INVITED DISCOURSES

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EXPLORING THE MOON

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A. A. Mihajlov
(Main Astronomical Observatory, Pulkovo, Leningrad, U.S.S.R.)

The exploration of this heavenly body has many different aspects. First of all there is the problem of the Moon's motion, which is one of the most complicated problems of celestial mechanics; then of its figure, which is a joint question of geodesy, astrometry and also of mechanics; then of the Moon's rotation, depending on the orbital motion, figure and distribution of mass; then comes the study of the structure and properties of the lunar surface and of the physical conditions on it, which was formerly restricted to collecting and interpreting photometric, colorimetric and radiometric data; the topographic features and different formations of the lunar surface have attracted many enthusiastic observers, and the explanation of the genesis of these formations pertains to the domain of geophysics and geology.

At last, or to say better at first, comes the most baffling question of all – that of the Moon's origin. Is the Moon a former planet, captured by the Earth, or is the Earth its mother, which gave birth to such an enigmatic child, or are the Earth and Moon twin sisters – we are still quite uncertain and very much in the dark, notwithstanding many ingenious theories advanced during more than a century.

There are still more problems connected with the Moon, such as its influence on the Earth, but they necessarily remain outside the scope of our discourse.

The most spectacular achievements of the latest years accomplished with the help of astronautics have greatly furthered our knowledge of the Moon, and we are sure that many even more brilliant results will shortly follow. Perhaps it is expected that my discourse will be restricted to these newest scientific and engineering conquests, but in order to recall them we must first pay a tribute to those branches of science that have made it possible to explore the Moon from a close vicinity and even reach its surface and probe its structure.

Thus first of all we must turn our attention to the motion of the Moon. Owing to the very strong attraction by the Sun and also to the flattening of the Earth, the Moon's movement around the Earth is extremely complex, pertaining to the most difficult problems of celestial mechanics. Only few mathematicians of the highest rank, beginning with Newton and Euler, tackled this problem, but it is astounding with what perfection and precision it was ultimately solved on the basis of the gravitational theory alone.

Perek (ed.), Highlights of Astronomy, 3–11. © *I.A.U.*

Quoting the great American astronomer Simon Newcomb on this subject "the men who have done it are in intellect the select few of the human race – an aristocracy ranking above all others in the scale of being. The astronomical ephemeris is the last practical outcome of their productive genius."

Let us consider for one moment this question. The Moon's ephemeris gives its position in advance, say for a score of years to within nearly 1 sec of arc, corresponding to about 2 km in its orbit. During 20 years it would travel some 700 million km and yet its position could be predicted with such a precision, amounting to a few units of 10^{-9}. The gravitational theory alone is sufficient to represent the motion of the Moon much more precisely than by the rotation of the Earth around its axis, now serving on this account to study the variations in the length of the day.

Now comes the still very difficult problem of the axial rotation of the Moon, closely connected to the Moon's figure, or more accurately speaking depending on the principal moments of inertia of the lunar globe. If this rotation were strictly uniform, it would have presented no difficulty producing the relatively simple effect of optical libration. The difficulties arise from the physical libration, consisting of very small pendulum-like oscillations excited by the attraction of the Earth on the Moon's bulge in the direction of the Earth. It is mainly the forced physical libration, induced and maintained by the deviation of the Moon's bulge from the exact direction towards the Earth. The amount of this libration depends upon the so-called mechanical ellipticity of the Moon

$$f = \frac{B(C-B)}{A(C-A)},$$

denoting the excess of the flattening of the Moon's meridian directed towards the Earth over the flattening of the meridian with longitude $\pm 90°$.

Now the mathematical treatment of this problem shows that there is a critical value $f = 0{\cdot}662$ when the denominator of one of the terms in the expression for the forced physical libration tends towards zero and the libration itself increases indefinitely. It seems, however, that this is only a result of the mathematical treatment of the phenomenon, not inherent to its physical nature. Professor Koziel of Cracow has recently shown that there is no discontinuity in the Moon's rotation for this value of f. The observations also give for f a value quite distinct from the critical one, but it is difficult to decide on which side it is located. There are two values of f, namely 0·73 and 0·60, around which the different determinations are grouped. Jeffreys in an important paper gives $f = 0{\cdot}639 \pm 0{\cdot}014$. Not going into details, we can sum up saying that the difference between the semi-axes of the Moon's ellipsoid directed towards the Earth and the Moon's poles lies between 1100 and 650 m, the third axis at right angles to the line of sight being from 140 to 280 m longer than the polar one.

The other dynamical method of determining the figure of the Moon is much simpler. The mean polar flattening is derived from the angular speed of rotation and the elongation towards the Earth is found from the force of the Earth's gravitational pull. Owing to the very slow axial rotation of the Moon, and consequently the smallness of centrifugal force, the polar flattening $(b-c)/b$ is very small, confined between the limits $\frac{5}{4}q$ and $\frac{1}{2}q$, q being the ratio of centrifugal force to the force of gravity. The upper limit corresponding to a homogeneous body, that in the case of the Moon is highly probable. In this case $b-c$ is only 17 m or from 8 to 16 times smaller than as derived from the physical libration.

The tidal force produced by the Earth's gravitational attraction at the present mean distance of the Moon can create a bulge $a-c=65$ m high, also some 10–17 times less than found previously. As the figure of the Moon deviates from a sphere much more than these amounts, it was supposed that the Moon acquired its present figure a long time ago, when it was much nearer to the Earth, its rotation was much faster and the tidal force much stronger. As the centrifugal force increases as the square of angular velocity, a flattening 16 times greater corresponds to a rotation 4 times faster than at present or to one revolution in 7 days. The tidal action is inversely proportional to the third power of the distance and the bulge mentioned corresponds to a distance 2·5 times nearer to the Earth, when according to Kepler's third law the orbital revolution was again 4 times shorter. Thus, the present shape of the Moon could have been acquired at a time when its distance from the Earth was about 150000 km, and owing to the Moon's rigidity this figure was preserved till the present time. Thus the large discrepancy of the Moon's figure as determined from physical libration and the forces to which the Moon is at present subjected can be explained by the hypothesis of a fossilized Moon that has kept its figure from bygone ages.

The third most direct though not easiest method is by optical observations. We have here two different sides of the problem – the determination of the figure of the Moon's limb or marginal zone and of the general shape of the Moon's globe, in a first approximation as an ellipsoid with three unequal axes. It would seem that it is very simple to determine the figure of the limb as projected on the background of the sky, but unfortunately we can usually see only the illuminated half of the same and it is very difficult to connect it with the other half, which remains hidden in darkness. Even the observations of occultations of stars do not remove this difficulty, as the errors of observation of ingress and egress are systematically different.

The figure of the visible limb and its irregularities have a direct influence on the determination of the Moon's position either with meridian instruments or photographically as well as by occultations of stars. Detailed charts of the profile of the Moon's marginal zone were prepared by Hayn in Leipzig, Weimer in Paris, Nefediev in Kazan, and Watts in Washington. These mappings meet the common difficulty that the entire limb can never be seen, as at the time of perfect full Moon a lunar eclipse occurs. Approximate to this is a penumbral eclipse when photographic observations allow a sufficiently exact determination of the figure of the entire limb. The most propitious method consists in photographing annular solar eclipses when the

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whole limb is projected on the solar disk. Unfortunately little attention was formerly given to such observations, and only in the last years this method was applied in praxis. Good results were obtained by an Anglo-American expedition which observed the eclipses of July 31, 1962 and January 26, 1963, in Africa. The fear that the two halves of the limb have different centres proved to be unfounded, but the best approximation was given by an ellipse with a flattening of about 1/1000 and direction of the major axis inclined by 35° to the polar axis of the Moon. A very close result was obtained also by Potter at Pulkovo from observations during the penumbral lunar eclipse of September 27, 1958. The semi-axes of such an ellipse differ by some 1·5–2 km, which is in strong disaccord with the dynamical results. It is possible that this discrepancy can be at least partly explained by the following considerations.

First it must be pointed out that the observations of two or three eclipses are insufficient for a determination of the whole profile of the marginal zone, as each eclipse can give the figure for only one phase of libration; meanwhile Yakovkin has shown that the curvature of the Southern part of the Moon's limb depends on the libration in latitude. But still more important is the real difference between the geometric and mechanical figures of the Moon. The first pertains to the physical surface somewhat distorted by a curious phenomenon, while the second applies to an equipotential surface of gravity. The distortion arises from the fact that an elevation near the limb is seen as projected on the sky at different phases of libration, whereas a valley can be noticed only if directed straight towards the Earth and even then only if it is of sufficient length. Thus a mountainous region is seen permanently and therefore exaggerated, but depressions are noticeable only if they are of very large extent, such as Oceanus Procellarum. The contour charts of the marginal zone show this very clearly. It is even probable that the elevations are isostatically compensated, in which case they will have very little connection with the mechanical figure of the Moon.

It is still more difficult to determine by optical means the general figure of the Moon's visible hemisphere. Heliometric and photographic observations give only the relative positions of points on the lunar surface in projection on the sky. The libration produces a stereoscopic effect, which can be used for determining the third coordinate of the measured points not too near the limb. This effect is rather small, moreover the changes of illumination create systematic errors so that the best measurements still have a poor precision.

Extensive measurements were made by Hartwig, Franz, Hayn in Germany, Sounder in England, Baldwin in the U.S.A., a group of observers at the Engelhardt observatory near Kazan in Russia, and recently at the observatory near Kiev. The measures of 150 points by Franz had been newly reduced by Schrutka-Rechtenstamm in Vienna. Professor Hopmann has also made valuable contributions to this question. New photographs were obtained for this purpose at the Pic-du-Midi observatory in France and taken with the U.S. Navy astrometric reflector at Flagstaff. Meyer and Ruffin have determined the selenocentric coordinates of 196 points to be used in the construction of large-scale lunar maps with contour lines of the Aeronautical and Information Center at St. Louis. Notwithstanding all pains the precision of the absolute elevations of these points or the distance from the Moon's centre of mass is not as high as desired, the probable error often exceeding 1 km, which gives hardly any reliable data on the general figure of the Moon. Moreover, the measured points are not without a statistical bias, representing chiefly peaks or other elevated features which are not typical for a figure approximating an equipotential surface. However, Goudas used them for an elaborate study of the Moon's figure by means of development into spherical functions.

The standard value of the mean radius of the Moon's globe is 1738·0 km. In order to determine the force of gravity on its surface, which is an important physical characteristic, we must know the Moon's mass as expressed in units of the mass of the Earth. Till recent times there was a perceptible uncertainty in this important constant, ranging from Newcomb's value of 1/81·58 to Spencer Jones' 1/81·27. This uncertainty arose chiefly from the difficulty of locating by observations the position of the barycentrum of the Earth–Moon system inside the Earth's body. At present the perturbations of artificial satellites give a much more precise method, which allowed the IAU at its Hamburg meeting in 1964 to adopt, among other astronomical constants, the value 1/81·30 with a possible error less than 0·01%. This gives the Moon's mean density equal to 3·343 g/cm^3, the mean acceleration of gravity 162·314 cm/sec^2, and the velocity of escape 2375 m/sec. Thus the force of gravity on the Moon is just 6 times less than on the Earth, and with the small velocity of escape the Moon could not keep an atmosphere, especially as the temperature on the illuminated side rises up to +120 °C when the kinetic velocity of gaseous molecules is too great for a permanent detention.

The visible side of the Moon amounting to 59% of its entire surface has been studied in great detail. Several enthusiastic observers spent many years of intensive labours in measuring the relative positions of reference points and drawing detailed charts. Such were the works of Mädler, Lohrman, Schmidt, Fauth, Neison, and others. Beginning from the end of the last century, photography was applied to this task with great success. The beautiful atlas of the Paris observatory prepared by Loewy and Puiseux must be mentioned. The observatories of Lick, Yerkes, Mount Wilson, Pic-du-Midi and the 200-inch reflector of Mount Palomar contributed large series of photographs, some of which were used by Kuiper in his lunar atlases. On the base of photography a chart of the visible side of the Moon is prepared by the U.S. Air Force on the scale 1:1000000 with a successful attempt of drawing contour lines with an interval of 300 m.

This is our knowledge of the topography of the visible side of the Moon. Its reverse side, comprising 41% of its total surface, has never been seen by a human eye. The more interesting and important are the first photographs transmitted to us by Luna-3 in 1959. Although at that time the television technique was not of the present high standard and the images transmitted from a distance of hundreds of thousand kilometres were not as distinct as at the second subsequent experiment in 1965, still an atlas of the Moon's far side could be compiled showing many details. In one important instance the reverse side differed from the visible one – in the nearly total absence of the so-called maria, i.e. extensive dark depressions which occupy an area of about 40% of the visible side. On the far side only one conspicuous rather small round sea was discovered – the sea of Moscow. In this connection I recall a most remarkable prediction made by Professor Franz of the Breslau observatory in his admirable booklet *Der Mond* published in 1906: "Auf der Rückseite des Mondes hinter seinem Nordostrand ein ausgedehntes helles, kraterreiches Hochland ohne Meere jenseits des Nordrandes des Gürtels der Meere liegt", or in English: "On the reverse side of the Moon behind the Northeastern limb lies an extended, bright, crater-rich highland without seas beyond the northern rim of the belt of seas."

The excellent photographs taken in 1965 by Zond-3 filled up the remaining part of the reverse side and confirmed the absence of extended maria. The far side proved to be very mountainous, covered by innumerable craters of different sizes, some of them forming regular, nearly rectilinear chains, consisting sometimes of a score of craters from very small ones and up to 20–30 km in diameter and many hundreds of kilometres long. In such numbers and extension we do not know similar formations on the visible side of the Moon.

The latest photographs transmitted by the American Orbiters showing many minute details, also contain many crater chains and no maria. Instead they show depressions called 'thalassoids', differing from maria in being not dark, but strewn with many bright craters, in this respect resembling the so-called continents.

We come now to the problem of the origin of the lunar relief. There are two different theories: one of exogenous or external origin through meteoric impacts, and the other owing to endogenous or volcanic action. There are very forcible adherents to either of these theories to the total exclusion of the opposite opinion. It seems to me, however, that the face of the Moon was formed by the action of both of these factors. First of all let us consider the formation of maria. It is quite improbable that such vast areas, being depressions thousands of kilometres in extent, originated from meteoritic impacts. If all craters were of meteoritic origin, we could expect a much more even distribution over the whole surface of the Moon with perhaps only a small preponderance on its Western side, which meets the meteorites with a slightly greater velocity. On the other hand, the polar regions of the Moon have slightly less chances of being hit by meteorites, although an excess of craters is observed near the Moon's Southern pole, which is again in conflict with the impact theory.

We could expect some indications from a statistical study of lunar craters. If, as seems probable to me, a part of chiefly large craters, more irregularly distributed, are of volcanic origin, whereas most of the smaller craters were caused by the fall of meteorites, we could expect some difference in distribution or in some other instance of these two kinds of craters. However, the recent statistical evaluation by Cross of the distribution of craters as counted on Ranger pictures, has shown the absence of any difference between the vast range of sizes from 1 m to 70 km, which, according to the author proves their meteoritic origin. It seems, however, that if the mixture of craters of these two different origins is the same for the whole range of sizes, there would be only an influence on the dispersion, but no difference in the law of distribution.

On the other hand, Fielder and Marcus found a very pronounced clustering of craters and also formations of crater chains, which can be explained only by an internal volcanic origin. This is confirmed by the chains revealed by Zond-3 and the Orbiters, which can be explained by the existence of rifts or fissures in the lunar crust through which gases or molten lava were erupted. The well-known observation of the Pulkovo astronomer N. Kozyrev, who obtained a spectrogram showing the escape of gases containing carbon from the central peak of Alphonsus, proves that vulcanism is not yet dead.

It is impossible to discard the idea of vulcanism when inspecting some of the pictures of the reverse side of the Moon. On the map drawn from the photographs of Luna-3 the crater Tsiolkovsky is clearly seen. On the image transmitted by Orbiter-I this crater has a level dark floor with a composite central elevation. It looks very like a caldera on Java, where the central mountain is surrounded by a lake of dark solidified lava and the inner wall has a complex structure. The perspective view taken with a telephoto lens by Orbiter-II closely resembles a landscape of a mountainous region on the Earth, the only difference being a black sky and the absence of aerial haze.

On the other hand, there are many superimposed craters, e.g. when a smaller crater is located on the rim of a larger one, or a crater interrupts a regular mountain ridge, giving the impression of an external influence. Therefore it seems very likely that both factors played a substantial role in the formation of the Moon's macrorelief, although we are yet unable to assign to which factor is due every individual feature. It is possible and even probable that in some cases a meteoric impact acted as a trigger weakening the Moon's crust and facilitating at the particular place the eruption of lava.

Passing to the microstructure of the lunar surface we must recall that quite a short time ago it was generally assumed that the Moon was covered with a deep layer of dust formed in bygone ages through innumerable meteoric impacts. This was emphasized by the belief that the very strong monthly variations of temperature activated the disrupture of rocks on the surface. A dust layer explained also the exceedingly small thermal conductivity and heat capacity of the outer stratum as revealed by the very rapid cooling of the surface during lunar eclipses, when the temperature falls from over $+100\,^{\circ}\mathrm{C}$ to about $-60\,^{\circ}\mathrm{C}$ at the beginning of total eclipse and after its ending again quickly attains the previous high level.

However, it was soon found that fine dust in a high vacuum especially exposed to great temperature fluctuations would coagulate forming grains of millimetre size without losing its low conductivity. Such a grainy surface is capable to bear a pressure of about 0·5–1 kg per 1 cm^2 in conditions of lunar gravity, still having a small density owing to its porosity. Photometric and polarimetric observations are in accord with such a structure.

Volcanic tuff or porous lava are good approximations to such material, which by its dark colour corresponds to the small albedo of the Moon. As radio-astronomical observations had shown, below this light and thermo-insulating layer lies a more dense rocky substance which during a lunation undergoes a much smaller variation of temperature. In many separate places were discovered 'hot spots' that remain much longer warm during eclipses or at the beginning of night. Many of them coincide with the floors of craters. The explanation seems to be that at these places the insulating layer is much thinner or is even absent, so that we receive the radiation from the deeper, warmer and more slowly cooling stratum. However, such a simple explanation is not sufficient to account for all observed peculiarities connected with the origin and subsequent history of these hot spots.

We have now touched some problems which have obtained a spectacular development owing to the astounding achievements of modern cosmonautics, especially of the soft landing of automatic stations on the Moon, which transmitted to us close panoramic images of the lunar surface. This was first accomplished by Luna-9 on February 3, 1966. After this followed the American Surveyor-I and the Russian Luna-13. The great difficulty of such an operation is obvious from the following considerations. The parabolic velocity on the Moon's surface is 2375 m/sec, but in order of passing the neutral point of attraction of the Earth and a passable time of transition the final velocity must be somewhat greater, about 2600 m/sec. For a soft landing to prevent damage to the spacecraft the velocity of landing must not exceed some 2–3 m/sec, and this must be achieved by reactionary breaking at the right moment with a precision of 0·1% in velocity and its direction. The landing place was every time chosen on level ground of maria in order to avoid steep inclines or deep valleys and also as a reconnaissance of a possible landing place for manned spacecraft.

The panoramas obtained confirmed the absence of dust, the grainy or porous structure of the outer surface, sufficiently resistant to bear the weight of the station itself and, in the future, to enable a cosmonaut to walk on the Moon without crushing the surface or sinking into the dust. A very interesting feature are stones or clumps apparently lying loosely upon the grainy surface of the Moon. They seem to be debris ejected by volcanic eruption or meteoritic impact some distance away.

Very important was the launching of satellites around the Moon. The symposium of the IAU on Astronomical Constants held in Paris in spring of 1963 adopted the following resolution: "We direct the attention of the authorities concerned to the importance of creating artificial satellites of the Moon, very desirably observable by various means, to obtain reliable information concerning the Moon's gravitational field and geometric form. We further recommend that specialists in celestial mechanics consider and specify the best values for the orbital elements of such satellites in order to obtain data for the Moon's gravitational field with the least number of satellites."

Less than 3 years had passed since this symposium, when the first lunar satellite was launched in April 1966 in the U.S.S.R. American Orbiters followed and this kind of research is continuing.

The symposium of the IAU restricted itself to problems directly connected with astronomical constants. However, satellites of the Moon give besides much important information on magnetic and radiational properties of the Moon, and also yield detailed pictures of both sides of the Moon. It is evident that before sending a cosmonaut to the Moon we must study its physical and chemical properties and get as much general information as possible in order to prevent him from many surprises and enable him the fullest utilisation of its natural resources. Otherwise it would be impossible to ensure his return to the Earth or to obtain the vast complex of information for which such a most difficult experiment would be undertaken.

I could only briefly touch some aspects of the investigation of our natural satellite, that seemed to me of main importance. Lunar research is carried on and developed in the U.S.S.R., the U.S.A., and some other countries at such a rate, so much information is received and accumulated, mostly concordant but sometimes disagreeing, that it is difficult to keep pace with it.

From the time when I finished the compilation of this discourse some further progress has been made; it is even possible that during the present General Assembly something new will be learned about the nature of the Moon. I am sure that at the meetings of the corresponding commissions, first of all of Commissions 16 and 17, we shall hear some more specialized and more profound discussions. At present I had to restrict myself to such aspects that seemed to me of general importance.

The unprecedented successes of the last years in the study of the nature and properties of the Moon give us the assurance that in the nearest future we shall witness new and possibly quite unexpected achievements in this field. We have every reason to look forward full of optimism and not follow the French philosopher Auguste Comte, who proclaimed in 1830 in his *Cours de philosophie positive* about the heavenly bodies that "nous ne saurions jamais étudier par aucun moyen leur composition chimique ou leur structure minéralogique...".

Well, the first – the chemical composition – is being investigated well nigh for a century, after the invention of spectral analysis. The second – the mineralogical composition of the Moon – we are on the threshold of investigating in our earthly laboratories when we will receive samples of rocks from the Moon or in lunar laboratories, first automatic ones and subsequently by human investigators transported by spacecraft to the Moon.

We can be confident that we are on the eve of still more brilliant and spectacular achievements in this field of science and technology.