EVOLUTION OF THE MOON: RECENT MODIFICATION OF PREVIOUS IDEAS

B. J. LEVIN
O. Schmidt Inst. of Physics of the Earth, U.S.S.R. Acadamy of Sciences, Moscow

New data on the Moon obtained from its study by space probes and analyses of returned lunar samples give new 'boundary conditions' for a study of its origin and evolution.

1. Proofs for a Hot Moon

First of all, the new data have brought to the end the dispute between proponents of a hot and a cold Moon. As lunar maria are flooded by basalt – a product of magmatic differentiation – the lunar interior must be hot and, at least sometimes, – partially molten. Earlier the partial melting of lunar interior and its present day hot state was obtained in calculations of thermal history for conductive models with chondritic radioactivity (Urey, 1952, 1962; MacDonald, 1959; Levin and Majeva, 1960; Levin, 1962, 1966a, b; Fricker *et al.*, 1967; McConnell *et al.*, 1967; Majeva, 1971). Some authors tried to modify the model regarding the Moon to be a throughout solid body. The others combined these results with the interpretation of lunar maria and flatbottom craters as lava-filled basins and predicted that the Moon indeed is hot and has a semi-molten interior.

Urey and other proponents of a throughout solid Moon regarded a hot Moon to be incompatible with its desequilibrium shape. One must remind, however, that the concept of hydrostatic equilibrium can be applied only to an isothermal body or a body in which isothermal surfaces coincide with equipotential ones. In the Moon the decrease of surface temperature from the equatorial zone toward the poles produce a flattening of isothermal surfaces for several tens of kilometers which load to a flattening of its figure for about 1 km (Levin, 1964b, 1966a, b, 1967; Safronov, 1967; Volkov, 1967). Indeed such flattening is the main deviation of the Moon from the hydrostatic equilibrium. As to the small ellipticity of the lunar equator, the stresses it produce, as well those produced by mascons, must be supported by the rigidity of the outer cold solid layer of the Moon.

2. Evidence from Magnetic Experiments

Few years ago the idea of a hot, semi-molten lunar interior seemed to be in conflict with low values of its electric conductivity derived by Ness from measurements of magnetic field perurbations in cislunar space. Later Ward (1969) stated that both cold and hot models of the Moon are consistent with evidence from magnetic experiments aboard of Explorer 35 lunar orbiting satellite available at that time. Recently Sill (1971) combining measurements of the lunar surface magnetometer and the magneto-

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meter on Explorer 35, dedused that the electric conductivity increase up to a depth of 200–300 km and beyond stabilise at the value which for an olivinlike composition corresponds to temperatures of beginning of melting. This is in accord with previous calculations for initially cold or warm Moon (Fricker *et al.*, 1967; Majeva, 1971) and with new calculations for initially hot Moon (Wood, 1971) provided the redistribution radioactive elements toward the surface in the course of magnetic differentiation proceeded at sufficient rate.

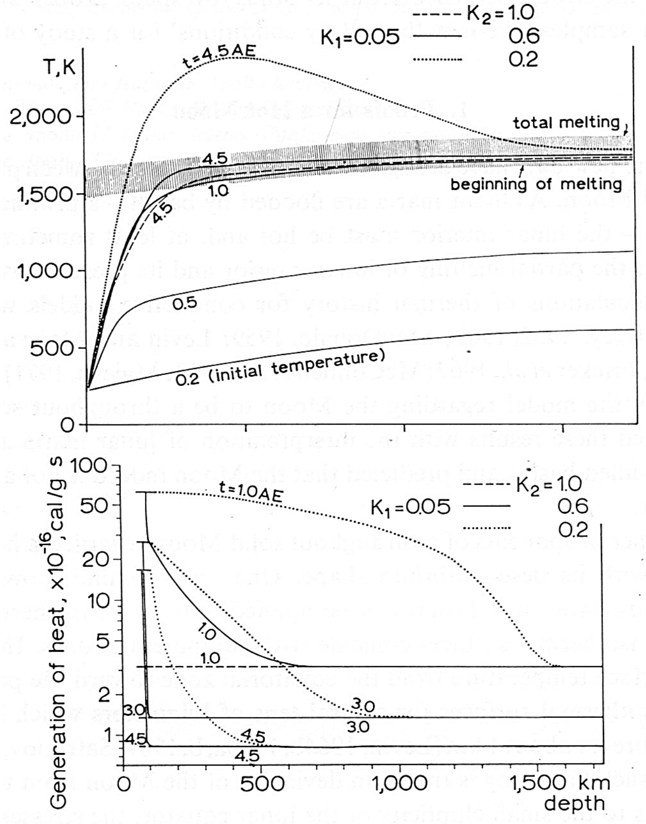

Fig. 1. Distribution of temperature (above) and generation of heat (below) in the lunar interior for different rates of redistribution of radioactive elements (variant with initial temperature giving melting about 3.5 AE ago).

Results of calculations for an initially warm Moon with simplified initial temperature profile are shown on Figure 1 for a case when the redistribution of radioactive elements toward the surface decrease 20 times their concentration in the interior ($k_1 = 0.05$) and for different rates of redistribution ($k_2 = 1.0$; 0.6; 0.2). For rapid redistribution ($k_2 = 1.0$ and $k_2 = 0.6$) the interior is semi-molten and the thickness of the outer solid layer is about 400 and about 300 km respectively. But for slow redistribution ($k_2 =$ 0.2) the interior, except the central part, is molten and the outer solid layer is only 150 km thick. The lower part of Figure 1 show profiles of generation of heat for three moments of time for different values of k_2. For $k_2 = 1.0$ and 0.6 the present day temperature profiles are in accord with the results by Sill (1971).

However Sonett *et al.* (1971) obtained from the same measurements as Sile a more complicated profile of electrical conductivity implying a layered structure of the upper 300–400 km. Assuming below 400 km a poorly conducting matter they obtained a temperature of about 1000 K only, while the melting temperature is few hundreds degree higher. A calculation based on more conducting matter would depress the computed temperatures. Thus there is a moderate but important disagreement in the interpretation of magnetic experiments.

3. Early Melting of the Moon

The convincing evidence in favour of the hot Moon was the immediate result of the presens of basalts in the returned lunar samples. Their further study showed that magmatic differentiation of the Moon began very early – nearly at the end of the accumulation of the Moon (Papanastassiou and Wasserburg, 1970, 1971). while according to previous calculations of lunar thermal history, melting had to begin only $1–2 \times 10^9$ yr after the formation of the Moon. The only reasonable way to account for such early melting is to assume a high initial temperature of the Moon. (Wood, 1971; Wood *et al.*, 1971; Papanastassiou and Wasserburg, 1971).

Besides evidence for early melting there is evidence that this early melting was restricted to outer parts of the Moon while melting of deep interior occurred about 10^9 yr later and produced dark basaltic lavas filling lunar maria. Such thermal history requires initially hot outer parts of the Moon and initially cool interior.

Calculations of the thermal history for several variants of such type of initial temperature profile were done by Wood (1971). His results clearly show that such initial profile can give a necessary course of lunar thermal history.

4. Composition of Highlands

Evidence for early melting and differentiation of the outer part of the Moon eliminates the problem of the fate of the primordial outer layer of the Moon and of the composition of highlands. The highlands are so densly covered by impact craters (on some places it is a saturated density (Marcus, 1970)) that their origin must be connected with intence bombardment by big bodies at the last stage of lunar accumulation. Previously when calculations of lunar thermal history had given that melting and consequently – magmatic differentiation began only $1–2 \times 10^9$ yr after the formation of the Moon, it seemed impossible to regard highlands to be composed of products of magmatic differentiation. It followed from these calculations that highlands, if composed of products of differentiation, should be formed after beginning of melting. But by that time intense bombardment of the Moon has to cease. Therefore some astronomers regarded the highlands as preserved parts of the initial outer layer (Kuiper, 1954, 1959; Levin, 1962). However it seemed strange why blocks of solid primordial lunar material which had to be denser than the molten differentiated magma, had not sink into the latter (Urey, 1955). Now when it is proved that melting and magmatic differentiation of the Moon occurred already near the end of its formation, it is no more difficulties to combine the igneous origin of highlands with the impact origin of craters on them. After the effusion of magma on the surface its cooling and solidification could be sufficiently rapid to permit the surface to be densely cratered during the abatement of lunar accumulation. According to the hypothesis by Wood *et al.* (1970a, b, 1971) the highlands are composed of anorthosites.

5. Origin of the Moon

To discuss possible sources of energy for early heating of the Moon at least some general idea of the origin of the Moon is required. We shall rest upon the idea of its accumulation from a circumterrestrial swarm of particles, which had to exist when the Earth in its turn accumulated from bodies and particles forming a circumsolar swarm. This hypothesis of origin of the Moon proposed 20 yr ago by Prof. O. Schmidt (1950) seems to be the most promising. It is similar to the so-called sediment ring hypothesis. The continuing discussion of the hypothesis of separation of the Moon from the Earth seems to the present author to be a curious episode in the history of science. Darwin's mechanical foundation of this hypothesis is since long refuted by Liapunov (1906–1914), Cartran and others (see Lyttleton, 1953, 1954) while recent attempts by Wyse and O'Keefe to save Darvin's scheme cannot withstand a critic. As to the capture hypothesis, it studied only the past evolution of the lunar orbit, the Moon being treated as a material point. But it never studied the origin of the Moon as a cosmic body. It simply shifted this problem away from the Earth – to some other place in the solar system. One can hope that further discussion of the capture hypothesis will stop because now all its supporter agree that when the evolution of the lunar orbit is extrapolated far into the past, this leads to a deep penetration of the Moon inside Roche's limit. This is possible for a material point or a small body but not for a body of lunar size.

6. Possible Sources of Energy for Early Heating of the Moon

As it was already said at the end of Section 3, a source of energy is needed which can not only produce an early heating, but can heat preferentially the outer parts of the Moon retaining a cool central part. If to accept the accumulation of the Moon from a circumterrestrial swarm, than the following ways of its early heating are in principle possible:

A. HEATING BY GRAVITATIONAL ENERGY LIBERATED AT ACCRETION

The gravitational energy if totally retained, could increase the mean temperature of the Moon for ~1800°. But the energy was liberated at impacts of accreting bodies and particles on the surface, causing local heating. Therefore most of heat was radiated into space. A substantial part of released gravitational energy could be retained in case of a rapid accumulation of the Moon from a pre-existing circum-terrestrial swarm. But it had to be a gradual accumulation from a swarm, which continued to be replenished in the course of accumulation of the Earth. Thus the duration of accumulation of the Moon was nearly the same as that of the Earth, namely about 10^8 yr.

As the specific energy (energy per unit of infalling mass) increased with increasing mass of the Moon, Wood (1971), assuming a retention of all accretional energy (or its partial retention proportional to specific energy) concluded that this source can produce the required increase of initial temperature toward the surface. However radiation losses are proportional to T^4 and besides the intensity of bombardment of the Moon had to decline to the end of the process due to exhaustion of accretable material.

Perhaps the gravitational energy could be retained and produce a preferential heating of the outer parts of the Moon if the latter by the end of the accumulation process posessed a temperary opaque atmosphere. It is possible that such atmosphere existed at that time due to degasing of infalling planetesimals at impacts.

The suggested existence of such temporary atmosphere seems to give the only possibility to retain a major part of gravitational energy. Without such atmosphere this energy was able to produce neither the sufficient heating of the Moon, nor the required temperature profile.

B. HEATING BY SHORT-LIVED RADIOACTIVITIES

It requires that the Moon should be formed no more than few million years after the nucleosynthesis of short-lived radioactive isotopes. The most promising isotope – Al^{26}, has a half-live of 0.74×10^6 yr and cannot survive in significant quantity more than $3–5 \times 10^6$ yr. Few years ago the formation of Al^{26} was ascribed to additional nucleosynthesis supposed to occur in the early solar system. But even then the time-interval of less than 10^7 yr between this nucleosynthesis and the formation of the Moon seemed uncomfortably small.

Recently all variants of additional nucleosynthesis were abandoned and the situation became much worse, because it is known that 30–200 m.y. elapsed between the last galactic nucleo-synthetic event in the solar matter and the condensation of solid protometeoritic particles. No anomalies in the isotope ratio Mg^{26}/Mg^{24} (Mg^{26} is the decay product of Al^{26}) were found in meteorites, as well as in lunar and terrestrial samples (Schramm *et al.*, 1970). Thus, there is neither theoretical, nor experimental evidense for the presence of Al^{26} in the early solar system.

C. HEATING BY ELECTRIC CURRENTS INDUCED BY THE EARLY INTENCE SOLAR WIND

The possibility of such heating is based on a premiss that the early Sun passed through a T-Tauri-stage when it had to have a corpuscular radiation 10^6–10^7 times more intence than the present-day solar wind. Corpuscular radiation of T-Tauri stars decrease e times in about 10^7 yr. Calculations confirming the efficiency of electric heating for the Moon, published by Sonett *et al.* (1968) are based on the implicit assumption that the Moon was formed nearly simultaneously with the Sun*. This is obviously incorrect. Only if for our Sun the decrease of intensity of the early solar wind occurred at much smaller rate than in typical case, the electric heating could play an important role for the Moon whose accumulation lasted about 10^8 yr. However calculations by Sonett *et al.* (1970) for small bodies show no preferential heating of the upper parts.

D. ACCUMULATION OF HOT PARTICLES

Analyses of returned lunar samples revealed a depletion of several trace elements in lunar basalts as compared with terrestrial ones (Keays *et al.*, 1970; Ganapathy *et al.*, 1970; Anders *et al.*, 1971). Some of these elements are largely concentrated in the crust and therefore their depletion is extrapolated by Anders and his co-workers on the whole Moon. Observed depletions they ascribe to accumulation of the Moon in the source of cooling of the solar nebula and consequtive condensation of more and more volatile elements and compounds. From analyses of Apollo 11 and 12 samples they conclude that the mean accretion temperature was about 620 K. (Anders *et al.*, 1971). However, the basic idea does not give an unambigious interpretation of chemical evidence while its astronomical aspect is in conflict with existing theories of the early evolution of the solar system. The cooling of the solar nebula had to last no more than 10^5–10^6 yr what is by 2 or 3 orders of magnitude shorter than the accumulation time for the Earth and Moon.

The mean accretion temperature estimated by Anders *et al.* (1971) is too low to explain the early melting of the Moon. Besides accretion during cooling would give a decreasing temperature profile with central parts of the Moon hotter than the outer parts (like that on Figure 1).

E. HEATING BY TIDAL DEFORMATIONS

Probably the newly formed Moon was in the state of free rotation which was rapidly decellerated by dissipation of energy of tidal deformations. At this stage the Moon had to be heated on the expense of energy of its rotation. When a free rotation changed into synchronous one (or if it was such from a very beginning) the Moon would continue to be heated due to changes of tidal deformations when it pass from apogeum to perigeum, and back. At this stage the Moon had to be heated on the expense of energy of the Earth's rotation.

A rapid recession of the Moon from the Earth had to cause a rapid decrease of tidal heating, so that the latter was practically restricted to the early stage of the existence of the Moon. A proper choice of inelastic characteristics of lunar and terrestrial globes probably will permit to attain a necessary heating.

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* Recently Sonett *et al.* (1971) wrote: "...the accretional time-span could not be more than 5000 yr and possibly much less". What origin of the Moon they have in mind is not explained.

The heating of the synchroneously rotating Moon caused by the eccentricity of its orbit was studied by Kaula (1963, 1964). I am not sure that his result that the main heating had to occur in the centrum is correct. It seems possible that the outer parts should be preferentially heated. One can hope that further studies of tidal effects will provide for early heating of the Moon and the necessary temperature profile.

7. Post-mare volcanic activity

The post-mare volcanic activity on the Moon is revealed by a study of high resolution pictures of Tycho, Aristarchus and Copernicus, taken by Lunar Orbiters (Hartmann, 1968; Strom and Fielder 1970). Manifestations of volcanic processes in Tycho are especially significant for two reasons: it is one of the youngest post-mare craters and it is situated not on a mare but on a highland. Lava lakes and lava flows are seen on the rim, slopes and floor of Tycho. It becomes more and more clear that impact formation of large craters on many, if not all, occasions was accompanied by volcanic processes of different intensity. Most aspects of these volcanic processes remain unknown. Even for circular maria not all students of the Moon agree that their flooding was trigged by impacts that formed maria basins and occurred shortly or even immediately after impacts (Levin, 1966a). Some authors suggest that a large interval of time elapsed between the formation of a mare basin and its flooding by lava (Shoemaker, 1964; Baldwin, 1970). The same question upon the interval of time between impact and the beginning of flooding by lava and other volcanic processes, remain unsolved for craters. For maria it is clear that lava had to come directly or indirectly form a semi-molten lunar interior. For young craters on highlands, like Tycho, the same deep origin of lava seems probable, although the generation of lava by impact cannot be excluded.

Unfortunately we have yet no reliable observations of present day volcanic activity on the Moon. It seems that good example of recent volcanic process on the Moon represent dark-halo craters photographed by Ranger 9 on the floor of Alfonsus. Their youth is manifested by a low density of small craters on the dark blanket as compared with surrounding terrain.

Few years ago it was thought that magmatic differentiation had to last a limited interval of time of the order of 10^9 yr and thus the volcanic activity on lunar surface abated about 2×10^9 yr ago. As the differentiation had to embrass the whole interior of the Moon up to the centrum, later epochs of lunar cooling were reagarded as unsuitable for volcanic activity. Now from the Orbiter pictures we see that, in spite of early beginning, volcanic activity was not completed long ago but lasted up to relatively recent time or even continues up to now.

8. A general picture of lunar evolution

New data obtained by cosmic studies and analyses of returned lunar samples required a rather serious modification of earlier ideas on the evolution of lunar interior.

But the idea of three stages of bombardment of lunar surface, including the relatively late impacts of big bodies which produced circular mare basins (Levin, 1964a), remain valid.

A modern picture of the evolution of the Moon was recently summarized by Baldwin (1970) in the form of 13 items. In essence it coincides with a picture discussed in the previous sections and will not be repeated here.

The evolution of lunar interior was to a large extent determined by its thermal history. The early melting of the Moon means the early concentration of radioactive elements to the surface and the early change of heating of the Moon into its cooling. The cooling affected mainly the outer parts and lead to an increase of thickness of the outer solid layer.

For lunar interior composed of different minerals there is no definit melting point but some interval of temperature within which melting occures. Probably the present-day temperature in the Moon is in the lower part of this interval.

At the present time we need new studies of the initial temperature of the Moon. We need new calculations of lunar thermal history – for improved models. We need data on the present-day generation of radiogenic heat in the Moon that can be obtained from measurements of the heat flow on its surface. We need better present-day temperature profiles that can be obtained from magnetic measurement. Probably it is not too long to wait when cosmic studies will supply us with these data.

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