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The Origin of the Planets

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Introduction

Pondering on the origin of the earth and planets has been one of the hobbies of the human race since early times. In earliest times actual data was very scarce and so the restriction on the types of theories advanced were very few, and most of those arose because of philosophical or religious reasons rather than conflict with hard data. The first major constraint came with the Copernican realisation that the Sun was the central object in the system. With the discovery of the telescope and the development of dynamics following the work of Newton and Kepler, the general features of the system became known and only minor changes in these have been recorded in the last decade. For information the current values are given in table 1. From the study of the mean densities of the planets, it becomes apparent that major compositional differences exist between certain groups of planets. Based on this, and the dynamical data, an alarming number of theories have been proposed, and these are described in reviews such as ter Haar and Cameron (1963), Williams and Cremin (1968). In the intervening period there have been a number of meetings devoted to the subject, and as a consequence, books of the proceedings have been published, for example Reeves (1972), Gehrels (1978), Dermott (1979).

One of the major difficulties facing any prospective cosmogonist is the diversity of topics which combine to define the whole problem. Ideally, one needs to understand dynamics (orbits and general motion) hydrodyamics (equilibrium of gaseous condensations) plasma physics (solar wind and magnetic effects) radiative transfer theory (temperature of the solar environment) solid state physics (behaviour of solids) chemistry (production of compounds) atomic physics (isotopic properties) geology (behaviour of solids under pressure) and many others. It is impossible to become an expert in all of these, and specialisation is inevitable, leading to communicational problems. The cosmochemist wants a single simple dynamical model of the situation so that he can apply his chemistry while the dynamicist wants a single chemical scenario so that he can perhaps build a computer model.

The task I have set myself, and inevitably I shall fail to achieve this, is to gather together the material from these diverse fields, to present it in a way which is comprehensible and to stress its cosmogonic importance. This I do by giving separate sections to each important fact, the ordering of the sections being of no significance.

Table 1.

Body	Mass (Earth = 1)	Inclination of orbit to ecliptic	Mean distance from Sun (A.U.)	Eccentricity
Mercury	0.055	7° 0′	0.39	0.2056
Venus	0.815	3° 24′	0.72	0.0068
Earth	1.000	-	1.00	0.0167
Mars	0.108	1° 51′	1.52	0.0934
Jupiter	317.8	1° 18′	5.20	0.0485
Saturn	95.15	2° 29′	9.55	0.0557
Uranus	14.54	0° 46′	19.2	0.0472
Neptune	17.23	1° 46′	30.1	0.0086
Pluto	0.003	17° 10′	39.5	0.0250

In the last section I present a possible scenario for the process of planetary formation. Most parts of the scenario have already been proposed in isolation in the other theories. What I have done is to take the best parts of a number of theories and joined them together into one, occasionally reversing the temporal order of events.

The Present Solar System

1. The Angular Momentum Distribution

It has long been recognised that there is a large discrepancy between the amount of specific angular momentum residing in the sun, and that in the planets, roughly 99% of the angular momentum resides in 0.15% of the mass. Indeed this single feature has been the central theme of a number of theories. It is however, not a fact which should be considered in isolation. With measurement of the interstellar medium becoming more common, it is clear that the planets have a roughly similar amount of specific angular momentum to that of dark clouds in the interstellar medium (in the region of 10^{20} cm^2/s). The problem is not therefore one of the distribution of angular momentum but rather of why the sun is rotating so slowly. The first question is obviously whether the sun is rotating differently from other stars. This was investigated by McNally (1965). His plot of angular momentum against mass for various stellar classes is shown as Fig. 1. This indicates that stars of spectral type A or earlier were fast rotators, while late type stars (including the sun) are slow rotators. It is thus not just a question of why the sun rotates slowly, but rather of why do all late type stars rotate slowly. In the sixties, the stock answer was 'because they have planetary systems'. However, there is another explanation. The discontinuity at type A/F occurs at just the spectral type where deep convective zones are developing in the stars. Such convective zones can drive a stellar wind of the same type as the well observed solar wind. In the case of the sun, the solar magnetic field interacts with the wind in such a way that the wind co-rotates with the sun out to about 20 solar radii. Because of this, the wind becomes an effective transporter of angular momentum from the sun to interstellar space. (A full description of this phenomenon and other aspects of the solar wind is given by Hundhausen 1972). According to this view, stars with a convective zone i.e. late type stars, will become slow rotators. Additional support for this view comes from the observation (Kraft 1967) that G-type stars in the two young clusters, the Pleiades and the Hyades, are rotating somewhat faster than the sun. The sun being older, has lost more angular momentum via the wind and rotates slower. Indeed the deduced rate of decrease in rotation is in agreement with calculations using the solar wind and it seems that the slow rotation of the sun may be irrelevant to the planetary formation process and is rather a natural consequence of normal stellar evolution.

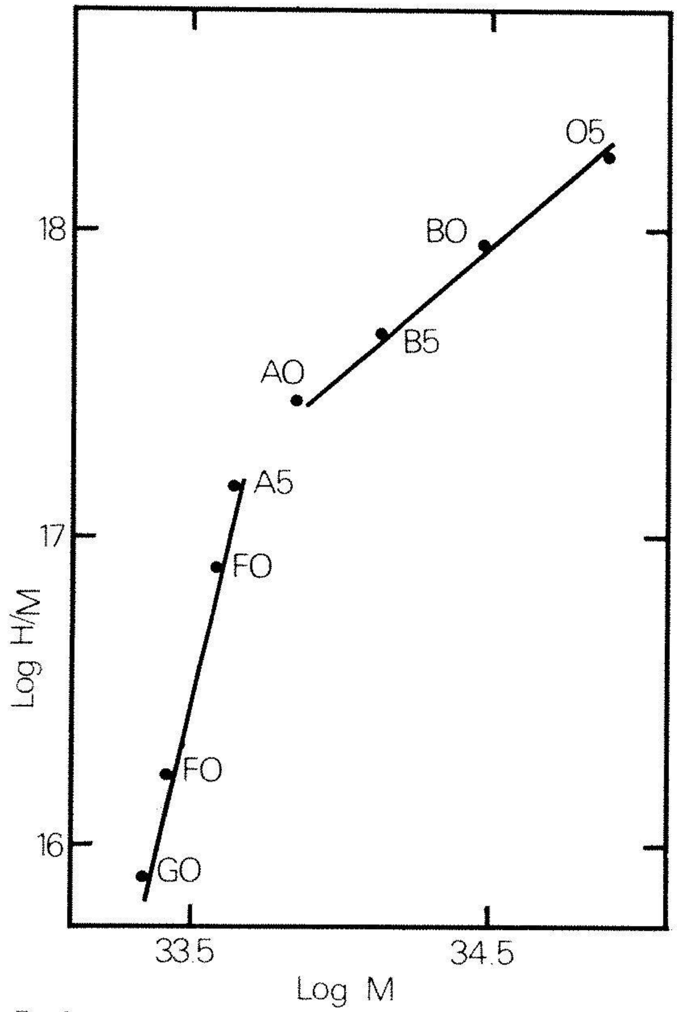

Fig. 1.

2. The Inturnal Structure of Jupiter and Saturn

The discovery that Jupiter and Saturn both emit more radiation than they receive from the sun led to the formulation of evolutionary models where these planets contract under gravity from some large initial state, the excess energy now observed coming from the very slow current rate of contraction. Early models (e.g. Donnison and Williams 1974) showed that rough agreement between this theory and observations existed. With the advent of space probes, our knowledge of these planets has increased considerably, and from moment of inertia calculations, we now have a knowledge of the central density as well as the mean density of these planets. Static models (i.e. those ignoring contraction) found it difficult to reconcile this data with a homogeneous solar type composition for the planets, and (Stevenson 1978) a large rocky core was found to be necessary. The evolutionary modelists also found it easier to match theory and observation if a rocky core was adopted. The topic was recently reviewed by Grossman et al. (1980) and in Table 2, the current estimates for the mass of the rocky core is given for both Jupiter and Saturn.

Table 2.

Author	Jupiter (Earth Masses)	Saturn (Earth Masses)
Pololak (1977, 1978)	16–18	21–25
Slattery (1977)	14–16	15–17
Hubbard & McFarlane (1980)	~15	~15
Grossman (1980)	19–20	19–20

There are two important and distinct points arising from this development:

(a) The need for a rocky core of about 20 $M_{\oplus}$ inside both Jupiter and Saturn implies that neither of them has a cosmic abundance as this requires them to have a mass of about 6000 $M_{\oplus}$. At some stage they must therefore have either not accumulated all the available hydrogen and helium or they must have lost these gases. A corollary is that the mass of any pre-planetary nebula has to be at least 15,000 $M_{\oplus}$, or close to 10^{32} g.

(b) Jupiter and Saturn were of larger radius in the past. Of course the evolutionary models are insensitive to the earlier stages of contraction and so one cannot deduce what the initial radius was. However, any large radius is consistent with the observations.

3. The Composition of Terrestrial Planets

There are of course no direct measurements of the internal composition of the terrestrial planets. However, their mean densities, given in Table 3, show considerable variation. Some of this difference arises because of the different levels of compression present in the different planets, but even when account of this is taken, major differences exist.

Table 3.

Planet	Mean Density (gm/cm^3)	Uncompressed density
Mercury	5.4	5.4
Venus	5.25	4–4.5
Earth	5.52	4–4.5
Mars	3.94	3.7–3.8
Moon	3.34	3.3

The only abundant element which has a significantly different molecular weight from other abundant elements is iron. Iron can also appear as a mineral with other elements with vastly different densities, ranging from metallic iron with a density of 7.6 gm/cm^3 through Troilite (FeS) with a density of 4.7 gm/cm^3 to Fayalite (Fe_2SiO_4) with a density of about 3 gm/cm_3. It therefore seems obvious that the differences in uncompressed densities between the different planets is explainable in terms of the amount and form of iron present. Both of these depend directly on the environment (pressure and temperature) at the time of the condensation of the terrestrial material.

There are two distinct lines of thought. One argues that initially all the grains present in the solar neighbourhood were vaporized and that as the temperature there decreases, so materials condense out at the appropriate temperature. Thus, Mercury, being the hottest acquires mostly metallic iron; Mars, the coolest, is formed from Troilite and Iron-Silicates, while the Earth and Venus form from an intermediate mixture. This scenario obviously requires a source of heat of sufficient strength to vapourize all the grains. When Hayashi (1961) proposed a high luminosity initial pre-main sequence phase for stellar evolution, it appeared that the source of heat had been identified. However, it has now become apparent that the early evolutionary stages will not be in hydrostatic equilibrium so that Hayashi's model is invalid. Larson (1972) shows that the Sun was never more luminous than about 10 times its present luminosity, too little to generate the high temperature in the planetary neighbourhood. Other possible sources of heat may be collisions, or friction and the contraction of the gas component in the preplanetary phase. It is very difficult to quantify these suggestions and so I will simply leave them as possibilities for now.

An alternative view for the whole process suggests that initially the ambient material was cool and that all the material capable of condensing at about 200 K had condensed. This produces a basic material of composition similar to Cl Carbonaceous chondrites (see later), that is a material commonly found in bodies which are thought to be primitive. Heating (to a lesser extent than in the first view) during the process of accumulation into planets in the presence of carbon, acting as a reducing agent, modifies the basic composition, turning iron oxides into metallic iron and outgassing CO and CO_2, this process again being more pronounced near the Sun.

It is possible to match the planetary composition in either model. The point to remember is that either an initial hot phase is called for, or a subsequent heating in the presence of reducing environment.

4. Meteorites

Meteorites produce a sample of interplanetary material which can be studied in the laboratory. It is important to realize that it does not give a random sample of the solar system. The preponderance of meteorites originates from a few asteroids and comets with near Earth-grazing orbits. Nevertheless, since both asteroids and comets produce a very inactive environment, they can yield information regarding parts of the system at an early epoch. Meteorites can be subdivided into four main classes.

a) Carbonaceons chondrites

These meteorites are distinguished by having hard mineral aggregates about 1 mm long embedded in a matrix of earthy material. The mineral deposits come in two forms, chondrules (which tend to be spherical) and irregular forms. The matrix consist of a mixture of minerals which condense at low temperatures. It is usual to assume that the chondrules are condensed dropletts from a liquid state while the irregular forms are condensates from a vapour state. To obtain a liquid state, it is usually necessary to have a pressure higher than prevalent in the interplanetary medium.

b) Ordinary chondrites

These were called ordinary as they are the most common on Earth, presumably because a number of similarly composed asteroids are on earth crossing orbits. They are composed entirely of minerals like olivine and troilite which condense at fairly high temperatures.

c) Achondrites

Chemically these meteorites are very similar to igneous rock and most have been broken up by some violent event in the past.

d) Iron

As their name suggest, these are essentially composed of a nickel-iron alloy. In fact, a large number consist of two discrete metallic alloys arranged in a characteristic geometry, called the Widmanstätten structure. This structure develops during the slow cooling of the material, cooling from 800 K to 500 K occurring at a rate of only a few degrees per million years. Clearly, for such a slow cooling rate to occur, the meteorite must have been enclosed, or be part of, a much larger body.

Thus a number of points clearly emerge, namely that iron and minerals became segregated, that in some, the liquid state implies pressure, the iron meteorites implies slow cooling, the irregular minerals imply condensation from a vapour state. All this suggests the existence of a number of large parent bodies, heated during formation, and subsequently cooling very slowly, collisions leading to the existence of the present small pieces.

5. The Allende Meteorite

In addition to the general chemical features in meteorites discussed above, the study of isotopic ratios and their comparison with terrestrial and solar ratios have revealed a number of anomalies. The Allende chondrite surpassed all others in the extraordinary mineralogy and isotopic anomalies associated with it. An anomaly involving oxygen was pointed out by Clayton (1973) but Allende is best known for the anomaly involving Mg^{26} and Al^{26} (Wasserburg et al. 1977). The half life for radioactive decay is short (7×10^5 y) while the only known source is subsequent to a supernova explosion. Accordingly, there is a requirement that a supernova explosion occurred in the vicinity (ie. a few hundred parsecs at the most) of the solar system close in time to its origin. Indeed, Cameron and Truran (1977) have suggested that this supernova was the trigger for the process of star formation which lead to the existence of the Sun. Such a scenario is also discussed by Schramm (1978). I am sure Bochsler (1981) will discuss these points further and so I will leave this topic now.

6. The Mass and Density of Pluto

The discovery of the satellite to Pluto has enabled an accurate determination of its mass to be made. This turned out to be considerably smaller than all previous estimates with a value of about 1.5×10^{25} g and leads to a density of about 0.5 g cm^{-3}. The most likely composition is thus methane ice, rather than water ice. The very low mass means that for all practical purposes we can regard the main part of the solar nebula (or whatever one wishes to call the solar envelope) as terminating with Neptune's orbit, that is about 30 A.U.

7. Dynamics and Computer Simulations

The development of computing hardware and computing technology have made it possible for models of pre-planetary situations to be developed and their evolution investigated. We are still a long way from being capable of producing a simulation which takes account of all the phenomena encountered in the real solar system but some progress has been made. For example, Greenberg et al. (1978) have shown that growth can occur within a distribution of matter consisting of an interacting family rotating about the Sun. In this simulation, orbital dynamics were ignored and the particles given a random velocity in addition to rotational velocity (ie a kinetic theory approach within a rotating box). Williams and Donnison (1973) were interested in the settling of a three dimensional distribution to a plane while orbital dynamics played an important part in Wetherill's (1978) simulation. In general terms these simulations succeeded in reaching their objectives (of necessity almost, otherwise they would not have been published), and it is becoming clear that growth into larger bodies is possible within a dust cloud. It has also become clear that growth is much faster if nucleii are assumed to exist for growth to occur around. One such simulation by Dole (1970) showed that the final product of a number of experiments produced a family of star systems, out of which it was impossible to pick out our own.

In the foregoing, I have discussed a number of new results and constraints. These are in addition to the standard list of constraints discussed in earlier reviews such as Williams and Cremin (1968). If he so desires, the reader can judge for himself how many of the theories described there are consistent with this new data. I shall now give a brief outline of a scenario which I think is consistent with most of the data. It contains no fundamentally new ideas – they have all turned up, though not all together, in previous theories.

A Scenario for Planetary Formation

Star formation can be observed to be ongoing in complexes like the Orion. It is clearly therefore an event which occurs and I will not concern myself with the details of the triggering process, remembering the earlier discussion regarding the solar angular momentum. The formation of a nebula surrounding the protosun has also been extensively discussed in the literature (eg Cameron 1962) and I will not discuss it further here, but am rather more interested in the evolution within the nebula. However, it is just as well to establish the general characteristics of the nebula. By the arguments in 2) above, it must have a mass of the order of 10^{32} g and by 6) extend out to 30 AU. Since radially pressure and rotation balance gravity, while perpendicular in the plane, only pressure balances gravity, it is relatively easy to obtain an estimate for the height of the disk as something of the order of $\frac{1}{40}$ of the radius. Thus the average density in the disk is of the order of 6×10^{-12} g/cm³. It should be noted that these are just values for information to give the general picture and should not be taken as quantitative estimates.

There exists a critical mass, known as the Jeans Mass (see Williams 1974) such that any mass larger than this critical mass, for a given mean density ρ and temperature T, will fragment into elements with the critical mass. This is given by the expression

$$M_J = \left(\frac{5RT}{\mu G}\right)^{3/2} \left(\frac{4\pi\rho}{3}\right)^{-1/2} \tag{1}$$

μ being the mean molecular weight, R the gas constant and G the gravitational constant.

Substitution of numerical values into (1) shows that $M_J \sim 10^{32}$ g and so the nebula has no tendency to fragment due to the Jeans instability.

Even if this tendency had been present, fragmentation need not have occurred for the Sun has also a tidal disruptive force on any condensation. This is expressed by the Roche limit (or the distance of the inner Legrangian point from the Sun). Accordingly, a condensation with density ρ (Williams 1975) can only exist external to a distance L given by

$$L = \left(\frac{9M_\odot}{4\pi\rho}\right)^{1/3} \tag{2}$$

For the given value of ρ, this gives 40 AU and so again no condensations could be expected.

In this situation, any non-volatiles that had been vapourized in the formation process will condense out, and together with any that had not been vapourized, will form grains within the nebula. Indeed, there is no reason to assume any condensation sequence drastically different from one of those described by Wood (1979) or Anders and Owen (1977). By the mechanism of gravitational segregation, these grains will settle to the mid plane of the disk as for example in Williams and Handbury (1974) (a poor nebula model but the general principle is clear there). Within this disk, some agglomeration into larger bodies may occur. At this point I diverge from the popular picture, partly as a result of the voyager pictures of the rings of Saturn. I suspect that the family of large rocks would tend to set up all kinds of resonance and that this together with the tendency for orbits to circularize, results in a very long time scale for accumulation.

I assume that the Allende meteorite gives a clue as to the next event, namely the occurrence of a supernova explosion in the solar neighbourhood and which was responsible for injecting Al^{26} into the solar system. By the snowplough effect, it also pushed into the system intervening parts of interstellar space, polluted by a lifetime of other supernova and stellar ejections, thus accounting for the isotopic anomalies. It is generally assumed that the shock wave following a supernova explosion can trigger star formation (e.g. Cameron (1978), Elmegreen and Lada (1978)). It does this through the shock wave compressing the gas so that a gravitationally stable unit is formed.

It is somewhat difficult to obtain the degree of compression to be expected, but we can obtain a rough estimate. Using standard conservation equations across a shock with $x = \rho_2/\rho_1 \equiv$ compression ratio and u as the ratio of shock to sound speed, we obtain:

$$u^2 = x\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{x^\gamma - 1}{x-1}\right), \qquad \gamma = 1,$$

$$u^2 = x, \qquad \gamma = 1\mu^2 = x, \qquad \gamma = \%$$

For a typical supernova, $u \sim 5 \times 10^3$, so that with $\gamma = 5/3$

$$x \sim \frac{2}{5} u^{6/5}, \quad \text{or} \quad x \sim 10^4.$$

with such a compression, we see from (1) that condensations with a mass of $10^{32} \times (10^4)^{-1/2} \equiv 10^{30}$ g would be stable, while from (2), these could exist beyond a distance of $40 \times (10^4)^{-1/3} = 1.8$ AU.

Thus there would be no change in the terrestrial planet region, but external to this, what might be termed giant gaseous protoplanets would be formed. The evolution of such

planets has been discussed in the literature. For example, McCrea and Williams (1965) showed that the settling grains would form a core while Donnison and Williams (1974) showed that such objects could contract to become Jupiter and Saturn. Handbury and Williams (1975) even suggested that the segregation of ammonia and methane grains liberated enough energy to drive away hydrogen and helium and so form the outer planets.
Of course, these giant gaseous protoplanets may also be involved in collisions. This will result in the rapid heating of them followed by a cooling under pressure which may have relevance to meteoritic evolution. Indeed, the existence of a liquid phase is more than likely. Another consequence of collisions is that protoplanets could cross into the terrestrial planet region. As soon as they do this, they become totally unstable and will be disrupted. However, any nonvolatile agglomerations within them will survive, to be injected, on initial eccentric orbits, into the non-volatile disk in the terrestrial planet region where they immediately serve as a nucleus for accretion, terminating in the terrestrial planets. In addition, of course, the asteroid belt region will have been polluted with minor agglomerations that had not reached the centre of a protoplanet when it disrupted.
It may also be possible to account for the major satellites of the system in terms of young cores lost during a glancing collision or interaction between two protoplanets.

Conclusions

In the foregoing I have attempted to describe our current state of knowledge regarding the planetary system in a fairly objective way. The use I have made of these facts in the preceding section is very subjective. Other authors reconcile these facts with either a solar nebula with accretion from a disk occurring throughout or with a protoplanetary picture in which protoplanets form the preplanetary stage of all the planets. What I have produced is a hybrid qualitative model, which to my mind is a logical deduction from the facts.

I would like to thank E. Anders, G. Arrhenius, W.K. Hartmann and G. Wetherill for discussions and correspondence which have directly or indirectly had influence on the formulation of my scenario.

Summary

During the last decade our knowledge concerning the individual members of the solar system has considerably increased, and a review of this recent data is given, and its implication for the process of planetary formation discussed. A scenario for the process, taking account of all these developments is also given.

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