesiveness of grains in collision are continuing (e.g. Kerridge and Vedder, 1972). More information may become available as the possibility of experimentation in outer space becomes practicable. Some evidence is already available from a study of moon rocks.

(5) Further studies of young stars may indicate whether a *continuous* nebula exists around them (as opposed to a circumstellar dust cloud) and give an estimate of its dimensions.

We may therefore look forward with pleasure and anticipation to the next few years of exploration and computation.

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DISCUSSION

Icke: You considered the most massive bodies as the most important. In this the natural thing to do? I would think that specific angular momentum is a more relevant parameter in a contracting rotating nebula, so that comets and meteorites should be considered.

Williams: If you do not consider mass then you have no planetary system to explain.

Vsehsvyatsky: The hypothesis of Williams seems a backward one compared with the classical. It does not explain the basic peculiarities of the solar system, namely the planets activity in the history of the solar system, and the eruptive formation of comets and other small bodies.

Poss: The observations of solar systems would be crucial for distinguishing among various general theories. Could you comment further on the reliability of the observational data on Barnard's star, the different interpretations (i.e. the existence of one, two, three or more planets) and whatever observations might be used.

Williams: Observations are only by van de Kamp, but there is a suggestion that a systematic error exists in his observations.

Owen: The observations of Barnard's star have been repeated in the sense that a different series of plates was analysed and no periodic oscillation was found.