OPEN DISCUSSION

The Chairman, J. S. Hall asked I. P. Willams (Reading, England) to speak on 'Planetary Formation'.

Williams: According to a theory by McCrea, published in 1960, after a protosun has been formed about 1000 unstable cloudlets, called floccules by McCrea, are captured in orbit around this protosun. Their orbital distance is roughly equal to the mean free path of the floccules in the original gas cloud from which both the sun and the captured floccules formed, taken numerically to the 60 AU. In order to conserve angular momentum about 600 of the captured floccules will be in prograde orbit while 400 will be in retrograde orbit. As an agglomeration of about 20 floccules is stable, when floccules adhere on collision stable condensations may be formed. We make a statistical investigation of this process. The problem is similar to that of having 400 red balls and 600 black balls in a bag which are pulled out and assembled into a pile. When 20 are in a pile a stable condensation exists and a new pile is started. If there are equal numbers of red and black balls in a pile this compounds to a condensation with very low angular momentum which falls into the Sun and so this is rejected and a new pile started. The number of stable condensations that is formed and the ratio of prograde to retrograde floccules in each of these condensations are obtained. This ratio determines the angular momentum, and hence the position, of the condensation.

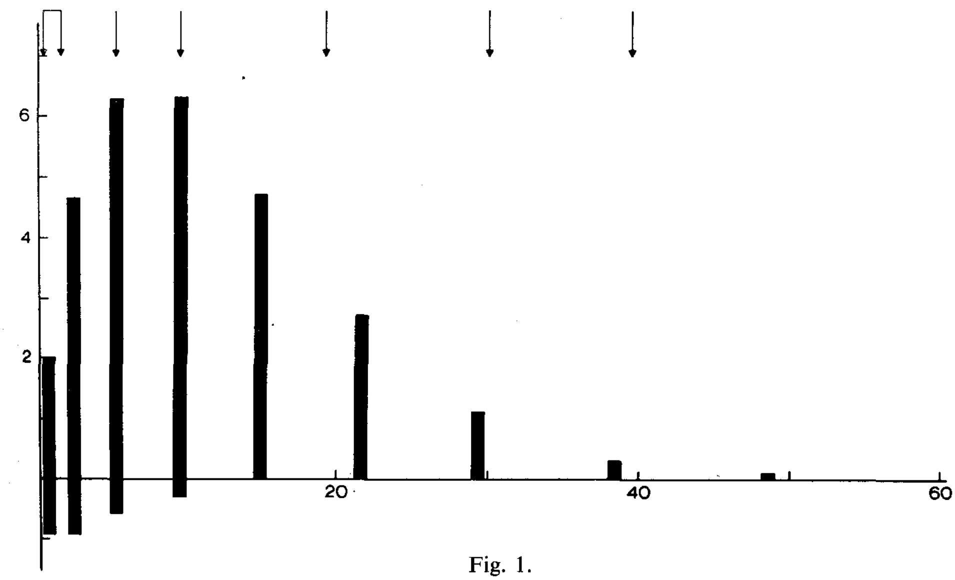

Fig. 1.

De Jager (ed.), Highlights of Astronomy, 239–243. *All Rights Reserved*

https://doi.org/10.1017/S1539299600000162 Published online by Cambridge University Press

The results are shown as Figure 1, the abscissa being orbital distance in AU and the number of condensates as ordinate, positive being the probable number of prograde condensations while negative gives the number of retrograde condensations.

The arrows give the position of the actual planets, the terrestrial planets being shown as a group. Positional agreement with the orbital distances of the real planets is very good. In order to obtain the terrestrial planets the rotational break up of the two innermost condensations is envisaged, and where compensation is made for the removal of hydrogen the prediction as regards Mars is also excellent, one condensation being of Mars 4×10^{29}. The mass of the major planets is also predicted to some accuracy.

The one discrepancy is the predicted existence of one object between Uranus and Saturn. The only comment is that one unusual event must have occurred here as Uranus is rotating at right angles to the usual plane of rotation while a very large number of satellites, some retrograde, also exist in this region.

Levin: I would like you to explain the initial character of this condensation. How does the break up of the planets produce such differences in composition and how do they have circular orbits orbits and not crossing orbits.

Williams: These ideas are Professor McCrea's (who is here).

Levin: You are speaking. You are responsible.

Williams: A comment about the composition. The hydrogen, helium and grains are at first all mixed up. Professor McCrea and I showed that a settling of the grains will occur, forming a core in the centre of any gaseous condensation. You can, by arguing that metallic grains will accrete better than silicate, show that metallic grains will fall faster than the silicate grains. At some stage, there will be regions with predominantly iron or further out predominantly silicate-type grains; further out still, it is hydrogen and helium.

Levin: Do you speak about the planets or about the condensation?

Williams: Gas condensation with a layer inside of iron and grains. You can get rid of this H-He envelope fairly easily. In the break up of the protoplanet, you would expect the Moon and Mars to come from the outer layers, the silicates, and leave the Earth essentially the iron with a little bit of silicate around the outside.

The compositions of Mercury and Venus are more doubtful. The mean densities are well known.

Levin: There is no way to juggle with the densities.

Williams: I think the same type of process will be taking place again.

As regards the intersection of the orbits we are still in the early stage of formation and there is plenty of gas around to produce a rounding off of elliptical type orbits. As you have described in your book, a two body problem will not produce captured orbits but a 3-body problem (with gas there) can do.

Levin: Is the Moon built up of fragments of the Earth?

Williams: Lyttleton has shown that in a break up of one body into 2, the mass-ratio will be of the order of 8 to 1, the right order for the Earth-Mars configuration. The Moon, a small fragment, would be captured in orbit around the larger of the two.

O'Keefe: The conventional ideas of geochemistry have been that the reason why the Earth is deficient in siderophile elements is that these went down into the core. They are also deficient in the Moon and to roughly the same extent. The Moon does not have a core, so they cannot have gone into an iron core on the Moon.

Levin showed from angular momentum considerations that such a core could be at most of the order of 1%. The most straight forward and simple solution is to adopt Levin's proposal that the Moon was formed from fragments of the Earth.

Anders: The Moon is 2 orders of magnitude more deficient in gold than is the Earth, and a further order of magnitude in iridium. If both had lost their siderophile elements in the same environment, their depletion values ought to be the same.

O'Keefe: The siderophile element deficiencies on the Earth are in part due to core-mantle separation. In the case of gold, this is partly hydrothermal. Water is highly deficient in the Moon.

McCrea: First, the idea of floccules is a schematization of super-sonic turbulence, just as mixing length theory is a schematization of subsonic turbulence. This morning, Professor Gold mentioned the importance of collisions in producing Bode's Law among other things. He and Hoyle mentioned the influence of small number collisions over the spin of the planets, essentially Williams' point regarding the formation of the planets from small numbers of flocculi. About the composition, Kaula attempted, a couple of years ago, to calculate the iron-nickel and silicon contents of the terrestrial planets, using the then available data on radii and densities. Venus and Mercury combined give a body in which Kaula's calculations lead to 29% of iron-nickel, and if you put the Earth, Moon and Mars together, you get a body in which 30% is iron-nickel and this seems to support the idea that these bodies broke off 2 original protoplanets.

Levin: I cannot understand how a small fragment, which formed Mercury can have a larger amount of iron than the big remnant. The same for the break up of proto Earth-Moon-Mars.

McCrea: As Williams says, the heavy material settles down towards the centre and as it does, it must spin faster and faster and the composition of the fragments depends on whether the break up occurs at an early or late stage, that is of the body as a whole or of the core.

For the core, we get the case of Mercury, a heavy small fragment. The break up of the whole produces a light small fragment.

Levin: What about the results of Liapounoff and Cartan about the break up of a single body that must be either elliptical velocity of ejection, when the fragments return, or a hyperbolic velocity of ejection when the fragments go out to infinity.

McCrea: Lyttleton has shown that if a body inside the orbit of Jupiter breaks up, although the smaller part will escape from the larger part, it will not escape from the solar system. If the process happens further out....

McCrea: Lyttleton showed that if the proto-Earth broke up into the present Earth and Mars then any small fragment has a good chance of remaining bound to the Earth, but not to Mars.

O'Keefe: Lyttleton's proof was the following:
If we are thinking of non-frictional processes, they are always reversible. Since two bodies in mutual orbit do not unite, it follows that you cannot start with a single body and break it up into two bodies. This kind of proof is fallacious, as we can see if we imagine a solid wall of water from which suddenly we remove a constraint. Water will go out in all directions and we know that they never will rebuild that rectangular wall with which we started; in the real world, never. Lyttleton's proof is an ideal case and does not apply to the real world.

Tombaugh: We need to remember the Moon's orbit more nearly concides with the ecliptic and not the Earth's equator and I think that is significant.

Hall: Perhaps we should start another subject. Anything is cricket (that is a good word here) that involves the formation of the Earth and planets.

De Marcus: This topic may have been covered in my absence. Recent studies have shown that the angular momentum per gram of a large number of bodies in the solar system, including the whole solar system itself, except for the Sun and to some degree the central planets, is constant. Coupled with the fact that the solar system, or the Sun, has a proper motion with respect to the local initial system, does that not scream that we really should deal with the solar nebula which originally was twofold, part of which has now gone off somewhere. In calculating these angular momenta, if we move the lever arm somewhere else, to the centre of gravity of the other fragment and us, we could certainly make things come out more equitable. These discrepancies would then be gone.

Whipple: We may transfer angular momentum from the Sun to the planets (Hoyle) or form planets with present angular momentum and transfer solar angular momentum to escaping gases, perhaps 10% or more of solar mass.

Öpik: Jupiter and Saturn cannot be built 'hot' from heavier elements (N, probably He, too) because, with the present values of their mass, radius and, thus density, a gaseous structure would result with a superadiabatic gradient. This will be overruled by turbulent convection, enforcing an adiabatic gradient and a high surface temperature, contrary to observation. Radiative cooling would reduce this structure to a cold degenerate (solid) state in 10^5–10^6 yr. The cold, preferentially solid hydrogen structure of Jupiter stands without doubt.

In the pre-planetary nebula the number load of molecules (atoms) over Jupiter's distance (10^{14} AU) is of the order of 10^{27} cm^2 which would blot out all kind of direct solar radiation (electromagnetic or corpuscular) which is scattered or re-radiated sideways through the thin sheet at right angles to the plane. With the present radiation field (starlight), cosmic rays, cosmic background radiation), a temperature of about 4 K would obtain in about 10^5–10^6 yr with snowing out of hydrogen which thus would form the first condensation around the Si-Mg-Fe and Ni-Fe grains or nuclei, helium being left behind and accreted but later gravitationally when nuclei of 10^{27}–10^{28} gr are already there. The kinetic energy of accretion is radiated away from the surface, keeping the gradient inside below the adiabatic value, without mixing.

For Jupiter, thus, an original core of about 5 Earth masses may have been preserved, the present seat of the magnetic field. The bulk may be solid hydrogen with very little helium, and an overabundance of helium in the atmosphere.

The observational abundance of helium in Jupiter's atmosphere is inversely related to the estimated abundance of H_2 which depends on an uncertain f-value Amounts of H_2 up to 150 km/atm (as has been sometimes suggested), would have blanketed completely Jupiter's surface detail by plain Rayleigh scattering and are unacceptable.

O'Keefe: We are overlooking the 19th century discussions of the stability of the solar system. Again and again the mathematicians of that period attempted to prove that the original condition of the solar system was identical with its present condition. These studies are reviewed by Hagihara in a paper published by Middlehurst and Kuiper in the series on the *Solar System*. It is a tremendous piece of work. The conclusion is that *we do not know*. E. W. Brown surmised, in 1932, that when it is a question of very long times, we do not know that the semi-major axes of the orbits remain the same; we do not even know that the *order* of the planets has remained constant.

There is a preliminary report of some numerical experiments by S. J. Hill at Michigan which indicate that if the planets are all started out in orbits of nearly the same radius, they will rearrange themselves under purely gravitational forces in a wide spread of radii like that seen in the solar system, and with the kind of spacing described by Bode's Law.

Mrs Brecher (summary of a recent theory of Arrhenius and Alfvén – see *Astrophys. Space Sci.* **8**, 338, and **9**, 3, 1970): Direct observations in space suggest that the primordial condensation of solids in our solar system took place from a low-density, partially-excited gas, and that the gas temperatures were much higher than the temperatures of the solid grains growing from this medium. Laboratory simulation of such condensation processes has provided information on the characteristics of the ensuing solids. Certain characteristics of meteorite components are hard to explain unless they are assumed to be primary and largely unaltered crystalline and vitreous solids grown in extreme thermal disequilibrium with the surrounding gas phase.

[*Ed. note:* Mrs Brecher read the whole paper of Arrhenius and Alfvén but, because of prior publication commitments, only an abstract is printed here.]