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

Concluding Remarks

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Phil. Trans. R. Soc. Lond. A 1988 **325**, 619-621
doi: 10.1098/rsta.1988.0074

Phil. Trans. R. Soc. Lond. A **325**, 619–621 (1988)
Printed in Great Britain

Concluding remarks

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This discussion on the origin of the Solar System has quite rightly focused on the chemical evidence. Harold C. Urey was fond of quoting Edward Teller's remark about the atomic bomb: 'Its physical effects disappear quickly but its chemical effects are lasting'. The chemical evidence, particularly the abundance of elements and isotopes, obtained from meteorites, by ground-based astronomical methods and from space missions continues to be the starting point for inferring the processes by which the Solar System came into being and reached its present configuration. When the origin of the Solar System was first discussed it appeared a natural assumption that the material from which the planets were made came from the Sun. Similarly before the importance of radioactivity in the Earth was recognized it seemed obvious that the planets originated as liquid drops by condensation from gases drawn from the Sun. The fact that the Earth's gravity field, for example, was almost exactly that of a hydrostatic body in equilibrium, under its self-gravitation and the centrifugal forces due to rotation, made this assumption a natural starting point. It was the discovery of the interstellar dust clouds by astronomers that first provided evidence for a nebula theory. We have been correctly reminded in this discussion that the idea of a close approach of another star from which material was drawn out by the Sun is still a possible theory, and it is entirely in the interest of a scientific approach that it should be further investigated so that its predictions can be more thoroughly tested.

It remains, however, true that the large majority of those studying the origin of the Solar System believe it to have originated from such an interstellar dust cloud whose condensation, possibly triggered by a supernova explosion or otherwise, leads by contraction from, say 200000 AU to about 50 AU becoming, through conservation of angular momentum, disc shaped. Out of this dust and gas cloud, grains would naturally form: the more refractory tending to condense close to the central Sun. The retention of hydrogen and helium and other volatiles in ice collect in the outer Solar System. Such a model gives a simple fundamental explanation of the differences between the major planets and the terrestrial ones.

There is one physical effect attending the formation of the Solar System which has remained essentially unchanged to the present day, but which has not been specifically discussed in this meeting. It is, of course, the orbital motions of the planets and their spins. The anticlockwise spin, as viewed from the north, of the planets, with the exceptions of Uranus and Venus, the same sense of orbital motion and the near coincidence of their orbital planes fit naturally into the solar nebular theory. The well-known linear relation between spin angular momentum divided by mass and planetary masses – with the exception of Mercury and Venus, whose spins have clearly been greatly changed by the tidal action of the Sun – again seems to suggest an explanation in the processes by which the solar nebula condensed eventually to form the planets.

Ralph B. Baldwin and Harold C. Urey recognized that the Moon's surface was a very ancient one recording the result of impacts of planetesimals and meteorites over 4000 Ma: the craters and basins are not of internal origin. Thus the study of the surfaces of the planets and satellites of the Solar System by space mission imaging has provided a record of the final processes of accretion of the planets and satellites and the sweeping up by them of small remaining solid bodies of the solar nebula. Thus it may be said that the chemical evidence has in broad outline clarified the early history of the solar nebula and the use of geological principles, e.g. superposition and crater counting as a means of the relative dating of surface strata, has clarified the final stages of planetary formation.

It is the intermediate stage after the formation of small bodies and the final stages by which the planets reach their present small number which is most obscure. Dr Wetherell has taken this subject much further by solving the difficult celestial mechanics problem of how large numbers of bodies, for example 500, orbiting the Sun can eventually by collisions coalesce into a small number of terrestrial planets. His work very much assists us in thinking about this great interval of time and showing us that the process might only take 10–100 Ma. However, valuable as such computer studies are, one remains somewhat sceptical of calculations that require the specification of the distance from the Sun and the initial velocities of these bodies and therefore the time that he finds for the coalescence to be completed may simply be a consequence of the initial configuration that he assumes. The question arises, therefore, of whether anything can be learned of bodies in the Solar System before the present, samples perhaps of the large number of 'Moon-sized bodies' that Harold Urey imagined populated the Solar System in this intermediate period.

I believe that a search for diagnostic evidence for early large bodies may indeed be required not only to explain the 95° inclination of the axis of Uranus from the pole of the ecliptic and possibly the retrograde rotation of Venus but also inclinations of the axes of the planets to the pole of the ecliptic, which range from $23\frac{1}{2}°$ for the Earth to 3° for Jupiter and 29° for Saturn. It seems difficult to explain how a planet can accrete from a vast number of small grains in the highly volatile solar nebula without the rotation axis of accreted bodies aligned perpendicular to the plane of the nebula. Evidence for collisions between the last remaining large objects and the planets need very careful study. Of particular interest are the Caloris basin of Mercury, the geological study of which requires complete imaging of the planet.

Evidence for such primeval bodies has in fact come from an unexpected source, the study of the remanent magnetization of the lunar crust. The study of the remanent magnetization of the returned Apollo samples provided evidence that the Moon had an early magnetic field generated by dynamo action in a small iron core, which between 4 and 3 Ga, had been convecting sufficiently vigorously to generate a dipole field. In this core the Coriolis force had been a dominant term in the magnetohydrodynamic equation so that it is reasonable to suppose that this early field was a dipole aligned along the axis of rotation. From the study of the remanent magnetization of crustal strata inferred from the magnetometer surveys made by the Apollo 15 and 16 subsatellites it has been demonstrated that the Moon was reorientated several times with respect to its axis of rotation as a result of the large impacts that produced the multi-ring basins. The important observation that the multi-ring basins were formed in low latitude has enabled a theory of this reorientation to be developed. The association of multi-ring basins and palaeoequators has demonstrated that the Moon had a satellite system, the orbits of which decayed by tidal friction resulting in each of three major satellites in turn breaking up at the Roche limit into a number of bodies which then impacted the Moon near

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its equator in rapid succession. As the velocity of the impacts would be relatively small, asymmetries in the basins could be studied giving the direction of the incoming body which is roughly parallel to the palaeoequator, strongly supporting this sequence of events. Although the physics of these gigantic impacts is not well understood, the bodies must have been about 50 km in diameter and, therefore, their impact must have contributed a substantial amount of material to the regolith. The re-study, therefore, of the lunar regolith may give information concerning the chemical composition of these primeval bodies. At any rate this is evidence that there were other bodies in the early Earth–Moon system and in consequence represents an important observational clue to its origin and also that of the planets.

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