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A Survey of Theories Relating to the Origin of the Solar System

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1. INTRODUCTION

The origin of the solar system is one of the topics that has been of interest, both to astronomers and to laymen, for a considerable period of time. Indeed as soon as men started having scientific thought, they attempted to explain the solar system. The very first theories, for obvious theological reasons, required the origin of the Earth and that of the Universe to be closely related. We shall not consider such theories but concentrate only on theories for the origin of the solar system where formation occurs out of raw material that has already been created, the actual creation of this material being of no consequence. Among the first scientific theories were those of Descartes (1) in 1644, Kant (2) in 1755 and Laplace (3) in 1835. Until recently, however, very little progress had been made towards formulating a theory, or even a type of theory, that was broadly acceptable. At the conclusion of his Bakerian lecture on the Origin of the Solar System in 1952, Sir Harold Jeffreys (4) said, 'There is hardly a feature of our system that I would regard as satisfactorily explained'. Since that date some advances have been made. While it is the intention of this article to review both the older theories and the newer theories, more space will be devoted to the more modern developments.

Before reviewing the theories that have been proposed to explain either the origin of the system as a whole, or indeed parts of the system, it is useful to outline some of the major properties of the solar system. If any of these properties are contradicted in a particular theory, then that theory must fail, though, of course, it is permissible to postulate that some of these properties exist in the initial stage considered. The major properties of interest are as follows:

(a) There is a central condensation, the Sun, that is many orders of magnitude (a factor of around 750) more massive than the whole of the remaining parts of the system.

(b) The system contains eight planets in rotation about the Sun. (According to present-day beliefs, Pluto is to be regarded as an escaped satellite rather than as a planet.)

(c) The Sun rotates at a very slow rate, the ratio of the present-day angular momentum of the planets to that of the Sun being about 200:1.

(d) The vectors associated with the angular momenta of the constituent parts are in most cases parallel, that is all the planets and most of the satellites move in roughly the same plane while their individual rotations are also in that plane.

(e) The four planets nearest the Sun, the terrestrial planets, are less massive than those farther out, the major planets, by a factor of about 100.

(f) The terrestrial planets are different in composition to the major planets, being predominantly heavy non-volatile material as opposed to hydrogen and helium. The major planets are similar in composition to interstellar material and hence to the raw material from which the Sun was formed.

It may be that planetary distance is an essential factor of the system. An empirical law giving the planetary distances in astronomical units is known as the Titus–Bode law and gives

$$r = 0{\cdot}4 + 0{\cdot}3 \times 2^n$$

where $n = -\infty$ for Mercury, 0 for Venus, 1 for the Earth and so on. If the angular momentum and mass of the planets are specified, then the planetary distance is determined and cannot be regarded as an independent variable.

It is difficult to decide whether all the major properties of the solar system have been included above, or indeed whether all the above properties are essential properties of any system formed under the same conditions as the solar system. This is because only one solar system is known to exist and so it is impossible to distinguish between phenomena that must come about as a direct consequence of some established law and phenomena that come about as a result of unlikely accidents. The existence of only one known system also makes it rather difficult to disprove completely some of the more imaginative theories that have been proposed from time to time. It is to be noted, however, that a number of stars are known to have companions with masses comparable to that of Jupiter. These companions have been detected by observing perturbations in the path of the parent star. It is impossible at the present time to detect them by any other method as they are very small and close to the parent. An account of this aspect of astronomy together with a list of stars with such companions is given by Van de Kamp (5).

In compiling the review that follows, we have only considered theories for the origin of the solar system that produce a system which is not in conflict with any of the properties stated above. Theories which reproduce all these points with a minimum of assumptions and postulates will be considered preferable.

2. CATEGORIES OF THEORIES

When summarizing the theories that have been proposed, it is possible either to list them in chronological order, or according to type using some classifying system. We shall adopt the second method as it allows for easier comparison between different theories and different categories. In 1931 Jeans (6) first divided the theories into two categories; those where the material for the formation of the planets came from the Sun, and those where it did not. We shall divide the theories according to a classifying system given by McCrea (7). In this system the theories are divided into two main categories:

(1) Theories that regard the origin and formation of the planets as being essentially related to the formation of the Sun. The two formation processes must either take place concurrently or consecutively.

(2) Theories that regard the formation of the planets as being independent of the formation process for the Sun, the planets forming after the Sun had become a normal star.

This last category can be subdivided into two sub-categories:

2(a) Where the material for the formation of the planets is extracted either from the Sun or from another star.

2(b) Where the material is acquired from interstellar space.

We shall now summarize the main theories in all of those categories, starting with theories of the type 2(a) as they were very prominent in the earlier part of the century but are currently out of favour. A number of these theories are very well known.

Theories of the type 2(*a*)

This type of theory is mainly associated with the names of Jeans and Jeffreys, though both Hoyle and Lyttleton at one stage produced theories of this type. Such theories became very popular when Jeffreys (8) showed that it was not possible to form planets, moving as the existing planets do, by the slow condensation of a gaseous mass moving in any plausible way, whatever density distribution was allowed. This conclusion is reached by considering the very unusual mass and angular momentum distribution which the solar system possesses. The actual distribution is given in the introduction under properties (a) and (c). It is evident that such a system could not form *directly* from one cloud.

At the time this conclusion appeared to dispose of all theories of type 1, and it is only in recent years that ways of overcoming this angular momentum difficulty have been found. Jeffreys thus came to the very natural conclusion that the Sun must have formed before the planets. In the same paper he showed, using a slight modification of an argument published earlier by Jeans (9), that the system cannot come about as a result of the fission of one rotating body, angular momentum again being the overriding criterion. These negative results ead Jeffreys to the conclusion that another star must also be involved at the formation of the planets.

Such theories, involving the Sun and another star, had been common for some time. As early as 1745 Buffon (10) had suggested that the planets formed out of material ejected from the Sun as a result of a collision between the Sun and a comet. In 1880, by which time the true nature of comets, and thus the impossibility of Buffon's hypothesis, were known, Bickerton (11) suggested instead a collision between the Sun and a passing star. As in Buffon's theory, the planets formed by direct condensation out of the ejected material. Early in this century, Arrhenius (12) also considered the collision between two stars, this time head on, leading to one star and a gaseous filament, while See (13) considered the collision between two nebulae, resulting in one nebular protosun which subsequently captured the planets.

Jeans (14) showed that an actual collision between two stars was not necessary in order to remove material, a very near encounter would cause a tidal bulge to form on the Sun, with some material actually being removed from this bulge. A variation of this theme was proposed independently by Chamberlin (15) and Moulton (16), whereby the field of a passing star served to intensify the solar activity, thus causing ejection of matter. These authors also suggested that the ejected material instead of being a fluid, as in most other theories, could be made up of small solid particles. These small particles were called planetesimals and this terminology has now become universally accepted. These two authors were the first to suggest that the planets could form from the agglomeration of small cold bodies rather than from the condensation of hot fluid.

In 1929 Jeffreys (17) returned to the idea of a collision, but this time suggesting that the Sun and the passing star would only graze each other. In common with beliefs held at that time, both stars were assumed to be in a fluid state and so a fluid filament would be formed as a result of the grazing, extending from the Sun to the other star. This filament would eventually break away from both stars and, as a result of instabilities, would break up into droplets, some of which remained captured by the Sun and condensed into planets. Jeffreys showed that this method produced masses that were in tolerable agreement with the observed masses of the planets. The break up of a fluid filament had earlier been studied by Jeans (18) who showed that droplets would form given a favourable filament density. In the same discussion Jeans suggested that the filament could come about as a result of the tidal effects of a passing star causing rotational instabilit in the Sun. Material in the form of two filaments, one each end of th rotating ellipsoid, would be thrown off from the equator. He extende these calculations (19) by showing that the filament would be cigar shaped. Consequently there would be more mass near the middle o the filament, resulting in the planets forming there, namely Jupiter an Saturn, being more massive than the planets forming in the other part of the filament.

Gunn (20) revived the theory that a single star broke up as a resul of rotational instability, forming the Sun and a companion star. Th rotational instability comes about as a result of electromagnetic effect in the initial star. Thermal asymmetry, one face of each of the newl formed stars being hot while the other is cool, causes these stars t move apart. In this way Gunn overcame the difficulty with this typ of theory mentioned by Jeans (9) and Jeffreys (8). The method o formation of planets in a filament between the two main masses, tor out when the stars are close, is identical to the method proposed in th other theories. In fact, the main aim of this paper was to offer a explanation as to why two stars came to be very close together in orde that a filament could be efficiently formed, Gunn having concluded tha the grazing collision proposed by Jeffreys was too improbable.

Qualitative objections against most of the theories mentioned abov were put forward by Luyten (21) in 1933. As a result minor change were made, but it was to be many years before any completely ne ideas were introduced. One change was proposed by Lyttleton (22 (23), who suggested that at one stage the Sun formed part of a binar system. Collision between the companion and a passing star occurre Lyttleton demonstrated that any material escaping from the collisio is likely to have a velocity comparable with that of the Sun and s capture of this material by the Sun is probable. The idea of a collisio between a binary companion of the Sun and another star had alread been suggested, and rejected, by Russell (24) in 1935. Russell did no however, carry out any detailed calculations on the problem.

Lyttleton (25) showed that the terrestrial planets were too small t condense on their own and suggested that initially one very larg proto-planet was produced. Because of rotational instability, th broke into two major parts, Jupiter and Saturn, with a connectin filament from which the remaining planets formed.

In 1940 Bhatnagar (26) showed that, in the two-body problem, th formation of a planetary ribbon was impossible. This conclusio invalidated most of the above theories. Bhatnagar also investigate Lyttleton's theory and concluded that the Sun's companion star woul have to be so close to the Sun at the time of the collision with th assing star that the Sun could hardly have avoided being involved in his collision as well.

Before Bhatnagar's criticisms were published, other difficulties with he tidal theories had been pointed out by Nölke (27) and Spitzer (28). Nölke showed that in order that the material torn from the Sun could e stable against the tidal action of the Sun, its mass would have to be omparable with that of the Sun. Spitzer's argument depends on the hermal dissipation of the filament. In order that the filament should ontain enough mass to form the planets, matter must have been drawn rom the solar interior and so must be at a temperature of about 10^6 °K. pitzer showed that, at this temperature, such a filament must expand o infinity unless it cools rapidly. He showed that the cooling time is ne order of magnitude greater than the expansion time and so dissipaion of the filament must occur.

Nölke (29) and Russell (24) had also cast doubt on whether any esisting medium could reduce the orbits of planets to ones of small ccentricity (in most of the above theories planets form with very large nitial eccentricity).

In an attempt to overcome the criticisms of Nölke and Spitzer, auvillier (30), (31) proposed a theory in which the tidal filament was onized. He showed that electromagnetic effects would stabilize the ilaments long enough for condensation into planetary twins to take lace. Condensations would occur at exponentially increasing distances rom the Sun. The twin planets usually merged while still gaseous but he Earth–Moon system is an exception.

As a result of the criticisms of Bhatnagar, Lyttleton (32), (33) sugested that the Sun formed part of a triple star system, consisting of a lose binary and the Sun. Due to accretion of interstellar matter the eparation of the two stars in the binary system will decrease, until they nally combine to form one mass. This mass will break up because of otational instability. After this fission the two parts escape from the ystem, and the filament formed between them is captured by the Sun. he objection of Spitzer also applies to this theory.

Hoyle (34) maintained that the Sun's companion did not break up s a result of rotational instability, but rather went through the normal rocesses of evolution and became a nova. Material ejected in this xplosion was captured by the Sun, and the planets formed from this. n order to produce the desired result he found that the amount of atter in the form of diffuse gas must be about $(\frac{1}{10})M_{\odot}$. He modified is theory one year later (35) by replacing the nova explosion by a uper-nova. When numerical values for the various quantities involved, aken from observations of the Crab Nebula, are introduced, all the equirements of his theory are satisfied. In another publication, weight was added by Hoyle (36) to Lyttleton's conclusion that the terrestria planets did not form directly, but were formed as a consequence of th rotational break-up of a protoplanet.

This was to be the last important development of theories in thi category for a considerable time, the next being in 1960 when Lyttleto (37) carried out detailed calculations on the orbits which small masse would follow under the action of two larger masses. He showed tha in most cases the orbits either go to infinity or intersect the surface o one or other of the two large masses. He concluded that it is almos impossible to form a planetary system by any of the methods describe under the category 2(a). At about the same time, however, Woolfso (38) proposed that a star of mass 10 $M_\odot$, approaching with a velocit of 100 km/s would form a tidal bulge on the Sun. Part of this bulg breaks away to form Pluto. As the star approaches the Sun, Neptune Uranus, Saturn and Jupiter, in turn break away. The Earth and th terrestrial planets form as the star recedes. This theory was severel criticized by Briggs (39) and as a result Woolfson (40) proposed considerably modified theory in 1964. In this modified theory th approaching star is taken to be a supergiant, thus having a low densit near the surface. A filament is drawn out of this star as a result of th tidal effects of the Sun. This filament breaks up into droplets as in th theories of Jeans (18) and Jeffreys (17). The argument is numerical; b choosing suitable initial conditions, Woolfson obtains a system that as far as mass and angular momentum are concerned, is in very goo agreement with the observed values for the solar system. The objection of Spitzer would once again seem to apply, however.

Two other theories of this category that deserve mention because o their ingenuity were proposed in this decade. In 1960 Egyed (41) place the problem against the general background of Dirac's cosmology. I this form of cosmology the gravitational constant decreases with time Therefore, under suitable conditions, there could be an instant whe the centrifugal force at the solar equator became equal to the surfac gravity. It was suggested that a planetary mass escaping at this tim would lead to a decrease in the solar radius. This process is repeate leading to the formation of a number of planets. It is difficult to se how this process ever terminates, and if it did the Sun would presumabl be rotating very fast.

A theory by Banerji & Srivastara (42) published in 1963 considered spherical magnetic star of mass 9 $M_\odot$. This star is assumed to oscillat radially with a small amplitude. Banerji & Srivastara showed that th nearby passage of a star of similar mass increases the amplitude of th oscillation of the magnetic star rendering it unstable. The instabilit leads to ejection of matter from which the planets may form. The concluded that the two stars need not pass very close, neither need the velocity be high in order to produce the required angular momenta of the planets.

Though both are unusual ways of producing ejection of matter, the theories appear to be subject to the criticisms of Nölke and Spitzer.

As a result of the objections of Nölke, Spitzer, Bhatnagar and Lyttleton, together with other objections, which we discuss in the next section, this type of theory is not now in favour.

Theories in category 2(b)

This also is a category in which the formation of the planets is independent of the formation of the Sun. It differs from the previous category in that the material for the formation of the planets is obtained from interstellar space rather than directly from another star or from the Sun.

Most theories in this category take as their starting point the existence of a cloud of gas and dust, called the solar nebula, in the form of a flattened disk surrounding the Sun. Such a disk may form when the Sun moves through an interstellar gas cloud which possesses some rotation. Material will be accreted by the Sun, but not all will fall into the Sun because of the effects of rotation. The formation of this nebula has been investigated by several authors (see for example Lyttleton (43), Hoyle (44) and Sekiguchi (45)), and it seems possible that such a nebula may form. However, as mentioned above, most of the authors whose theories are given below postulate the existence of such a nebula as part of their initial conditions, the nebula being flattened because of angular momentum effects.

It may be argued that one of the very first theories of the origin of the solar system, the theory of Kant (2), belongs to this category. However, Kant did attempt to form the Sun as part of the same process and so his theory is described in the next section. His theory forms the basis for a theory proposed by Berlage in a series of seven papers (46)–(52).

The basic idea in Berlage's theory is the formation of concentric rings in the captured nebula. The planets form from these rings by some unspecified method. The rings are assumed to form as a result of viscous interactions dissipating energy because all the volume elements follow Keplerian motion. Berlage assumes that an encounter with another star is responsible for the angular momentum distribution. Berlage's theory thus embodies aspects from many previous theories.

One of the very first cosmogonical theories was the theory of Descartes (1). He assumed that the Universe is filled with ether and matter. In consequence the only possible motion is a vortex motion.

The Universe initially was filled with circular eddies of all sizes. The friction between the eddies would smooth down the rough shape of the initial matter. The resulting filings would tend towards the centre of the vortex, forming the Sun. The coarser bodies are captured in the vortex and these form the planets.

Though this theory also strictly belongs to category 1 we have included it here as the ideas outlined are very similar to those given in more modern times by von Weizsäcker (53). He first showed that a gaseous envelope surrounding the Sun, and possessing angular momentum, will assume a disk shape which is not stable, and that the velocities of parts of the disk closely follow Kepler's laws, so that viscous forces will be present which try to set up a rotation of a rigid body; hence the outward part of the disk will accelerate and move outwards while the inner part will decelerate and fall inwards, and in time the disk will dissipate completely. As a result of this dissipation, material of zero angular momentum falls into the Sun, slowing its rotation down. In this way von Weizsäcker attempted to explain the slow rotation of the Sun. He postulated that the matter flowing to infinity is the lighter material and so the planets are formed out of the heavy elements. Von Weizsäcker then considered the pattern of vortices which would be set up in the disk. He concluded that they would tend to form as 'roller-bearings' in between rings of different velocity in the disk. He suggested that condensation could take place inside these 'roller-bearings' very easily and showed that the time required to form planetary sized condensations in the disk is comparable to the life of the disk. It was expected that the ratio of the radii of two consecutive circles would be constant, thus giving vortices at the distances obeying roughly the Titus–Bode Law.

Von Weizsäcker's theory was modified and extended a few years later by Ter Haar (54), (55). The regular eddies of von Weizsäcker were discarded and replaced by random turbulence. This leads to a very thick nebula and so gravitational instability would not occur. Ter Haar thus concluded that the planets must have formed by accretion. He explained the difference in composition between terrestrial and major planets on the grounds that the inner part of the nebula would be considerably hotter than the outer part. Thus only non-volatile material condensed in the inner regions. A major difficulty with this theory is that turbulent dissipation takes place in a fairly short time of about 1000 years. Condensation into planets must thus take place in an interval of time shorter than this.

Kuiper (56), (57), (58) also argued that the regular vortices of von Weizsäcker would be impossible and suggested instead that large gravitational instabilities might occur in the solar nebula, forming condensations. The nebula could either form contemporaneously with the Sun or be captured by it. Depending on the density distribution in the nebula, either a planetary system or a stellar companion to the Sun could be formed. Thus Kuiper, indirectly, postulated the masses and angular momenta of the planets. The separation of planets into two types, terrestrial and major, was assumed to be due to the existence of the Roche limit (see Jeans (**18**) for a definition of this limit). Terrestrial planets, being higher in density, are the only ones that can form inside the orbit of Jupiter. No explanation is offered for the slow rotation of the Sun; Kuiper considered this as part of a more general problem of explaining why most G-type stars rotate slowly.

In the same year as von Weizsäcker, Schmidt (**59**), a Russian astronomer, first put forward his theory for the origin of the planets. He assumed that the Sun passes through a cloud of dust and gas, capturing some of it to form the solar nebula. As this cloud possesses angular momentum, collisions will in time reduce it to a bun-shaped disk. The mass and angular momentum of this nebula, and thus of the planets, is postulated rather than derived, as indeed is the case with most theories in this category.

As this disk contains dust, the parts nearer the Sun will absorb the solar radiation and warm up, while parts farther away will remain cool. This heating results in the dispersal of all volatile material from near the Sun. The remaining non-volatile material then agglomerates to form the terrestrial planets. In the cooler parts, farther away from the Sun and its heating effects, all the material will agglomerate to produce the major planets. Hence Schmidt's theory offers an explanation for the difference in mass and composition of the planets. It also explains the rotation in one plane of all the planets. By a postulate, the mass and angular momentum of the planets are also in agreement with the requirements. The theory makes no attempt to explain the slow rotation of the Sun. There have been extensions of this theory by the Russian school that grew up around Schmidt. An account of some of these is given by Levin (**60**).

A completely different type of theory was proposed in 1942 by Alfvén (**61**)–(**63**) when he included electromagnetic effects in the equations of motion of particles. Slight modifications were later published (**64**), (**65**). Some attempt at this had already been made by Birkeland (**66**) as early as 1912. In his theory, Birkeland assumed that ions were emitted by the Sun; under the influence of the solar magnetic field these ions will spiral out towards their limiting circular orbits. He never followed up this idea to produce a detailed mathematical theory.

Berlage, in another three publications (in fact, prior to the seven already discussed) (**67**)–(**69**) had also made use of the ejection of ions from the Sun. In his proposed initial state, the Sun is surrounded by a flattened solar nebula. Charged particles are emitted from the Sun into this nebula which acquires a space charge as a result. This space charge was assumed to increase with distance. Berlage found that the equilibrium configuration, on ignoring centrifugal forces, is a series of concentric rings, each ring consisting of one particular element, those of heaviest atomic weight being nearest the Sun. The planets form from these rings. There are many invalid points in this theory; for example centrifugal force is neglected and it is known that ionization in a solar envelope is negligible, hence the space charge will not form.

Alfvén, without being aware of either Birkeland or Berlage's theories, considered the Sun to be surrounded by an interstellar gas cloud. The atoms of this cloud will fall towards the Sun, thus increasing their velocity. At some stage this velocity will become high enough for the energy released at a collision to cause ionization of the falling atoms. When this takes place the ion is forced to follow the lines of magnetic force to an equilibrium position in the equatorial plane, thus generating a high density in this plane. Condensation in this plane now accounts for the major planets. However, the process of capturing ions cannot explain the formation of the terrestrial planets, as the radius at which ionization occurs is much greater than the mean terrestrial planetary distance from the Sun. Alfvén thus considered interstellar grains. These will follow the same general history as the ions but in this case the mass to charge ratio is much higher. As a result the equilibrium position will be much nearer the Sun. The terrestrial planets condense from this material. The mass of the planets is once again a matter of postulate but now the angular momentum distribution is explained and so is the composition difference.

These are the major theories under this category. As can be seen, some of them do explain the very slow rotation of the Sun. None, however, explains how an initial gas cloud could rotate slowly enough to allow the Sun to form without encountering rotational instabilities.

Theories of type 1

In all of the following theories the formation of the planetary system must come about as a direct consequence of the formation of the Sun. The nebular theories of Kant (2) and Laplace (3) are theories of this type. In the theory of Kant the Universe is assumed to be roughly uniformly filled with gas. Regions of slightly higher density act as nuclei for condensations to form. A contraction process occurs in these condensations and protostars are formed. As the condensations were assumed to be initially rotating, conservation of angular momentum required all the protostars, in particular the protosun, to flatten. In the resulting disk, secondary condensations form, and the planets originate at the centre of these. The major difficulty with this theory is to explain the distribution of angular momentum in the present system.

In Laplace's theory, the Sun is formed out of a large diffuse gas cloud possessing a small amount of angular momentum. As this condenses its angular velocity must increase and so the cloud takes up a lens shape. At some later stage, the gravitational attraction will clearly be balanced by the centrifugal force, and further contraction can now proceed only after the ejection of a ring of material. In time the same effect will repeat itself, resulting in the ejection of another ring. This process is repeated until the Sun reaches its present-day form. A planet forms in each of the ejected rings and so a planetary system is formed. This simple theory also clearly breaks down on a number of points, notably because the Sun would still be rotating on the verge of rotational instability today; also it cannot explain the observed mass and composition of the planets. However, some of the ideas of Laplace's theory are incorporated in more modern theories, especially the idea that material first forms into rings and then into planets. The most recent of Hoyle's theories is of this type. This theory was proposed in qualitative form in 1955 (70) and with more mathematical detail in 1960 (71).

Like Laplace, Hoyle starts with a cloud of gas possessing angular momentum, its numerical value being roughly what it would be if the cloud rotated with the general galactic rotation, that is 4×10^{51} cgs units. For a star of mass $M_{\odot}$, rotational instability sets in when the radius of the star is 3×10^{12} cm, or roughly equal to Mercury's orbital radius. A ring of material is ejected, allowing the star to contract further. Hoyle differed from Laplace in that he postulated that a magnetic torque comes into existence between the disk and the star. This must come into effect immediately, otherwise more and more matter is ejected resulting in a planetary system comparable in mass to the Sun. The existence of the torque depends on the lines of magnetic force from the Sun being frozen into the disk. (This is a consequence of a well-known theorem on frozen-in lines of force. See any book on magneto-hydrodynamics, e.g. Ferraro & Plumpton (72), for more details.) For the torque to be effective Hoyle finds that the magnetic field strength has to be of the order of 1 gauss, while ohmic decay will not cause uncoupling provided that the conductivity of the disk is at least 10^{11} cgs units, requiring 1 atom in 10^7 at the edge of the disk to be ionized.

These numerical values are reasonable and so Hoyle concluded that the existence of the proposed mechanism of magnetic coupling is possible. The effect of the torque is to transfer angular momentum from the Sun to the disk, resulting in the disk moving outwards from the central condensation while the condensation itself contracts further, now with roughly constant angular velocity.

Edgeworth (73) in a short note, proposed a slightly different coupling method which also depends on the existence of a magnetic field and would require the disk to be highly conducting. The proposed mechanism requires that the lines of magnetic force are frozen in the disk, the torque being similar to the one generated when a metal object is moved through a magnetic field. This does not differ substantially from Hoyle's method but it indicates further that coupling is possible.

The temperature of the solar condensation at the epoch when the disk was ejected, could not be much in excess of 1000 °K and so a number of non-volatile materials must be in solid form, probably as fine smoke particles. These particles will grow in size as a result of further condensation and accretion. Hoyle showed that these particles will be swept outwards with the disk only if their diameter at the Earth's orbit is less than 100 cm. Thus as the main disk moves out, a subsidiary disk consisting only of non-volatile material remains behind. Hoyle suggested that the formation of the terrestrial planets naturally takes place in this subsidiary disk. The terrestrial planets are therefore different in composition from the Sun.

When the disk reaches the Jupiter–Saturn region, the gravitational field of the Sun is weaker, hence particles of diameter less than 10 m are now swept along. However, the temperature is now much lower and ice particles can form. By the time the condensations here are large enough to capture the gas by their own gravitational field most of the gas will escape from the system. Hence Jupiter and Saturn, forming first, each have a large amount of gas, whereas Uranus and Neptune do not. Hoyle thus obtained very good agreement with observations for the mass and composition of the planets. The slow rotation of the Sun is also explained. In fact, all the features mentioned in the introduction are explained provided the idea of magnetic coupling is acceptable. It should be mentioned that the method of magnetic coupling adopted by Hoyle is somewhat similar to one proposed in a slightly different context by Lüst & Schlüter (74). In a study of nucleosynthesis during the early history of the solar system by Fowler, Greenstein & Hoyle (74a) it is shown that the DLiBeB abundances lead to a requirement that 10 per cent of the terrestrial material must be irradiated with a thermal–neutron flux of 10^7 n/cm^{2}s for an interval of 10^7 years. It is shown that Hoyle's model for the origin of the solar system meets this requirement.

An earlier theory by Edgeworth (75) also proposed that the planets formed out of a rotating disk; however, the disk in this case is formed in a very different manner to that of Hoyle. In an earlier publication the same author (76) had demonstrated that direct condensation of the Sun and planets was not possible. This was much the same conclusion as Jeffreys (8) had reached earlier, but Edgeworth considered more possibilities. In his second paper he therefore had to form the planets and the Sun by other methods, methods that did not involve direct condensation of a gas cloud. He postulated that during the formation of the Sun, some material is captured in orbit around the Sun and does not actually fall into the Sun. Because of collisions between different parts of the captured material, it will eventually form into a disk surrounding the Sun. Edgeworth recognized the need for transfer of angular momentum in order to slow the rotation of the Sun, but at the time he decided that the use of magnetic fields was too speculative; instead he used viscous forces for the transfer process. As a result he concluded that eddies will form in the disk and these will grow as a result of the viscous effects at their edges. Collisions between these eddies will also cause an increase in the mean size. He estimated the time required for a mass of planetary size to be formed by this process as 10^5 years near the Earth's orbit, increasing to 5×10^6 at Neptune's orbital distance. He suggested two planetary sequences, one containing the planets from Mercury to the asteroids and the other containing the planets from Jupiter to Pluto. The tail of each sequence did not contain enough mass to form a planet and so gave rise to the asteroids and the comets. The theory thus obtains the difference in the terrestrial planets and the major planets by postulate rather than by calculation. Also, viscous friction can only be effective if the disk touches the Sun at all times, hence we would expect material to be found closer to the Sun than Mercury. It is also doubtful how effective viscosity would be in diffuse media even if it did touch the Sun. Consequently grave doubts must be cast on this theory. However, it has many points in common with a more recent theory, first proposed in 1960 by McCrea (77), (78).

McCrea envisaged the formation of the Sun as taking place at the same time as the formation of a number of other stars, these stars eventually forming a stellar cluster. Consequently he envisaged an initial cloud of several hundred solar masses. This is taken to be at a relatively high density of about 4×10^{-12} g/cm^3, having followed a process of contraction described by him (79) in 1957, its temperature being about 50 °K and composed mainly of molecular hydrogen. At this stage McCrea diverged from the usual treatment assuming homogeneity and isotropy by taking this cloud to consist of small deformations, so that it is broken up into many cloudlets or 'floccules' as he calls them, these being in random motion amongst themselves with a mean speed of about 1 km/s, their mean free path being $R = 5 \times 10^{14}$ cm. He assumed that about 10^5 floccules occur in a sphere of radius R. When two of these floccules collide the parts directly concerned will coalesce while the other parts will proceed as smaller floccules. A larger than average floccule may thus result from a collision. By a series of such favourable collisions minor condensations are formed throughout the cloud. Some of these may survive, some clearly do not. A reasonably large condensation will have a gravitational field which attracts further material, resulting in a growing condensation. Material entering this condensation must initially have been travelling towards this region and so material joins the condensation from all directions, ensuring that very little angular momentum is carried into the condensation.

McCrea argued that what occurs inside a region of radius R is likely to be duplicated in other such regions and each such region develops more or less independently. With the adopted numerical values, the mass inside a radius R is about a solar mass. Most of this will form one major condensation in this region, but McCrea showed that about 1000 floccules will be captured in orbit about the major condensation. He also estimated that the time taken for 90 per cent of the material to form in the major condensation is less than 10^5 years and that the space requirement for this condensation is less than half the orbit of Mercury. Hence in this theory there is no difficulty in forming a planet at Mercury's distance from the Sun.

The remaining 1000 floccules orbiting the Sun will tend to flatten towards the invariable plane defined by the angular momentum, the time taken being only about 5000 years. At the same time as the flattening process occurs there will be a tendency for collisions. In this way floccules orbiting in opposite directions will lose all their angular momentum and fall into the Sun. By this mechanism the Sun obtains the last 10 per cent of its mass. There remains about 200 floccules, all orbiting in the same direction; these will tend to condense in the same manner as operated in the formation of the Sun. As a condensation must be about 20 floccule mass in order to hold together, about the correct number of planets will be formed by this process. All the protoplanets will be roughly similar, having about the same mass and composition as the present-day Saturn and Jupiter. Near the outer edge of the system the gravitational field is weak and some mass loss thus occurs, resulting in the proto-Neptune and proto-Uranus being smaller than the other protoplanets. The major planets now form out of these protoplanets by direct condensation. Another process, that of separating the heavy elements from the hydrogen, must now play a part in the formation of the terrestrial planets. In his original paper McCrea showed that, with the assumed density of 4×10^{-12} g/cm^3, the major planets are outside the Roche limit and can condense while the terrestrial planets are inside the limit and so will be torn apart. He suggested that a heavy element core is formed in all the protoplanets.

Inside Roche's limit the core is all that remains after the tidal action of the Sun has torn away the outer layers. This forms the planets of the same mass and composition as the terrestrial planets.

The problem of the formation of a heavy element core has been investigated by McCrea & Williams (**80**). They concluded that the time taken for both gas molecules and normal interstellar grains to settle to the centre under the gravitational field of the condensation is very large (greater than 10^9 years in all cases). As this time is comparable to the age of the Sun, no appreciable core formation in the condensation can take place as a result of the settling of interstellar grains. However, if some grains accrete all other grains that collide with them, then the time scale is considerably shortened (less than 10^4 years in all cases of interest). The final size of the grains in this case is about 100 cm, very similar in size to the grains required by Hoyle for his formation of the terrestrial planets. If this mechanism of growing grains is feasible, then a heavy element core can be formed and the formation of the terrestrial planets may come about as suggested. McCrea & Williams also indicated that the energy released by the core-forming process is of the same order as the energy required to disperse the surrounding hydrogen. This also presumably helps towards leaving only the heavy core as a planet.

We thus see that if the initial values for the floccules, together with the idea of a growing grain are acceptable, then McCrea has proposed a method that produces all the features of the solar system.

The methods of Hoyle and McCrea both recognize the need to remove angular momentum from the Sun. The methods advocated for doing this both result in the formation of a planetary system about the Sun. On the other hand Whipple (**81**), (**82**) suggested that the solar system formed out of one cloud in the Galaxy that had very little angular momentum, much less than it would have due to galactic rotation. This cloud is assumed to have a radius of about 3×10^4 a.u. The planets form in a stream in this cloud, and so by postulate they have the correct angular momentum. They accrete the surrounding gas which has zero angular momentum and so they must spiral inwards, towards the Sun. This clearly is in conflict with the observed solar system as the more massive planets would have accreted more gas and so would be nearer the Sun. The theory postulates the correct mass and angular momentum—consequently it explains hardly anything.

This completes the survey of theories for the origin of the solar system; we must now compare them and select the theory or theories that are most likely to be correct. Valuable information, which is of assistance in making this selection, can be gained from some recent scientific advances, not all directly concerned with the problem, which we summarize in the next section.

3. RECENT SCIENTIFIC DEVELOPMENT

In the introduction we have given a number of basic facts with which any model of the solar system must conform. Recent developments in astronomy have given us much more information about certain aspects of the problem, thus giving far more rigid constraints on some points. This allows us to reject certain theories and renders other theories unlikely.

A number of authors, notably Urey (83), Latimer (84), Chamberlain (85) and Brown (86), have shown that some of the elements and compounds found both on the Earth and in meteorites are not compatible with the Earth having condensed out of a hot gas cloud of solar composition. The compounds include water, chlorine, nitrogen, carbon, sulphur, cadmium, zinc and oxidized iron. All these are either gaseous or are reduced in the presence of oxygen and hydrogen at any temperature higher than about 0 °C. Ringwood (87) has investigated thermal properties of the Earth and has concluded that it is not impossible for the Earth to have had a cold origin. The evidence of these authors thus suggests strongly that we must consider as incorrect any theory of the origin of the solar system that involves direct condensation of the terrestrial planets from hot gas. The separation of the elements of the Earth from the surrounding hydrogen must have taken place at low temperature.

Geological evidence (see Mathers (88)) also suggests that the terrestrial planets came about by an aggregation of planetismals.

Small diamonds of good crystalline form are found in iron meteorites but production of such material was marginal and so was its destruction (see Urey (89)). In view of this, Urey concluded that temperature, pressure and time were barely sufficient to produce and destroy diamonds. It is to be noted that in the above paper Urey also proposed a model for the origin of the solar system. We have not included it in our survey above as it is a theory where he works backwards from the given solar system, deducing from the available evidence what the state of the system must have been at different epochs. His postulated theory is as follows.

A disk of gas and dust is formed around the primitive Sun. As no geochemical evidence of this can be found, Urey did not concern himself with its formation. Using stability equations given by Chandrasekhar (90) he obtained the density distribution in the solar disk. In order that volatile elements like mercury could be retained by the terrestrial planets, Urey postulated that a halo of dust and gas of moderate thickness must have been present in the plane of the disk so as to shield the planets from the Sun. In order to form diamonds, approximately lunar sized objects must now form in the disk (the mass of these to be about 6×10^{28} g, that is the present lunar mass plus the solar gas). At a later stage, the gas and dust cloud between these objects and the Sun was dissipated. The pressure fell as gas was lost and diamonds were converted to graphite, while the gas became illuminated by the Sun. Under these conditions considerable ionization would be present and the gas would be accelerated by magnetic fields; hence angular momentum could be transferred from the Sun.

As the lunar sized objects are no longer present in the solar system they must have been destroyed. Collision seems to be the only possible mechanism for this. The smaller fragments resulting from these collisions could be driven far out into space while the larger fragments stayed behind; accretion of these fragments into planets then occurred.

Another cosmochemist, Anders (91), proceeding in the manner of Urey, has suggested that the following stages must have occurred. The material in a solar nebula must have cooled rapidly leading to the formation of chondrules, metal grains and other solid particles. This nebula was irradiated by charged particles, the level of irradiation varying with distance from the Sun. The planets and meteorite parent bodies accreted at low temperature, fractionation of metal and silicate particles took place and the gases were lost. The meteorite parent bodies were heated to a varying degree by a transient heat source of unknown nature and after final cooling some redistribution of the noble gases took place.

Each stage in the above theories are postulated to exist in order to explain some phenomenon found in the solar system today. In general no reason is given for the development from one stage to the next. Strictly they are not therefore theories but rather a table of events that must occur. We have therefore included them in this section for they serve as a test for the correctness of other theories, at least in as far as other theories for the origin of the planets must have stages whereby all the effects mentioned by Urey and Anders must come about.

Other valuable information concerning the origin of the solar system has come from the study of interstellar gas. In particular, a great deal of information is now available about the behaviour of interstellar grains. Investigations on the possible growth of such grains was first started by Lindblad in 1935 (92). Such investigations were later carried out by van de Hulst, Oort and others. Useful references on this subject are given by McCrea & McNally (93). One important development is that it is now generally accepted that under suitable conditions these grains can agglomerate and form into larger bodies. Donn & Sears (94) have brought crystallographic techniques to bear on this problem and have concluded that the formation of such large grains can easily come about. This clearly makes theories involving planetesimals and the growth of large bodies from small grains seem more feasible now than it did at the time tidal theories were popular.

The search for planetary systems other than our own, as mentioned in the introduction, and the discovery of objects with planetary mass must make it fairly likely that planetary systems are commonplace, thus making it more difficult to justify theories that involve unlikely collisions and accretions.

In recent years the advances made in the field of stellar evolution allows astronomers to follow the evolution of a star with great certainty. The model of Hayashi (95) for the contraction of a star from a gas cloud, and the very good agreement it has with the observations of Walker (96), (97) and others, has given us a very good idea of the time scale involved in forming a star. It also indicates that while the star is in the early phases of contraction the luminosity decreases very rapidly while the temperature remains almost constant. This is in contrast with the previous picture of Henyey, Le Levier & Levée (98) where the luminosity remains almost constant.

Other evolutionary models by Faulkner, Griffiths & Hoyle (99) and Ezer & Cameron (100) confirm the general picture outlined by Hayashi for the early contraction phase. The work on evolution has also confirmed that stars are found in clusters, each star in a particular cluster being of the same age. Stars must thus form at the same time in groups, they must also form under conditions that can be observed today. Very recently Neugebauer, Martz & Leighton (101), in an infra-red survey of the sky have discovered objects that are so young that they may well prove a useful test between theories relating to the origin of stars in general and to the origin of the solar system in particular when more information is known about them.

Williams & Cremin (102) have shown that these results are consistent with the model of Henyey, Le Levier & Levée, and so there may be an initial low luminosity stage followed by the high luminosity phase predicted by Hayashi.

Finally, there have been great developments in mathematics and mathematical techniques. The use of modern computers has meant that many a problem that used to be considered insoluble can now be solved. In particular, rates of cooling of gas clouds have been accurately determined. The equations of motion of bodies under many different force fields can also be solved, an example of this being the work of Lyttleton (37) showing that collisional and tidal theories lead to orbits that intersect the parent body.

Though a large number of the theories which we have listed above do in fact produce a solar system in agreement with the general description mentioned in the introduction, we now see that in order to be acceptable they must satisfy many more conditions. It is also evident that of the theories that remain after these conditions have been imposed, it is likely that at least one must be very near to the truth.

4. DISCUSSION AND CONCLUSIONS

The conclusion that stars are forming in the Galaxy under conditions that exist today, in particular under the general rotation of the Galaxy, means that the problem of removal of angular momentum from the Sun is a real one. It cannot be overcome by allowing the formation of the system to take place at an epoch when there was no rotation. There must therefore exist a mechanism for the slowing down of the rotation of stars and the only ones in evidence result in the formation of a planetary system. Thus the lack of a slowing down mechanism must count against theories that postulate a steady star before the planetary system is formed.

Taking this conclusion together with the work of Lyttleton (37) and the fact that planetary companions are expected to exist with other stars, we must regard the theories in category 2(a) with the gravest of doubts. When we also take into account that all of these theories produce the planets by direct condensation from material of solar composition, in direct contradiction of the conclusions of the last section, and consider the work of Spitzer and Nölke, we must conclude that this type of theory does not offer a satisfactory solution to the problem of the origin of the solar system.

Of the theories in category 2(b), the theory of von Weizsäcker is in many ways qualitative, not making exact predictions, but it is doubtful if sufficient slowing down of the Sun would come about, and as most of the other points suggested by him are incorporated and improved upon in other theories, we must reject his theory. Schmidt has postulated the angular momenta and masses of the planets, hence his predictions are in some ways rather insignificant. Separation of the heavy and light elements comes about by a process of evaporation and some of the elements found on Earth must be lost, and so his theory is also doubtful. Of this category of theories there thus remains only the theory of Alfvén. From category 1 we must retain only the latest of the theories in two types of work, that of Hoyle and that of McCrea. We are left with these three theories for the origin of the solar system. Clearly none of them is perfect, but neither can any of them be instantly dismissed.

The theory of Alfvén does not account for quite so much as the other two, the ratio of the terrestrial planet mass to the major planet mass comes about essentially as a postulate. It is also not clear that very violent collisions of smoke particles would lead to ionization, fragmentation would be a far more likely effect. He also has the difficult task of building planets out of charged particles that repel one another. We are thus left with the theories of Hoyle and McCrea as the two most satisfactory theories. They both produce a solar system in agreement with the introduction; they both account for the low angular momentum of the Sun. Planets are formed out of material that segregated when at a relatively cold stage; in fact, apart from their initial postulate and mechanism, the resulting solar system is almost identical in both cases. The amount of evidence we have available at present does not permit us to distinguish between these theories but it is likely that the correct theory for the origin of the solar system will be somewhat similar to one or other of these.

REFERENCES

(1) Descartes, R., 1644. *Principia Philosophiae,* Amsterdam.
(2) Kant, I., 1755. *Allgemeine Naturgeschichte und Theorie des Himmels.*
(3) Laplace, P.S.de, 1796. *Exposition du système du Monde,* Paris.
(4) Jeffreys, H., 1952. *Proc. R. Soc.,* **A214,** 281.
(5) Van de Kamp, P., 1956. *Vistas Astr.,* **2,** 1040.
(6) Jeans, J.H., 1931. *Nature, Lond.,* **128,** 432.
(7) McCrea, W.H., 1963. *Contemp. Physics,* **4,** 278.
(8) Jeffreys, H., 1918. *Mon. Not. R. astr. Soc.,* **78,** 424.
(9) Jeans, J.H., 1917. *Mon. Not. R. astr. Soc.,* **77,** 186.
(10) Buffon, G.L.L., 1745. *De la Formation des Planètes,* Paris.
(11) Bickerton, A.W., 1878. *Trans. N.Z. Inst.,* **11,** 128.
(12) Arrhenius, S., 1913. *Das Werden der Welten,* Leipzig.
(13) See, T.J.J., 1910. *The Capture Theory of Cosmical Evolution: Researches on the Evolution of the Stellar System,* Vol. 2, Nichols Lynn, Massachusetts.
(14) Jeans, J.H., 1916. *Mem. R. astr. Soc.,* **77,** 84.
(15) Chamberlin, T.C., 1901. *Astrophys. J.,* **14,** 17.
(16) Moulton, F.R., 1905. *Astrophys J.,* **22,** 165.
(17) Jeffreys, H., 1929. *Mon. Not. R. astr. Soc.,* **89,** 636.
(18) Jeans, J.H., 1928. *Astronomy and Cosmogony,* Cambridge University Press.
(19) Jeans, J.H., 1931. *Nature, Lond.,* **128,** 432.
(20) Gunn, R., 1932. *Phys. Rev.,* **39,** 311.
(21) Luyten, W.J., 1933. *Z. Astrophys.,* **7,** 46.
(22) Lyttleton, R.A., 1937. *Mon. Not. R. astr. Soc.,* **90,** 531.
(23) Lyttleton, R.A., 1940. *Mon. Not. R. astr. Soc.,* **100,** 546.
(24) Russell, H.N., 1935. *The Solar System and its Origin,* Macmillan, New York.
(25) Lyttleton, R.A., 1937. *Mon. Not. R. astr. Soc.,* **90,** 633.
(26) Bhatnagar, P.L., 1940. *Indian J. Phys.,* **14,** 253.
(27) Nölke, F., 1932. *Mon. Not. R. astr. Soc.,* **93,** 159.
(28) Spitzer, L., 1939. *Astrophys. J.,* **90,** 675.
(29) Nölke, F., 1930. *Der Entwicklungsgang unseres Planeteneystems,* Bonn.
(30) Dauvillier, M.A., 1942. *Archs Sci. phys. nat.,* **24,** 5.
(31) Dauvillier, M.A., 1942. *Archs Sci. phys. nat.,* **24,** 65.
(32) Lyttleton, R.A., 1940. *Mon. Not. R. astr. Soc.,* **100,** 546.
(33) Lyttleton, R.A., 1941. *Mon. Not. R. astr. Soc.,* **101,** 216.
(34) Hoyle, F., 1944. *Proc. Camb. phil. Soc. math. phys. Sci.,* **40,** 256.
(35) Hoyle, F., 1945. *Mon. Not. R. astr. Soc.,* **105,** 175.
(36) Hoyle, F., 1946. *Mon. Not. R. astr. Soc.,* **106,** 406.
(37) Lyttleton, R.A., 1960. *Mon. Not. R. astr. Soc.,* **121,** 551.

(38) Woolfson, M.M., 1960. *Nature, Lond.*, **187**, 47.
(39) Briggs, M.H., 1960. *Nature, Lond.*, **187**, 1102.
(40) Woolfson, M.M., 1964. *Proc. R. Soc.*, **A282**, 485.
(41) Egyed, L., 1960. *Nature, Lond.*, **186**, 621.
(42) Banerji, A.C. & Srivastara, K.M., 1963. *Proc. natn. Acad. Sci. India*, **A33**, 125.
(43) Lyttleton, R.A., 1961. *Mon. Not. R. astr. Soc.*, **122**, 399.
(44) Hoyle, F., 1956. *Vistas in Astronomy*, **2**, 1702.
(45) Sekiguchi, N., 1961. *Publs astr. Soc., Japan*, **13**, 241.
(46) Berlage, H.P., 1932. *Proc. K. ned. Akad. Wet.*, **35**, 553.
(47) Berlage, H.P., 1934. *Proc. K. ned. Akad. Wet.*, **37**, 221.
(48) Berlage, H.P., 1935. *Proc. K. ned. Akad. Wet.*, **38**, 857.
(49) Berlage, H.P., 1940. *Proc. K. ned. Akad. Wet.*, **43**, 532.
(50) Berlage, H.P., 1948. *Proc. K. ned. Akad. Wet.*. **51**, 796.
(51) Berlage, H.P., 1948. *Proc. K. ned. Akad. Wet.*, **51**, 965.
(52) Berlage, H.P., 1953. *Proc. K. ned. Akad. Wet.*, **56**, 56.
(53) Von Weizsäcker, C.F., 1944. *Z. Astrophys.*, **22**, 319.
(54) Ter Haar, D., 1948. *Kgl. Danske Videnskap Selskab, Mat-Fys. Medd.*, **25**, 3.
(55) Ter Haar, D., 1950. *Astrophys. J.*, **111**, 179.
(56) Kuiper, G.P., 1949. *Astrophys. J.*, **109**, 308.
(57) Kuiper, G.P., 1951. *Proc. Natn. Acad. Sci.*, **37**, 1.
(58) Kuiper, G.P., 1951. *Astrophysics*, ed. by J.A.Hynek, Chap. 8, McGraw-Hill, New York.
(59) Schmidt, O.Y., 1944. *Dokl. Akad. Nauk. SSSR*, **45**, No. 6.
(60) Levin, B.J., 1958. *Origin of the Earth and Planets*, Moscow.
(61) Alfvén, H., 1942. *Stockh. Obs. Annlr*, **14**, No. 2.
(62) Alfvén, H., 1942. *Stockh. Obs. Annlr*, **14**, No. 5.
(63) Alfvén, H., 1943. *Nature, Lond.*, **152**, 221.
(64) Alfvén, H., 1946. *Stockh. Obs. Annlr*, **14**, No. 9.
(65) Alfvén, H., 1954. *On the Origin of the Solar System*, Oxford University Press.
(66) Birkeland, K., 1912. *C. r. hebd. Séanc. Acad. Sci., Paris*, **155**, 892.
(67) Berlage, H.P., 1927. *Ergänzungsband Gerlands Beitr. Geophys.*, **17**.
(68) Berlage, H.P., 1930. *Proc. K. ned. Akad. Wet.*, **35**, 614, 719.
(69) Berlage, H.P., 1930. *Het Ontstaan en Vergaan der Werelden*, Amsterdam.
(70) Hoyle, F., 1955. *Frontiers of Astronomy*, Chap. 6, Heinemann.
(71) Hoyle, F., 1960. *Q. Jl R. astr. Soc.*, **1**, 28.
(72) Ferraro, V.C. & Plumpton, C., 1966. *An Introduction to Magneto-Fluid Mechanics*, 2nd edn, Oxford University Press.
(73) Edgeworth, K.E., 1962. *Observatory*, **82**, 219.
(74) Lüst, R. & Schlüter, A., 1955. *Z. Astrophys.*, **38**, 190.
(74a) Fowler, W.A., Greenstein, J. & Hoyle, F., 1962. *Geophys. J. R. astr. Soc.*, **6**, 148.
(75) Edgeworth, K.E., 1949. *Mon. Not. R. astr. Soc.*, **109**, 600.
(76) Edgeworth, K.E., 1946. *Mon. Not. R. astr. Soc.*, **106**, 473.
(77) McCrea, W.H., 1960. *Proc. R. Soc.*, **A256**, 245.
(78) McCrea, W.H., 1960. *Ciel et Terre*, **76**, No. 11.
(79) McCrea, W.H., 1957. *Mon. Not. R. astr. Soc.*, **117**, 562.
(80) McCrea, W.H. & Williams, I.P., 1965. *Proc. R. Soc.*, **A287**, 143.
(81) Whipple, F.L., 1946. *Astrophys. J.*, **104**, 1.
(82) Whipple, F.L., 1948. *Harv. Obs. Monogr.*, No. 7.
(83) Urey, H.C., 1956. *Astrophys. J.*, **124**, 623.
(84) Latimer, W.M., 1950. *Science*, **112**, 101.
(85) Chamberlain, R.J., 1952. *The Atmospheres of the Earth and Planets*, ed. by Kuiper, Chicago University Press.

(86) Brown, H., 1952. *The Atmospheres of the Earth and Planets*, ed. by Kuiper, Chicago University Press.
(87) Ringwood, A.E., 1960. *Geochim. cosmochim. Acta*, **20**, 241.
(88) Mather, K.F., 1939. *Science*, **89**, 65.
(89) Urey, H.C., 1966. *Mon. Not. R. astr. Soc.*, **131**, 199.
(90) Chandrasekhar, S., 1946. *Rev. Mod. Phys.*, **18**, 94.
(91) Anders, E., 1962. *Rev. Mod. Phys.*, **34**, 287.
(92) Lindblad, B., 1935. *Nature, Lond.*, **135**, 133.
(93) McCrea, W.H. & McNally, D., 1960. *Mon. Not. R. astr. Soc.*, **121**, 238.
(94) Donn, B. & Sears, G.W., 1963. *Science*, **140**, 1208.
(95) Hayashi, C., 1961. *Publs astr. Soc., Japan*, **13**, 450.
(96) Walker, M.F., 1957. *Astrophys. J.*, **125**, 636.
(97) Walker, M.F., 1959. *Astrophys. J.*, **130**, 57.
(98) Henyey, L.G., Le Levier, R. & Levée, R.D., 1955. *Publs astr. Soc. Pacif.*, **67**, 154.
(99) Faulkner, J., Griffiths, K. & Hoyle, F., 1963. *Mon. Not. R. astr. Soc.*, **126**, 1.
(100) Ezer, D. & Cameron, A.G.W., 1963. *Icarus*, **1**, 422.
(101) Neugebauer, G., Martz, D.E. & Leighton, R.B., 1965. *Astrophys. J.*, **142**, 399.
(102) Williams, I.P. & Cremin, A.W., 1967. *Phys. Lett.*, **24A**, 326.