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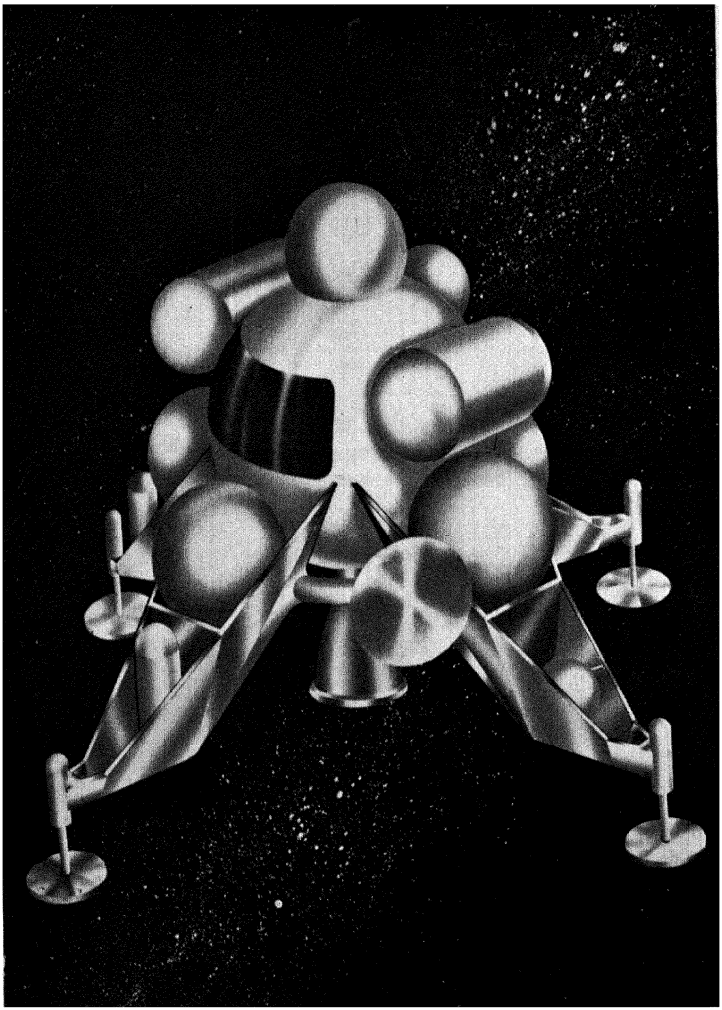
THE MOON

OUR NEAREST CELESTIAL NEIGHBOUR



Proposed excursion module of the Apollo spacecraft, designed to land a team of two men on the Moon in the forthcoming decade

Courtesy of the Astronautics Division, Chance Vought Corporation, Dallas, Texas

frontispiece

THE MOON

OUR NEAREST CELESTIAL NEIGHBOUR

ZDENĚK KOPAL

Professor of Astronomy, University of Manchester

Second edition

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PREFACE TO SECOND EDITION

AFTER spending a long time in astronomical semi-obscurity, the Moon—our nearest celestial neighbour—has of late suddenly emerged to claim widespread interest all over the world; and the reasons for this are indeed of historical significance.

From the dawn of time, astronomy has been debarred from the status of a genuine experimental science by the utter remoteness of its objects of study. With the exception of the meteors—those small freaks of interplanetary matter intercepted by the Earth on its perpetual journey through space—the properties of all celestial bodies could be studied, at a distance, only from the effects of attraction exerted by their masses or from the ciphered message of their light carried by nimble-footed photons across the intervening gaps of space.

A dramatic emergence, in the last decade, of long-range rockets bids fair to bring about a fundamental change. On September 13th of 1959—a memorable date in the annals of human endeavour—the first Russian spacecraft crash-landed on the surface of our satellite to end its age-long separation from the Earth, and was already followed by an American spacecraft that landed similarly on the far side of the Moon in April 1962. Moreover, the continuing advances in rocket development make it a virtual certainty that these first flights will soon be followed by others carrying instruments—and, eventually, men—to the Moon, thus opening up a new era of direct exploration of this first one of the heavenly bodies outside the gravitational confines of our Earth.

PREFACE

On the eve of this new age, which the current technological advances have so suddenly thrust upon us, it may be timely to take stock of our present knowledge of the strange world of the Moon which is awaiting the astronauts at the end of their long and perilous journey. For the technical reader the writer attempted to bring together all the relevant data, in two volumes recently published*, of which the present book can be regarded as an abbreviated popular version.

Events have indeed moved fast in the field of its subject since the first edition of this book appeared three years ago. In particular, manned exploration of the Moon could at that time be discussed only in general terms. The present second edition is, on the other hand, reaching the reader as the story of space exploration is well on its way to a dramatic climax towards the end of the present decade, when the first men born on this Earth are expected to set foot on the surface of our nearest celestial neighbour.

There is no doubt that, in the next ten years, our acquaintance with our only natural satellite is going to become very much more intimate than it has been so far. It is, however, equally certain that this will be possible only on the basis of all the knowledge which astronomers and physicists were so far able to gather at a distance from our terrestrial vantage point—knowledge which, by itself, represents a remarkable triumph of the inquisitive human mind—and of which the present little volume attempts to give a popular account for the general reader.

Z.K.

* *Physics and Astronomy of the Moon* (ed. Z. Kopal), pp. xvi + 538, Academic Press, New York and London, 1962; and *The Moon* (ed. Z. Kopal and Z. K. Mikhailov) pp. xiv + 572, Academic Press, New York and London, 1962.

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1

PROLOGUE

AT the time when you, dear reader, may be ready to open the pages of this book, perhaps the Sun is shining outdoors and your garden around is in full bloom, or the countryside is covered by snow; perhaps the autumn fog hovers over the ground, or wind howls and rain batters against your windows. What of it? The human mind is not bound by what goes on around us, and can readily conjure up a setting appropriate for our thoughts.

And thus, let there be night; or rather early evening, when darkness slowly descends after a glorious day, and the pale silvery face of the Moon sails quietly in the darkening sky on the fathomless depths of the glacial lake of the stars. Many a time we may have watched this restful scene after a long and strenuous day; but to-day is a special occasion: for we are going to pay our satellite a visit.

Let no-one's mind immediately jump, at this invitation, to rockets or other interplanetary vehicles by which we could actually accomplish this feat; for that achievement still lies in the future—albeit not very distant if measured in terms of human generations. Our proposed journey can, instead, be successfully (and more safely) accomplished from an armchair as long as the reader is willing to share in his mind the scientific adventures described in this book—for, unlike the human body, our thoughts can travel faster than light, unencumbered by gravity or relativistic fetters.

What the writer proposes is, in brief, to take his readers on a guided tour of the store of the principal items of our information concerning the physical properties of our satellite and the conditions prevailing on its surface—obtained, to be sure, not yet from an autopsy, but rather by telescopic examination, at a distance which never becomes less than 238,000 miles. In spite of this rather wide gap of space separating us from the Moon, our knowledge of the conditions obtaining on its surface is remarkably complete—in particular, we may already be actually in possession of most part of the information which the first intrepid interplanetary travellers of the future, stepping out of their space ships, will need in order to have a fighting chance of survival. We propose now to share this knowledge with the readers who wish to precede the actual travellers in their thoughts.

We propose, however, to do more than to quote mere arrays of facts. Just as every terrestrial explorer may wish to test each crucial piece of his equipment before placing full faith in its performance, so everyone presented with astronomical facts inferred at a distance may wish to know at least something of the experimental methods by which the data were obtained, as well as of the reasoning at the basis of their interpretation. As these methods, and the logic behind them, often represent veritable triumphs of scientific thought, an account of them should constitute an essential part of our narrative. Whenever presenting any interesting results we shall, therefore, take pains to explain also the methods by which such results were obtained (as far as this can be done in non-technical language), hoping that the reader may find both of equal interest. And when he thus gets acquainted with at least the salient facts which have transpired from lunar explorations carried out by remote control, the reader will—we hope—agree that the methods and results of actual astronomical research can be far more dramatic and exciting than any amount of science fiction.

After these introductory remarks, let us revert our sights to the Queen of the Night sailing—serene and remote—high above

our heads in the sky, which by now may have become completely dark; and, on the waves of light constituting our sole means of communication, let us embark on our journey. We shall be led to visit a very strange world—so near (astronomically speaking) and yet totally different from anything we know around us—of weird surface features and ancient mountains, of bone-dry surface covered with a thick accumulation of cosmic dust, parched by the full blast of sunlight unmitigated by any atmosphere, and alternately heated from temperatures in excess of boiling point when the Sun stands above our heads and cooled to that of liquid air before sunrise after a long spell of cold interplanetary night. We shall picture a world so strange that there is nothing to breathe, the stars are visible on a pitch-black sky equally well at noon as at midnight, and our own weight has been reduced to one-sixth. And yet, in spite of this setting—worthy of a new Alice in Wonderland, and yet based on the sober facts of modern science—we shall end up with an optimistic account of weighty reasons why we should actually go up there, to see for ourselves. Can indeed any fiction be more enthralling? But before commencing with our story, let us first get acquainted with some basic facts and figures which should provide a background for its narrative.

2

FACTS AND FIGURES

'GENTLEMEN, all of you have doubtless seen the Moon —or at least heard of her.' With these words, according to Jules Verne, President Barbicane opened his famous address before the Baltimore Gun Club on the feasibility of firing a projectile to the Moon. To-day, less than a century after that memorable meeting, such a preamble seems hardly necessary for this book; for after spending several decades in astronomical semi-obscurity, our satellite has of late come very much to the forefront of attention on the part of the professional scientists as well as of the general public. To the astronomers, the Moon is indeed a friend of old standing—though never did we feel the limitations of this acquaintance more acutely than at the present time—but how many of our lay fellow-citizens are acquainted with the results of its astronomical investigation? The aim of the present chapter will, therefore, be to introduce to the interested public the Moon as a celestial body and to review its basic properties and characteristics—such as its distance, size, mass, and many others on which our subsequent story will depend.

As the first such characteristic in order of importance of its implications, consider the *distance* separating us from our satellite. How far is it to the Moon? A determination of the mean distance separating us from our nearest celestial neighbour does not represent any recent addition to our knowledge. Its correct order of magnitude was known already to Hipparchos more

than twenty centuries before our time, and determined from the relative duration of the successive phases of lunar eclipses. In more recent times, astronomers have determined this distance—much more accurately—by the method to which we resort whenever we wish to measure the separation of an inaccessible point on land or sea: namely, the triangulation. The astronomical triangulation of lunar distances using a known fraction of the terrestrial diameter as a baseline revealed that the relative orbit of the Moon around the Earth is (very approximately) an ellipse, with a radius-vector varying between 356,000 and 407,000 km. The mean distance of the Moon in the course of a month amounts to 384,400 km, and is equal to 60.267 times the Earth's equatorial radius, or 0.00257 times the mean distance separating us from the Sun. It represents less than 1 per cent of the distance separating us from our other two nearest celestial neighbours – the planets Venus and Mars —at the time of their closest approach. Many a terrestrial traveller has probably averaged a greater mileage by car, during his lifetime, than would be involved in a round trip to the Moon. Light traverses this distance in 1.28 of a second; and an average space rocket which can disengage itself from the gravitational field of the Earth will reach the Moon after a free flight lasting between one and two days.

We may add that, still more recently, the physicists sending out radar pulses to the Moon, and timing the return of their echoes reflected from the lunar surface, re-determined the distance to the Moon by a highly precise laboratory method relying on the known velocity of propagation of the radio waves through empty space (which is known within an error of less than one part in a million). Although—if truth be said—their results do not agree as yet with other astronomical observations as well as we could wish, the distance separating us from the Moon at any moment can nowadays be regarded as known to better than one kilometre; and further refinements of the radio-echo techniques are capable of reducing the margin of error to less than 100 metres.

The *orbit* of the Moon around the Earth is only approximately an ellipse (of eccentricity 0.055), distorted somewhat by the attraction of the Sun (as well as the polar flattening of the terrestrial globe), and its plane is inclined to the ecliptic (i.e., the plane in which the Earth revolves around the Sun) by a little more than 5°9′. The mean period of revolution of the Moon around the Earth is equal to 27.32166 . . . days; and based as it is on century-long series of observations, it constitutes by far the most precise measured quantity known to our science; astronomers can spell it out to at least twelve decimal places. Knowing the size and form of the Moon's orbit, we can easily compute the mean velocity of its motion. It averages 3,681 kilometres per hour, or about 1,023 m/sec—corresponding to a mean angular velocity in the celestial sphere of about 33′ per hour (which is just a little greater than the apparent diameter of the Moon itself).

The mean apparent diameter of the lunar disk in the sky amounts to 1,865″.2 or just over half a degree (oscillating by 102″.4 between perigee and apogee), which at a mean lunar distance of 384,405 km corresponds to a radius of an essentially spherical globe of the Moon of 1,738 km. The Moon is, therefore, about one-quarter of the Earth in size. It rotates around an axis which is almost perpendicular to its orbital plane with a *uniform* angular velocity in *exactly* the same period as it revolves —thus showing us each month always the same face. However, since the angular velocity of revolution in an elliptical orbit varies inversely with the square of the radius-vector, the rotation is sometimes ahead and sometimes behind the orbital motion by as much as 7°7; hence, actually more than one-half of the Moon's surface can be seen from the Earth. This phenomenon is known as the *libration in longitude.* Besides, the axis of the Moon is not exactly perpendicular to the plane of its orbit; the angle between this plane and the lunar equator being about 6°5. This means that, in the course of one month, we can again see sometimes more of one polar region and sometimes more of the other. This gives rise to a *libration in latitude.* Again, when

the Moon is rising for the observer on the Earth, we look over its upper edge, seeing a little more of that part of the Moon than if we were observing it from the centre of the Earth; and when the Moon is setting the converse is true. This *diurnal libration* (not of the Moon, strictly speaking, but of the observer) amounts to about 1°, and superposes upon all other librations to enable us to see considerably more than one-half of the Moon from the Earth. On the whole, not less than 59 per cent of the whole lunar globe can be seen from the surface of the Earth; only 41 per cent being permanently invisible and 41 per cent never disappears; the remaining 18 per cent is alternately visible and invisible.

The next quantity of interest which should contain a clue to further fundamental characteristics of our satellite is its *mass*. The mass of the Moon—like that of any other celestial body—can be determined only by the effects of its attraction on another near-by body of known mass: and in the case of the Moon, this will be our Earth. The oft-repeated statement that our planet revolves around the Sun in an ellipse is not sufficiently precise: for, in actual fact, it is the centre of gravity of the Earth-Moon system (and not the Earth's centre) which describes this ellipse; while both the Earth and the Moon revolve together around their common centre of gravity in orbits which are exactly alike in form, but whose absolute radii are in inverse proportion to their masses.

The Earth does not, therefore, roll around the Sun in an ellipse; rather it wobbles around it; and the necessary result of this monthly wobbling is a slight alternate eastward and westward apparent displacement, on the celestial sphere, of every astronomical object viewed from the Earth—as compared with the place this object would be seen if the Earth had no satellite and its motion were governed by the Sun alone. In the case of the stars, or of more distant planets, the displacement is not sensible; but can be measured in the apparent motion of the Sun, or, better still, of one of the nearer planets or asteroids.

From extensive observations of this kind it has been found

that the radius of the monthly orbit of the Earth's centre (i.e., the mean distance between the Earth's centre and the common centre of gravity of the Earth-Moon system) is 4,670 km. This places the centre of gravity of the Earth-Moon system well into the interior of the Earth (though nearer to its surface than to the centre), and represents just about 1/82.31 times the mean distance from the Earth to the Moon; and by elementary principles of mechanics it follows that the mass of the Moon is then $1/(82.31 - 1) = 1/81.31$ times that of the Earth.

There exists another gravitational method by means of which the mass of the Moon can be ascertained: and that consists of interpreting the observed rate at which the axis of rotation of the Earth (inclined to the ecliptic by 66°.5) precesses in space—like a spinning top—in a period of just over 25,700 years under the combined attraction of the Sun and the Moon. This method confirms that the Earth is, very approximately, 81.3 times as massive as the Moon—which weighs, therefore, but a little more than 1 per cent of the terrestrial mass. As the latter is known to be 5.977×10^{27} g in absolute units, the mass of the Moon results as 7.35×10^{25} g or over 73 trillion tons. This figure may loom large in comparison with all terrestrial units, but on cosmic scales it constitutes but a relatively tiny speck.

And neither is the mean density of the lunar globe at all impressive. Dividing the mass just quoted by the lunar volume of 2.20×10^{25} cm^3, we find that its mean density comes out to be 3.34 g/cm^3—i.e., only a little higher than that of the common terrestrial rocks. The gravitational acceleration on the lunar surface proves to be 1.62 m/sec^2, which is less than one-sixth of the terrestial one; and the velocity of escape from the lunar surface (i.e., the velocity which a mass particle must exceed if it is to escape from the Moon into space) is only about 2.38 km/sec. The relatively low gravitational acceleration prevailing over the lunar surface means that much less work would be required there to lift weights or throw stones at a distance. However, it would also mean that our own weight would work

for us less effectively when we wished to compress anything, or drive a shovel into the ground by stepping upon it.

Incidentally, the velocity of escape from the Moon just quoted would be constant all over its surface only if the lunar globe did not rotate about an axis, and if the additional gravitational pull by the Earth were disregarded. When we take into account (by a recourse to appropriate properties of the surfaces of zero-velocity of the restricted problem of three bodies) both the centrifugal force arising from axial rotation as well as the terrestrial attraction, it transpires that the velocity sufficient for disengaging a mass particle from the gravitational field of the Moon is lowered to 2,322 m/sec; though the particle cannot leave the Earth-Moon system unless its velocity exceeds 2,326 m/sec.

The proximity of the Earth reduces, therefore, the escape velocity in the plane of the lunar equator by 53 m/sec. The additional presence of the Sun will, at the time of the full Moon (when the solar mass pulls in the same direction as that of the Earth), reduce it still further by 118 m/sec, and increase it by the corresponding amount when the phase of the Moon is 'new'. As a result, the escape velocity from the regions of the lunar surface having the Earth near their zenith may become as low as 2,204 m/sec and to increase to 2,440 m/sec half a month later. Its variation is, therefore, appreciable; but the advantages—if any—to be gained from such changes are still uncertain.

The smallness of the mass of the Moon and the relatively low value of the surface escape velocity entail several important consequences: and perhaps the most important one is the complete *absence of any atmosphere* or protective gaseous mantle around the surface of the Moon. What should enable any self-gravitating body—such as a planet—to surround itself with a gaseous envelope? It is the attraction exerted by its mass on the molecules of our gas, preventing at least the majority of them to acquire a velocity sufficient for making escape from the gravitational field of the parent body, in spite of their thermal

agitation stimulated by the heat received from the Sun. The continued existence of an atmosphere around any celestial body testifies to the result of a perpetual struggle waged between two opposite tendencies: on one hand, the gravity of the central body, which weighs on each gas molecule in the same way as on any macroscopic object and will attempt to prevent its escape if it can; while, on the other hand, the heat pumped into our gas by the Sun's radiation (as well as that of the surface of our planet) maintains its molecules in a constant state of agitation, and thus keeps the atmosphere distended.

In general, the velocity of the molecules constantly bouncing against each other will be the greater, the higher the temperature of our gas; though heavier molecules will require higher temperatures to acquire the escape velocity than the light ones. This velocity of escape depends, in turn, on the mass as well as the radius of the astronomical body in question (being, in general, greater for heavy or dense bodies than for light or distended ones). To give some numerical examples, the escape velocity from the gravitational field of Jupiter—the greatest and most massive planet of our solar system—is over 61 km/sec. For the Earth this velocity turns out to be 11.2 km/sec; and for the Moon, only 2.38 km/sec. On the other hand, thermal agitation corresponding to a mean temperature of Jupiter's daylight hemisphere of about 130°K (i.e., −143°C) is barely sufficient to endow even hydrogen—let alone heavier molecules —with a mean velocity of 1.3 km/sec, which is utterly insufficient for any kind of escape.

For the Earth or the Moon enjoying (on account of their greater proximity to the Sun) a warmer climate, the mean velocities of thermal agitation of different molecules would be proportionally higher. Thus, at 0°C, the mean velocities of the hydrogen molecules or helium atoms are found to be 1.84 and 1.31 km/sec, respectively; for molecular nitrogen or oxygen the respective values become 0.49 and 0.46 km/sec; while for water vapour or carbon dioxide the corresponding figures are 0.62 and 0.39 km/sec, respectively. If, moreover, the gas temperature

should rise to 100°C (actually encountered on the Moon at the time of high noon), all the foregoing velocities would be increased about 1.17 times.

These all are, to be sure, mean velocities, possessed by the greatest number, but not necessarily all, molecules of our gas. Some of them can, at any time, temporarily acquire by particularly energetic (or weak) collisions chance velocities considerably higher (or lower) than the average—possibly higher than the velocity of escape from any planet. The number of such particularly fast particles bears, however, a constant ratio to the total number of all gas molecules, predictable statistically for each temperature from the kinetic theory of gases. Hence, it is possible to estimate theoretically a fraction of the molecules or atoms of any gas that are in a position to escape from the atmosphere of any planet in a given time. A more detailed analysis reveals that if the mean molecular velocity of thermal agitation is one-third of that of escape, one-half of the corresponding atmosphere will be dispersed in a few weeks; should it amount to one-fourth, the half-life of our atmosphere would be increased to about 50,000 years; while if this ratio were one-fifth, the atmosphere should last for 100 million years.

On the basis of these results we are led to expect that the large and massive outer planets of our solar system—Jupiter, Saturn, Uranus, and Neptune—are sufficiently cool to retain even the lightest gases (such as H_2 or He) practically for all time; their high escape velocities (61, 37, 22, and 25 km/sec, respectively) render them virtually fool-proof against any leak into space. This inference has indeed been confirmed by spectroscopic observations, which reveal the presence of vast atmospheres around these planets, containing large amounts of hydrogen and its compounds.

As for the Earth, its gravitational attraction proves too weak (and its mean temperature too high) to retain the lightest gases in its atmosphere permanently. Any free hydrogen or helium will 'leak' out into space at a (cosmically) quite rapid rate. Heavier gases—such as molecular nitrogen or oxygen—can, on

the other hand, be retained almost indefinitely. The chemical composition of our atmosphere may have changed profoundly in the course of the long astronomical past of our Earth, but there appeared never to be any dearth of volatile elements in its gaseous mantle.

When, however, we turn to the Moon, whose mean temperature would not differ greatly from that of the Earth (as both these bodies are equally far from the Sun and receive, through its rays, equal amounts of heat per unit area) but whose surface escape velocity is only 2.38 km/sec (i.e., $4\frac{2}{3}$ times less than on the Earth), a more extreme situation is encountered. Any hydrogen or helium atmosphere would dissipate from the Moon in a matter of days. Water vapour would escape more slowly, but still would be lost (geologically speaking) in a very short time. At noon temperatures, oxygen, nitrogen, as well as carbon dioxide would also completely escape in a relatively short time. In fact, the rate of dissipation into space of all but the heaviest gases (which are, again, cosmically very scarce) is so high on the Moon that we should not expect to find any appreciable permanent atmosphere around it; and this expectation has indeed been borne out by all aspects of the observational evidence available to us so far.

Perhaps the most direct observation which suggested the absence of any air on the Moon already to the early students of its surface was its general telescopic appearance and perpetual absence of any visible clouds over its face. The parts of the Moon near the edge of its apparent disk (which would be seen through the greatest depth of its hypothetical atmosphere) are always clearly visible without the least obscuration. All shadows on the Moon appear to be perfectly dark (though they must all be bordered by a penumbra, since the Sun is not an illuminating point source but a disk of finite angular diameter), and there is no twilight at the cusps of its crescent.

Moreover, no evidence of *refraction* has ever been found at the Moon's limb whenever our satellite intervenes between us and any more distant object. During an eclipse of the Sun, the

outline of the solar limb remains completely free from any distortion where the Moon intercepts it. Furthermore, whenever on its apparent journey through the sky the Moon happens to occult a star, the latter's light is seen to vanish instantaneously (or as suddenly as is permissible by the laws of diffraction and the angular diameter of this star), and does not fade away gradually as it should if it were dimmed (selectively) by extinction in any perceptible lunar atmosphere.

This absence of refraction constitutes by itself a sufficiently stringent test to enable us to conclude that the density of a hypothetical lunar atmosphere—if any—above the surface must be less than one part in ten thousand of the terrestrial air density at sea level. In more recent years, this upper limit has further been lowered by repeated but so far fruitless quests for an indication of *twilight phenomena*, which should be produced in a hypothetical lunar atmosphere during sunrise or sunset.

In order to appreciate more fully the power of this method, consider the light reaching us, say, from any spot near the central part of the apparent lunar disk at the time of the first quarter just before sunrise, when the ground is still immersed in darkness but the space above it already receives the first rays of the rising Sun. This light should, in general, consist of three parts:

1. the light from the lunar surface as illuminated by the Earth;
2. the light of the Sun scattered in the direction of the line of sight in a hypothetical lunar atmosphere; and
3. the moonlight scattered in the terrestrial atmosphere in the direction of the observer.

In the efforts to separate the component (2)—which alone bears on the presence of any gas around the Moon—from the parasitic (but much more intense) diffuse light arising from the sources (1) and (3), Nature lends us fortunately a helpful hand: for the light scattered on gas in a direction which is perpendicular to that of its original incidence should be completely

polarized, while the diffuse light arising from the lunar as well as the sky background should be essentially free from polarization. A search for the manifestation of a hypothetical lunar atmosphere reduces, therefore, to the detection of a polarized component in the diffuse light reaching us from an element of surface area of the Moon just before sunrise near the first quarter.

Actual measurements of this type were first performed with sufficient accuracy by the well-known Russian astronomer V. G. Fessenkov, and their results reported to the world in 1943. Their outcome was again negative; no trace of polarization was detected; and the precision of the experiment was such as to lead Fessenkov to conclude that the density of a hypothetical lunar atmosphere—if any—must be less than one part in a million (or 10^{-6}) of that of the terrestrial atmosphere at sea level. If, incidentally, a hypothetical lunar atmosphere were as dense as 10^{-4} of the terrestrial one, the twilight zone illuminated by the Sun at the time of the new Moon would endow the lunar disk with an aureola whose light would, in fact, be more intense than the earthlight on the dark side of the Moon and thus be readily detectable—which it certainly is not.

In more recent years, this limit has been further lowered by the brilliant French astronomer Bernard Lyot, who, by examining the light reaching us from the regions just beyond the cusps of a lunar crescent eliminated the effect of earth-light represented by (1). By making his observations from the lofty height of the Observatory on Pic-du-Midi in the French Pyrenees, through clear atmosphere renowned for its superlative seeing, and using the coronograph (a telescope specially designed by him to minimize the amount of light scattered in the instrument itself), Lyot was in a position to detect much smaller traces of polarization in the light of the cusps of the Moon than Fessenkov was able to do near the centre of the lunar disk. However, in spite of this greatly increased instrumental precision, all Lyot's results were again purely negative: no trace of polarization was detected; and from its absence Lyot concluded in 1949 that the

density of any hypothetical lunar atmosphere must be less than 10^{-8} of that of the terrestrial one. Moreover, after Lyot's premature and lamented death in 1952, his work was continued by his pupil and collaborator Audouin Dollfus, who by resorting to further ingenious refinements in 1956 depressed the possible upper limit for the density of a hypothetical lunar atmosphere to 6×10^{-10} of the terrestrial one. If the Moon possesses any gaseous atmosphere, its density above the surface cannot, therefore, exceed some 7×10^{-13} g/cm^3; and how much smaller it may be remains still conjectural.

A gas density of the order of 10^{-12} g/cm^3 would represent a pretty hard vacuum from the point of view of the terrestrial physicist—and one which is, incidentally, attained in our own atmosphere at an altitude of approximately 180 km above sea level. However, even at such great heights, the number of gas particles remains still of the order of 10^{10} per cm^3; and although the mean free path of such particles between mutual collisions is of the order of 100 metres, even so rarefied a gas could manifest itself in different observable ways. It would not, to be sure, offer any protection to the surface beneath from impinging meteorites. A hypothetical lunar atmosphere of surface density of the order of 10^{-12} g/cm^3 would not decelerate any meteoritic material—small or large—enough to cushion significantly its impact. All solid particles in space intercepted by the Moon must hit its surface essentially with their cosmic velocities, and spend themselves on the surface rather than in their passage through the atmosphere as is the case on the Earth. Needless to say, the rate of impact of meteoritic matter (of all sizes) per unit area of the Earth as well as of the Moon must be very approximately the same. In quest of its observational verification on the Moon we should not, however, look for any luminous trails during approach; but rather for instantaneous flashes of light which should be produced by impact of a meteorite on solid rocks. For meteorites of sufficient mass such flashes should be visible from the Earth through suitable telescopes—especially against the dark surface of the night hemisphere of the Moon—

and their systematic observation may thus extend the field of meteor astronomy to our satellite.

However, returning to our own atmosphere such as exists at an altitude of 180 km above sea-level, even though it is insufficient to affect the velocity of the meteors shooting through it, it can give rise to other interesting phenomena. Between 180–200 km above sea level we would find ourselves in the midst of the auroral zone, where luminescent gas stimulated by the impact of corpuscular sunrays produces the beautiful displays of 'northern lights'. Are there similar aurorae on the Moon? Herzberg pointed out some time ago that a search for emission spectra of such displays around the bright limb of the Moon might constitute one of the most sensitive tests of the presence of a hypothetical atmosphere of our satellite. No trace of any such emission has, however, so far been detected above the surface of the Moon; though a quest for fluorescent radiation from the Moon led quite recently to some very interesting discoveries on its surface, which will be briefly described in the subsequent Chapter 4.

So far as our present knowledge goes, however, the Moon does not possess any atmosphere of density in excess of 10^{-12} g/cm^3 at its surface; and how far below this limit its actual density happens to be we can only guess. Let us add that, for the astronomers concerned with the relative abundances of the elements in cosmic matter, even the upper limit just stated is already becoming rather uncomfortably low; for, after all, there really should be more gas around the Moon than this limit seems to admit.

We explained already earlier in this chapter that, on account of the feeble lunar attraction, all light gases would escape indeed completely from its gravitational field in the course of the Moon's long astronomical past; and most of the heavier gases (such as SO_2, for instance) would react again with surface rocks to form solid compounds. This should, however, not apply to the so-called 'inert gases'—like argon, krypton, or xenon—which for reasons of their atomic structure do not enter into

compounds, and are at the same time sufficiently heavy for their rate of escape from the gravitational field of the Moon to be moderately low (the mean atomic velocities of thermal agitation of these gases at 0°C being 414 m/sec for A, 287 m/sec for Kr, and 229 m/sec for Xe).

The case of argon is particularly arresting, because—quite apart from any aboriginal amount of this element which the Moon may have retained from primordial times—its supply must be continually replenished by radioactive decay of the heavy isotope of potassium (K^{40}). If (as is highly likely) the chemical composition of the Moon is similar to that of the outer mantle of our Earth, the element potassium constitutes about 0.12 per cent of it by weight. The total mass of the Moon, which is known to be 7.35×10^{25} g, should then contain about 8.8×10^{22} g of potassium; and of this about 9.7×10^{17} g should be the radioactive K^{40} decaying (by β^--disintegration) into the common isotope of argon (A^{40}).

The total disintegration of all lunar K^{40} should, therefore, create 9.7×10^{17} g or 1.5×10^{40} atoms of argon—as compared with some 10^{44} gas particles now constituting the terrestrial atmosphere. Just how much of this argon managed to escape to the surface from the bulk of the lunar mass by gradual degassing (caused by the rising internal temperature) remains conjectural within fairly wide limits. However, on almost any reasonable guess (coupled with the known rate of escape of argon gas from the gravitational field of the Moon) the amount of argon in the lunar atmosphere should add up to more than the upper limit of the lunar air density consistent with the absence of perceptible twilight phenomena.

How to explain this apparent discrepancy? The correct way may have been recently indicated by Herring and Licht, who pointed out that a good many atoms of heavy gases contained in whatever primordial atmosphere the Moon may once have had (or created there by radioactive decay as well as nuclear disintegrations attending the impact of cosmic rays) can be 'blown off' into space by collisions with the corpuscular

radiation (mainly the protons) emitted spasmodically in great 'puffs' by our Sun. The existence of such gusts, associated usually with the flares and other disturbances of the solar surface, is well known and attested by such terrestrial phenomena as polar aurorae and magnetic storms. Herring and Licht argue that the knocking-off power of this 'proton wind' of solar origin is, in fact, sufficient to remove most of the argon and other rare gases from the lunar neighbourhood, and thus despoil the lunar surface even of such exceedingly tenuous traces of gas vesture as its own feeble gravitational attraction would enable it to retain.

We may add that, still more recently, Singer and Öpik pointed out another mechanism for relatively rapid gas removal from above the lunar surface: and this is by ionization. As long as this gas remains neutral, its atoms or molecules can be removed only by collisions—be it with other molecules, or the particles of the 'solar wind'. Should, however, the gas particles get ionized and acquire thus positive electric charge (and Singer with Öpik have shown how easily this can happen to the lunar argon), the electrostatic charge of the sunlit hemisphere of the Moon, acquired by photoionization of light elements in its crust (of which more will be said later; cf. p. 95)—which is likewise positive—can remove ions by repulsion even more effectively than the collisions with the protons of the solar wind. It seems, therefore, possible to explain the well-nigh complete absence of free gases around the Moon in more than one way, and thus to reconcile expectations based on theory with actual observations to the complete satisfaction of all parties.

If, therefore, the Moon possesses no detectable atmosphere, because of its low gravitational field and relatively high daytime temperature as well as expected electric charge, it cannot, of course, maintain any liquid on its surface. Near its poles, to be sure, depressions may exist which are never reached by direct sunlight (and which are illuminated, at best, by sunlight scattered from neighbouring landscape). In such regions, condensed volatile substances may possibly be present in the form

of some kind of a permafrost; but should they ever evaporate, they would be irretrievably lost to the Moon in a very short time. Hence, no liquid—or even solid—water could be present almost anywhere on the Moon, except possibly for very short intervals of time. The surface of the Moon is thus apparently bone-dry, and has been so from time immemorial. No feature visible on the surface of the Moon could thus have been formed, or modified by the effects of running water, or of freezing and melting water. One of the most important agents for geological changes on the Earth's surface has, therefore, been absent on the Moon, and cannot be invoked to explain any common structural characteristics on the surface of our satellite, which we shall discuss in more detail in the forthcoming Chapter 3.

Before we do so, however, we must turn our attention to the interior of the lunar globe containing the bulk of its mass; for (as is true of every celestial body—be it a star, a planet, or its satellite) this interior is the seat of the 'engine room' which controls the large-scale structure and cosmic evolution of the respective body. The visible surface represents only the 'boundary conditions' of all thermal and stress processes going on in the interior, as well as an 'impact counter' of external events which our satellite must have experienced since the days of its formation. In no other sense can an interpretation of the formations seen on the lunar surface possess any meaning.

If we wish to examine the essential properties of the lunar interior, the primary clues are already in our hands: namely, the observed mass and the size of our satellite, combining as they do in a mean density of 3.34 g/cm^3. What is the pressure prevailing inside this mass? It goes without saying that, even in so small a celestial body existing under the influence of its own self-attraction, the internal pressure is essentially hydrostatic throughout most part of the interior—meaning, in other words, that the strength of the material is unable to withstand its weight anywhere except, possibly, in the very outer part of its crust. If so, however, an application of the elementary theory of hydrostatics reveals that the internal pressure in a globe of the

lunar mass and size cannot exceed some 50,000 atmospheres even at its centre—a pressure exceeded at a mere 150 km below the surface of the Earth—regardless of the kind of material of which the Moon consists. Pressures of this order of magnitude are readily attained in terrestrial laboratories to-day; and the changes in density exhibited by common rocks under such pressures have already been measured. On the basis of all the evidence we now possess it is reasonable to conclude that the actual density of the lunar sub-surface material is very approximately equal to 3.28 gc/m^3, and increases by compression to 3.41 g/cm^3 near the Moon's centre. Such a model fits in satisfactorily with the observed mean density of the lunar globe as a whole, and leads us to believe that the Moon consists of material which is very similar to that constituting the outer crust of our own planet.

Does the Moon represent then a solid and nearly homogeneous spherical rock, or is it partly molten in its interior? The answer to this question is inseparably connected with the problem of the internal temperatures of the Moon, on which considerable light was thrown in recent years—particularly by Urey. First, let it be mentioned that in the present state of astronomical research it appears probable that the Moon—in common with all other bodies of the solar system—originated by an agglomeration of solid particles of small sizes at relatively low temperatures—decidedly lower than those required for complete volatilization. It does not seem possible to envisage a physical process which could lead to the formation of the planetary bodies—let alone of so small a mass as that of the Moon—by condensation from gas at high temperature. Therefore, the view prevalent to-day among serious students of the subject assumes that the original mass of the Moon accumulated from pre-existent smaller solid particles some 4.6×10^9 years ago, and that the temperature of this initial agglomeration (which may have formed, under favourable conditions, in a surprisingly short time) was not more than a few hundred degrees on the absolute scale. The value of 4.6×10^9 years,

currently accepted for the age of the solar system, is based on laboratory determinations of relative abundances of certain radio-active elements (disintegrating spontaneously at a known rate) and their decay products in meteoritic debris falling on the Earth, representing the left-over material floating through space from the time of the formation of the entire solar system. A conspicuous clustering of their ages around 4.6 billion years appears to have fixed the origin of this system within an uncertainty of not more than 100 million years; and its value is of pivotal importance for efforts to unravel the lunar past since that time.

Once the body of the Moon thus grew up by coalescence of solid particles at low temperatures, its subsequent thermal history becomes quite interesting. For, since that time, heat must have been continuously generated in the Moon's interior by spontaneous decay of such traces of long-lived radio-active elements (such as potassium K^{40}, thorium Th^{232} and the two isotopes of uranium U^{235} and U^{238}) as are likely to be present in lunar matter in percentual amount comparable with that found in chondritic (stony) meteorites incident on the Earth. The amount of radiogenic heat liberated by a gram of such elements is known from terrestrial laboratory measurements and so is the rate of their spontaneous decay (10^9 — 10^{10} years). The heat so dispersed in microscopic amounts through the entire mass of the Moon then flows outwards towards the cooler surface; but its progress is impeded by very low thermal conductivity of lunar rocks, which renders this cooling an exceedingly slow process.

The solution of the problem of the balance between this heating and cooling (at the hands of Urey, Levin, and other investigators) led in recent years to the realization that the bulk of the mass of the Moon must, at present, be heated to a temperature in excess of 1,000°K which, in central parts of the Moon, may have risen to 1,500°–2,000°K. The interior of the Moon—if we could only see it—should, therefore, glow like the inside of a terrestrial blast furnace and radiate light which

can help in the outward transport of heat. Such is, however, the opacity of lunar rocks to red light that the radiative transfer of heat, though significant, does not alter appreciably the high internal temperatures mentioned above. Since temperatures so elevated may lead to partial melting of the material exposed to them, the Moon may indeed possess a plastic core of appreciable dimensions; and as, moreover, the adiabatic temperature gradient in the central regions of the Moon turns out to be much smaller than the one based solely on conduction, it would follow that in any material susceptible to flow convection currents should arise to the extent permitted by viscosity. The actual role of convection in the lunar interior and its effects remain still largely conjectural. But whatever the detailed balance of the heat transported by conduction, convection and radiation in the lunar interior may turn out to be, there appears to escape from the conclusion that the bulk of the mass of the Moon must at present be regarded as being at 1,000°–2,000°, and is, moreover, still heating up; for the long life-times of the principal radioactive elements responsible for this increase—in particular of Th^{232} and U^{238}—will see to it that the Moon will keep secularly warming up for a few billion years more before eventual cooling—though the maximum internal temperatures which the Moon may be expected to attain should not be much higher than those prevailing at the present time.

Is it definitely ruled out that the Moon could have ever been completely molten? The final answer cannot be given until more will be known about the possible role, in this connection, of certain short-lived radioactive isotopes of common elements—such as iodine I^{129}, palladium Pd^{107} and, in particular, aluminium Al^{26}. The half-lives of these radioactive elements are of the order of only 10^6–10^7 years—and, therefore, if any of these were present in the initial mass of the Moon or other bodies of the solar system, they would now be almost completely extinct. The decay products of their spontaneous disintegration appear, however, to occur in meteoritic matter

in abundances which raise seriously the question of the importance of former radioactivity of their mother substances; and a reasonable abundance of these in the primordial matter of the Moon might indeed have been capable of melting the Moon's mass completely in the first few million years of its existence—before such long-lived radioactive elements as K^{40}, Th^{232} or the two isotopes of uranium had time to exert any effect.

Urey argued persuasively against such a possibility on grounds of the fact that if the Moon was ever completely molten, $4\frac{1}{2}$ thousand million years would not have been long enough time for it to solidify to its present state. This would indeed be true if cooling were to take place by conduction of heat only. In actual fact, however, a Moon completely melted by radiogenic heat sources would almost certainly have been violently convective; and the convection currents caused by the prevailing temperature gradient would drain off the internal heat much more effectively than conduction alone would have been capable of doing. In other words, even if the Moon was completely molten at some initial stage of its evolution, convective cooling should have enabled it to solidify again in a time-span comparable with the period of heating—so that, at any rate, the surface of our satellite must have been solid throughout most part of its long astronomical past, while the internal temperature was slowly rising as a result of spontaneous disintegration of the long-lived elements like K^{40}, Th^{232}, U^{235} and U^{238}.

This gradual increase of lunar internal temperatures throughout the long past of our satellite entails several interesting consequences; and one of them is the inevitable desiccation and degassing of its interior. If the Moon originated—as we now believe—by an accumulation of essentially cold matter, this matter was bound to contain also a finite concentration of certain volatile compounds (such as H_2O, SO_2, etc.) which could, at low temperatures, have been absorbed into the crystal lattice of many minerals and thus be present in the initial Moon in the solid state, from which they would have been liberated by secularly increasing temperature.

The case of water (H_2O) is particularly arresting, because of its relatively high proportion (up to 0.1 per cent by weight) in stony meteorites and of the high cosmic abundance of its constituent elements as well as the great stability of its molecule. In order to estimate the probable amount of juvenile water in the mass of the Moon, let us avail ourselves of the following analogy with the Earth. The total amount of water in all the oceans of the Earth is such as to cover its entire globe with a uniform layer of approximately 1,800 metres in depth; and if all this water was produced by desiccation of the whole mass of the Earth (which is equal to 5.98×10^{27} grams), each gram of this mass would have had to contribute 1.54×10^{-4} grams of juvenile water. If this latter proportion were to hold for the Moon as well, its smaller mass of 7.35×10^{25} grams should contain an amount of juvenile water which, if squeezed out completely to the surface, would have been enough to cover the lunar globe with an ocean of a uniform depth of some 300 metres.

Now we know from laboratory physical chemistry that, at temperatures above 1,000°K, water should have been expelled from almost all solid hydrates and penetrate, as superheated steam, through any cracks or cavities existing in the crust (the steam could not percolate through molten magma itself, as the local hydrostatic pressure exceeds the partial pressure of water vapour at 1,000°–2,000°K throughout the relevant parts of the interior) towards the outer and cooler layers—where it would condense into the liquid phase and eventually freeze in the sub-surface layer, beyond the reach of the diurnal heat wave, where a constant temperature prevails of some −30°C (cf. p. 86). Along crustal fissures which can serve as ducts for more rapid escape the formation of ice may, in fact, take place very close to the actual surface and give rise to morphological phenomena which could suggest the presence of sub-surface lunar glaciers to the external observer on the Earth. The evidence that this may indeed have taken place will be examined in the next chapter, when we shall inspect the visible

face of our satellite and try to understand the nature of the processes which have been shaping it in the past. Whatever the case may be there seems, however, no escape from the conclusion that, as a result of secular rise of internal temperature of the Moon caused by radioactive heating in the past $4\frac{1}{2}$ thousand million years, the bulk of its mass must have been largely despoiled of its more volatile compounds—which must, in turn, have considerably enriched the sub-surface layers of the lunar globe, or even escaped into space.

In view of this situation, the global chemical composition of the Moon should be that of the non-volatile primordial matter from which the solar system originated, with iron in an unknown state of oxidation; at least the mean density of the Moon corresponds closely to the density of such matter with the iron very highly oxidized. Silicates of basaltic composition (olivine) may be present in larger quantities; though their closer identification may have to await petrographic examination that should become feasible—with the aid of rockets now in design stage—in the relatively near future.

In one respect the chemical composition of the Moon turns out, however, to be anomalous; and this is in relation to the iron content of our own Earth. We have already mentioned that the mean density of the Moon tallies well with the probable composition of the primordial matter from which the solar system was formed—and whose unadulterated sample accessible to quantitative chemical (spectroscopic) analysis we find at present in the solar atmosphere: unadulterated because the large mass of the Sun prevented the escape of any elements from its gravitational field even at the relatively high temperature to which they are exposed; and because (unlike in the interior) this temperature is still far too low to have caused nuclear transformations on any appreciable scale. When we take a sample of the gases now found in the solar atmosphere, allow for the escape of its lighter elements by relaxing the gravitational field to that prevalent on the Moon, and condense the rest, the resulting matter of density close to 3.3 g/cm^3 should contain,

according to Urey, between 11–14 per cent iron by weight—which is less than a half of the recent estimates of the iron content of the Earth (28 per cent). Therefore, either the Moon is approximately of solar composition with respect to its iron content while the Earth (and other terrestrial planets) possesses a distinctly higher concentration of this important element—or, if its iron content is the same as for the Earth, its mass must contain an anomalously high proportion of some sufficiently common low-density substance (such as 2–3 per cent of water, or 10 per cent of graphite) to make up the mean density of its globe to 3.34 g/cm^3, as deduced from the Moon's mass and size. Surprises may be in store when the first samples of lunar rocks are returned by rockets to Earth; but Urey considers it probable that the Moon contains substantially less iron than the terrestrial planets. This would require a marked difference in the chemical processes which preceded the formation of the lunar and planetary globes (which would, indeed be equally true if there were excess water or carbon in the Moon), rendering our satellite a very special object.

A profound difference in chemical composition between the Earth and the Moon indicates that these bodies may be of considerably different origin. Earlier theories attempting to create the Moon by tidal disruption of the liquid Earth, brought about by resonance, which supposedly developed at one time between the duration of the day (i.e., the period of the solar semi-diurnal tides) and that of the free non-radial oscillation of the primordial terrestrial globe, ran more recently against insuperable difficulties (caused mainly by the relatively high viscosity of the terrestrial matter) and had virtually to be abandoned. Instead, the main weight of the present scientific opinion inclines to regard the origin of the Earth and the Moon as essentially unrelated events; and assumes that both took place at the time of the creation of the solar system as a whole—by processes which are as yet but very incompletely understood. Indeed—Urey argues—the Moon may possibly be older than the Earth and may have grown to its present size before another

lump of cosmic matter accumulated to form our planet. If these views are correct, the Moon represents the Earth's foundling rather than a true-born child; but when and by what means our planet acquired its only natural satellite remains as yet largely conjectural.

3

THE STRANGE WORLD OF THE MOON

IN the preceding Chapter 2 we got acquainted with some of the fundamental physical properties of the lunar globe as a whole. The aim of the present section will be to look more closely at some of the diverse surface features visible on the face of our satellite, and try to understand the nature of the principal forces that have been shaping the face from time immemorial.

What is so arresting about this face, and what can we hope to learn from it at a distance? The Moon is a very old body (probably not less than 4,500 million years of age) and has probably been a close companion of the Earth since the days of its formation. The permanent absence of any air or water on the Moon, discussed already in Chapter 2, makes it, moreover, virtually certain that most part of the composite fossil record exhibited by its familiar features must be of very ancient date—its oldest landmarks being, perhaps, not far removed in time from the days of the origin of our whole solar system. On the Earth or other near-by planets, all landmarks of comparable age must have fallen prey and been completely obliterated by the joint action of their atmospheres or oceans aeons ago. However, as any changes on the lifeless Moon can proceed only at an exceedingly slow rate, its present wrinkled face must still bear scars and traces of many events which have taken place in the inner precincts of our solar system since the days of its

formation some 4,500 million years ago; and if so, their correct interpretation holds indeed a rich scientific prize.

Even to the naked eye the Moon is a beautiful object, diversified with markings which have been associated with numerous popular myths. If we look at its wrinkled, pock-marked face through a telescope—or, better still, at a composite photograph of the two quarters (Plate I)—the most cursory glance reveals that the lunar surface consists of essentially two different types of ground. One type, rough and broken, is comparatively light in colour (reflecting, in places, as much as 18 per cent of incident sunlight); the other is darker (reflecting, on the average, but 6–7 per cent of incident sunlight), much smoother and frequently so flat as to simulate the surface of a liquid. The first type of ground we shall generally call the 'mountains'. They occupy large continuous areas—particularly in the southern hemisphere of the Moon—and cover, on the whole, a little less than two-thirds of the entire visible face of our satellite. The flat lands—'maria' or seas, as they were misnamed by early observers of the Moon, before the true nature of its surface was properly understood—checkered by faults and sparingly dotted with cliffs, occupy the rest. They are, on the whole, remarkably uniform in reflectivity and general appearance—whether they be small or large.

A closer look at the Moon with the aid of a telescope magnifying a few hundred times, or at photographs of the lunar surface secured with some of the world's largest instruments (cf. Plates II and III)—approximating the view which will face the future travellers to the Moon as they peer out of the portholes of their space-ships some hours before the landing—reveals an almost bewildering array of formations and structures, no two of which are exactly alike. However, the dominant type of formation among them, and by far the most numerous on any part of the Moon, appear to be ring-like walled enclosures commonly called the *craters*. They occur almost everywhere on the Moon—in mountainous regions as well as in the maria—in truly prodigious abundance, giving the lunar surface

an appearance of a pock-marked face: the number of craters with diameters in excess of 1 km is estimated to be more than 300,000 on the visible hemisphere of the Moon alone; and those still smaller are probably too many to be counted.

The largest of these craters attain dimensions in excess of 200 kms, and their representative examples are shown on the accompanying Plates IV and V. Plate IV represents a portion of the lunar surface near the south pole of the Moon (which we saw already, from greater distance, on Plate II) in the centre of which we see the great walled plain bearing the name of Clavius—named so after Father Christopher Clavius (1537–1612), distinguished astronomer of the Collegium Romanum in Rome and older contemporary of Galileo Galilei. The diameter of its enclosure exceeds 230 km; and by its size (as well as the height of its ramparts) it recalled to Galilei—the first telescopic observer of the Moon—the aspects of the central European land of Bohemia. Plate V shows a sunrise photograph of another walled plain—as yet unnamed on the western slopes of the 'Sea of Clouds' (Mare Nubium), almost equal in size to Clavius and only a few hundred kilometres north of it.

There are altogether five craters on the Moon whose dimensions exceed 200 km, and an additional thirty-two objects with diameters between 100 and 200 km. Coming down the scale of lunar formations, on the shores of a plain bearing the poetical name of Mare Nectaris we find an impressive group of craters, the largest of which—Theophilus—possesses a diameter of just over 100 km and is beautifully shown on a sunset photograph reproduced on Plate VI. On the opposite quadrant of the Moon, the extensive plains of the 'Ocean of Tempests' (Oceanus Procellarum) are dominated again by the magnificent example of a crater bearing the name of Copernicus, whose regular structure—90 km across—dominates the surrounding landscape (Plates VII and VIII). Many other specimena of similar walled mountains can be seen on the same photographs, and their more detailed description could continue almost without end.

No two mountains or craters on the Moon are exactly alike. However, apart from individual distinguishing features, most craters possess also many characteristics in common. Their distribution in size ranges continuously from the largest specimena, which we have already described, down to the smallest pits discernible with our telescopes; and the distribution of craters—of all sizes—on the visible face of the Moon appears to be entirely at random.

Secondly, *the heights of the ramparts of all lunar craters prove*, in general, *to be very small in comparison with their absolute dimensions.* The measurement of the latter is simple enough: knowing the angular scale of our photographs, the linear diameters as measured on the plates can be readily converted into minutes or seconds of arc. As, moreover, at a mean distance of the Moon each second of arc corresponds to 1,864 metres of the lunar surface, the conversion of angular measures into absolute distances on the Moon is quite straightforward and poses no difficulty.

On the other hand, the height of any mountain or of the wall of a crater must be determined from measurements of the shadows which the respective eminence casts over the surrounding landscape. The length of these shadows will, of course, vary with the altitude of the Sun above the lunar horizon: it will be greatest (and also change most rapidly) at the time of sunrise or sunset. As the instantaneous position of the Sun in the lunar sky anywhere on the Moon is known to us with great accuracy, a continuous photographic record of the shortening or lengthening shadows filmed during sunrise or sunset can then be reduced not only to reveal the height of any particular eminence above the surrounding landscape, but to indicate also any unevenness of the ground on which the shadows are cast. The precision of the positional measurements on the lunar surface attainable with modern telescopes is such as to enable us to measure the location of any individual point relative to others with errors of the order of 300–400 metres; while the height of any mountain can be determined by the shadow method within ± 10

metres—a very respectable accuracy considering the fact that the triangulation must be done at a distance which never becomes less than 356,000 km!

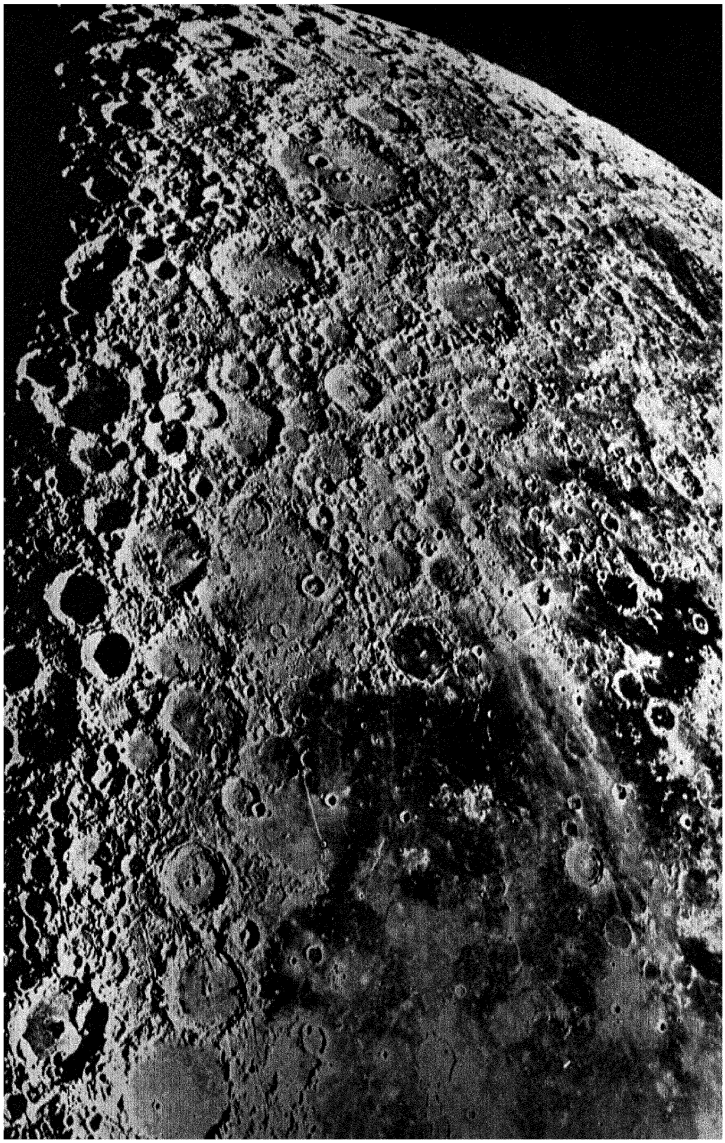
Extensive measurements of the heights of the ramparts of individual lunar craters have revealed that their altitudes are, in general, very moderate. Thus the maximum height attained by the rims surrounding the crater Clavius (see Plate IV) is barely 1,600 m above the surrounding landscape (i.e., just about the same as that of the highest mountain of the chain surrounding the Bohemian plateau in Central Europe), and not more than 4,900 m above the lowest point of the crater's floor. This height is so small, and the dimensions of the whole crater so large, that an observer standing in the middle of the floor of Clavius would not see even the rims of its ramparts at all—they would all be below his horizon! For the two other conspicuous craters exhibited on Plates VI to VIII—Theophilus and Copernicus—the circumstances are nearly the same. The maximum height of the Theophilus ramparts does not exceed 1,200 m over the surrounding landscape, and 4,400 m above the bottom of its bowl; its central mountain rises to an altitude of 2,200 m above its immediate surroundings. For Copernicus, the corresponding figures are 1,000 m and 3,300 m for the ramparts, and 1,200 m for the central peak.

The profiles of these and a few other craters are diagrammatically shown on the accompanying Figure 1. A glance at the dimensions of these configurations plotted on the same horizontal scale as the curved lunar surface reveals eloquently the essentially flat nature of all craters. Moreover, *their floors all appear to be depressed below the surrounding surface*, and the volume of the depression seems in many cases to come close to the volume of the ramparts raised around them—suggesting that the material contained in the rims may have been displaced from the crust by forces which produced the crater pit. Very small craters do not appear to possess almost any ramparts at all, and represent mere pits sunken in the lunar surface. The craters on the Moon thus hardly deserve the name or descrip-

The synoptic view of the visible face of the Moon, on which photographs of the two quarters are merged together

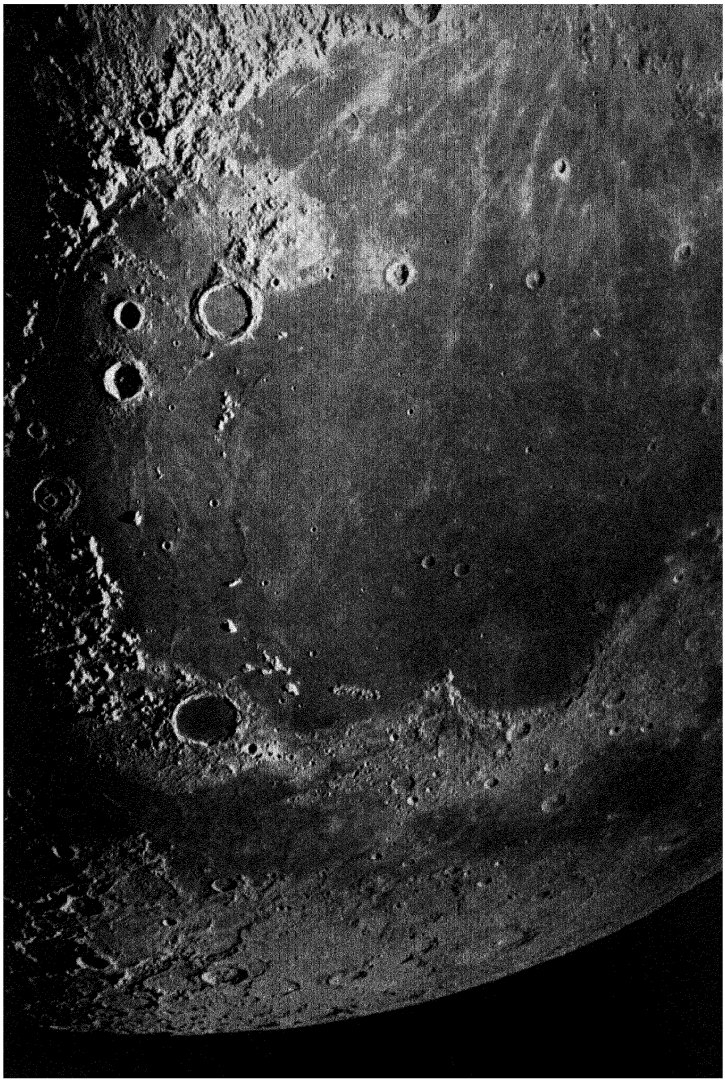
Lick Observatory photographs, taken with the 36-inch refractor and mounted by H. C. Urey

PLATE I



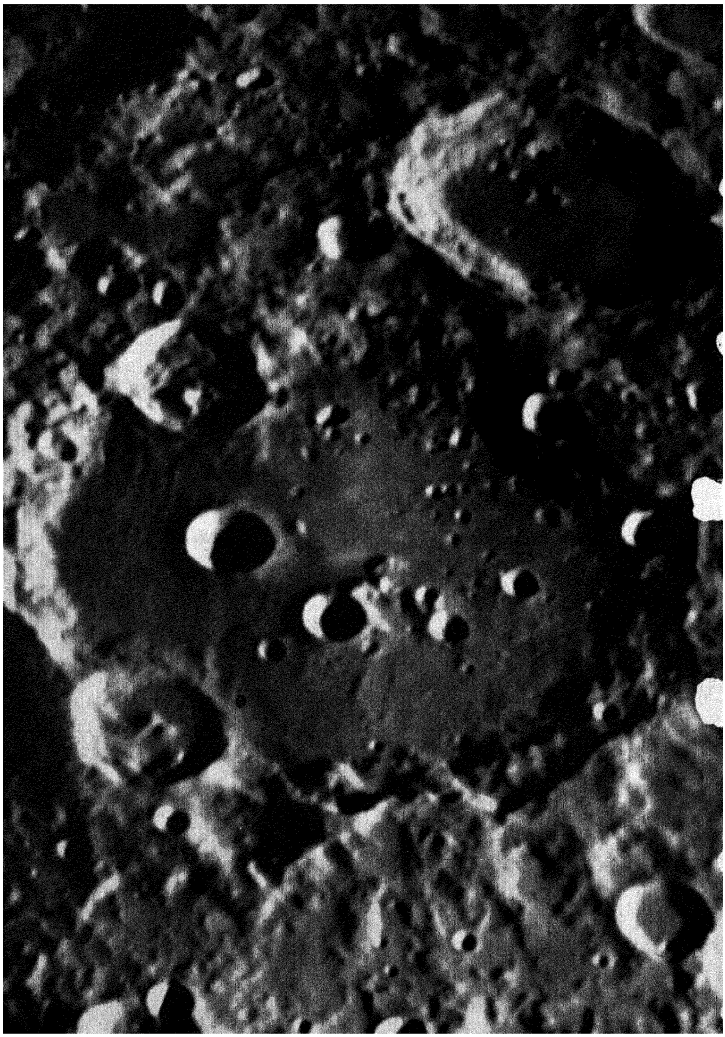
Southern portion of the Moon's surface at the time of last quarter (age $21\frac{1}{2}$ days), including the region of the craters Clavius and Tycho with its ray system

Mt. Wilson Observatory photograph, taken with the 100-inch Hooker reflector



Northern portion of the Moon's surface at the time of last quarter (age 21½ days), showing the entire region of Mare Imbrium from the crater Copernicus (in upper right corner) to north pole

Mt. Wilson Observatory photograph, taken with the 100-inch Hooker reflector



The crater Clavius near the lunar south pole at sunset time. The dimensions of this largest of lunar walled mountains are approximately equal to the distance between London and Birmingham. The impression of height of its ramparts is greatly exaggerated on the photograph by the shadow effect. Actually, they stand only 1,600 metres above the surrounding landscape, and would be below the horizon of the observer stationed near the centre of the crater

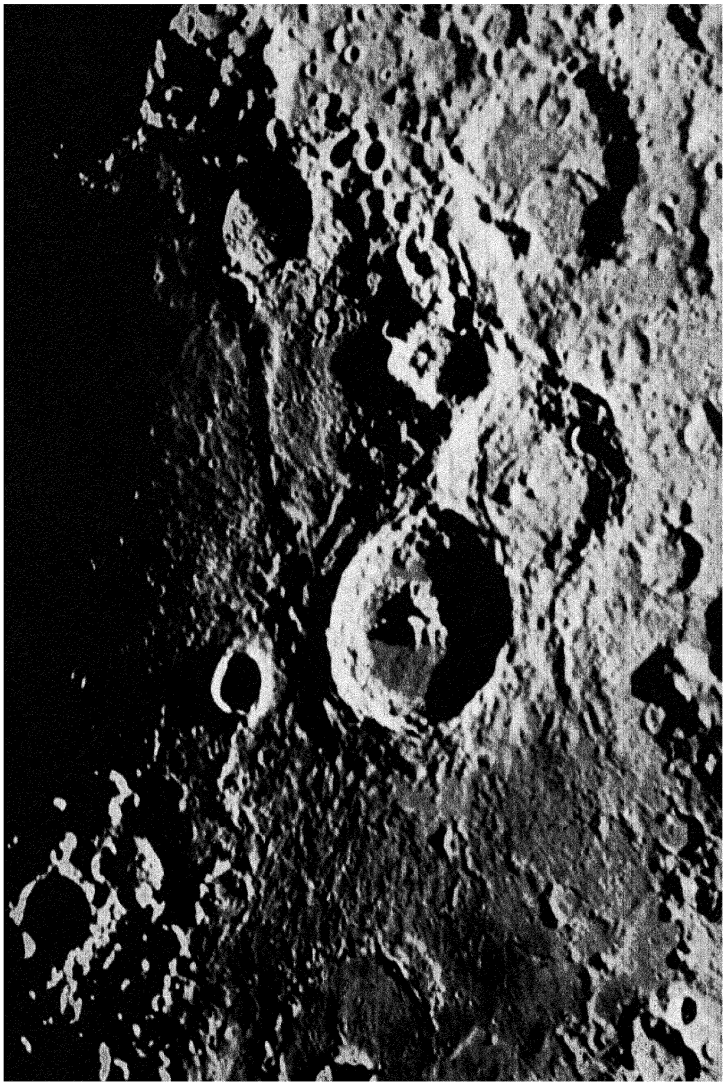
Mount Palomar Observatory photograph, taken with the 200-inch Hale reflector

PLATE IV

Sunrise over the great walled plain near the south-east bay of Mare Nubium. The smallest details discernible on its floor are less than one kilometre in size. A white arrow inside the adjacent crater Regiomontanus indicates one of the rare 'hill-top craters' on the Moon, which are probably of volcanic origin

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

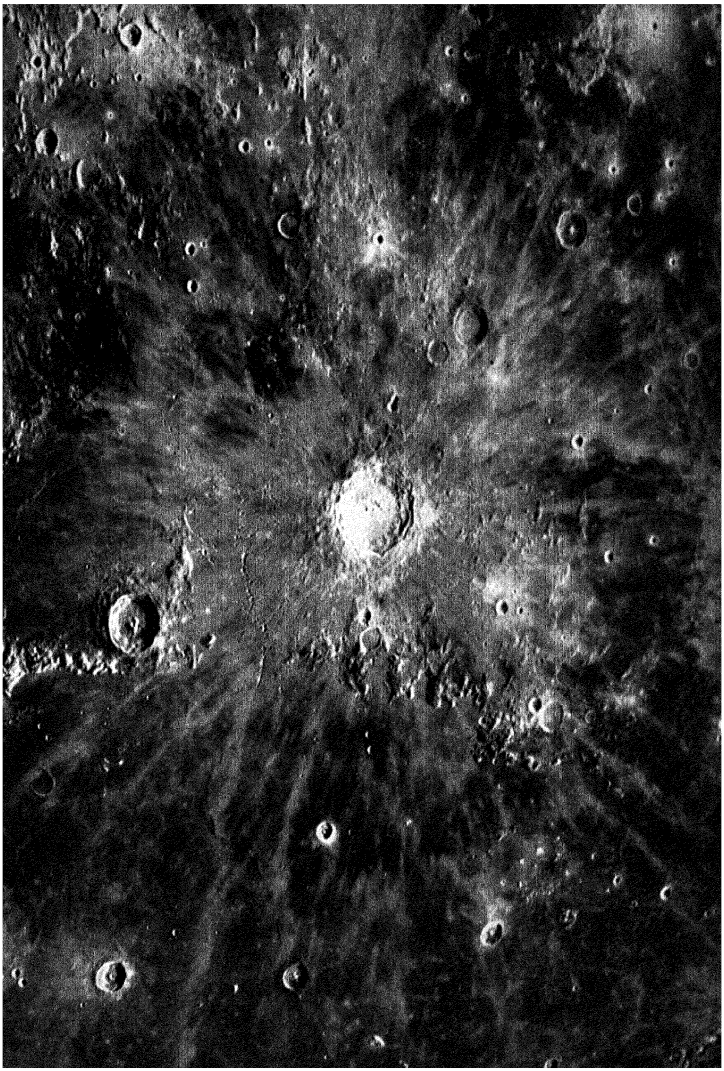
PLATE V



Sunset over the lunar crater Theophilus and its surroundings (including its neighbours Cyrillus and Catharina). The diameter of this walled mountain is just over 100 km, and its ramparts do not rise more than 1,200 m above the surrounding landscape. Its central peak towers some 2,200 m above the floor of the crater

Yerkes Observatory photograph, taken with the 40-inch refractor

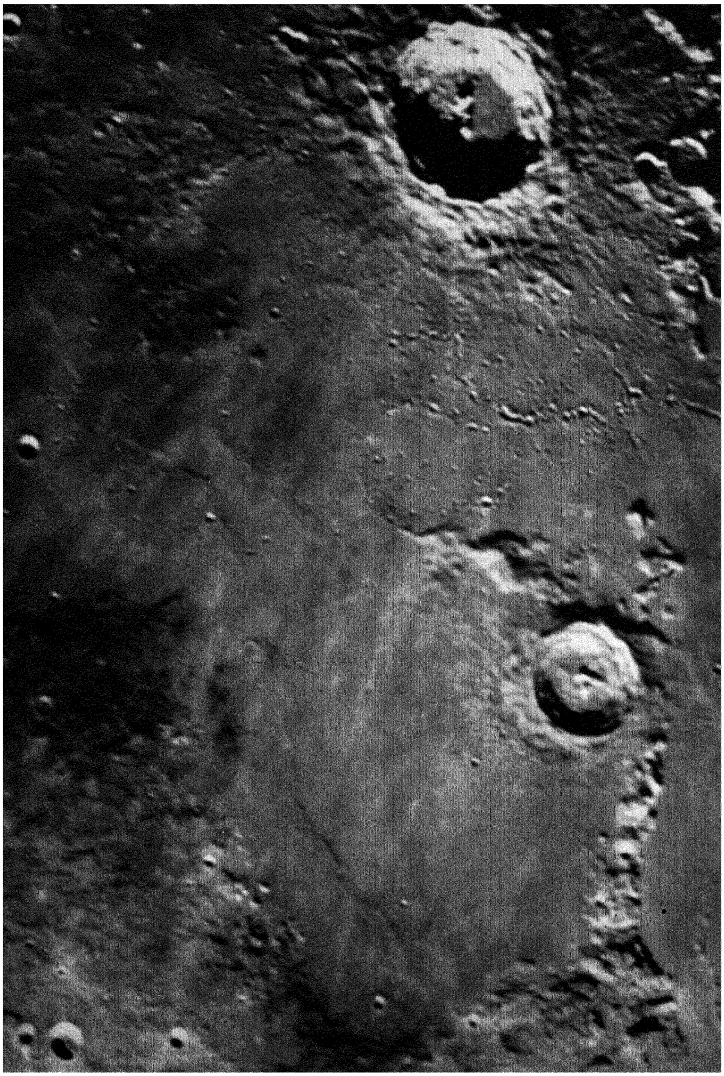
PLATE VI



Region of the crater Copernicus in the Oceanus Procellarum, showing clearly the system of bright rays diverging from its central structure. The crater on the left is Eratosthenes, at the tail of the great Apennine chain of mountains

Mt. Wilson Observatory photograph, taken with the 100-inch Hooker reflector

PLATE VII



A sunrise photograph of the craters Copernicus (above) and Eratosthenes (below), with the plains of Sinus Aestuum

The ramparts of Copernicus—about 90 km across—rise no more than 1,000 m above the level of the surrounding plains; and its central peak is but some 1,200 m high

Mt. Palomar Observatory photograph, taken with the 200-inch Hale reflector

PLATE VIII

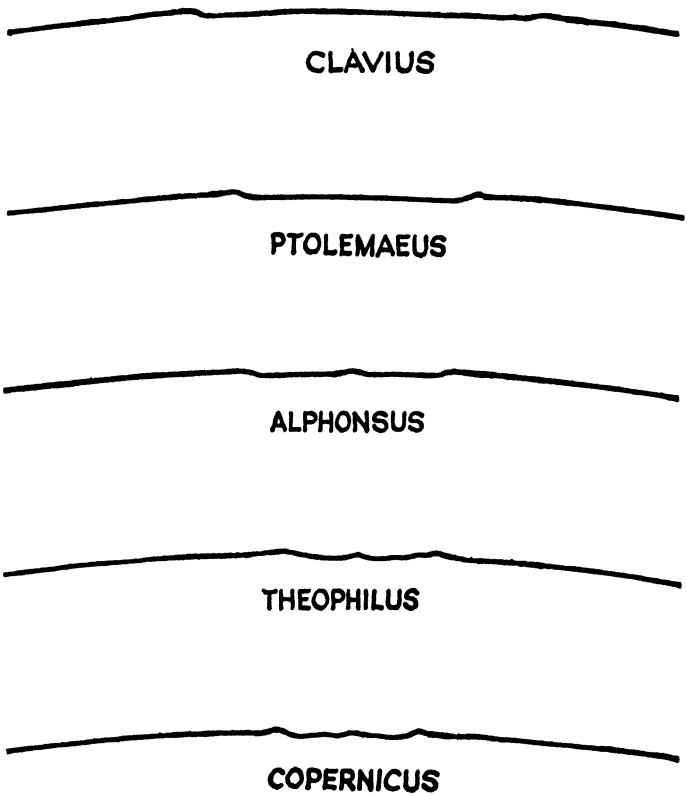


FIGURE 1. Schematic profiles of five large lunar craters: Clavius (234 km; Plate IV), Ptolemaeus (144 km; Plate XIV), Alphonsus (120 km; Plate XIV), Theophilus (106 km; Plate VI), and Copernicus (90 km; Plates VII–VIII) drawn on the same horizontal scale as the curvature of the lunar surface. Vertical scales are twice exaggerated to bring the outlines of these craters into perceptible relief. In actual fact, they are still flatter than shown on the diagram!

tion of real mountains; they resemble rather pockmarks spread profusely over the ageing lunar face and do not appear to have any obvious terrestrial analogy.

The relatively small heights and gentle slopes of lunar craters —the impression of which is so greatly exaggerated by their long shadows cast during sunrise or sunset—are characteristic of all other mountains on the Moon as well. In order to demonstrate it on further examples, let us visit in our pictorial survey the north-west quadrant of the lunar surface (Plate IX), dominated by the great plain of the 'Sea of the Rains' (Mare Imbrium)—perhaps the most impressive lunar configuration of this type, some 1,100 km across, and over a large part of its shores bordered by great mountain chains of the lunar Alps and the Apennines, attaining in their highest peak (Mt. Huyghens) an altitude of 5,500 m. It is, in fact possible that these mountain chains represent nothing but broken and incomplete ramparts of a gigantic crater whose floor is the actual mare; and the same may be true of the neighbouring Mare Serenitatis (bordered on three sides by the Caucasus, Haemus and Taurus mountains), Mare Crisium farther to the west, and possibly others.

We shall have more to say of these circular maria later on; but for the present let us merely visit the western bay of Mare Imbrium (bearing the somewhat odorous name of Palus Putredinis) as shown on the photograph reproduced on Plate X. Three craters dominate its landscape: Archimedes (diameter of approximately 80 km), Aristillus (56 km across, with central mountain), and Autolycus (38 km across)—probably well known to anyone who ever looked at the Moon through a telescope. The specific object of our visit will, however, be the mountain Piton (marked on the plate with a white arrow)—a solitary cliff rising from the plains and casting a long shadow in the rays of the setting Sun at the time of the last quarter.

Looking at this mountain from our vantage point in space, we might be inclined to imagine it as a steep rock—a kind of lunar Matterhorn. Yet nothing would be further from the

truth. When the length of the shadow was recently measured and analysed by Rackham at the University of Manchester, it transpired that, for an observer standing on the Moon, the mountain would loom far less impressive. The actual cross-section of Piton established in this way is shown on the accompanying Figure 2. It reveals that, although this mountain attains a respectable altitude of over 2,300 m, its base is so

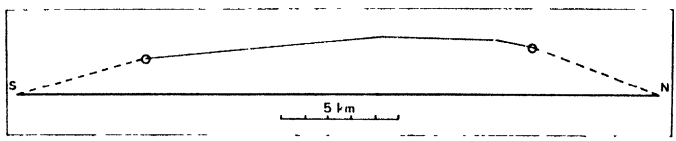


FIGURE 2. Profile of the lunar mountain Piton in the western plains of Mare Imbrium (cf. Plates IX and X). Horizontal and vertical scales are equal (*after Rackham*).

wide (almost 28 km) as to give it an appearance of a large hill rather than of any steep cliff. It does not possess any well-defined summit. Such is, moreover, the curvature of the lunar surface that even the top of Piton would set completely below the horizon of an observer standing on the Moon at a distance of approximately 90 km (marked on Plate X by a broken white line delimiting an oval); anyone standing outside the area of this oval would see nothing of the mountain at all!

In order to give a further example of the essential flatness of lunar surface features, let us turn next to the south-eastern part of the 'Sea of Calm' (Mare Tranquilitatis)—not far from the Theophilus region—whose topography was recently studied by Turner likewise at Manchester. When we consider the altitudes of the walls of various craters in this region (whose photograph is reproduced on Plate XI) in connection with the known curvature of the lunar surface, what would be the horizontal panorama confronting an observer on the Moon standing at (say) points marked by the letters *X* and *Y* on the plate? The answer as found by Turner is diagrammatically shown on the following Figure 3. We note that the observer standing at *X*

would see nothing at all above the flat outline of his western horizon; and his eastern horizon would reveal only the low outlines of the near-by crater Arago B. But even from point *Y*

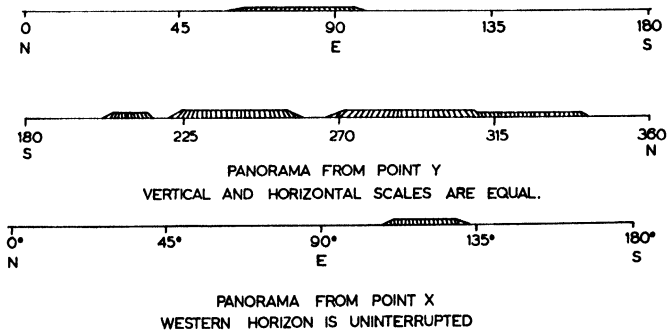


FIGURE 3. Horizontal panorama on the shores of Mare Tranquilitatis, as seen from the vantage points marked by *X* and *Y* on Plate XI (*after Turner*).

—in the immediate neighbourhood of the craters Ritter and Dionysius—the horizontal panorama as seen from the surface would by no means loom impressive. It should bear some resemblance to a desert area with a few mesas showing in the distance—rather than to any really mountainous terrestrial region.

In fact, wherever we turn on the Moon and ascertain the linear dimensions as well as altitudes of diverse formations on the lunar surface by actual measurement, we find much the same story. Perhaps the most surprising result of all from more recent work on lunar topography has been a realization—so contrary to earlier impressions based on visual inspection rather than measurement—that *there appear to be no steep slopes anywhere on the Moon of any appreciable size.* All slopes of large crater walls or mountains, whose gradients have so far been measured, seem inclined by less than 10° to the direction of the horizontal. The impression of ruggedness, gained by a cursory glance at photographs of the sunrise or sunset on the Moon, largely disappears when the appropriate altitude of the Sun above the horizon

(not readily apparent to inspection) is duly considered. When, in addition, we recall the large curvature of the relatively small lunar globe, we cannot escape the conclusion that the horizontal panorama visible from most points on the Moon would be rather dull and unimpressive, with but few landmarks on which the eye could safely rest in search of orientation.

As a result, the lunar landscape should hold little in store for the climber accustomed to face the challenge of major terrestrial mountains: no ice or glaciers, no sudden change in weather or snowstorms to fear, no steep slopes which could not be by-passed, no need for crampons, or pitons—and, on top of it all, a surface gravity so low as to make the task of carrying equipment or supplies weighing 60 pounds on the Earth a real promenade. Only one commodity would be very much more in demand there than on the Earth: namely, oxygen, without which we could not make a step. Also, no grand view could probably be expected to reward the scaling of a summit; and the taking of a sunbath or bivouacking at night in the open would entail swift retribution from which there would be no awakening. When, in addition, we consider the distance one would have to travel to attain the objective, it appears rather unlikely that the climbing of lunar mountains will develop into a national sport that may threaten to deflect the major stream of terrestrial mountaineers from the Himalayas.

Besides the craters and the maria, the surface of the Moon exhibits a great many other interesting features of lesser magnitude—domes, rills, rays—which may contribute further significant clues to its past. But there seems no room for doubt that the craters and the maria—by their number as well as the area they occupy on the lunar surface—constitute by far the most distinctive physical characteristics of the surface of our satellite; and any effort to reconstruct the history of its composite fossil record will have to clarify the problem of their origin before other and lesser details are ripe for interpretation.

What can we say at present about the origin of the lunar craters? A glance at the almost bewildering array of such

formations of all sizes—as shown on the photographs reproduced on Plates II–XIV in this book—makes it unlikely that they all originated in the same way or at the same time; and a more detailed analysis of their features reveals that a suspicion of different origin is probably well founded. In fact, the most reasonable approach to our problem can probably be made if, from the start, we ask ourselves the question: what are the principal physical processes which could have conceivably co-operated in shaping up the surface of our satellite? Once we formulate our problem in this way, we at once encounter two contending theories of crater origin: the external theory—invoking the effects produced by impacts of other celestial bodies (asteroids, comets, or meteorites) on the lunar surface—and the alternative theory relying on the internal processes connected with the gradual defluidization or degassing of the lunar globe and local volcanic activity.

That the surface of the Moon is 'full of inequalities', was reported already by Galileo Galilei in his *Sidereal Messenger* of 1610; and this fact caused at first no small commotion among philosophers of the peripatetic school. Fifty-seven years later, Robert Hooke—who was also interested in the Moon—dropped bullets into a pipe clay and water mixture and, behold, saw formations arise which one could call an 'impact crater'. But being an inquisitive soul, Hooke did not stop at that: as he tells us in his *Micrographia* (1667), he also boiled a mixture of powdered alabaster with water, and observed that this too produced transient crater-like structures on the surface of the liquid. Thus he started a very interesting controversy about the origin of lunar craters, which has never really been settled. In order to assess the relative merits and drawbacks of these theories as objectively as can be done at the present time, let us outline, in turn, their principal arguments and supporting evidence.

To begin with the theory of external impacts, it is well to remember that the interplanetary space through which the Earth and the Moon continue to circle around the Sun is not entirely empty. Far from it; for it contains a wide variety of

ingredients of all weights and sizes: from the ubiquitous gas of free electrons reaching us from the Sun and extending well beyond the radius of the terrestrial orbit, through microscopic specks of dust and larger meteoritic debris (representing probably the left-overs from the time of formation of the whole solar system), to major meteorites, asteroids, or comets whose orbits through space may intersect the path of the Moon and occasionally collide with it. The frequency with which the surface of the Moon—like that of the Earth—undergoes direct hits by major chunks of cosmic matter in the form of asteroids or comets is as yet difficult to assess with any accuracy at the present time—let alone what it could have been in a more distant past. As, however, in the course of the long lunar past some such hits must undoubtedly have been scored, it is important to realize the consequences which such an event would entail; and these should indeed be awe-inspiring.

In an attempt to visualize them at least to some extent, let us consider a large meteorite—of the size and mass of a rock weighing a million tons and moving through space at a velocity (relative to the Moon) of say 30 km/sec. The total kinetic energy of such a body—equal to one-half of the product of its mass times the square of its velocity—would be of the order of 10^{25} ergs. Now if such a body were to crash against the surface of the Moon at full speed, it would penetrate into its crust like a bullet and get buried well underneath the surface before coming to a complete stop. The kinetic energy which the body of the meteorite possessed before impact cannot, however, be lost. Its entire amount must re-appear in other guises to which it was converted in accordance with the known laws of physics—mainly as heat which should be sufficient to volatilize completely the whole impinging mass and convert it into an extremely hot gas bubble (of temperature of the order of 1,000,000°) imprisoned some two diameters of the original body beneath the original surface.

Needless to say, so large a quantity of so extremely hot gas cannot be contained for an instant by the weight of the overlying

debris. It would immediately explode with great violence and the expanding gas should affect severely regions that are very large in comparison with the size of the original missile. The main effect of the explosion should, therefore, be essentially similar to that of a point-charge; and the initial direction of the impinging body would not have much influence on the symmetry of the surface markings produced by the explosion. The probable result is diagrammatically shown on the accompanying Figure 4, which represents the expected cross-section of a

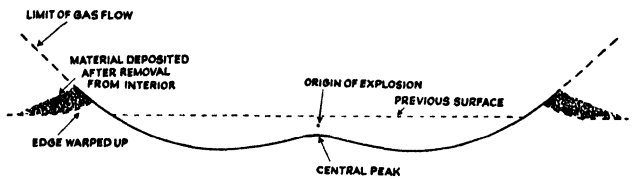


FIGURE 4. Schematic representation of a hypothetical impact crater on the Moon (*after Gold*). Vertical scale exaggerated.

lunar impact crater. The amount of actual solid material left around by the intruder should be negligible; most of it should have evaporated and escaped back into outer space, or become dispersed over a large part of the adjacent lunar surface.

Diverse terrestrial experiments with explosive charges detonated in suitable media are indeed found to produce local surface effects simulating the ramparts of some types of lunar craters with remarkable fidelity. It is, however, difficult to match in this way all different types of lunar craters to a satisfactory approximation. Thus the circumstances of the origin of craters of the type of Theophilus or Copernicus (Plates VI–VIII), whose ramparts surround a concave bowl with central peak, must obviously have been different from those which led to the formation of a Clavius (Plate IV), Plato (Plate IX, bottom), or Ptolemy and Alphonsus (Plate XIV), whose floors are completely flat—without the trace of any central mountain —and seem to consist of exactly the same dark material as covers the neighbouring maria. A few of the relatively deep craters—like Tycho (Plate II, top) or Copernicus (Plate VII)—

appear, moreover, to be the convergent points of radial systems of bright streaks spreading like tentacles from the central formation in all directions to a considerable distance, and suggesting vividly a 'splash' of the surface material ejected on impact; but again other craters of otherwise very much the same type (Theophilus, for example) possess no trace of any such rays.

Besides, the weight of circumstantial evidence based on the analogy between the observed lunar surface features with the laboratory impact experiments or other terrestrial analogues (bomb craters, etc.) should not be overestimated; for the differences between the scale and total energy involved in the terrestrial experiments and the hypothetical impacts capable of giving rise to major craters on the lunar surface amount to many orders of magnitude. R. B. Baldwin, one of the principal recent protagonists of the impact theory of the origin of lunar craters, asserted in his well-known book, *The Face of the Moon*, that in order to produce by impact a crater 30 km in diameter, kinetic energy of the order of 10^{26} ergs would have to be expended in the effort; and to double or quadruple its size, energies 10 or 100 times as large would be prerequisite. The size of the impinging bodies should, moreover, be approximately 240, 540 and 1,160 metres across if they were to consist of stony material ($\rho \sim 3$ g/cm^3), and be 20 per cent smaller if their principal constituent were nickel-iron ($\rho \sim 7$ g/cm^3). More recent investigations of the same subject by W. G. van Dorn suggest, moreover, that Baldwin's figures should be revised sharply upwards, and that energies of the order of 10^{28} ergs would actually be required to produce a crater 30 km in size (the diameter varying, in general, as the cube-root of the energy of impact). Thus impact production of craters as large as Clavius (Plate IV) would call for energies associated with high-velocity impacts of small asteroids—of the size of Eros, Hermes, or Adonis (to name a few which paid rather close calls on the Moon in recent decades)—whose dimensions are estimated to 10 km, and masses to 10^{13} tons.

The sudden expenditures of such prodigious amounts of energy would, however, trigger off a chain of events which would not only be devastating beyond imagination on (and around) the actual point of impact; but whose consequences should be felt, in a varying degree, all over the Moon through the medium of *seismic waves*. In order to assess the intensity of disturbances which can be caused by such waves, let us return to our impinging meteorite as it comes to a complete stop at some depth beneath the lunar surface—an event necessitating the conversion of its entire kinetic energy into other forms. Just how will this large energy store be apportioned? While its actual partition would depend rather critically on the actual depth of penetration, such knowledge as we possess indicates that only about one-half of the kinetic energy of the incident body may be converted into heat and bring about its volatilization. Most of the other half should be absorbed in a ground shock and largely used up for irreversible heating (though not volatilization) of underlying rocks at a very short distance. Only when the shock pressures have degraded to the order of the elastic strength of these rocks (which should be about 1 kilobar) will the remaining energy be available for propagation as seismic waves; and its amount can be estimated to a few per cent of the total kinetic energy of the impinging body.

Thus we are back again to a figure of the order of 10^{26} ergs of seismic energy which would emanate from an impact capable of producing a lunar crater 30 km in diameter, with proportionate modification for craters of other sizes; and the seismic waves excited by it should carry in their train the message of the event throughout the lunar globe to all parts of its surface. In other words, any impact of a body capable of producing a lunar crater would also be bound to set off a 'moonquake', characterized by a very shallow epicentre; and their effects on the Moon as a whole require some attention.

In order to appreciate more fully the seriousness of such 'moonquakes', let us recall that the most destructive earthquakes experienced on our planet within the memory of man-

kind entail energy expenditures of the order of 10^{26}–10^{27} ergs only—i.e., ten to a hundred times *less* than that of a hypothetical moonquake accompanying the origin of a crater 100-120 km in diameter. When one considers the fact that there are almost fifty craters of this size or larger on the visible hemisphere of the Moon alone (the largest attaining the dimensions of about 230 km), and that the total number of those exceeding 1 km in size is several hundred thousand, one is bound to inquire with some doubt: if all, or even a majority, of these formations have been produced by impact, how could any old mountain or wall anywhere on the Moon have survived such a long series of sudden and devastating seismic disturbances which would have been caused by each new arrival of an impacting body from space?

Of the different types of destructive seismic waves which are bound to get excited by impacts of external bodies on the solid globe of the Moon, the surface (Rayleigh) waves should be of particular interest because of their relatively low damping. On the Earth, their amplitudes are found to be reduced approximately to one-third at a distance of 5,000 km; and in the feeble gravitational field of the Moon they may be damped still less. As, moreover, the circumference of the lunar globe is only 10,921 km in length, the Rayleigh waves produced by meteoritic impacts should converge on their antipodal points from all directions carrying a total energy of the order of one-thousandth of that of the original impact. This fraction would probably be sufficient to devastate (by fragmentation and other symptoms of the terrestrial earthquakes) the antipodal region to a large extent. While such antipodal points of all visible craters are, of course, bound to be located on the far side of the Moon, one wonders what kind of phenomena may have been produced on the visible lunar face by impacts on its far side. The individual and cumulative effects of all such impacts have not so far been taken into account at all by those that defend the purely meteoritic origin of the lunar craters. What the eventual verdict of an appropriate investigation of their significance will turn

out to be, no one as yet can say. But until the seismic effects of meteoritic impacts on the Moon have been duly considered in addition to the locally produced events, we cannot be at all sure that such impacts represent the only, or even the principal, clue for deciphering the enigmatic hieroglyphics of the visible lunar face.

Throughout all our discussion we have so far been concerned with the effects of collisions of the lunar surface with solid bodies—like meteorites, small asteroids, or planetesimals—which could account not only for the craters themselves, but conceivably also for the existence of extended lunar plains—such as Mare Imbrium (Plate IX) or Mare Serenitatis—which may indeed be regarded as huge craters, produced by nearly grazing collisions of the lunar surface with low-velocity planetesimals in the early days of our solar system. This view, proposed first by the American geologist Gilbert in 1893, has more recently been ably defended by Urey. However, any effort to explain the origin of the principal features of the lunar surface by impacts of solid bodies would be seriously incomplete without a simultaneous consideration of the effects which could be wrought on the lunar face by collisions with other known denizens of the interplanetary space—namely, *the comets*.

According to the statistics available to astronomers at the present time, comets appear to be at least as frequent at our distance from the Sun as are meteorites or asteroids of comparable masses (i.e., 10^{16}–10^{18} g); and the wide distribution of the elements of cometary orbits is bound to render high-velocity collisions (in the range of 30–70 km/sec) with the Moon more frequent than would be the case with the asteroids. On the Earth, examples of both types of collisions are on record: while the well-known Barringer crater in Arizona was produced by the impact of a major meteorite in prehistoric times, the Siberian Tunguzka crater of 1908 was apparently produced (according to Fessenkov) by the collision of the Earth with a comet. Moreover, it is now known that cometary heads—the only part of their anatomy which matters in the case of collision—represent but

loose conglomerations of frozen hydro-carbons, with appreciable admixture of unstable chemical compounds (such as solid hydrogen peroxide, or azides); and these on impact would behave like high explosives—thus releasing chemical energy in addition to the kinetic energy of the head as a whole. Now, unlike a solid meteorite, cometary heads possess no tensile strength, and their impact on the Moon would scarcely indent the lunar surface to any appreciable extent. Instead, they would be completely volatilized at once and envelop, for a short time, the surrounding region in a stream of hot gas rapidly dispersing into vacuum.

Quite apart from the chemical binding energies, the kinetic energy of a major comet—such as Halley's, for instance—represents alone a quantity of the order of 10^{31} ergs; and the latter, if it could be converted totally into heat, would be equivalent to 2×10^{23} calories. If we assumed, reasonably enough, that 2,000 calories are necessary to melt one gram of lunar surface matter into fluid lava, a single cometary impact of this calibre could provide, in principle, some 10^{20} grams of lava capable of covering the 400,000 sq km of Mare Imbrium to a uniform depth of some 100 metres. This may possibly furnish another explanation of the origin of lunar maria, compatible with the fact that no maria show any deformation in their central regions (where impact should have taken place) and that their ramparts (as represented by the Alps and Apennine chains in the case of Mare Imbrium) are well below the horizon at the centre of these great plains. No destructive seismic effects of the impacts of planetesimals of masses postulated by Gilbert or Urey need to be feared in this hypothesis.

Comets with kinetic energies of the order of 10^{31} ergs are, to be sure, relatively rare. On the other hand, the number of plains on the Moon of the size of Mare Imbrium is also limited; and the probability that, in the past 4,500 million years, the Moon may have suffered a sufficient number of collisions with comets of requisite masses may even be considerable. Collisions with smaller comets may, in turn, have produced craters of the

type of Ptolemy (Plate XIII), Plato (Plate IX), or Archimedes (Plate X) whose floors, surrounded by relatively low ramparts, bear a striking similarity to the surrounding maria. So far, however, such a suggestion can be put forward merely as a possibility; and further investigations will be necessary to place it on a more solid basis.

Having taken stock of the principal *external agents*—namely, the impacts of various celestial bodies, which can mutilate the lunar face over long intervals of time—let us next turn to examine the *internal processes* whose action can similarly affect the surface of our satellite. These latter processes are, in general, connected with the gradual build-up of internal heat by radioactive decay (which we discussed already in Chapter 2), forcing all gases and other volatile elements gradually to make their way from the Moon's interior to the surface, and to accumulate there or escape into space. This defluidization and degassing, which must be continuously operating in the Moon as it has been in the Earth, can—in its last stage—produce (by upwelling and withdrawal of a molten rock column) local surface areas of depression or subsidence, which the geologists on our Earth call 'calderas'. A schematic view of some such well-known terrestrial calderas is shown on the accompanying Figures 5 and 6. Their essential features bear indeed a striking similarity to those of many large lunar craters (with cross-sections akin to those shown on Figure 1), the principal characteristics of which—and this cannot be emphasized too strongly—are not so much their relatively low rims as the *general depression of their floor levels* considerably below that of the surrounding landscape.

Thermal expansion and contraction phenomena accompanying the defluidization process early in the Moon's history could have brought about the occurrence of fracture patterns in the relatively cool lunar crust, which may have provided ducts of escape for the molten lava beneath. Many typical mountain-walled plains on the Moon appear indeed to be distinctly polygonal (cf., in particular, the group of large craters shown

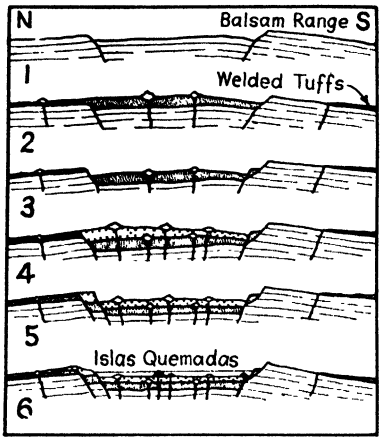


FIGURE 5. Schematic origin of a typical terrestrial 'caldera of collapse', filled now by the Lake Ilopango in El Salvador (*after H. Williams and H. Meyer-abich*, 1955).

on Plate XIV)—a pattern which would be next to impossible to explain on impact hypothesis. The conclusion seems, therefore, reasonable that some—and possibly just the largest—craters on the Moon originated in this way, side by side with others which may be due to impact.

The escape of volatile elements by degassing constitutes an inevitable long-drawn cosmic process, which is bound to occur in any solid body heated radioactively from inside, and should not be confused with volcanic processes as we know them on the Earth. The latter represent essentially superficial phenomena, of much smaller order of magnitude and lateral extent. Yet volcanic activity would, in general, follow as an aftermath of defluidization, and may have produced many of the internal features of lunar calderas as it did on the Earth (cf. again Figure 6). These are likely to be less conspicuous than the calderas themselves, but still easily demonstrable by their particular characteristics.

In an attempt to identify at least some such formations on the

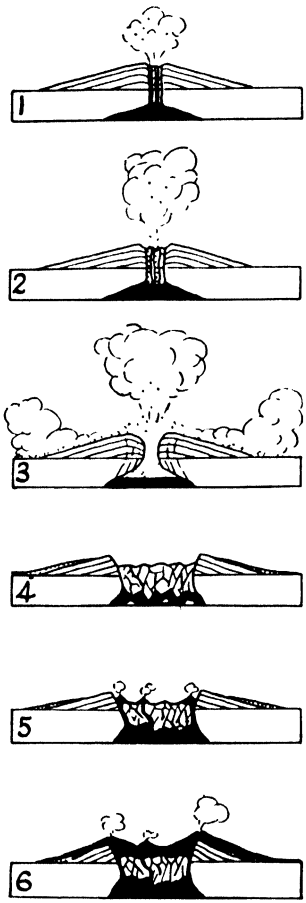
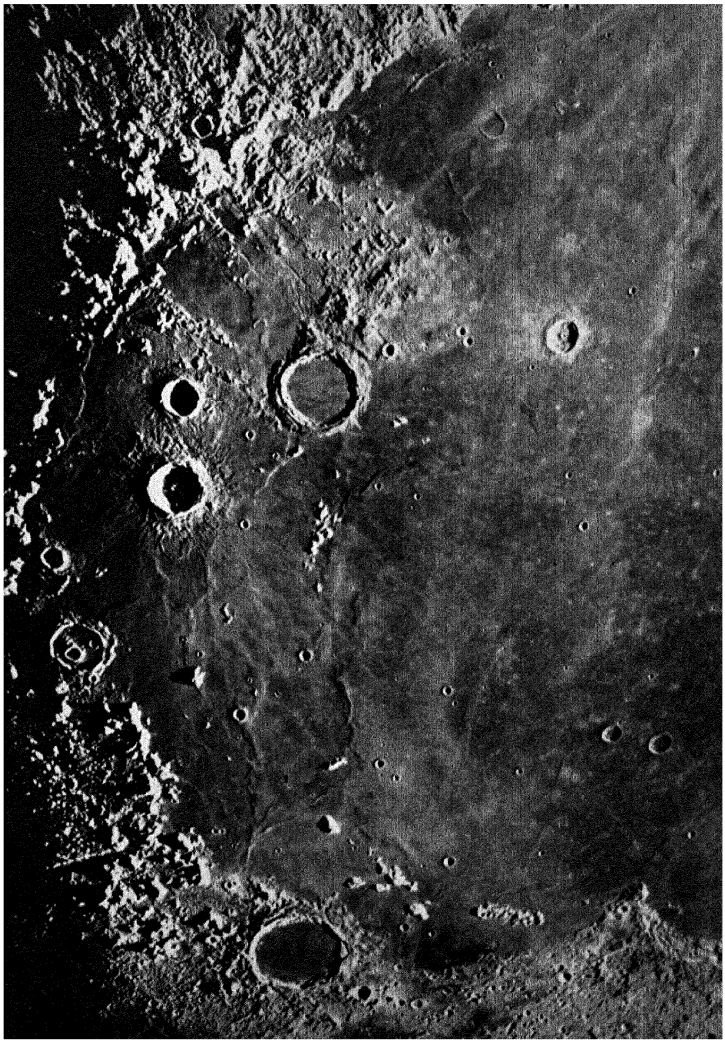


FIGURE 6. Evolution of a terrestrial caldera crater of the Krakatoa type. Pumice eruptions, followed by collapse, give rise to subsidiary craters on the caldera's floor (*after H. Williams*, 1941).



Western part of the Mare Imbrium on the Moon, photographed at the time of the last quarter. At the upper right corner, the crater Eratosthenes marks the end of the chain of Apennine mountains; while the large crater Plato (near the bottom) marks the end of the lunar Alps. The three craters Archimedes, Aristillus and Autolycus are conspicuous in the central part of the photograph; while below Aristillus the long shadow reveals the position of the mountain Piton

Mt. Wilson Observatory photograph, taken with the 100-inch Hooker reflector

PLATE IX

PLATE X (*See opposite*)

PLATE X

Sunset over the western bay (Palus Putredinis) of Mare Imbrium, bordered at left by the Apennines and Caucasus mountains. The craters Archimedes, Aristillus and Autolycus are prominent in the field

The solitary mountain near the lower right corner is Piton, rising 2,300 m above the surrounding plains. The broken white circle around it denotes the limits of its visibility on the Moon, owing to the curvature of the lunar surface

The white cross (×) denotes the place at which the Soviet space capsule crashed near Autolycus on September 13th, 1959, at 21 h 2 m 24 sec GMT after its memorable flight to the Moon—the first terrestrial messenger to bridge the intervening gap of space. The actual fall was not visually observed; but radio tracking enabled the scientists to locate approximately the longitude of the point of impact to 0°, and its latitude to +30°. If the original aim of the missile was to reach the centre of the apparent disk of the Moon, it missed scoring a bull's eye hit by a relatively small margin of only 900 km on the lunar surface—at a target distance of 380,000 km!

At the time of landing, the capsule travelled with a velocity of 3.3 km/sec in a direction inclined by 60° to the lunar surface. As its weight was given as 390 kg, its total kinetic energy was approximately 2×10^{16} ergs—i.e., barely sufficient to produce, on impact, a crater 15 metres in diameter (utterly too small to be visible from the Earth). The last (third) stage of the carrier rocket (weighing 1,121 kg) fell on about the same place of the Moon somewhat later

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

Sunrise over the eastern shores of Mare Tranquilitatis. The points marked by **X** and **Y** denote the positions from which an observer on the ground would face the horizontal panorama as shown on Figure 3

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

PLATE XI

surface of the Moon, let us return to the photograph reproduced on Plate V. Inside a walled mountain—possibly a caldera—called Regiomontanus we come across a small 'hilltop crater' (marked on the plate by a white arrow) which, like others of its type, probably did not originate by impact; for the likelihood that an impinging meteorite would happen to land right on the top of so small a hill appears to be vanishingly small. The whole hill rises barely 650 metres above its surroundings, and its crater on top is 5½ km across. Its base of some 100 km in circumference renders the whole formation not unlike (and, in fact, smaller than) the well-known terrestrial volcano Krakatoa off the coast of Java. This is indeed what Krakatoa would look like at the distance of the Moon. The relatively large size of such presumably volcanic lunar craters, transpiring from this comparison, can (at least to some extent) be rationalized by a much lower gravity on the Moon (enabling a given force to disgorge volcanic ejecta more than six times farther than would be the case on the Earth), coupled with a well-nigh complete absence of an atmosphere which on Earth weighs down on the crater from above and whose resistance could decelerate the ejecta in flight. Hypothetical volcanic eruptions on the surface of the Moon would represent, in fact, discharges of gas and magma into vacuum; and this could possibly enable such phenomena to attain considerably larger proportions than on the Earth.

In the face of these and other facts it is very difficult to escape the conclusion that *both* types of formative processes—external impacts as well as internal defluidization and degassing—had their hand in shaping up the present face of our Moon. The 'ray craters' like Tycho (Plate II) or Copernicus (Plates VII–VIII) are almost certainly due to impacts—whether their ray systems represent ejecta or cracks of the surface; while others—like Clavius (Plate II), Ptolemy or Alphonsus (Plate XIII) may represent old calderas of collapse or other artifacts and surface manifestations of plastic or viscous flow once prevalent in the sub-surface layers.

As far as the maria are concerned, equal uncertainty still prevails. While many serious students of the subject would regard them as solidified lava flows, Urey seeks the origin of the lava in large-scale melting caused by low-velocity impacts of solid planetesimals; the present writer pointed out a possible relevance of cometary impacts in this connection; while Green regards them as extrusions of probably basaltic material which accompanied the process of defluidization.

Of the latter processes, by far the most important in this connection may be related to the gradual extrusion of water from the lunar interior. The reasons which lead us to expect that such extrusion may indeed take place we discussed already in the preceding chapter, when we pointed out that secular warming up of the Moon's interior by spontaneous disintegration of long-lived radioactive elements like K^{40}, Th^{232} or the two well-known isotopes of uranium is bound to expel water from solid hydrates and drive it—in the form of superheated steam—along any crack or fissure opening outwards.

Unless this argument contains some flaw (which is very difficult to imagine), there seems but little room for doubt that most part of the deep interior of the Moon (where the prevailing temperatures are in excess of 1,000°) must now be rather completely desiccated, and its outer crust greatly enriched with water. But how far can this water penetrate to the surface? For the sub-surface layers of the Moon are again quite cold (how we know this will be explained in more detail in the subsequent Chapter 5)—some 30°C below the freezing point of water. Therefore, we should expect that, before reaching the surface, the hot steam seeping outwards will gradually condense into liquid and eventually form ice. Along crustal fissures, which can serve as ducts for more rapid escape, the formation of ice may in fact take place very close to the surface and give rise there to formations which can possibly reveal the presence of sub-surface lunar glaciers to the external observer.

It was recently suggested by Gold that such sub-surface lunar glaciers (covered by dust and other debris) are observed

by us as the so-called lunar 'domes'—minor bulges found in great numbers on the visible lunar surface and occurring usually in clusters. The largest such bulges, occurring in the neighbourhood of the crater Copernicus, are over 20 km across (see Plates XVI and XVII); but the majority of them attain the dimensions of 3–6 km, and the height of 100–300 metres. A typical cluster of such domes (containing at least thirty-five such formations on the area of a few hundred square kilometres) can be seen inside the great walled plain east of the crater Regiomontanus, on the shores of Mare Nubium, as shown on Plate V. Such formations bear perhaps more than a superficial resemblance to the 'pingoes' found in Alaska and northern Canada, which may indeed represent their terrestrial homologues; but closer examination will be necessary before such a suggestion can be placed on a more secure basis.

Other lunar surface formations which might be indicative of the presence of sub-surface moisture are the so-called wrinkle-ridges—resembling flat sand-dunes of the terrestrial deserts when viewed from above and occurring in many parts of the lunar maria; a typical example of such formations in the southern part of the Oceanus Procellarum, photographed at the time of sunrise, is shown on Plate XVIII. Salisbury and Urey have recently suggested that this wrinkling of the surface may have been caused by hydration of sub-surface beds of anhydrid minerals (such as olivines)—a process which is generally accompanied by an increase in volume just about sufficient to produce the observed bulging. But this view represents again but a highly tentative hypothesis so far; and much work remains to be done before science can pronounce its final verdict.

But coming back to water finding its way to the lunar surface—suppose that, as an extreme case, juvenile water escaping from the hot interior may reach the surface in occasional spurts as a geyser. No such phenomenon has, to be sure, so far been actually observed on the Moon (though it would be very difficult to detect, except under special circumstances). Certain

largest lunar 'domes' show, however, some evidence of central depressions which may indeed represent possible springs of such geysers. If hot water occasionally spurts through them into space, what can happen to it afterwards?

The exact answer depends, of course, on the actual temperature of the geyser and the altitude which it may attain. But there is little room for doubt that, should such an outburst occur during the lunar night (or in places shielded from direct sunshine), a good part of the squirting water would not evaporate, but would condense into ice. The mean lifetime of ice thus formed and exposed directly to the conditions of interplanetary space would depend on the prevailing temperature, which varies widely between day and night. Its actual variation and the methods for measuring it will be discussed in more detail in Chapter 5 of this book; here it should suffice to say that while a piece of ice on the surface exposed to sunlight would not last more than a (lunar) day, the mean lifetime of ice in areas shielded from sunlight could be surprisingly long. In such areas, the prevailing temperature on the surface turns out to be around 120°K (i.e., not much above that of liquid air). At this temperature, the rate of evaporation of ice in vacuum is known to be approximately 3.1×10^{-14} g/cm² sec, giving rise to a vapour pressure of only 1.4×10^{-12} mm of mercury. At this rate, only 4.6×10^{3} g/cm² or about 46 metres of ice would have evaporated through the entire age of the Moon! Watson, Murray, and Harrison Brown (to whom much of the preceding argument is due) estimate that a few per cent of the mountainous areas near the poles of the Moon remain permanently in shade, and over a somewhat larger area the Sun never rises totally above the horizon. Such areas are exposed to lunar night temperatures most of the time; and it is there that one can expect to encounter exposed ice on the surface. Below the surface, at a depth of not more than a few feet, prevailing temperatures are relatively much higher (close to −30°C) and remain constant day and night. At such a depth the ice, shielded by surface dust and intermingled with it,

may be present for long periods of time as permafrost several hundred feet deep, representing a fossil reservoir from which water may one day be tapped by human hand.

Nevertheless, in spite of the plausible nature of the arguments which we have advanced to reach these conclusions, the critical reader may still wish to view them with some reserve, and await for complete conviction the results of the actual drilling. There is nothing like the geologist's hammer on the spot to settle academic arguments advanced at a safe distance.

Once we admit, however, that different processes have co-operated in the formation of the lunar face as we see it to-day, the question arises about their relative importance in different stages of the long lunar past. Can we fit the origin of the principal features we see on the Moon to-day into some kind of reasonable time sequence? Absolute dating seems, unfortunately, impossible as long as we are constrained to inspect the Moon at a distance (unless it be by an indirect method to be outlined briefly in the next chapter); but relative dating can indeed be attempted to-day with some hope of success.

Of various indications of relative age of the craters (or maria) the 'principle of overlap' is perhaps the most obvious and dependable. If there are two craters that overlap each other—and our photographs reproduced on Plates II–XIV show many examples of such overlaps—then the one with the unbroken rim must be younger than the one whose rim was damaged or entirely removed. In the case of two overlapping craters of comparable diameters (such as the pair of Theophilus and Cyrillus on Plate VI, for instance) the application of this principle seems indeed to admit of no doubt (i.e., in our example, the formation of Theophilus must have been posterior to that of Cyrillus). But it can also be applied to such cases in which a large crater contains smaller ones within its rim (for an illustrative example of such a situation, cf. a photograph of the crater Clavius reproduced on Plate IV). No kind of process that raised the ramparts of the large formation could have left the small interior craters intact; hence, the latter must represent

creations subsequent to that of the large configuration. On this reasoning Clavius must, therefore, be considerably more ancient than all other craters (at least forty of them) which can at present be seen on its floor. The greater the density (per unit area) of small craters inside a large one, the greater should be the disparity between their ages.

Crater overlaps of great multiplicity can be found in certain parts of the lunar surface, and in some places it is possible to arrange thus five or six craters in a time sequence. Another relative age criterion (supplementing overlap) is afforded by the existence of the streaks of bright material (the 'rays') which are seen diverging in all directions from certain impact craters (like Copernicus, for instance; cf. Plate VII). As these rays must have originated (by some kind of a splash) at the same time as the parent crater at their convergent point, the crater should obviously be younger than any features overlaid by the ray. Such rays represent, indeed, a system of bright tentacles spreading widely over certain parts of the lunar surface and enabling us to extend our system of relative dating as far as they reach.

The main importance of the preceding age criteria lies, however, in their application to the dating of the maria. If we accept the foregoing premises, there seems no escape from the conclusion that *the oldest parts of the visible lunar surface are those which are most rugged*, and contain the greatest number of craters or other types of mountains per unit area. For irrespective of whether the rate of operation of both the external or internal processes of crater formation on the Moon has been uniform or diminishing with time, the oldest parts of its surface should obviously have accumulated the greatest number of scars. If this is indeed so, then the oldest parts of the visible surface of the Moon are no doubt the regions surrounding its south pole—the lunar Antarctic—which may indeed contain a continuous record of events which have affected it since the time of the formation of our satellite (or, at any rate, since the solidification of its crust). But as the mean density of craters in most of the

great dark plains of the lunar surface is much less than that encountered near the south pole, it follows that the maria are not only younger, but should be considerably younger than the mountainous regions; and some of the great craters—like Copernicus, Kepler or Aristarchus—which spread the tentacles of their bright rays over large parts of these surrounding maria, must be younger still. They may, possibly, represent the latest additions to the full exhibit of surface features, of appreciable magnitude, engraved on the face of the Moon—perhaps—in the last 100 million years.

This should conclude our brief survey of the strange world of the Moon as it will beckon one day in the not too distant future to the first interplanetary travellers peering through the portholes of their rocket shortly before landing. No such survey would, however, be complete to-day without at least a brief reference to what is in store for us on the far side of our satellite. For a very long time—ever since the tidal friction in the Earth-Moon system has synchronized the velocity of axial rotation of the Moon with the period of its revolution around the Earth—our satellite has shown only one face to the inhabitants of this planet—the other being permanently concealed from direct view, and a favourite target of all kinds of speculation about its nature. Quite recently—on 7 October of last year—the veil of mystery was at last dramatically removed forever from its face when the third Russian interplanetary rocket circumnavigated for the first time the entire lunar globe and secured photographs of a major part of its far side which, a few days later, were successfully televised down to the Earth. This brilliant achievement of advanced astronomical instrumentation should command a full measure of our admiration and become a source of justified pride to all inhabitants of this Earth who take interest in the sky above our heads. How could we finish this chapter without giving to the reader at least a brief account of this tremendous achievement?

The year of A.D. 1959 is destined to remain memorable forever in the annals of celestial exploration by two outstanding events:

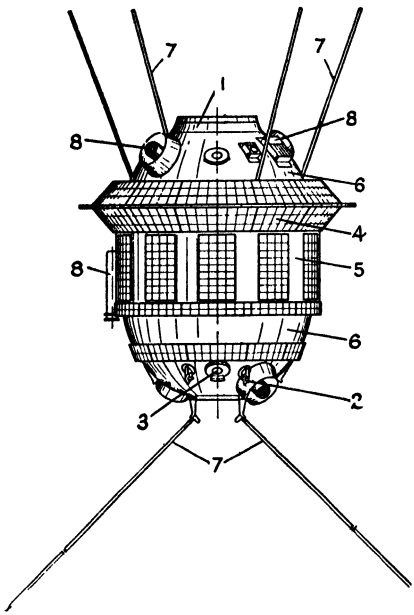


FIGURE 7. Schematic view of the Russian space station which photographed the far side of the Moon on 7 October, 1959.

The individual numbers on the diagram indicate: (1) Location of the photographic objectives; (2) Motor for the phototropic orientation of the vehicle; (3) Photoelectric sensory cells; (4) Location of the solar batteries; (5) Shutters of the temperature control system; (6) Heat screens; (7) Antennae; (8) Other apparatus (*from an official publication of the U.S.S.R. Academy of Sciences*).

on 13 September, at 21 h 2 min and 24 sec GMT, the first Soviet cosmic rocket launched the day before from Central Asia crashed against the lunar surface in the western part of Mare Imbrium (see Plate X; the position of impact being marked there by a white cross); and barely a month later, on 4 October another Russian rocket took off which was destined to circumnavigate the Moon and to relate to us the picture of its far side. The last stage of this rocket, a space station of little more than one metre in size and weighing 435 kg (see Figure 7)

reached the distance of the Moon on 6 October around 14 hrs GMT, missing its surface by a margin of approximately 6,200 km and continuing up to an apogee distance of 470,000 km attained on 11 October. Henceforward the station turned back to the Earth and passed through its perigee on 18 October at a distance of 47,500 km from the centre of our planet. It constitutes now another artificial satellite of the Earth, describing a very eccentric orbit ($e = 0.84$), highly inclined to the ecliptic, with a semi-major axis of approximately 259,000 km and orbital period of 15 days. After its last close approach to the Moon the station may follow its present orbit for a relatively long time.

Twice a month it attains the distance of the Moon; but the next time when our natural satellite should be there again for another rendezvous with its new little brother will not occur till in 1967, when the space station should by-pass it at a distance of approximately 10,000 km. It is, however, very questionable whether the rocket will last long enough to keep that date; for its present orbit is expected to shrink gradually as a result of the cumulative effects of perturbations suffered around each successive perigee passage; and long before the next appointed time it may be drawn near enough to the Earth to burn up in our atmosphere in an auto-da-fe that may brilliantly illuminate our sky for a brief moment—as did so many of its predecessors, sent out by human hand, which never ventured so far afield in the interplanetary space.

But let us return to the last close conjunction of 7 October, 1959, and the feats attained by the Soviet space station at that time. Its main objective was to photograph the far side of the Moon; and this could not have been well accomplished at the time of greatest approach (as only a relatively small part of it would have been visible at that time). Instead, the station continued on its journey a little farther, awaiting its chance. It took advantage of the gravitational attraction of the Moon which deflected its course as shown on the accompanying Figures 8–10, and brought it eventually to a position from

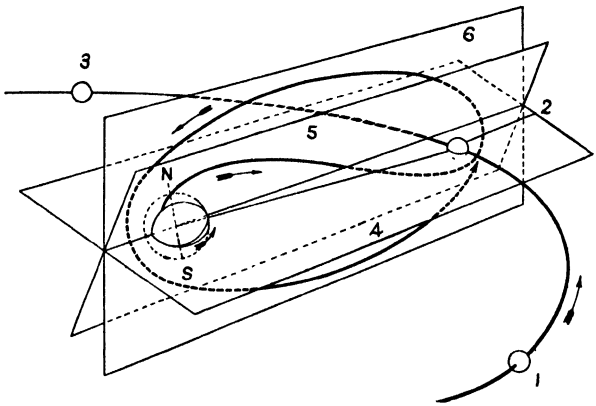


FIGURE 8. Schematic representation of space motion of the Russian rocket which photographed the far side of the Moon in October 1959.

The individual numbers indicate: (1) Position of the Moon at the time of the launching of the rocket; (2) Position of the Moon at the time of its conjunction with the space station; (3) Position of the Moon at the time of the perigee passage of the space station after the conjunction; (4) Plane of the lunar orbit; (5) Orbital plane of the space station before its close approach to the Moon; (6) Orbital plane of the space station after its close approach to the Moon (*from an official publication of the U.S.S.R. Academy of Sciences*).

which more than 70 per cent of the far side became visible for the photographic cameras mounted in the station (cf. again Figure 7). This came to pass on 7 October in small hours of the morning when, following a command relayed from the Earth, the rocket turned (by means of appropriate photo-electric devices) its lenses towards the Moon and, in approximately 40 min between 3 hr 30 min–4 hr 10 min GMT, fulfilled its historic mission at a distance increasing from 65,200 to 68,400 km. At this distance the Moon would have appeared to an observer travelling in the station as a disk with angular diameter of 3° (i.e., about six times as large as we see it from the Earth).

In order to take the desired photographs, the space station carried two cameras with lenses of 200 mm and 500 mm focal distances, by which a number of different exposures (of the

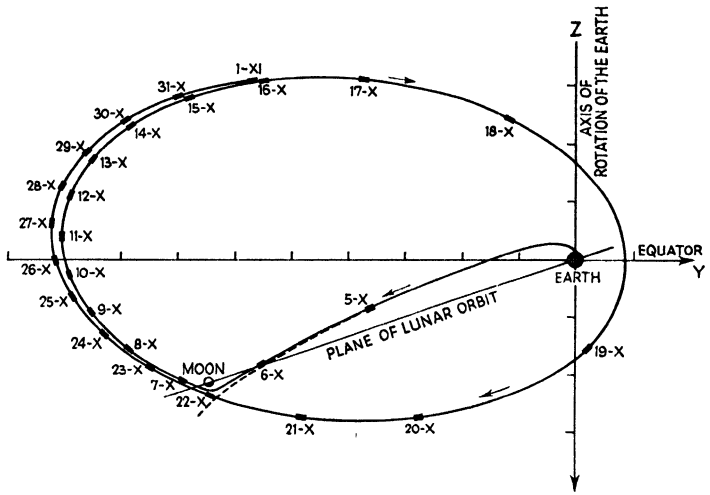


FIGURE 9. Schematic representation of the motion of the Russian space station which photographed the far side of the Moon in October 1959, projected on the meridional plane of the Earth, as seen from the direction of the vernal equinox. The actual positions of the station are marked at daily intervals (*from an official publication of the U.S.S.R. Academy of Sciences*).

order of 0.01 of a second) were taken simultaneously on a 35 mm film. The lens with the focus of 200 mm gave a picture of the lunar disk varying from 14 to 12 mm in diameter and completely contained on single frames. The large lens formed an image of 29–25 mm, affording greater resolution, but only partly recorded on individual photographs. After the task of taking exposures was completed, the films were automatically developed and fixed aboard the moving space station, and subsequently scanned by a miniature television camera which transmitted their actual information content down to us on the Earth. The television system employed on this task made it possible to vary the number of lines along which the picture was scanned; their maximum number being 1,000 per frame.

The technical difficulties which had to be overcome to make this experiment a success just stagger imagination. First, the

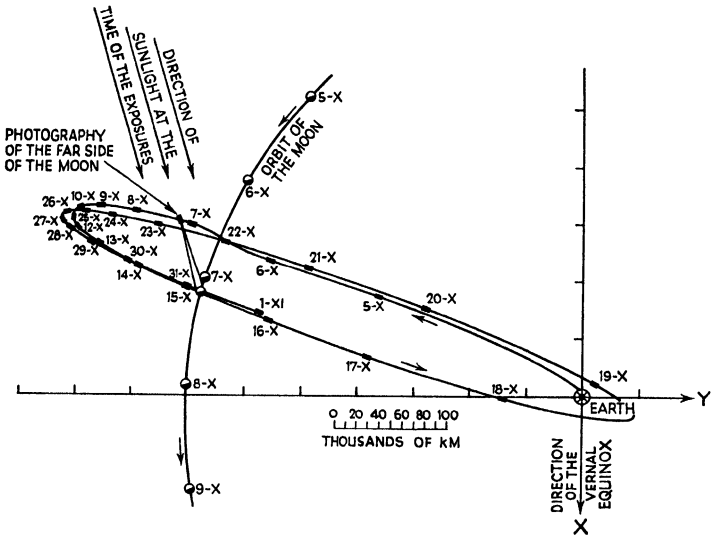


FIGURE 10. The actual orbit of the third Russian lunar rocket between 4 October and 1 November, 1959, projected on the plane of the terrestrial equator.

The diagram shows the daily position and orientation of the space station (■) and of the Moon (◒); the scale below the *y*-axis is calibrated in thousands of kilometres (*from an official publication of the U.S.S.R. Academy of Sciences*).

station had to follow its course with a precision which would not have tolerated anywhere an angular deflection greater than 0°.1, or a variation of velocity in excess of 1 m/sec. Secondly, after the station had circumnavigated the Moon, it had to orient its axis on a command received from the Earth so that its lenses would view the Moon during the times of the exposures. One-half of the station was smarting under the merciless glare of the Sun, while the other was exposed to the cold embrace of the interplanetary space; and yet, inside the station, the temperature had to be controlled automatically not to exceed 25°C (for otherwise the photographic emulsions would have been spoiled). In addition, the films had likewise to be suitably shielded at all times to prevent their fogging under the action

of cosmic rays. Last but not least, in order to save on payload, the power of the television transmitter on board had to be limited to a few watts—and yet its signals were to be received on the Earth at a maximum distance of 470,000 km! The success of this experiment demonstrated that it is indeed possible to transmit across such gaps of space half-tone pictures of relatively high definition without substantial distortion—a feat encouraging great hopes for further lunar and planetary explorations at close range.

What did the eyes of the cameras see on 7 October when facing the far side of the Moon? A sample of the photographs secured with the lens of 200 mm focal length is reproduced on the accompanying Plate XII. Only about 70 per cent of the lunar surface recorded on it constitutes the far side. About 30 per cent of its western (i.e., left) limb is also visible from the Earth and contains many features (the whole of Mare Crisium, for instance; and many other smaller maria or craters—Langrenus, Petavius, etc.) well known to us under a different projection. A corresponding portion of the far side remained still hidden from the camera's view beyond the eastern horizon on the right. It should also be kept in mind that the phase on the far side was nearly 'full' at the time when all photographs were taken; hence, the ground irregularities cast no shadows and the view they offer lacks plasticity associated with pictures taken at the time of sunrise or sunset. Nevertheless, a number of new craters (of dimensions up to 70 km) were located by the Russian investigators on their photographs, and given proper names by their discoverers (designations which subsequently received sanction of the International Astronomical Union in 1961). It was only to be expected that the majority of new features received Russian names—after their great scientists Lomonosov, Lobachevskiy, Tsiolkovskiy, Kurchatov, and Popov. The fiery Giordano Bruno (who found no favour at the hands of the lunar cartographers of the seventeenth century) had now his name bestowed on a conspicuous ray crater on the far side of the Moon—much akin to Tycho on the visible side—rubbing

shoulders uneasily with the doughty Scot James Clerk Maxwell. The French scientists are represented by Louis Pasteur, Mme Sklodowska-Curie, her son-in-law Frederic Joliot Curie, as well as the unforgettable Jules Verne. The German physicist Heinrich Hertz, the American inventor Thomas Alva Edison, and the Chinese mathematician Tsu-Chun-Chih complete this recent list of members who have so far been admitted to the far side of the lunar Pantheon—a select club whose election rules (as codified by the International Astronomical Union) require that each candidate first pass through the gate of Saint Peter. Frederic Joliot Curie (who died in 1959) had, therefore, the shortest waiting period for admission.

However, by far the most interesting fact revealed by the Russian recent photographs is a realization that *the far side of the Moon consists predominantly of mountainous terrain and contains very few maria*—the small sea of Moscow (Mare Muscoviae) or of Mechta (Mare Ingenii) being but meagre substitutes for the vast plains of Mare Imbrium or of the Oceanus Procellarum, visible on the Moon from the Earth with the naked eye. This disparity in the distribution of the continents and the maria on the two hemispheres of our satellite may be analogous to the well-known continent-ocean antisymmetry characteristic of our own terrestrial globe—on which the Eurasian and African land masses are also largely antipodal with the vast expanses of the Pacific—and may possibly be due to the same cause (slow internal convection?). However, the reason why the two lunar hemispheres should be so oriented with respect to the Earth–Moon direction remains still largely conjectural.

Needless to say, any attempt to develop further such a thesis will require more detailed information on the topography of the far side of the Moon than the first inkling of it which we possess to-day. This should, to be sure, in no way minimize the great achievement of the Russian scientists and engineers who provided us in 1959 with an inkling, which then represented the ultimate attainable at that stage of rocket and communication development. But it is probable that photographs of the

One of the memorable photographs of the far side of the Moon, secured from the Russian space station on October 7th, 1959, at a distance of 66 thousand kilometres from the Moon. At that time, the phase on the far side of the Moon was nearly 'full' and, hence, no mountains or craters threw appreciable shadows. Approximately 30 per cent of the territory shown around the western (left) limb of this photograph is visible from the Earth; therefore, an equal proportion of the lunar surface around its eastern limb remains as yet uncharted

Photographed from the third space rocket of the U.S.S.R. Academy of Sciences ('Soviet Weekly' photo)

PLATE XII

lunar far side secured from spacecraft of the future will bear about the same comparison with that shown on Plate XII as do the first photographs of the visible side of the Moon, secured by the middle of the nineteenth century by Rutherfurd or Warren de la Rue, do to modern photographs such as reproduced in this book.

4

THE STORY OF MOONLIGHT

FROM time immemorial, the moonlight has excited peculiar fascination in the human mind. In pre-historic times, the waxing and waning of the lunar phases and the light changes accompanying them provided the first basis for the reckoning of the time—whenever we go sufficiently far back in the history of any primitive civilization, we find them invariably dependent on the lunar calendar. No wonder that the Moon on its regular and periodic journey among the stars was endowed by many such civilizations with the attributes of a benign deity: the semitic Astarte, Tanit of Salammbo, or the nimble-footed Artemis of the Greeks bear witness to its cult. In more recent days, with the gradual retreat of the mythical element, the influence of moonlight on such esotheric activities of the human mind as poetry and art has continued unabated. Many of you may recall from childhood days the graceful tale of Princess Moonbeam and the Chinese Emperor; and some, in more mature years, may have fallen under the spell of the sublime music of Beethoven's Moonlight Sonata. Other examples of inspiration which the pale silvery disk of ancient Selene exerted on human art could be multiplied almost indefinitely.

In contrast to the impressionable artists, astronomers are—I am afraid—not always too appreciative of moonlight, or enamoured of its poetic qualities. And by this I do not mean only the stellar astronomers, whose professional interests lie far beyond the confines of the lunar orb, and to whom moonlight

scattered in the terrestrial atmosphere constitutes only an unmitigated nuisance. Even the astronomers concerned directly with lunar studies treat moonlight in a rather cavalier manner which, to a layman, may connote a shocking lack of respect.

Whenever we wish to study the Moon—or any other celestial body inaccessible to direct approach—all information we hope to get can reach us across the intervening gap of space through two different channels: their gravitational attraction, and their light. And, we may add, the messages reaching us through these channels are analysed and interpreted by astronomers whose interests and training are very different. The gravitational attraction controls the motion of the celestial bodies, manifesting itself by the continuous change of their position with time. Both position and time can be measured by modern techniques to a very high degree of accuracy (at least one part in 10 millions); moreover, the laws of nature (or differential equations based upon them) relating the position with the time are very well known and understood. As a result, the scholars concerned with them are of the austere type, know always what they are doing; and their professional interests centre, in general, around the last decimals of their results. The motion of the Moon in the sky has, for many generations, been regarded by them as the supreme challenge to their skill and ingenuity; and we owe them much of the data expounded in Chapter 2.

The astronomers concerned with the study of light are, on the whole, a very different lot. Their measurements are seldom more accurate than one part in a thousand—and the laws of light emission, or of its interaction with matter, are much more complicated than those governing gravitational interaction, and as yet much less securely known. As a result, their students have to rely on imagination and combinatory powers to an extent which may often exasperate their more sober-minded professional confrères; and, in order to extract any information from light, they have to treat it at their observatories in a way reminiscent of the medieval torture chambers. First, they

collect with their telescopes as much of it as the aperture would permit; and the light-photons—those nimble-footed messengers reaching us with the speed of light from distant bodies across the intervening space—are then made to pass through prisms, or to bounce off gratings, to sift them out into a spectrum; they must reduce silver grains on photographic plates, to heat the joints of thermocouples; or—worse still—by an intervention of a photosensitive surface they are converted into an electric current and sent down the wire to operate the pen of automatic recording instruments. This is what the astrophysicist must needs do in order to extract from the light all the information he desires to know; and will not be satisfied until he has converted all moonlight into clusters of silver grains on photographic plates, or to various curves recorded by a pen driven by photocurrents.

Before we unfold the full story which comes out of such an ordeal, let us briefly pause to consider the question: what does the light of the Moon really consist of? As is known to every schoolchild these days, most part of the moonlight visible to the eye is nothing but sunlight incident on the Moon and scattered by the lunar surface in the direction of the Earth. The amount of light scattered by the Moon at different phases (i.e., different altitudes of the Sun above the lunar horizon) offers, in turn, a possibility to find out something about the nature of the scattering surface—whether it is rough or smooth, for instance; and more can be learned from the degree of polarization brought about by the scattering (the incident sunlight being unpolarized), which can also be measured nowadays with an accuracy of a few parts in ten thousand. Many of the results of such investigations have already been recounted in the preceding chapter. As far as our tool—the light—is concerned, however, we wish to stress two facts.

First, that the lunar surface is, on the whole, a rather poor reflector. Only about 7 per cent of the light incident normally is scattered by the Moon as a whole; though the actual amount may fluctuate considerably from spot to spot. Thus the immediate

surroundings of the crater Aristarchus (about which we shall have to say much more later on in this chapter) in the midst of the lunar 'Ocean of Tempests' (Oceanus Procellarum), undoubtedly the brightest spot on the Moon, reflects more than 17 per cent of incident sunlight; and isolated spots in the 'Sea of Calmness' (Mare Serenitatis) or certain spots inside the crater Alphonsus, reflect but 2–3 per cent. These differences are undoubtedly connected with differences in chemical composition or texture of the lunar surface; and if we compare them with similar differences obtaining among various samples of terrestrial materials, we can conjecture (as we did in the preceding chapter) on the type of rocks or lava constituting lunar mountains or plains, and their degree of pulverization.

One fact should, however, be stressed in this connection: namely, the spectral distribution of the light scattered from different parts of the lunar surface—be they bright or dark (maria, mountains, or even bright rays)—appears to be everywhere approximately the same, and corresponds within the limits of observational errors (which are of the order of 1–2% of the measured intensity) to the distribution of intensity in the spectrum of the illuminating source—i.e., the Sun. In other words, sunlight scattered from all known types of lunar ground appears to retain the same colour all over the apparent disk of the Moon, in spite of conspicuous local differences in reflectivity. The Moon is, therefore, not a colourful body; and its visible light is just about as white as sunlight. Visual impressions of large colour differences, reported by earlier observers, turned out to be mainly due to the differences in contrast of illumination; modern spectrophotometric measurements leave but little room for doubt that this is actually the case.

The principal difference between sunlight and moonlight rests, therefore, on their very different intensities of illumination; for, on account of its distance from the Sun, as well as a relatively poor scattering power, the face of the full Moon reflects to the Earth but little more than two millionths of direct sunlight. Even more interesting is, however, the way in which

the intensity of moonlight varies with waxing or waning phase. As is well known, astronomers are accustomed to express light intensities in the so-called stellar magnitude scale, rather arbitrarily designed so that a difference of five magnitudes corresponds to an intensity ratio of 100 and, therefore, one magnitude corresponds to an intensity ratio of $\sqrt[5]{100} = 2.512$.

On this scale, the apparent brightness of the Sun amounts to -27 stellar magnitudes, while the apparent brightness of full Moon is only -13 magnitudes—corresponding to an intensity ratio of $(2.512)^{-27+13} \simeq 2.5 \times 10^{-6}$, as already mentioned. But the brightness of the Moon at the time of the first (or last) quarter amounts, however, to only -10 magnitudes—corresponding to a luminosity twelve times smaller than at full Moon, while the size of the illuminated area has only been cut by half. Indeed, one of the most striking photometric characteristics of the Moon is the steepness of its light curve around the time of full Moon—the speed with which its light increases with waxing phase, and diminishes (symmetrically) when its phase is on the wane. This could not be so if the oblique rays of the Sun were illuminating on the Moon a smooth surface, no matter what its substance might be; and can be understood only if *the small-scale structure of the lunar surface must be highly vesicular* and honeycombed by small pits—so that a relatively large fraction of it can be in shade already at small zenith distances of the Sun. This appears, moreover, to be true not only of the moonlight as a whole, but also of the variation of the intensity of illumination with the phase of any individual element of surface so far investigated—whether in the maria, mountainous regions, or bright rays—regardless of reflectivity.

This inference comes out in striking contrast with the directly observed behaviour of the majority of large-scale features of the lunar surface, which (as explained already in the preceding chapter) appear to be essentially flat. And to make the situation still more complex, measurements of the polarization of moonlight have revealed that the scattering of sunlight on the surface of our satellite must actually be produced by fine

dust, of the average grain size of 1–2 microns, which clings to the ground regardless of its slope.

An attempt to reconcile this seemingly divergent evidence and to construct a model of the lunar surface which is consistent with all known facts will be made in the next chapter. For the present, let us return to the bulk of the sunlight incident on the Moon, only a small part of which is actually scattered out into space. What happens to the balance? This radiation (over 90 per cent of incident sunlight) is *absorbed* by the lunar surface and converted into heat. But any body possessing a temperature above absolute zero must emit also a radiation of its own; and if this body behaves as 'black' (as is very much the case of the lunar surface) its emission will be governed by what the physicists call Planck's law, and its amount as well as distribution in frequency will be determined solely by its absolute temperature. For the Sun, whose absolute temperature is but little more than 5,700°, most part of the radiation is emitted at optical frequencies between the violet and the red end of the visible spectrum (with a maximum in the yellow), giving together an impression of what we call the 'white light'. This is also the colour of the reflected moonlight; but the lunar radiation proper is of a very different kind.

The sole—and sufficient—reason for it is the fact that the temperature of the lunar surface is so much lower than that of the Sun. The Moon—like the Earth—receives all its heat by radiation from the Sun; but as their average distance from the Sun amounts to 214 solar radii, each square centimetre of lunar surface receives only about one $(214)^2$th or a 46,000th part of the heat flux passing through each square centimetre of the surface of the Sun. As this flux is (for a black body) known to be proportional to the fourth power of the absolute temperature, it follows that the mean temperature of the Moon should be $\sqrt{214}$ or about 15 times lower than that of the Sun—or approximately 380° Kelvin (i.e., about +107°C). This supposes, of course, that the Sun stands in the zenith, and its light falls normally on the illuminated surface; should it fall

obliquely, the radiation would be diluted, and the temperature maintained by it would be lower.

Now these elementary theoretical considerations lead us to expect that the temperature of the Moon will not be more than 380°K; and if so, Planck's law discloses that its radiation should be very different from white light—most part of it being emitted in the deep infra-red—with the maximum around the wavelength of 10μ or 0.01 mm. Light of this colour is, of course, quite invisible to the human eye, and incapable of impressing the photographic plate. It will, in addition, experience considerable difficulty in penetrating through our terrestrial atmosphere in between the interlocking absorption bands of the water vapour and carbon dioxide. However, that part of it which does get through can be detected —and, in fact, measured quite accurately—by its thermoelectric effect.

It is a well-known fact of physics going back to Seebeck (1821) and Peltier (1834) that if a contact between two suitably chosen metals is heated, an electric current is set up, the intensity of which can be measured (directly, or after appropriate amplification) with great accuracy. Such measurements afford, conversely, the quantitative means for ascertaining the amount of heat flux giving rise to the current—and thus the temperature of the emitting source if its distance from the observer is known. The physical devices making this possible are known as thermocouples, and are used frequently to measure the temperature of sources which, for one reason or another, we cannot probe with an ordinary thermometer. The metallurgical engineer measuring thus the temperature prevailing inside a blast furnace from the heat it sends out, or the astronomer measuring the heat received from distant stars, are using the same techniques to attain their end; but whereas the engineer will have plenty of heat to work with, the astronomer will have to measure minute amounts, and to develop special techniques for doing so with sufficient accuracy.

Astronomers are, in general, old hands at doing the seemingly

impossible and pulling off feats which stagger imagination. You have doubtless heard them boasting before on occasions of their proverbial 'astronomical accuracy'; and the present problem affords perhaps another example of it. Suffice it to say that the thermocouples (and their associated electrical circuits) have been developed to such a pitch of perfection that such a couple, placed in the focus of the 200-inch telescope at Mount Palomar, is reputed to be capable of detecting the heat sent out by a standard candle at a distance of 6,000 miles! On the lunar surface (which is but forty times as far) the heat of some 1,600 candles should thus be detectable; and if its temperature is anywhere near 100°C, a square mile of this surface should give off much more heat than that. The actual amount of heat emitted by even the full Moon in the direction of the Earth is, to be sure, still very small in comparison with most terrestrial sources with which we are familiar. It is, in fact, barely sufficient to raise the temperature of a moonlit landscape by something like 0.001 of a degree (and all yarns of old gardeners about the effect of moonlight on plant growth must, therefore, be summarily discounted). But even so minute a heat flux can nowadays be measured by astronomers with such precision that the temperature of any part of the lunar surface can be inferred from its heat rays with the precision of a few degrees—almost as well as if we could be there now to measure it with an ordinary thermometer.

The actual temperatures prevailing there, and their day-to-night variation, will be discussed in more detail in the subsequent Chapter 5, in connection with our imaginary exploration of the lunar surface. For the present, we are concerned with the moonlight as a mere carrier of messages to be deciphered at a later stage; and we wish to stress again that all light reaching us from the Moon is nothing but sunlight—original or transformed. Most part of this light falls on the Moon directly, and the rest indirectly by way of the sunlit Earth (which must appear many times as bright on the Moon as the full-moon does to us). A few per cent of this light are

scattered back into space from the rough lunar surface, with its white colour unchanged. This is the component of moonlight visible to the naked eye, and responsible for the 'silvery moon' of our songs and romance. Most part of incident sunlight is absorbed by the lunar surfaces and re-emitted in the deep infra-red at frequencies which are invisible to the human eye. This moonlight cannot be seen or photographed; and for this reason we do not readily recognize its existence; but thermoelectric detectors leave no room for doubt that we are, in fact, living under an 'infra-red' rather than 'silvery' moon—notwithstanding all poetical fiction woven by the past generations.

There exists, however, still another way in which the lunar surface can transform incident sunlight and emit—under certain conditions—a characteristic light of its own: and that is by a process of non-thermal emission commonly called the *luminescence*. As is well known, luminescence represents the ability of certain substances to absorb light of relatively high frequency, and re-emit it by instalments of certain discrete lower frequencies. In order to describe this mechanism in more specific terms, suppose that the atoms of a suitable substance are exposed to radiation (wave or corpuscular) capable of ejecting electrons from their normal positions in the ground state. Such a damage to atomic structure is usually quickly repaired by the capture of another free electron from the neighbourhood. This electron may descend to the 'hole' left by the ejected electron in one jump—in which case radiation would be emitted in the same frequency as that which caused the initial damage—but it may also (under certain conditions) accomplish its descent in steps. In this case, each time it drops down a step, it loses an amount of energy equivalent to the energy difference between the two levels—emitting discrete quanta at each transition (the sum of whose energies should add up to that of the original disturbance). The light emitted by such a cascade process is generally called the luminescent radiation, and should be familiar enough to the reader. Whenever you admire the beautiful colour display of certain minerals

(such as the uranium salts, for instance) under the illumination by the 'black light' of an ultraviolet lamp, you see an example of this process in action. To the civil engineer or architect, luminescence offers an important tool for modern lighting techniques; and most gaseous nebulae photographed by astronomers in the sky owe their luminosity (excited by the neighbouring hot stars) to this process.

Now, in the absence of any protective atmosphere, the lunar surface is continuously exposed to sunlight of all frequencies—from the radio-waves to the X-rays. Does any portion of the lunar surface exhibit luminescence under its impact? Indications that this may indeed be the case have been accumulating for some time. It was, for instance, pointed out by several observers—and particularly by F. Link in Czechoslovakia—that the brightness of full-moon appears at times to vary from month to month by appreciable amounts, while the intensity of the illuminating (visible) sunlight remains sensibly constant. This phenomenon alone indicated the presence of some luminous process on the Moon other than thermal emission or scattering; and these indications have now been greatly strengthened by some recent spectroscopic work by N. A. Kozyrev of the Crimean Astrophysical Observatory in the U.S.S.R. (and also by J. Dubois of Bordeaux, in France). Their work, carried out independently and reported in 1957, seems to leave but little room for doubt that some parts of the lunar surface—notably the system of rays spreading around the crater Aristarchus (cf. Plate XIII)—exhibit indeed luminescent emission in certain discrete bands of their spectrum. The method by which such luminescence can be detected is simple. We mentioned that—in the absence of any luminescence—the visible spectrum of moonlight should be essentially a true replica of that of the Sun, with all its absorption lines faithfully reproduced in the same width and intensity. A superposition of luminescence of lunar origin should render the solar absorption lines in the spectrum of the Moon shallower—at the respective wave-lengths—than in the spectrum of the Sun directly

observed; and this is what Kozyrev as well as Dubois claim to have found and measured. The total energy emitted by the lunar luminescent bands in the violet was, according to Kozyrev, a quantity of the order of 10^5 ergs/cm. sec, amounting to about 1 per cent of the entire incident solar energy.

Which part of this store of energy undergoes this transformation? If the luminescent emission were stimulated by absorption of sunlight, it would be necessary to assume that all its ultraviolet component (to the violet of approximately 2,900Å) is absorbed by the respective lunar substance in order to account for the observed intensity of its band-spectrum; and this is most unlikely on many physical grounds. Besides—even more revealingly—the intensity of lunar emission bands appears to fluctuate from month to month by as much as a factor four (Kozyrev), while the total (integrated) light of the Sun is known to remain constant within less than 1 per cent. This shows conclusively that the actual source responsible for the excitation of a fluctuating lunar luminescence cannot be sunlight proper—i.e., the solar electromagnetic radiation—but rather the solar *corpuscular radiation* (most likely protons) which is known to be ejected spasmodically in bursts from disturbed regions of the solar surface, and whose impact on the upper atmosphere of the Earth has long been known to give rise to the beautiful and impressive phenomenon of polar aurorae.

As the Moon does not possess any atmosphere to speak of, the streams of solar corpuscles intercepted by it impinge directly on its surface. The 'lunar aurorae'—for this is what the phenomena reported by Kozyrev and Dubois actually are—originate, therefore, right on the ground rather than (as on the Earth) high above it. The observations available so far indicate, however, another difference that appears to be of fundamental importance for the study of a hypothetical magnetic field of the Moon: namely, whereas, on the Earth, aurorae occur also at night (because the incident solar protons can be deflected by the Earth's magnetic field), lunar luminescence seems always to be quenched as soon as the sun has set

below the horizon. This would indicate that, *near the surface of the Moon, the charged particles move along essentially straight lines*, which could *not* be the case if any appreciable magnetic field were present. The lack of any evidence of bending indicates, therefore, that the intensity of any magnetic field around the Moon cannot exceed 0.01 of a gauss, which is but a small fraction of the intensity of the corresponding field of the Earth.

And this is where our knowledge of this subject stood until the memorable journey of the second Soviet space rocket, which crash-landed on the Moon in the region of its Mare Imbrium (see Plate X) on 13 September, at 22 hrs, 2 min and 24 sec GMT, after a flight of some 30 hrs through space. It carried in its payload a magnetometer designed to detect a lunar magnetic field—if any. The instrument functioned normally up to the time of impact, and the last measurements whose readings were automatically transmitted to the Earth were made while the rocket was but approximately 50 km above the surface of the Moon. An analysis of the precision of measurements revealed that if the Moon possessed a magnetic field whose intensity at the lunar surface exceeded 0.001 gauss, it would have been detected. None was found, however, and the absence of any observable indication led our Russian colleagues S. Sh. Dolginov, E. G. Eroshenko, L. I. Zhuzgov, N. V. Pushkov and L. O. Tyurmina of the U.S.S.R. Academy of Sciences to conclude that the surface intensity of any hypothetical magnetic field on the Moon must be more than 400 times smaller than that prevailing on the surface of the Earth if it was to escape detection with their instruments; and that the mean magnetization of the Moon thus does not exceed 0.25 per cent of the magnetization of the Earth.

However, until all details of these measurements have been published, some doubts still persist concerning the upper limit of a possible field strength on the surface of the Moon (or in its interior). Did, in particular, the Russian investigators extrapolate safely the possible intensity of surface field from measurements terminating some 50 km above the Moon? For it has

recently been shown by Neugebauer that the actual strength of a hypothetical lunar magnetic field above the sunlit hemisphere would be bound to diminish rapidly with the height, as a result of the 'solar wind' of charged particles blowing constantly—and sometimes in gusts—across the Moon in space. If the lunar globe were completely devoid of magnetism, the trajectories of these particles passing by the surface would be unaffected by the Moon's presence. Any field of surface strength of the order of 0.001 gauss would, however, deflect these particles from rectilinear motion; and the electromagnetic field arising from such a current would tend to cancel the Moon's field above the lunar surface (and to intensify it below).

A more detailed analysis of this problem by Neugebauer reveals that, on the sunlit side of the Moon (i.e., one exposed to the 'solar wind'), the strength of the magnetic field should diminish to 14 per cent of its surface value at a height of only 1 kilometre. A well-nigh complete absence of any measurable field at an altitude of 50 km over the sunlit surface is only to be expected—virtually no matter what its strength may be on the ground. The dark side of the Moon (which is shielded from the solar wind) would offer a much better opportunity for probing the magnetic properties of the lunar globe; but, unfortunately, no magnetometer has yet approached it at a sufficiently close range. The quenching of the luminescence at sunset—i.e., the lack of deflection of charged particles at the terminator, incompatible with a surface field strength in excess of 0.01 gauss—represents, therefore, perhaps the best evidence we still possess on the upper limit of the intensity of the Moon's magnetic field.

Coming back to the earlier astronomical observations of lunar luminescence, a second independent argument leading to the same general conclusion can be drawn from Kozyrev's work. As is well known from the observed time-lag between the corresponding solar and terrestrial phenomena, the bursts of solar protons and electrons (containing some 10^3 particles per cm^2) travel through space at an average speed of about 1,500

km/sec; and Kozyrev has shown that the stoppage of such a flux by the lunar surface is indeed adequate to account for the observed intensity of the luminescence. Now, in the neighbourhood of the Earth, the local magnetic field is known to accelerate the solar protons by a factor of 2–3 at the end of their long journey. A similar acceleration near the Moon should, however, render the lunar luminescence to be 4–9 times brighter than is observed. If (as is highly probable) the solar protons arrive at the Earth and the Moon in the same numbers, its actual intensity leads, therefore, again to the conclusion that their acceleration in the neighbourhood of the Moon must be small—if any—indicating once more the hypothetical lunar magnetic field to be insensible.

If the arguments advanced in the foregoing paragraphs are somewhat tentative, it is mainly because the survey for luminescence of the visible face of the Moon is still very far from being complete, and also because the photographic observational techniques (adopted by Kozyrev as well as Dubois) are really marginal for problems of this delicacy; this work evidently calls for a resort to photoelectric spectroscopy, which is indeed responding to this challenge. Thus Grainger and Ring, of the University of Manchester, recently brought to bear on this problem the searching powers of their new high-resolution photoelectric spectrometer, mounted in the focus of the 50-inch reflector of the University of Padua Observatory at Asiago. The optical power of this telescope is comparable with the one used at Crimea by Kozyrev; but the resolving power of the Manchester spectrometer was ten times greater; and the photoelectric registration of observed line profiles was at least five times as accurate as photographic spectrophotometry—the combination of which gave Grainger and Ring an overwhelming advantage over their predecessors.

The work by Grainger and Ring is still in progress; but the results obtained by them so far leave but little room for doubt that the luminescence of the lunar surface, the presence of which was indicated previously by the work of Link, Kozyrev

and Dubois using rather marginal observing techniques, indeed exists; and that it is, moreover, both localized and possibly transient. However, the precision work by Grainger and Ring confirmed the results of their predecessors only insofar as their qualitative features were concerned; and indicated also that much more extended observations will be necessary before more definite conclusions can be drawn both on the nature of the exciting solar radiation as well as on the specific quantum processes which render the lunar surface as efficient an 'image convertor' as observations seem to indicate.

Not all of the visible surface of the Moon can, moreover, be expected to exhibit luminescence; for the latter is known to be characteristic mainly of substances containing the atoms of heavy elements; and these are likely to be as rare on the Moon as they are on Earth. Needless to say, the observed characteristics of the luminescent spectra might sometimes help us to identify the element—or even its compound—giving rise to them; though the situation is greatly complicated by the fact that the nature of the luminescent spectra of many substances are greatly influenced by the traces of other elements possibly present as impurities.

Kozyrev claims to have identified the two bright bands observed by him around $\lambda\lambda = 3{,}900$ Å and 4,300 Å in the spectrum of the rays surrounding the crater Aristarchus with those of ordinary quartz—an identification which is, however, still highly tentative and disputable on cosmochemical grounds. This is even more true of Dubois's identification of his observational results with the luminescence spectrum of the mineral known as 'willemite'. The willemites are well-known and rich ores of zinc; and if such were available on the surface of the Moon in large quantities, the prospectors of the future would certainly face a juicy bait across the intervening gap of space. But, again, much work remains yet to be done before any such identification can be considered as really established.

In conclusion, one additional consideration should be pointed out which may eventually become of great importance for

absolute dating of the events which produced various distinct features on the lunar surface throughout its long astronomical past. If, as Kozyrev conjectures, the material splashed out around Aristarchus in the form of its radial system of rays is really quartz, it is well known from the laboratory experiments that its luminescence can be quenched very effectively by small admixture of iron deposited sufficiently long on its surface. Now—like the Earth—the Moon is continuously sweeping up on its journey through interplanetary space a certain amount of dust containing a definite proportion of metals. This proportion can be experimentally established by a chemical analysis of the samples of deep-sea mud dredged magnetically from the bottom of great oceans (whose metallic component must be of cosmic origin). If we assume, reasonably enough, that the Moon is likewise sweeping up an amount proportional to its effective cross-section, approximately 10^{-11} grams of iron should be deposited on each square centimetre of lunar surface each day. At this rate of deposit, the luminescence of quartz in vacuum should be effectively quenched in some 50 million years. Therefore—suggests Kozyrev—it would appear that the crater Aristarchus and the system of bright rays diverging radially from it cannot be much older than 50 million years—possibly less—and the reason why similar ray systems around other craters (like Copernicus or Tycho, for instance) appear no longer to show any detectable luminescence may be due to their greater age (a view supported also by their lower reflectivity to ordinary sunlight). But, again, much additional accurate spectrophotometric work remains to be done before such conjectures can be placed on a more secure basis.

5

THE LUNAR SURFACE

OUR armchair imaginary trip to the Moon—anticipating the bold interplanetary travellers of the coming decades—is, in the meantime, drawing to its end, and our goal is near at hand: in fact, in a few moments we shall be landing, and getting ready to set foot on the actual surface of our nearest celestial neighbour. What kind of a world awaits us at the end of this long and perilous journey?

Once our rocket has landed, and the protective covers removed from its portholes, the view facing us will probably bear but little resemblance to the rugged landscape which we surveyed from above during our approach. The reason is simple: most of the jagged craters and mountains which may have dominated the aerial view will probably be well below the horizon of the observer on the ground. The large curvature of the relatively small lunar globe will effectively conceal all but the nearest or highest peaks; an eminence of 3,000 metres in elevation would totally disappear below the horizon of the observer at a distance of 100 km. This fact cannot but hamper considerably local orientation; moreover, the absence of any air and consequent complete space transparency would inevitably mislead the visitor, accustomed to terrestrial conditions, into grossly underestimating distances.

What kind of conditions must we expect to meet on the surface of the Moon once we step out of the protective shelter of our rocket? In principle the answer is simple: the conditions

prevailing on the lunar surface will be such as are bound to obtain as a result of the causes which have been acting upon it for a long time. These are simple and relatively well understood. In attempting to answer our question we should, therefore, merely recapitulate them and follow up their appropriate consequences.

Of the circumstances shaping up the detailed structure of the lunar surface, the absence of any protective gaseous atmosphere—elaborated already in Chapter 2—is of paramount importance; for it means that the surface of the Moon is in virtually direct contact with the interplanetary space, and exposed to all matter as well as radiation falling on it from outside. What will, therefore, be the temperature prevailing upon it by day or night?

The method by which the temperature of any element of the lunar surface can be deduced from the amount of heat received from it per unit time has already been described in the foregoing Chapter 4; so that here we can merely state the results. Repeated and careful thermoelectric measures have indicated that at the subsolar point in the lunar tropics—when the Sun stands directly overhead—temperatures as high as 110°C are attained each day. During the afternoon—as the zenith distance of the Sun is increasing—the temperature steadily declines to well below freezing at the time of sunset, and continues further to decline in the course of the night until an appalling minimum of between −170° and −180°C is attained before sunrise. The total range of day-to-night variation in temperature on the Moon is, therefore, but little less than 300°C, and ranges from the temperature above that of boiling water at noontime down to that of liquid air at dawn. This is, of course, the maximum range encountered in lunar tropics. Near the poles, where the sun never rises high above the horizon nor sets completely for very long, the temperature variations become correspondingly smaller; but even there its range is rather frightening and apt to cool down the enthusiasm of many a young but inexperienced space explorer!

The mean sub-surface temperature of the lunar globe appears to be well below the freezing point of the centigrade scale, and by many degrees less than the mean temperature of the Earth; but it is the extremes which concern us in the first place. Why does the Moon behave so differently from the Earth in this respect? For both the Earth and the Moon the principal source of heat is, of course, sunlight; and as our planet and its satellite are, on the average, equally far from the Sun, both are bound to receive equal shares. But their particular properties allow them to husband this energy in essentially different ways. The visible light of our satellite—which is sunlight scattered on its stony surface—represents only a few per cent of the total energy actually received from the Sun. The bulk of incident sunlight is absorbed by the lunar surface and re-radiated as infra-red light—far too red to be visible to the human eye, but well measurable by its thermoelectric effect. The Earth does the same; but its own absorbing and protective mechanism is completely different from anything existing on the Moon.

From the global climatic point of view, by far the most important reason for this difference is the fact that approximately three-quarters of the Earth's solid surface is covered with oceans; and their water is a substance of very remarkable physical properties. For our globe as a whole, the ocean is the great regulator and stabilizer of temperatures. It has been aptly described as a 'savings bank for solar radiation, receiving deposits in seasons of insolation and paying them back in time of want'. Because of their enormous heat capacity, the oceans can absorb a great deal of heat from the Sun without becoming too hot, and lose much of this heat without becoming too cold. Moreover, through the agency of ocean currents, the heat and cold can be distributed over thousands of miles of the terrestrial surface by mechanical action.

And this is not all. For over the globe the continents and oceans are surrounded by a gaseous atmosphere. This atmosphere is almost completely transparent to the bulk of the 'white light' of the Sun; but two of its minor constituents—namely,

water vapour and carbon dioxide, constituting together but 0.1 per cent of the entire atmospheric mass—are almost completely opaque to the infra-red radiation given off by the Earth and its oceans. The bulk of the heat sent out by a black body of approximately 300°K absolute temperature is effectively trapped by the absorption of CO_2 and H_2O in our atmosphere which acts like a greenhouse—thus making its own contribution to the mitigation of extreme temperatures encountered on the Earth.

How different is all this on the Moon! The absence of any atmosphere precludes the existence of any liquid over the free surface (which would evaporate and dissipate almost immediately even during cold spells of the night); and solid rocks possess indeed very small heat capacity in comparison with water. As a result, their surface can rapidly become hot during the daytime and cold again at night; and as there are no means of storage, the extremes are so large—though the mean temperature of the Moon is not so very different from that of the Earth.

In one respect, however, the lunar climatic changes are not so drastic as a first glance at the foregoing figures may indicate: namely, although the extremes are great, the duration of the lunar day—lasting 27.32 days or 656 hrs of our time—is again so long that the rate of change of the temperature is not actually so impressive: a drop from 110°C to −180°C in 13½ days separating the lunar noon and midnight corresponds to a mean temperature gradient of less than 1° per hour—which is certainly not so out of the ordinary. It is its persistence over so many hours of rise and fall which makes the extremes in temperature so wide.

There exists, however, a time when the temperature changes do become very much more rapid: and that is during the relatively brief intervals of lunar eclipses when—for a period of a few hours—the Moon passes through the shadow of the Earth. The relative dimensions of the Earth and the Moon and the present characteristics of their orbits are such that about

once a year—i.e., after each twelve days of the lunar calendar—the Moon passes through the shadow cone cast into space by the Earth. This passage lasts only a few hours. The thermo-electric measurements reveal, however, that, during this brief spell, the eclipsed lunar surface in the shadow cone of the Earth experiences virtually as large a variation in temperature as between day and night. In particular, the emergence of the Moon from the shadow brings about so frantic a 'heat wave' that the temperature on the surface rises precipitously by almost 200°C within less than one hour. This constitutes virtually a rock-breaking temperature gradient, and the reader can almost hear the surface cracking as the Sun continues to vanish or re-appear behind the occulting limb of the Earth.

If the extreme range of temperatures prevailing on the surface of the Moon as a consequence of its lack of any protective atmosphere may, perchance, give some less courageous individuals second thoughts about visits to such inhospitable places, let us reassure them quickly that these large climatic variations appear to be limited strictly to the exposed lunar surface, and become very much less immediately beneath it. The realization of this fact is another gift which our ancient science of the heavens owes to its junior branch of radio-astronomy; and although it is barely ten years old, it is of such intrinsic interest that we must share its account with the reader.

In the preceding Chapter 4 we already mentioned that the moderate absolute temperature of the lunar globe (ranging from about 200° to 400°K on the surface) will cause most of its own thermal radiation to lie in the far infra-red—with a maximum around $\lambda = 10\mu$ and falling off gradually towards the shorter and the longer wave lengths. Most part of this moonlight proper of wave lengths between $\lambda\lambda$ 10 and $1{,}000\mu$ will be irretrievably gobbled up by the absorption of the water vapour and carbon dioxide in our own atmosphere; but beyond $1{,}000\mu$ or 1 mm this atmosphere becomes transparent again and opens up another window for viewing the universe in a new and strange light.

It is just about 15 years since the thermal radiation of the Moon reaching us in this range was first reliably detected by Piddington and Minnett in Australia at the wave length of 12.5 mm (24,000 Mc/sec) using an antenna of 0°75 beam-width; and since 1949 the accessible part of the lunar radio-spectrum has rapidly been explored by a number of investigators—at wave lengths ranging from 33 cm at the long end (beyond which the lunar radiation becomes too weak to be properly measurable) to 1.5 mm (just where the atmosphere clears up to transmit the requisite signal)—this latter record being held since 1956 by W. H. Sinton, a young American astrophysicist, who used a 24-inch searchlight mirror as his telescope, a Golay infra-red cell as a detector, and a mere sheet of paper as the 'band-selector'.

These measurements of thermal emission of the Moon in the microwave range (at frequencies between 3,000 and 300,000 Mc/sec) revealed several noteworthy facts of highest interest for the study of the physical properties of the lunar surface, which can be briefly re-capitulated as follows. First, the range of temperature variation deduced from the measurements of thermal emission in the radio-frequencies turns out to be *less* than that measured in visible light—becoming the more reduced, the longer the wave length. Secondly, the maxima or minima of microwave temperatures do not follow in phase the altitude of the Sun above the horizon, but *lag behind* their surface (i.e., infra-red) values by amounts increasing with the wave length. For instance, at $\lambda = 12.5$ mm, Piddington and Minnett found the intensity of thermal radiation to correspond to temperatures ranging from −70° to 30°C—as compared with the corresponding extreme of −160° and 110° measured by Pettit and Nicholson in infra-red light—and the phases of the microwave extreme shifted by one-eighth of the cycle (i.e., more than three days). In the light of 1–2 mm wave length, Sinton found the temperature to vary only between −100° and 30°C, with the phase-lag reduced to 2–3 hrs. On the other hand, Denisse and Le Roux, working at $\lambda = 33$ cm (frequency

900 Mc/sec), found the lunar temperature approximately constant and equal to $-50° \pm 30°$C both day and night. Seeger, Westerhout and Conway, working at still longer wave length ($\lambda = 75$ cm) confirmed essentially the same result. This agrees satisfactorily with the mean temperatures established by all other observers, and reveals that the mean temperature of the lunar globe—about $-30° \pm 10°$ if deduced from the ensemble of all existing observations—is distinctly *lower* than that of the Earth.

What is the cause of all these diverse phenomena? The basic reason offering a clue to their explanation is the fact that the waves of different frequencies do not originate all at the same depth; but are coming from layers which are, in general, the deeper, the longer the wave length. In other words, the surface of the Moon—opaque to visible and infra-red light—becomes partially transparent in the domain of the microwaves; and the lower their frequency, the deeper inside we penetrate. In practice, a limit to this prospecting is imposed by the fact that the thermal emission of the Moon diminishes rather rapidly with increasing wave length in the microwave domain; and the lunar radiation at wave lengths in excess of one metre could scarcely be disentangled from the instrumental noise and that of the sky background. In the millimetre to decimetre ranges the readings are, however, significant and enable us to penetrate approximately as much as one yard beneath the surface in tracing the flow of heat due to diurnal insolation. As sunshine is never interrupted by clouds on the Moon, the insolation of the lunar surface proceeds each day with clock-like regularity; and the heat incident upon it should make its way inside in accordance with the well-known equations of heat flow.

Now if the diurnal variation of microwave temperatures is damped as rapidly with increasing depth, and continues to lag in phase behind the infra-red (surface) temperatures, as the observations appear to indicate, the only reason of it can obviously be a very poor thermal conductivity of the lunar surface

layers. The observations definitely indicate that the diurnal variation in temperature at a depth of one foot already amounts to less than one-third of its surface range, and the effects of diurnal heat waves do not make themselves felt till after a time lag of some 80 hrs. Moreover, at a depth of about one yard any diurnal variation completely disappears, and a constant temperature obtains day or night. These data should make it possible for us to evaluate the coefficient of heat conduction of the lunar surface material, sufficient to retard the flow and attenuate it as is observed.

When such computations were made for the first time, the investigators who made them received a considerable jolt; for the computed coefficient of heat conduction turned out to be as low as 3×10^{-6} in c.g.s. units—which is very much less than that of any known terrestrial solid substance. This was, however, so only as long as we confined our attention to solid rocks, in which the heat flows through their entire cross-section, Suppose, however, that we grind this rock to a powder; the heat propagating by conduction will be able to flow only through such areas at which the individual dust grains are actually in contact; and their sum total will be very much less than the cross-section of the original rock. When the computed coefficients of lunar heat conduction were first compared with those of known terrestrial powders of common rocks or volcanic lava, some discrepancy still persisted; but was completely removed when the experiment was repeated in vacuum (as, during ordinary terrestrial conditions, the major part of heat can propagate through the air in between the dust grains).

By an inversion of this argument, the local variations of lunar surface temperatures (measurable as fluctuations of the intensity of infra-red thermal emission from place to place) could be used to study the different degree of compactness of the outermost layers of the Moon reflecting the rate with which its internal heat can leak out to the surface. In order to give a specific example, consider the lunar craters—formations already described in Chapter 2—many of which originated

probably by collisions of external bodies with the surface of the Moon. Whatever the circumstances of such an impact, however, it is reasonable to expect that the material compressed by impact should be more compact than the loose debris ejected outside the ramparts. This difference should, in fact, enable us to differentiate craters of impact origin from those which may have been produced by some other cause.

How to establish this difference by observations from the Earth? We may recall that approximately a yard or so below the surface we expect the temperature of the Moon to remain virtually constant and equal to −30°C. This is about 140° less than the surface temperature at the sub-solar point, and by the same amount warmer than the surface temperature at night. Over most part of the lunar globe the thermal conductivity of the surface material is so low that heat flow from the depth of one yard scarcely reaches the top layer in the interval of one lunar day. Suppose, however, that (due to its greater compactness) the material on the floors of impact craters is a better effective conductor of heat. If so, the sub-surface layer at −30°C could communicate its temperature outwards more readily inside the crater than outside—and, as a result, the floors of such craters should be systematically warmer than their surroundings at night-time, and cooler during the day.

It is of interest to note, in this connection, that Sinton and Shorthill recently found indeed the temperatures of the floors of several conspicuous craters whose features suggest impact origin—Copernicus (Plates VII, VIII), Tycho (Plate II), or Kepler—to be some 30–50° higher during the lunar eclipses (simulating night conditions) than their surroundings; and other measures secured since indicate that the converse may be true (to a lesser degree) during day-time. If these results are confirmed by further work, the day-to-night temperature excesses in opposite sense exhibited by the floors of different craters may not only enable us to segregate those of impact origin from others due possibly to different causes, but the extent of their excess (which should, in time, be lessened by

gradual deposit of cosmic dust on the surface) could be utilized as an indicator of their absolute ages.

The extremely poor thermal conductivity of the lunar topmost layers is also fully attested by the microwave observations made during the total eclipses of the Moon. As the Moon gradually enters into the shadow of the Earth and emerges again from it, thermoelectric measures of its radiation in the infra red reveal that the temperature on the exposed surface varies almost as much as between day and night. However, at the wave length of 12.5 mm, Piddington and Minnett found no variation whatever in the intensity of thermal emission during the hours of the eclipse; and neither did Gibson at Washington record any at $\lambda = 8.6$ mm. It was not till at $\lambda = 1.5$ mm that Sinton found some response of the thermal radiation to the advancing shadow; but again delayed in phase and of reduced amplitude —in conformity with the measurements of diurnal variations.

The meaning of all these observations is quite clear. It reveals that most part of the visible lunar surface cannot consist of bare rocks, but must be covered by a fine dust—of average grain size of the order of a few microns—whose chemical composition is probably that of common rocks or volcanic ashes. This is completely in agreement with the reflectivity of such material and its degree of polarization when illuminated by the Sun at different angles. The existence of this powder or dust covering most part of the Moon is so well attested by different and independent lines of investigation that it can be taken for granted without doubt.

When it comes, however, to gauging the total depth of this dust layer we immediately find ourselves on much more hypothetical ground. The low thermal conductivity of the lunar surface—as established by the microwave observations discussed in the preceding paragraphs, requires that this dust be at least a few inches, and possibly several inches, deep; but how much more dust may be beneath observations no longer reveal; for no radiation coming from greater depth could so far be recorded. Our best way of assessing the total amount of dust covering the

lunar surface, is therefore, to consider the processes which may produce such dust and to estimate their efficiency.

That the lunar surface should be covered by dust was, in fact, only to be expected; for no solid bare rock may stand indefinitely the strenuous day-by-day heating and cooling to which the surface is exposed—particularly the precipitous temperature changes experienced during lunar eclipses. Under such conditions all rocks should keep cracking into smaller and smaller bits; and ultraviolet radiation together with solar corpuscles and primary cosmic rays may do further significant damage to the crystal structure of smaller fragments.

This 'native' dust produced by inevitable gradual cracking of the lunar surface must, furthermore, be intermingled with 'cosmic' dust swept up by the Moon on its journey through the interplanetary space. As is well known, the space between the planets is not entirely empty, but contains a surprising array of ingredients—of which the principal ones are hydrogen gas, free protons and electrons, and a certain amount of meteoritic dust and debris. The gas and charged particles are mainly of solar origin—for we veritably move still in an extension of the solar corona, in which the total density of matter is of the order of 10^{-20} g/cm^3 (or about 10,000 times as high as in the interstellar space)—and have been ejected from it by various means; after all the whole solar corona evaporates and becomes regenerated in the course of every few years. On the other hand, the meteors and interplanetary dust in general are probably as old as the solar system itself, and may represent in fact the material left over from the days of its formation. Its amount is not large; but bodies of the size of the Earth or the Moon must have accumulated quite a bit of it in the course of their long astronomical past.

In the case of the Earth, the amount of meteoritic deposits can be estimated from chemical samplings of material in the regions of the terrestrial surface (such as the mud deposits at the bottom of great oceans, for instance) where the geochemical balance has not been disturbed by human hand. It is,

of course, impossible to separate the cosmic light elements from the terrestrial ones; for their isotopic composition is exactly the same. However, it is known that the meteoritic material contains an appreciably greater abundance of certain heavy and non-reactive metals (such as osmium or palladium, for instance) than is found in the crust of the Earth; and if so, the excess osmium or palladium extracted from deep-sea mud provides a good indicator of the total amount of cosmic debris deposited there in the course of time. Moreover, the deeper we dredge the sea beds in oceanographic surveys, the farther in time can we penetrate in this way.

The longest cores of mud extracted so far from the deep Pacific take us, in this way, a few million years into the past; and their chemical analysis at the hands of Pettersson and Rotschi, Parkin, and a number of other investigators has led to the conclusion that the total amount of cosmic material swept up by the entire surface of the Earth is approximately 1 to 10 thousand tons per day—so that each square centimetre of the terrestrial surface should receive about 10^{-7} g of dust per day or 10^{-6} g per year. This should add up to a layer of a few centimetres in thickness in 100 million years and—provided that the present rate of deposit has remained reasonably constant—to not more than 2–3 ft of dust since the time of formation of the solar system.

As the Moon is so near the Earth, the average rate of deposit of cosmic dust on its surface would be approximately the same or—if anything—less; for the absence of any appreciable magnetic field around the Moon should reduce its effective cross-section for the capture of metallic particles; and also the process of impact may entail larger losses. On the Earth, major meteorites (weighing from kilos to tons) reach the surface with their cosmic speeds and bury their mass deep underground. Smaller meteors (whose weight is measured in grams) will mostly melt by heat caused by atmospheric friction and get volatilized in the air; while the micro-meteorites—the real cosmic dust—get slowed down high up in the air by numerous collisions with

atmospheric molecules and, being so decelerated before matter becomes too hot, they make their way down like through a sieve—until they reach the surface unharmed in solid state.

Now, on the Moon, this will all be different. As there is no atmosphere around it to cushion the fall, all bodies impinging upon it will hit the surface with their cosmic velocity—be they small or large—penetrate into it a certain distance and volatilize completely upon impact. Thus, unlike on the Earth, the collectors of meteorites should have very little chance of finding any original cosmic samples with their preserved characteristic texture; for all such material would have volatilized on impact and escaped partly back into space, or re-solidified in its new surroundings. In fact, recent laboratory experiments with high-velocity impacts under vacuum conditions (Gault, Shoemaker) have revealed—surprisingly enough—that a fast-moving meteorite striking the Moon may actually eject from the lunar surface an amount of debris weighing a great many times the mass of the intruder—to eject it at much lower velocity, to be sure; but some of it still sufficiently fast for escape from the gravitational field of the Moon. It appears, therefore, that *the secular effect of meteoritic bombardment is likely to be a removal of matter from the Moon rather than any net accretion of it;* and a slow abrasion of its surface, in the course of which the newly crushed material gets intermingled with the swept-up interplanetary dust.

Be that as it may, however, one conclusion emerges from our discussion with increasing clarity: namely, that—whatever its origin—the amount of dust formed or deposited all over the lunar surface should not exceed, at most, a yard. Unless the rate of deposit of cosmic dust was, perchance, very much higher in the past than it is now, more could have scarcely fallen on the Moon from outside even in the whole course of its long astronomical past; and as to the indigenous dust produced by gradual disintegration of lunar rocks, once a few inches have been formed on the top, the rocks beneath would be completely shielded from any further temperature or radiation effects. No

more dust could therefore be produced—unless, of course, the dust, once formed, could *move* to another place and thus expose the parent rock to continued erosion.

But how could anything move over the dead and inert landscape of the Moon? There is certainly no gaseous atmosphere significant enough to give rise to any wind; and in its absence, what could stir the dust to motion? Apart from occasional impacts of major meteorites which, as we have seen in the preceding Chapter 3, can produce crater-like structures on the surface and, in so doing, stir a large amount of mass (settling down, however, again with the speed of free fall), one physical agent ever present to provide continuous gentle stirring is, of course, the temperature—giving rise to thermal random motion of the grains. The principle is the same which keeps our atmosphere distended above our heads: the tendency of the air molecules to respond to the terrestrial gravity is resisted by mutual collisions sending off particles bouncing in random directions—and the actual extent of the atmosphere is the resultant between these two tendencies: gravity pulling the air down, while the thermal collisions tend to disperse it. If its temperature were much lower than the one which we now enjoy, the atmosphere would 'settle down' and eventually liquefy; while if it were much higher, gravity might become unable to restrain it and the air might disperse altogether into space.

This is, indeed, the reason why the Moon with its small mass and relatively low surface gravity cannot retain permanently any such atmosphere of light gases as we possess around the Earth. The kinetic theory of gases reveals, however, that the chances of acquiring by collisions a velocity sufficient for escape diminishes rapidly with increasing molecular weight of the constituent gas. Suppose now that we consider fine dust particles as gigantic molecules of very high weight: what are the properties of an 'atmosphere' to which this dust can be stirred (in the absence of any gas molecules) by the temperature prevailing on the Moon? This question admits indeed of a simple answer; and the requisite calculations reveal that if, at

110°C (i.e., the temperature of lunar noon in the tropics), the density of our dust atmosphere is to diminish to one-half at the height of 10 cm above the surface, the mean 'molecular weight' of the dust grains should be approximately 7.8×10^{-17} grams, corresponding (for a mean density of 3 g/cm^3) to the size of 3.7×10^{-6} cm. If, moreover, the scale height of this atmosphere were to be increased ten times to one metre, the molecular weight should be further diminished by a factor of 10, and the mean size to 1.7×10^{-6} cm or 170 Angstrom units. It would, indeed, have to be an extremely fine dust to remain stirred above the surface by its own temperature even to a very small height. No natural process is known which would grind it to such a degree of perfection; and, besides, the polarization of light scattered by the lunar surface as well as the coefficient of thermal conductivity resulting from the microwave measurements are conclusive in indicating that the mean size of the dust grains covering the lunar surface is of the order of a micron or two—i.e., about a hundred times as large. Such dust cannot be stirred by temperature to form an atmosphere of more than millimetre scale height; and so minute a layer cannot, in turn, provide any effective means of transporting the dust from one place to another in daytime—let alone at night.

This argument may, however, be altered somewhat when we come to consider the electrostatic forces, arising from the electrical charges which our dust is almost certainly bound to accumulate. In order to appreciate the weight of this point, let us consider first some basic facts of lunar electro-dynamics. In Chapter 2 we learned, from the absence of any twilight phenomena on the Moon, that the density of any gas above the lunar surface cannot exceed some 10^{-12} g/cm^3. In our own atmosphere, this air density is attained at about 180 km above sea level—just in the midst of the F1 layer—and the solar radiation at that height is known to be intense enough to bring about ionization producing some 10^5 free electrons per ccm. We do not know, of course, how much less gas there is on the Moon than the above upper limit; and besides, whatever there

may be left, will probably consist of inert gases characterized by relatively high ionization potentials.

However, the absence of any appreciable gaseous envelope around the Moon will expose its solid surface itself to the full blast of undiluted sunlight; and the consequences of this exposure are profound. For not only will (as we have seen in Chapter 4) the lunar 'auroral zone' be relegated on to the solid surface, but the 'lunar ionosphere' as well. For, on the surface the solar ultraviolet and X-ray radiation is bound to produce ionization not only from the ground state (which, by recombination, may give rise to the visible luminescence), but from all atomic levels. This ionization would, in fact, be very much more intense than that encountered in the E or F-layers of our atmosphere, because there the undiluted sunlight meets only gases characterized by relatively high ionization potentials; whereas on the surface of the Moon the elements possessing weakly bound electrons are very much more abundant. In addition to all this, we must also keep in mind the ionizing effects of fluctuating solar corpuscular radiation, as well as of the continuous flux of primary cosmic rays striking the lunar surface at a rate of approximately one per square centimetre every ten seconds. On the whole, however, all three processes—namely,

1. photo-ionization, due to solar hard ultra violet radiation;
2. impact of solar corpuscular radiation (essentially protons);
3. impact of primary cosmic rays (again essentially protons),

are bound to keep charging the surface of the Moon *positively* in the course of time—the first source acting only during day-time; the second (in the absence of any appreciable magnetic field) also in day-time; and the last continuously.

How long can, however, this charge actually accumulate? For it is obvious that a growing positive charge at the surface is bound to retard, or prevent altogether, the escape of electrons below a certain increasing energy threshold—thus gradually slowing down the growth of the charge—and, besides, the

surface charge must also be lessened by the sweeping up of free electrons from interplanetary space. The density of such electrons at our average distance from the Sun is not yet definitely established. It certainly is not more than about 500 per cm^3—a figure obtained by ascribing the total observed intensity of the zodiacal light to the scattering of sunlight on free electrons—but some recent work by Blackwell on the line spectrum of the zodiacal light, photographed from the top of Chacaltaya in the Andes, indicates that the actual density of free electrons in interplanetary space around us may be as low as 50 per cm^3 or even less.

Therefore, the actual density and extent of a lunar electron atmosphere surrounding the surface should be the resultant of a contest between the growth of a positive charge of the surface by the processes (1)–(3)—which, however, is by itself bound eventually to inhibit further electron escape—and a discharge into space through the medium of neutralizing interplanetary electrons. The combined effect should be to envelop the sunlit face of the Moon with a space charge or a transient atmosphere of free electrons, whose density and scale height should fluctuate in the course of the day. Its actual quantitative analysis is, unfortunately, made rather difficult by several factors (such as the unknown electron density in space, or the 'quantum efficiency' of the lunar surface) for which even their order of magnitude is as yet difficult to bracket down within reasonable limits; but that it exists can scarcely be in doubt.

Could the existence of such an electron cushion over the sunlit hemisphere of the Moon, and its density, be established directly by the observations? This should indeed be within the bounds of possibility—thanks to the magnificent development of radio-echo techniques, which have taken place in the last twenty years and which enabled already the astronomers to establish actual contact with our satellite somewhat in advance of the rocket age.

In January 1946—another memorable landmark in the history of our subject—the scientists of the U.S. Army Signal

Corps at Belmar, N.J., headed by de Witt and Stodola, beamed on the Moon a series of short pulses (of 0.25 sec duration) emitted by a mere 3 kw transmitter at 110 Mc/sec, and—behold—2.56 secs later echoes were recorded, demonstrating that within these brief intervals their signals had completed a round-trip of half a million miles to the Moon and back. The real triumph was to amplify the returning echoes sufficiently to make them discernible; for whereas the energy fed into the antenna of the transmitter was 3 kilowatts, the returning echoes carried an energy of but little more than 10^{-17} of a watt—corresponding to an attenuation of 250 trillion times!

In 1950, the same feat of long-distance communication was repeated in Australia by Kerr and Shain, working on the frequency of 20 Mc/sec (15 m waves); and, since that time, several places in the world—in particular, the Jodrell Bank Experimental Station of the University of Manchester—have maintained an almost daily contact with the Moon through the medium of short waves.

A study of the radio-echoes reflected from the Moon has advanced the solution of many interesting problems. First the return of the echoes can nowadays be timed by standard electronic techniques with a precision of the order of one part in a million; and as the velocity of propagation of radio waves in vacuum is now known to the same order of accuracy, the measured time-lag of the echoes should enable us to determine the distance of the reflecting element of the lunar surface from the transmitter or receiver on Earth within ± 100 metres—independently of any other astronomical observations. The Doppler shifts of the returning pulses should, moreover, reveal the (instantaneous) relative radial velocity of the two places with a similarly high accuracy—and thus contribute to our knowledge of the motion of the Moon (both through space and around its centre of gravity).

Secondly, a study of the polarization of returning echoes discloses much on the transmission of electromagnetic waves through different layers of the terrestrial ionosphere, as well as

on the reflecting properties of the lunar surface. Last, but not least, one can make use of the lunar disk as a convenient screen provided by Nature in outer space for bouncing back short waves which are not reflected by our ionosphere. Thus in November 1951, the U.S., National Bureau of Standards, in collaboration with the Collins Radio Company, succeeded in transmitting intelligible signals from a 30 kw radio station broadcasting at the frequency of 417 Mc/sec (72 cm wave length) between Cedar Rapids, Iowa, and Stirling, Virginia—separated by a distance of 1,200 km—using the Moon as a reflector, and thus inaugurated a new epoch in long-range radio transmission in UHF. The first sentence sent out by the American radio-engineers via the Moon paraphrased deliberately the first message sent on 24 May, 1844 by Samuel Morse over his new telegraph line between Washington and Baltimore: 'What hath God Wrought'—a message which may become the forerunner of future relays of transatlantic television programmes of probably a more frivolous nature.

Our present interest in lunar echoes is, however, not connected with their future commercial possibilities, but rather with whatever light they can throw on the physical properties of the reflecting lunar surface. One fact seems of considerable interest in this connection: namely, that the echoes received back on Earth reproduce so closely the characteristics of the original signals as if their reflection from the Moon were specular —i.e., if the reflecting surface were smooth rather than rough, as we surmised it to be already on other grounds. Indeed, the profiles of the returning echoes as recorded and analysed in recent years by several investigators (Evans, Pettengill, Siegel, and others) reveal that the essential flatness of the lunar surface—noted earlier for objects of more than a kilometre in size by direct observation—continues to hold good down to objects of 10-metre scale; at least an average inclination of the lunar surface to the horizontal on that scale appears to be less than one in twenty.

Another explanation of this phenomenon could be the fact

that the terrestrial signals do not penetrate to the actual surface of the Moon, but are reflected from an electron cushion extending above the surface up to a certain height. If so, we should expect the reflection to be of different type at the time of the full Moon (when the electron density of the cushion should be maximum) and of the new Moon (when it should virtually disappear and denude the actual surface). Night-time radar reflections have, however, not yet so far been observed; and it is doubtful whether the electron density of the day-time space charge above the lunar surface can be sufficiently high to enable this cushion to act as a mirror for radar signals in the frequencies at which they have been observed.

Lastly, there exists still another way in which the electron cushion around the Moon could manifest its presence to the terrestrial observer: and that is by the refraction phenomena taking place during the lunar occultations of cosmic 'radio stars'. As is well known, many distinct spots in the sky were found in recent years to emit strongly in the domain of radio-frequencies; and while some of these have so far not been identified with any specific visible object, the majority in our galaxy have been associated with gaseous nebulae containing turbulent plasma. The so-called 'Taurus source', consisting as it does of the gaseous remnant (the Crab nebula) of the famous Chinese supernova of A.D. 1054, is a good example of this class of objects; and situated as it is in the constellation of Taurus not far from the celestial equator, it lies in the belt which the Moon occasionally reaches in the course of its apparent motion around the ecliptic.

When this happens, and the lunar disk occults the radio source, then just before the ingress the radio-waves pass tangentially to the dark lunar surface, to emerge after a while from behind its sunlit limb. The last such occultation took place on 24 January, 1956, and was observed by the Cambridge radio-astronomers Costain, Elsmore, and Whitfield, in England, at the wave length of 3.7 metres. These investigators noted that the radio waves of the Taurus source did not vanish and

reappear at exactly the same moment as the visible light of the Crab nebula was hidden by the lunar limb or emerged from behind it, but that the time interval between the visible ingress and egress was somewhat shortened by refraction of the radio-waves amounting approximately to 22″ (or less). If, in turn, this refraction was produced by free electrons immediately above the sunlit limb of the Moon, its observed amount (whose significance is, however, still open to some doubt) would be indicative of an electron density of the order of 10^4 particles per cm^3—or about 100 times as high as in interplanetary space around us. This is, therefore, the possible density of electron gas above the sunlit landscape of the Moon; and future observations of the occultations of this and other known radio-sources situated sufficiently near the ecliptic will doubtless establish its value precisely and place it on a more secure footing.

However—and this we wish to stress—many of these free electrons can be temporarily captured by (or released from) the dust grains lying on the surface or hovering low above it—and the electrostatic repulsion thus produced may stir the dust against gravity much more effectively than any random motions produced by the prevailing temperature. If so, an electrostatically charged dust atmosphere might possibly attain appreciable height above the sunlit landscape of the Moon—or experience some kind of wind as the noon meridian travels around the lunar equator. Even then it is, however, quite unlikely that much mass could be transported across the lunar surface in the form of electrified dust. The bulk of the dust has probably remained where it has grown (or fallen); and if so, it should be nowhere too deep to impede seriously the progress of those who may one day have to thread their steps through it. Admitting, however, that our chain of evidence in favour of this view is not entirely solid, it may perhaps not be entirely superfluous to warn those intrepid souls to watch their step just the same—and be ready for any surprise!

Summarizing all that we have learned so far on the characteristics of the lunar surface, the following facts should be kept

in mind. Direct observations of surface irregularities (measurable down to the size of 300–500 metres) indicate that, on the kilometre scale, the Moon is rather uniformly flat; and its landscape is not broken by many steep slopes of any appreciable size. Somewhat more indirectly, the nature of the radar echoes reflected from the lunar surface indicates that essentially the same kind of flatness may persist down to a scale of 10 metres. On the other hand, the conspicuous steepness of the lunar light changes around the time of the full Moon have demonstrated that, on a substantially smaller scale (metre to centimetre in length) the surface of the Moon must become very rough and rugged—so rough that a relatively large proportion of it will find itself submerged in shade when the Sun has departed no more than a few dozen degrees from the zenith. Lastly, we know from the polarization measures that, on a still smaller scale (0.001 to 0.01 mm), much of the lunar surface must be covered by fine dust clinging to all slopes of the rugged micro-relief as well as to all larger inclines; for Dollfus measured carefully the polarization of moonlight scattered from areas of different inclination (in particular, across the inclined face of the 'Straight Wall' in Mare Nubium) and found it to be everywhere the same.

The actual scale of ruggedness of the lunar surface following from the photometric observations, can so far be only guessed at. If the Moon is rugged on a metre-scale—an assumption implied in Sytinskaya and Sharonov's 'meteor-slag' hypothesis —its surface should consist largely of a loose agglomeration of boulders (of external as well as internal origin) which would make the landing of space rockets on such ground a very hazardous operation, and any lateral travel progress excruciatingly difficult. The Russian school of astronomers believe that this is indeed so, because surface unevenness on any smaller scale (1–10 cm) would have been smoothed out by the infall of cosmic dust in the course of time. Nevertheless, the present writer believes it possible that the roughness of the surface responsible for the steepness of the lunar light changes

may exist on the centimetre scale. Such a micro-relief could not, to be sure, remain an immutable feature of the lunar face during its long astronomical past, as it would get gradually submerged by incident cosmic dust; but may it not, in fact, be constantly re-created by the infall of micro-meteorites producing their tiny craters on it—much as raindrops on Earth keep checkering dry dusty surface?

At any rate, one feature emerges clearly from the foregoing discussion: namely, that whatever electrical space charge there may be above the surface of the Moon, the scale-height of the atmosphere of dust stirred by it must be such as not to obscure the rough micro-relief of the lunar surface from view—whether it may be on the centimetre or metre scale—for otherwise the changes of light of the Moon with phase could not be so rapid. It is, therefore, unlikely that a diurnal cloud of electrified dust would reach as far as the height of an average man. Should it, however, do so perchance, it is an exciting thought to try to anticipate the impressions of a traveller making cautiously his way through it. The sunlight should be scattered by it almost equally in all directions, so that there would be no shadows—it might be like walking through a thick fog, though it may extend no more than some yards above the surface. And above it we would behold the pitch-black fathomless depths of space, with the Sun shining on it somewhere as a disk of unsurpassed brilliance, but its glare would not lessen in the least the magnificent splendour of the myriads of stars.

The principal features of the weird world which will await our intrepid travellers of the future, as they step out of their spaceships on the surface of our satellite—can be gathered to some extent from the contents of the preceding chapters. We know, of course, that from the first step our travellers will have to carry their own air to breathe in their space suits wherever they go, and that the armour of these modern knights without fear will have to be thermally insulated in order to protect them as well as possible against the great temperature differences between sunshine and shade.

Once outside the rocket, the first task confronting our travellers would be one of orientation: just where did they land on the Moon and where on the map should they pin the flag marking their point of arrival? This task may prove to be more difficult than an armchair traveller down on the Earth might perhaps anticipate. If our travellers turn around to scan their horizontal panorama, most part of the familiar landmarks which loomed so impressively through the portholes of their rocket during the approach will probably be out of sight on ground; the large curvature of the relatively small lunar globe will conceal all but the nearest or highest surface irregularities. The lunar horizon in most parts must, therefore, be expected to be quite flat—exhibiting probably but few, if any, points on which the eye searching for familiar landmarks could rest with any confidence. Everywhere around us we should expect to see monotonous desolation of a brilliantly sunlit landscape punctuated by pitch-black shadows accompanying each unevenness of the ground.

Visible landmarks will, therefore, be likely to be too few and far between to serve for unambiguous identification of locality almost anywhere on the surface of the Moon; and a magnetic compass would likewise be of little avail, as the Moon does not possess any measurable magnetic field. The best—and, in fact, the only—method of orientation should be a resort to the 'celestial navigation', which leads to a determination of position of the observer from the instantaneous aspects of the starry sky above him. Such celestial navigation guided the sailors of many generations across the expanses of terrestrial oceans before the advent of modern radio communications, and will undoubtedly play the same important role on the Moon in the future. The fact that (in the absence of any appreciable atmosphere) the stars are continuously visible from the Moon day or night, should make this method all the more readily available for any stranded group to find their bearings.

Suppose that this has been done, and that the next task of

the newly arrived party would be to communicate with another group which may have landed before them on some other spot of the Moon—a task which may possibly spell the difference between life and death for the newcomers. How to communicate with them? By radio? This problem also entails peculiar difficulties. As there is no appreciable ionosphere around the Moon to deflect radio-waves, all such waves will propagate there in essentially straight lines and will, therefore, be audible only at points at which the antenna of the transmitter remains visible above the horizon. But the curvature of the lunar surface is such that an antenna as high as the Eiffel Tower or the Empire State Building would set completely below the horizon, and the message would pass well overhead, at a distance of no more than 10 kilometres. Radio transmission would be no more effective on the Moon than communication by means of light signals. Both are limited to a small radius of action, and unable to help us to send any message very far. If, by the time when this problem becomes of practical importance, the Moon should possess an artificial satellite, its surface could be used to reflect radio-waves; or (if sufficient energy were available) a message could be relayed via the Earth, which remains the home-base and haven of security for the lonely creatures stationed as advanced sentinels on the lunar outpost to space. While a re-transmission through the Earth may well become feasible in more advanced stages of lunar exploration, the initial radio-communications, whichever way or method is adopted, may prove very difficult indeed.

Perhaps the most feasible, and technically also the simplest, method for initial long-distance communication on the Moon will be by *seismic waves*, produced artificially by suitably timed micro-explosions and propagating through the solid crust of the Moon (beneath the dust layer). Such waves are relatively easy to produce as well as to detect by means of quite simple equipment; and their discrete nature lends itself readily as a tool for a Morse-code communication. If there is no atmosphere to propagate sound, or ionosphere to reflect radio-waves, the

solid ground of the Moon itself can be used as the transmitting medium to propagate seismological signals.

It is easy to visualize the scene, at an already established lunar base-station, of its inhabitants watching the arrival of a new rocket from the Earth. At first observable only through a telescope, the rocket becomes eventually visible to the eye as a brilliant sunlit object slowly sliding towards the lunar surface. Its radio signals become inaudible as the rocket disappears below the horizon just before landing. Will it be a crash or soft landing? The seismic waves are potentially capable of relating the end of the story all over the lunar globe. Will the message arrive in the form of a wave indicating total destruction of the impinging space vehicle, or will an eventual sequence of seismic dots and dashes disclose the arrival of a new party of fellow-men from the Earth? We can just visualize the relief reflecting in the tense faces of the rugged explorers as the latter turns out to be the case; and once the survival of the newcomers has thus been signalled, the most pressing problem becomes one of communications: how to effect liaison speedily with the new-comers and replenish, perhaps, much-needed supplies—not to speak of the letters from home!

Unfortunately, the need for any transport by means of a moving vehicle across the rugged lunar landscape confronts us with at least as many new difficulties as does the problem of orientation or communication. To mention at least a few—if the lunar vehicle is to contain any turning parts (axes, wheels, etc.), their lubrication would constitute a difficult task; for no known oil or grease would stand exposure to a complete vacuum for a long enough time—quite apart from the large differences of temperatures—and the fine ubiquitous lunar dust, stirred by the motion of the vehicle, would find its way into all movable parts to act as an abrasive.

It is also obvious that the motive power propelling a vehicle on the Moon could not be generated by any internal combustion engine; for the latter could not operate in a vacuum. Jet engines will probably have to be used; though the actual design of

the requisite 'jet helicopters' astronomers leave gladly to the aeronautical engineers—in the hope that, if these engineers succeeded in producing spaceships which reached the Moon, the design of a suitable vehicle which could move over its surface and overcome the relatively gentle slopes in its way will not baffle them for long.

But wherever we may turn on the surface of the Moon, the scenery meeting our eye will be one of supreme desolation. The lunar plains are more barren than any rocky terrestrial desert. The lava beds of our extinct volcanoes are more inviting than lunar craters. Pitch-dark lunar caves are abodes of eternal silence. Above all, almost nothing ever happens on the Moon; and such changes as are prompted by external cosmic influences continue to grind the Moon's surface exceedingly fine, as we have already learned, but also at an exceedingly slow rate. A spider's web across a dim recess of any cavity would have a good chance of remaining undisturbed for millions of years. Not a very exciting place for a holiday-maker perhaps; but for the scientist—what an Aladdin's cave, full of heavenly wonders—both on the ground and above!

Only at certain times of the year is the calm over the lunar surface apt to be rudely disturbed from outside; and this will be when the Moon on its journey around the Sun with the Earth encounters a major meteor shower. Consider, for example, the month of August or the early part of November, when we are due for our yearly rendezvous with the Perseids or the Leonids. From our vantage point on Earth—with the whole atmosphere above us—such an encounter gives rise to an innocent meteor shower; but no particles of it will actually reach us on ground, as they spend themselves completely (due to atmospheric friction) many kilometers above our heads.

However, on the Moon—unprotected by any atmosphere—it will be a very different story. There the meteor particles of all sizes will pounce on the ground with their full heliocentric velocity relative to the Moon; and such is apparently the havoc caused by the bombardment of the Leonids (impinging on the

lunar surface with speeds of the order of 70 km/sec) that some dust gets ejected from the Moon and falls over all the way down to the Earth! At least the artificial earth satellites equipped with micro-meteorite detectors registered a secondary maximum of the frequency of impacts following the maximum of the Leonid shower by a time-interval corresponding to the time of free fall from the Moon to the Earth—occurring with velocities of about 11 km/sec rather than the 70 km/sec of the original Leonids. There seems indeed but little room for doubt that this secondary maximum signifies an infall of lunar surface dust stirred by the energetic Leonids.

This indication that such meteors can apparently knock off an overspill of dust on Earth gives us some idea of the violence which must descend on the Moon during such spells; and to a visiting astronaut such a shower might prove deadlier than machine-gun fire. Viewed from the relative safety of our terrestrial abode, all that the flashing of a meteor across the night sky may prompt us to do is to make a quick wish; but the only wish that an astronaut on the exposed surface of the Moon would be apt to make under such conditions is that he were not there! Not all seasons of the year will, therefore, be equally suitable for lunar holidays; and the times of major meteor showers will certainly merit emergency insurance rates.

6

CHANGES ON THE MOON

THE reader who has followed us in our account of the present aspects of lunar landscape, as given in the preceding chapters, has probably been confirmed in an impression that the Moon as we see it to-day is a dead body, completely petrified throughout the ages, and that most—if not all—of its visible features were wrought on its surface by impacts of other celestial bodies—be they asteroids, meteors, or comets—colliding with the Moon on its perpetual journey through space.

Such was, indeed, until quite recently the prevalent view among many serious students of the subject; and nobody expressed it perhaps more succinctly than Professor Harold Urey, a leading contemporary expert in this field, who on a recent occasion went on record to say that . . . 'It is a characteristic of science that different objective observers studying the same evidence come to the same conclusions, and that the overwhelming majority of such observers agree substantially. When this occurs, we regard the conclusions of such scientists as *true.* For this purpose . . . I am concluding that the volcanic hypothesis (of the origin of lunar surface features) is false and that the collision one is true . . .' These words, reflecting indeed the view of most investigators of the subject, were written in 1956. And, behold, barely more than two years later Nature confronted us with certain indubitable facts—in the form of a story centering around the crater Alphonsus—which necessitated at least a partial revision of former views; and as this

process of continuous revision represents one of the most exhilarating aspects of our science we wish, in what follows, to recount this story in some detail.

Before we do so, however, let us consider briefly some of the time aspects of the impact theories. Does anything ever happen according to them on the Moon even now? We mentioned earlier that the visible face of the Moon alone contains at least 300,000 craters with diameters exceeding one kilometre; and smaller ones can be observed only with really large telescopes. As, however, the Moon is not less than some 4,500 million years old, the formation of impact craters at a rate of one per every 15,000 years would be sufficient to account for them all if their production proceeded uniformly in time (and much less than that if the majority of them originated—as is possible—in the early days of the history of the solar system). If we consider the fact that telescopic astronomy is barely more than three centuries old, we readily see that, accordingly, the chances of observing any single meteor impact capable of producing a visible crater on the Moon are pretty slim indeed.

And yet—the annals of selenography contain a number of sporadic reports that certain small changes on the surface of the Moon have actually been observed. Most of such indications were, however, based on visual observations in the days when the critical faculty of the observer was perhaps not what we should like, and their impact on lunar studies has not been very profound; for many astronomers were unwilling to take them seriously. Give us the photographic evidence, they said, showing any change which we can measure and re-check. Visual work is susceptible to more pitfalls—personal, instrumental, atmospheric—than the observer himself can fully realize; and transient changes reported visually are seldom capable of verification.

There is indeed much to be said for this critical attitude; for, in particular, the early selenographic literature is replete with observations which could scarcely have had a basis of fact. Yet the reports of changes of a few specific spots on the lunar

surface—such as the crater Linné in the middle of a large plain which we call Mare Serenitatis or, more recently, in the crater Alphonsus near the centre of the apparent lunar disk (cf. Plate XIV)—have been too persistent to be entirely disregarded. And what is more, photographs of the Moon in the light of different colours, secured in the last decade (notably by Alter, working with the 60-in reflector of the Mount Wilson Observatory) have provided some independent evidence in line with the reports of visual observations. Or again, the Russian observers Dzhapiashvili and Ksanfomaliti, working with a photoelectric polarimeter of the Abastumani Observatory of Georgian Academy of Sciences in the Caucasus, reported that the degree of polarization on the floor of the crater Aristarchus (Plate XIII) diminished from approximately from 10 per cent around 1950 to 4 per cent by 1960—thus indicating that a significant (though otherwise imperceptible) change had apparently taken place in the micro-structure of the scattering surface within the last decade.

The changes suggested by such work were not as profound as the appearance of any new mountains; but rather a temporary obscuration of some features—in particular, at the bottom of Alphonsus—which are ordinarily quite distinct, but on occasions appeared as veiled in haze (particularly in blue light). Now such a phenomenon is well known to terrestrial photographers; for the diffusion of light in the Earth's atmosphere causes all photographs of distant objects to show considerably less contrast in blue light than in the red.

Could the same cause be operative on the Moon as well? Scarcely so; for earlier in this book we hope we made it abundantly clear that, on account of its small mass, the Moon does not possess any permanent atmosphere to speak of; and any gas possibly escaping through any surface fissure would be discharging into vacuum and dispersing into space as quickly as it escaped. Its density at any height above the surface would, therefore, be hopelessly too low to produce any observable diffusion of light. There are, however, two other ways by which

gases escaping from beneath the surface could veil its neighbourhood in haze. The first is by stirring the fine dust which must cover most part of the lunar surface to some depth—and dust diffuses the light much more effectively than any gas molecules; the second is the possibility that the escaping gas may become self-luminous under the action of sunlight, and envelop the region by a fluorescent veil whose light would dim the stark contrasts of the sunlit landscape beneath.

Provided that the exciting solar radiation is sufficiently energetic, this second mechanism could produce a loss of contrast about 10^{10} times more effectively than diffusion; and an appreciable 'obscuration' could be produced by as few as 10^{15} gas molecules per square centimetre between us and the ground (i.e., a gas layer at 10^{-10} of atmospheric pressure). The existence of localized lunar 'atmosphere' of such density, produced temporarily by gas escape through surface cracks cannot be ruled out for any good reason; but whether or not it is indeed the cause of occasional dimming of certain details of the lunar landscape reported by various observers in the past remained largely hypothetical—until the night of 3 November, 1958, when by a sheer chance Nature gave away a valuable clue to lunar research, which was picked up by N. A. Kozyrev, a Russian astronomer working at the Crimean Astrophysical Observatory in the U.S.S.R. As the events of that night represent one of the most exciting recent episodes in the history of lunar studies, and may remain unique for some time, we shall describe them in this chapter in some detail.

Dr. Kozyrev was, at that time, no novice to lunar research—as is borne out by his work on the luminiscence of the lunar surface described earlier in this book. It was, in fact, this work—coupled with Alter's photographic evidence—which attracted his attention to Alphonsus in quest of possible luminescence of its surface in October and November 1958. As in his previous work, he used the 50-in reflector of the Crimean Astrophysical Observatory of the U.S.S.R. Academy of Sciences, with the spectrograph giving a linear dispersion of 23 A/mm at $H\gamma$; the

scale of the image in the focal plane was such that 1 mm corresponded to about 18.6 km on the lunar surface. The exposure time on Kodak 103a-F emulsions ranged between 10 and 30 minutes.

Nothing particular was noted on the spectrograms of Alphonsus up to the night of 2–3 November, when three spectrograms were taken by Kozyrev and Ezerski with the slit running through the central peak of the crater (as shown on the accompanying Plate XV). The 50-in telescope at Crimea does not possess a separate guiding telescope; and the observer has, therefore, to guide on some object visible through the slit. As Kozyrev was thus guiding on the image of the central peak, while taking the first spectrogram at 1.00 GMT after midnight, he noticed that the outlines of the peak became indistinct and covered by an unusual reddish tinge.

After the exposure was over, Kozyrev and Ezerski turned the instrument to Mars (according to a pre-arranged programme) and did not return to Alphonsus for another exposure till between 3.00–3.30 GMT. Only the central peak was visible through the slit, and Kozyrev was struck by its unusual brightness and white colour. This did not, however, last for long; and watching continuously through the slit, Kozyrev noticed that the glare suddenly disappeared. The exposure was immediately stopped, and another taken between 3.30–3.40 GMT, with the same position of the slit.

While guiding on these spectra Kozyrev did not, he confessed, pay any special attention to the visual appearance—believing that the peculiarities he witnessed may have possibly been caused by a change in the observing conditions. At any rate, the unusual phenomena did not last long; and if visual evidence alone were available, Kozyrev might well have rubbed his eyes in distrust.

However, when his spectrograms were developed next morning, it transpired beyond a shadow of doubt that the central peak of Alphonsus—an inconspicuous hill, barely 1,000 yards in height—must, on the previous night, have been the scene of

Sunrise over the crater Aristarchus in the north-eastern quadrant of the visible face of the Moon—in the midst of the plains of the Oceanus Procellarum
The bright rays spreading around this crater have been reported by Kozyrev to exhibit luminescence under the impact of solar radiation

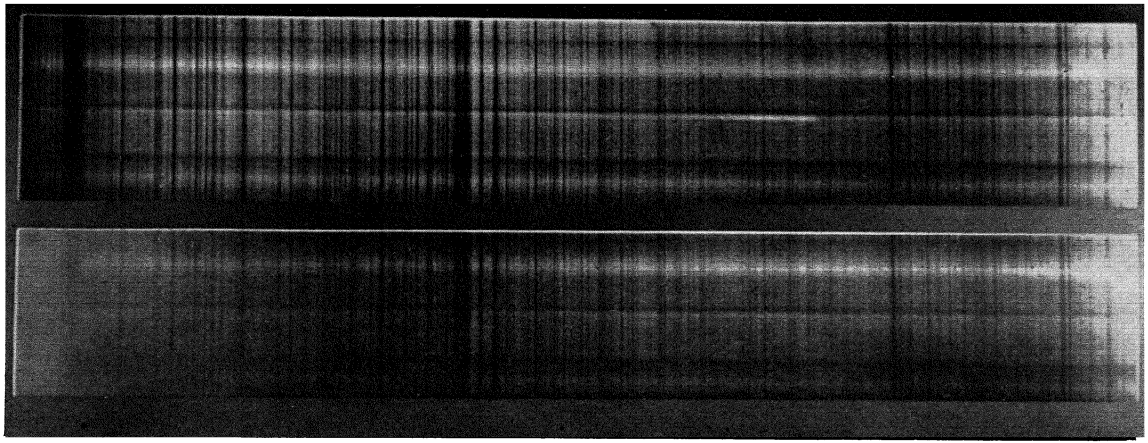
Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

PLATE XIII

Sunset over the central part of the visible face of the Moon, containing the three large craters of Ptolemy (bottom), Alphonsus (centre) and Arzachel (top) The central peak of Alphonsus, 912 metres in height, which on November 3rd, 1958, became the focus of events described in Chapter VI, is marked by an arrow

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

PLATE XIV



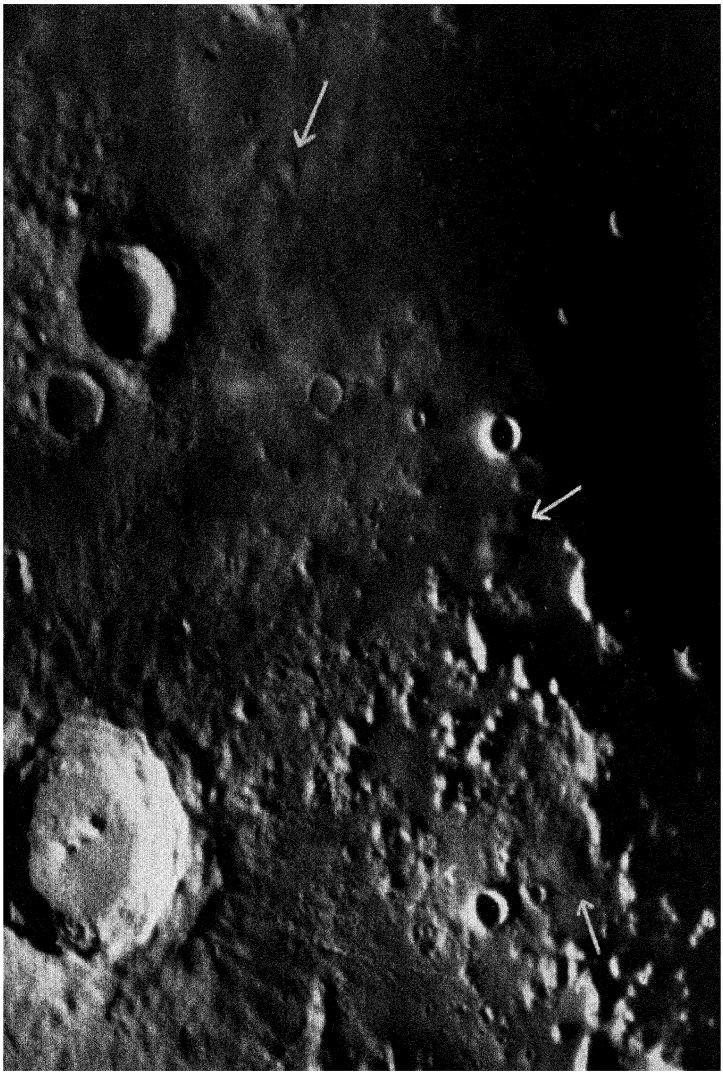
The spectra of the crater Alphonsus taken by Drs. N. A. Kozyrev and V. I. Ezerski on November 3rd, 1958, containing evidence that some kind of volcanic eruption occurred on the Moon at that time. The upper spectrum was exposed between 3.00–3.30 a.m., and the lower between 3.30–3.40 a.m., GMT

Each spectrogram analyses the light from a narrow strip oriented east-west in the sky (i.e. horizontally on Plate XIV), and bisecting the entire crater through its central peak

Note in top picture (more strongly exposed one) the narrow bright streak running through the centre of the spectrum, but not extending all the way to the right. This streak was impressed by the light of the eruption, and shows characteristics of an incandescent cloud containing carbon—a common constituent of volcanic gases. The upper spectrum was exposed for 30 minutes. Immediately afterwards, a 10-minute exposure was taken (lower spectrum) in which the evidence of luminous gases no longer appears. All other light analysed in the two pictures is nothing but scattered sunlight. A more detailed key to the individual features shown on these spectra is given on Figure 11

Crimean Astrophysical Observatory photograph, taken with the Observatory's 50-inch reflector (by courtesy of 'Sky and Telescope')

PLATE XV



Lunar 'domes' south-west quadrant of the crater Copernicus examples of which are marked by white arrows. The large dome due west of Copernicus shows evidence of central depression

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

PLATE XVI

extraordinary events. On the first spectrogram taken after 1 a.m. (and not reproduced here) the image of the central peak was considerably weakened, in violet light, in comparison with the neighbouring details of the crater—a fact which was not observed on earlier spectra. The measurement of this photograph showed that the amount of this absorption was inversely proportional to the wave length; and the total dimming in the visual region proved to be about 10–20 per cent.

On the second spectrogram (as reproduced on Plate XV, top) this absorption had already disappeared; but an entirely new emission spectrum, consisting of an interlocking series of bright bands, had made appearance on that part of the plate where the slit of the spectrograph intercepted the central

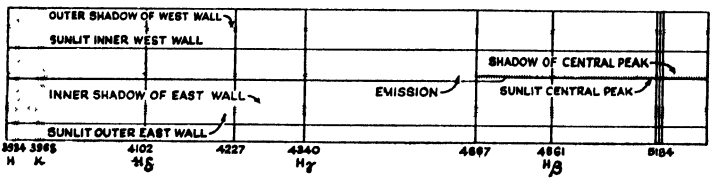


FIGURE 11. A schematic diagram containing the key to different features of the spectrograms of the crater Alphonsus, as reproduced on Plate XV. (*By courtesy of 'Sky and Telescope'.*)

mountain (cf. also Figure 11). The most noticeable peculiarity of this emission spectrum is a group of bands commencing at λ 4737 Å and rather sharply terminated on the red. Other bands, with maximum emission around λλ 5165 and 5636, appeared to belong to the same system, and Kozyrev identified them tentatively with the so-called Swan bands of the carbon molecule (C_2); the distinct maximum at λ 4737 marks the beginning of the vibrational band of this molecule. Moreover, further to the violet (between the hydrogen line Hδ and the H-line of CaII) Kozyrev found evidence of a fainter system of bands belonging apparently to the tri-atomic carbon molecule (C_2), so that the presence of carbon gas above the central peak of Alphonsus in the small morning hours of 3 November, 1958, appears to be attested almost beyond doubt.

A further peculiarity of the emission spectrum of the central peak (well shown on the upper spectrum reproduced on Plate XV) was the fact that the emission was not superimposed directly on the peak, but slightly shifted in the direction of the setting Sun. This shift amounted to approximately 0".7 or 1.3 km on the Moon's surface. It is possibly due to the fact that the ejected cloud of gas was optically thick to the Sun's short-wave radiation, which penetrated (and excited luminiscence) in only that part of the cloud which was facing the Sun.

What is the most likely interpretation of these unusual observations? Kozyrev maintains that, on the morning of 3 November, the crater Alphonsus on the Moon was the scene of a genuine volcanic outburst. According to him, the whole phenomenon commenced with an ejection of volcanic ashes from an active (though invisible) crack in the central peak, appearing as a reddish cloud in the guiding eyepiece, and was followed by a gas discharge which gave rise to the emission spectrum, and of which molecular carbon may have been only one of the constituents (as the spectrum contains evidence of other, as yet unidentified molecules).

The times at which the spectra were taken permit us, moreover, to conclude that the actual gas discharge lasted not more than 2½ hrs, and not less than half an hour. At least the spectrum taken between 3.30–3.40 a.m. (as well as those taken the following night) was thoroughly normal and showed no particular feature of interest (cf. Plate XV, bottom). During the outburst the spectrum of the central peak of Alphonsus looked, however, very much like that of a comet—except, perhaps, for a complete absence of the ultraviolet bands of the cyanogen molecule (CN), so prominent in comets, of which there appeared to be no trace on the Moon.

Kozyrev believes that the origin of the gas discharged by Alphonsus was molten magma that had risen to the lunar surface from the interior; and if this view were correct, the existence at present of at least isolated heat pockets beneath the Moon's crust would have to be taken for granted. This con-

clusion is, however, not yet inevitable; for even relatively cold gas escaping from the interior by some accidental fissure could stir surrounding dust (not necessarily volcanic ash) by jet action; and there seems no doubt that the carbon gas was both produced (by photo-dissociation of more complex original molecules) and induced to shine by the action of sunlight—or, more specifically, of solar ultraviolet radiation which does not penetrate to the surface of the Earth.

Yet the hypothesis of a cold gas discharge would seem to fall short of giving an adequate account of one essential phenomenon: namely, why did the dust not remain stirred during the entire gas discharge? As the Moon possesses no atmosphere, the dust, once stirred, would settle down rapidly with the speed of free fall; but would remain stirred as long as the gas blows. Why was there, then, no evidence of light scattering by dust (weakening, selectively, the ultraviolet part of the spectrum) throughout the whole outburst, but only in its opening phase—unless the dust did not come from the surface, but from the volcanic crater itself?

Sunlight on the Moon is certainly intense enough to excite the carbon molecules to shine; but which parent carbon compounds did it dissociate? Acetylene? Or hydrocarbons—such as may be present in oil? It is decidedly too soon yet to jump to conclusions that there is oil beneath the crust of the Moon—in the face of the widely held belief in organic origin of oil on Earth. But the solar system is known to be fairly infested with hydrocarbons—the atmospheres of the major planets contain tremendous amounts of them—and although oil on the Earth has so far been found only under sedimentary deposits, it is perhaps because these rocks are easy to drill, and because nobody has looked for it under igneous rocks. At any rate, should further astronomical work strengthen the conjecture that lunar carbon may be due to the decomposition of hydrocarbons, the current theories of the origin of oil on Earth might be due for drastic revision.

Needless to say, we are still far from this stage; for even

Kozyrev's identification of the emission features of his spectrum with the Swan bands of the carbon molecule did not pass unchallenged. Thus G. P. Kuiper pointed out that the λ 4737 Swan band should have been observed in absorption, rather than emission, against the sunlit lunar surface; and that at λ 5129, only weakly in emission. But, according to Kozyrev, the clue to the emission nature of the spectrum is to be sought in the exceedingly low density of the effusing gases (at which molecular collisions cannot play any appreciable role). The measured intensity of the observed emission required the presence of some 10^{14} molecules of C_2 over each square centimetre of the lunar surface covered by the cloud—which extended over about 100 square kilometres. The total number of carbon molecules present in it at any particular time during the crucial stages of the outburst was, therefore, of the order of 10^{26}.

The velocity of the C_2 molecules, formed as sunlight dissociated their parent compound, must have been of the order of one kilometre per second. Hence, a halt in the outflow of gas would have stopped all radiation phenomena within some 10 sec. For their maintenance, an outflow of 10^{25} molecules per sec of C_2 was necessary—an amount contained in approximately one cubic metre of this gas at terrestrial atmospheric pressure. Since the gas flow continued for not less than half an hour, the total amount of carbon gas that emerged from the central peak of Alphonsus would have filled a few thousand cubic metres at standard pressure. As, moreover, only about one per cent of the primary molecules formed C_2 by dissociation, the total amount of gas released from the central peak on 3 November, 1958, should have been of the order of a few hundred thousand cubic metres at standard pressure; though, on the Moon, it expanded (discharging into vacuum) to a cloud many kilometres in size, at a probable density of 10^{-9} that of the Earth's atmosphere at sea level (and at least a thousand times higher than any gas envelope around the Moon as a whole).

Whatever may be the uncertainty regarding some aspects of the interpretation of the luminous phenomena exhibited by Alphonsus on 3 November of last year, and observed spectroscopically by the sheerest of chances, one fact stands out without a shadow of doubt: namely, they were not due to any impact. Quite apart from all observed appearances and time scale of the phenomenon, which were utterly different from what one would expect on any impact hypothesis, what are the chances that any colliding body would just happen to strike the small central peak of a large crater? No; whatever happened was prompted by internal reasons; and volcanism may be as good a name for them as any. Besides, the main problem confronting us in this connection is not a detailed interpretation of the underlying mechanism, but rather how widespread can it be.

There is no doubt that the whole phenomenon, if not corroborated spectroscopically by an unusual stroke of good luck, would have passed completely unnoticed—as may indeed have a great many others in the past, whether somebody spotted them or not. And what are the chances that when a volcanic eruption of this kind occurs in a brief time span of 1–2 hours, a great telescope equipped with a suitable spectrograph will be turned on it to record this elusive phenomenon? The chances are certainly very small; and the fact that Kozyrev's observations are so far unique (and may remain so for some time) discloses next to nothing about the actual frequency of such outbursts over the entire visible face of the Moon.

Yet even this first instance of such a phenomenon on record is extremely valuable, because it reveals what to expect. If the spectrum recorded by Kozyrev last year is a typical example of a lunar volcanic outburst, we know that the principal discrete luminous phenomenon is to be expected in the blue—between 4650–4750 Å. Therefore, the contrast of any such outburst would be greatly increased for the visual observer if he were watching the Moon through a narrow-passband (interference) filter centred on this domain of the spectrum. In order to monitor the Moon for possible future outbursts, it would be

desirable to watch the whole disk (under a low magnification) through such a filter: a sudden brightening of any spot in the spectral range including the λ 4737 Swan band would point to a volcanic gas eruption much more reliably than any observations in integrated light.

Professional astronomers are, unfortunately, too few to undertake such work systematically. It is, however, almost ideally suited for amateurs—who outnumber their professional colleagues all over the world by at least ten to one. The work calls only for a small telescope, and the necessary filters can be easily procured. The increase in contrast of the phenomenon as seen through such a filter—though appreciable—would still require, of course, corroboration before its reality could be taken for granted. The best corroboration—the spectroscopic evidence—would not be easily forthcoming, particularly on short notice; for astronomical instruments of the requisite power are still too few and far between in the whole world. Yet if a sudden brightening of the same lunar spot in the expected spectral range were reported simultaneously by more than one independent observer, the probability that the phenomenon was real would be correspondingly increased.

Visual observations of this kind may, indeed, prove very valuable for spotting such regions on the entire face of the Moon as may be active in this sense at the present time; and their watch may provide amateur astronomers dedicated to lunar observation with another important and timely task.

7

DESTINATION MOON

THE idea, or hope, of reaching the Moon—in dream or reality—has been with mankind from time immemorial. The entrancing visions of Kepler's *Somnium*, or the professionally less competent excursions of Swift, Cyrano de Bergerac, and many others belong more properly to the domain of belles-lettres. Listen, however, to the following extract of a letter which nobody lesser than Sir William Herschel, then at the beginning of his great career, wrote on 12 June, 1780 to the fourth Astronomer Royal, the Reverend Dr. Nevil Maskelyne:

I beg leave to observe, Sir, that my saying there is almost an absolute certainty of the Moon's being inhabited, may perhaps be ascribed to a certain Enthusiasm which an observer, but young in the Science of Astronomy, can hardly divest himself of when he sees such wonders before him; and if you will promise not to call me a Lunatic, I will transcribe a passage . . . which will shew my real sentiments on the subject.

Perhaps conclusions from the analogy of things may be exceedingly different from truth; but . . . seeing that our Earth is inhabited and comparing the Moon with this planet: finding that in such a satellite there is a provision of light and heat: also, in all appearance, a soil proper for habitation fully as good as ours, if not perhaps better—who can say that it is not extremely probable, nay beyond doubt, that there must be inhabitants on the Moon of some kind or another.

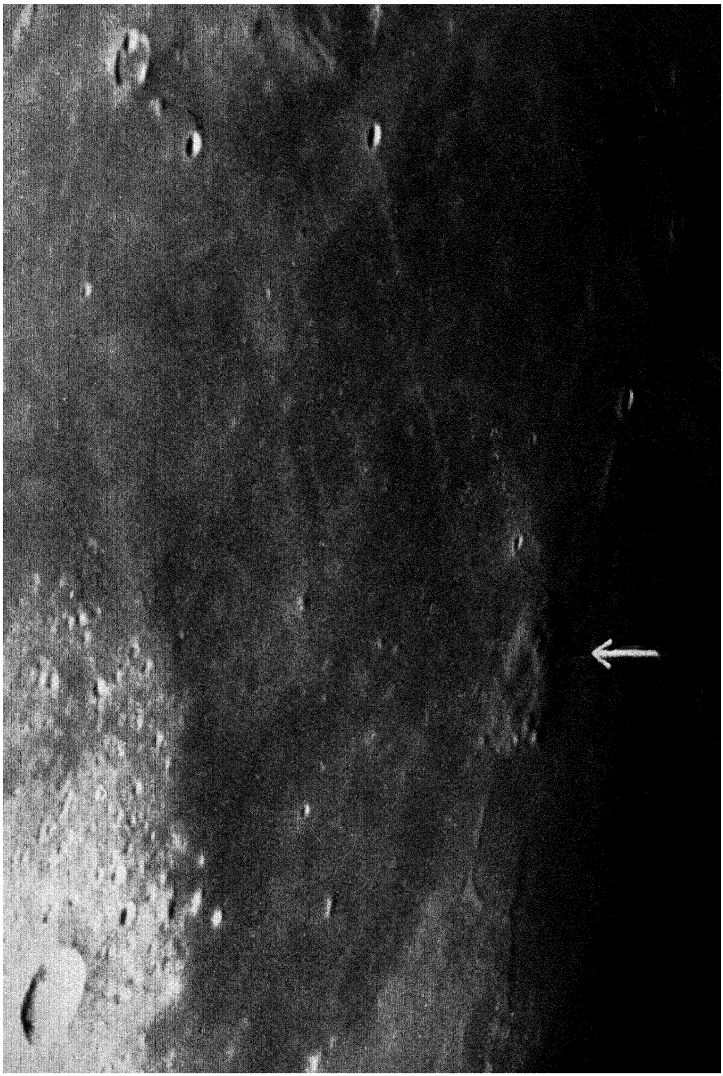
What a glorious View of the heavens from the Moon! How beautifully diversified with hills and valleys! No large oceans to

take up immense plains fit for pasture etc. Uninterrupted day on one half, and on the other a day and night of noble length, equal to many of ours! Do not all the elements seem at war here when we compare the Earth with the Moon? Air, Water, Fire, Clouds, Tempests, Vulcanos, etc: all these are either not on the Moon, or at least kept in much greater subjection than here. . . .

For my part, were I to chuse between the Earth and Moon, I should not hesitate a moment to fix upon the Moon for my habitation.

We do not know what the kindly Reverend Maskelyne replied to this effusion by his correspondent; some of his successors would, I am afraid, have been very much more outspoken. Besides, we dare say, the readers who followed in the preceding chapters the account of our present knowledge of the conditions prevailing on the lunar surface may be considerably more reluctant in choosing the Moon for their own habitation. We know, in particular, that no life—in any form—can await us there; but the 'glorious view of the heavens' beckoning from its surface constitutes an attraction even more irresistible for the modern astronomer than Herschel could have ever dreamt of.

After we have described, in preceding chapters, the principal results of astronomical investigations of the lunar surface available to us so far, many a reader may be tempted to ask: when do we actually go up there, to see for ourselves and find out to what extent the story outlined by the astronomers is really in accord with the actual facts? To-day, 180 years after Herschel's letter, the time on the cosmic clock just about strikes the hour when this is becoming a practical possibility; and—after a separation lasting some 4,500 million years—some particles of terrestrial matter have already been transferred to the lunar surface. On 13 September, 1959—a memorable date in the history of human endeavour—at 22 hours, 2 min and 24 sec of Greenwich mean time, the first 'lunar probe' of Russian origin crashed against the surface of the Moon in the region of the Mare Imbrium, dramatically to end this separation; and shortly thereafter, on 4 October of the same year, another Russian rocket circumnavigated the



A dome-like formation Rumker in Sinus Roris west of the crater Mairan, representing probably a conglomerate of small domes

Observatoire du Pic-du-Midi photograph, taken with the 24-inch refractor

PLATE XVII

Sunrise over the central parts of the Oceanus Procellarum showing a well-developed system of wrinkle ridge between the craters Euclides and Wichmann

Yerkes Observatory photograph, taken with the 40-inch refractor

PLATE XVIII

Moon and secured the first photographs of its far side. The time of the 'voyages of discovery' to the Moon is already on; and impacts of inanimate probes will no doubt be followed, in due course, by soft landings of craft carrying instruments and eventually even human beings. The date of this last achievement is perhaps more difficult to foresee with any accuracy; but there seems little room for doubt that manned landings on the Moon will be accomplished within our lifetime.

At the commencement of Chapter 2 we briefly referred to an attempt of reaching the Moon by means of a manned projectile fired from a gun—the legendary Columbiad of the Baltimore Gun Club—which the fertile imagination of Jules Verne conjured up for his readers a century before our time. Now, after the lapse of a hundred years, it is easy to see what would have gone wrong with it in practice. The gravest mistake Verne committed was, in fact, to place men (as well as living animals) in his projectile; for should President Barbicane and Captain Nichols have really been induced by Michel Ardan to enter with him the cylindrical shell designed by the worthy T. J. Maston, their fate would have been gruesome beyond description. Suffice it to say, in brief, that in order to accelerate a projectile to the velocity of 11 km/sec (necessary for escape from the gravitational field of the Earth) inside a gun barrel of the dimensions of the Columbiad, it would have been necessary to expose the astronauts to an initial acceleration of 2.9×10^7 cm/sec^2 or almost 30 thousand terrestrial g's—which no living organism could possibly survive for a fraction of a second.

And not only the travellers inside, but also the projectile itself would have been subjected to a crushing strain in between the expanding gases of the explosive charge and the resistance offered by air to a body moving through it at a velocity of more than 30 times that of sound. A more detailed analysis of the actual fate of the projectile of the Columbiad (undertaken many years ago by Oberth and others) revealed that the hollow aluminium cylinder would have been squashed to a cake and heated to several hundred degrees to become a

crematory for its crew within a few seconds of their flight, which would have ended not far from its origin—to the intense disappointment of countless spectators and to the horror of their friends. Although, from a technical point of view, the event envisaged by Verne would thus have ended in a colossal and grim fiasco, in one respect the great French novelist did anticipate keenly the future: namely, by placing the scene of his narrative—Tampa Town in Florida—only a little more than 100 miles from Cape Canaveral where the modern sequel to his story is making history this decade. In it the giant guns of the past have been completely abandoned and their place taken by their modern successors—the rockets.

This is not the place to go into details of the reasons for this change—the gradual acceleration permitting the attainment of escape velocity outside the atmosphere being the most important one—but only to say a few words on the role of rockets in the exploration—both manned and unmanned—of the Moon. The spectacular achievements of the Russians in this field in 1959 have frequently been referred to in this volume before; but lack of information prevents us from saying much about their boosters. The U.S. Atlas, currently propelling to the Moon the series of hard-landing space-craft of the Ranger class (Plates XIX and XX) are, on the other hand, well known; and so is the present state of development of the Centaur booster which is to transport to the Moon the soft-landing Surveyors (Plate XXII), as well as the early model of Saturn (Plate XXIII).

Nevertheless, the landing on the lunar surface of instruments of increasing degree of complexity, several of which we can expect with confidence to witness in the next few years, is to be but a preview of major events to follow on their heels. For the United States, the first real target was boldly defined on 26 May of 1961, when President Kennedy told Congress: 'I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth.' To make a manned voyage to the Moon and back constitutes, to be sure, a difficult

task—far more difficult than cartoonists, writers of space fiction, or even most scientists and engineers may think. Nevertheless, backed as it is by prestige and technical resources of the greatest industrial power on Earth today, this project—which received the code name 'Apollo'—represents an attainable goal, worthy of the effort which it will require; and, incidentally, its estimated cost of 30–40 milliard dollars should render it the most expensive experiment so far undertaken by the human race on this planet—at a cost far in excess of those spent in previous decades for the development of nuclear energy on an industrial scale, and comparable so far only with the costs of protracted large-scale warfare by which major nations on this Earth have attempted from time to time to settle their mutually conflicting interests.

To transport a party of men to the Moon with any hope of return will, to be sure, call for the use of much larger rocket boosters than those so far available. The U.S. Project Apollo expects to employ to this purpose an advanced model of the Saturn booster—the so-called Saturn C-5—which is now under design by the U.S. National Aeronautics and Space Administration's Marshall Space Flight Center at Huntsville, Alabama, under the direction of Wernher von Braun. A schematic view of this giant three-stage rocket can be seen on the accompanying Plate XXIV side by side with its existing predecessor, and the Statue of Liberty in New York placed in their midst for the sake of comparison in size.

A few words of description of this Columbiad of the twentieth century may well be of interest to the general reader. Its first stage, 43 feet in diameter, towers 170 feet above the ground; the second and third stages being approximately 80 feet in length (and 22 feet in diameter), adding up to a total height of 330 feet or 100 metres. The total weight of this spacecraft (when loaded)—about 6 million pounds at take-off—is equal to the combined weight of twenty-five Boeing-707 jets or (for those who prefer to think in naval terms) of one light cruiser.

To sail a light cruiser at 30 or even 40 knots through the

seven seas of this Earth is one matter; but to lift it vertically into the air and accelerate it to a velocity of 11 km/sec or over 20,000 knots is obviously another! In order to accomplish this feat, vastly more powerful engines are necessary. The first stage of our modern Columbiad is to be lifted from the ground by a cluster of five giant jet engines (of the type F1, already built by the North American Aviation, Inc., of Los Angeles), each of which is 18–20 feet tall and measures 16 feet across the end of its thrust chamber. According to the static tests already performed, each one of these five engines will supply a vertical thrust of 1,500,000 lb; and their cluster will thus provide for the first stage of Saturn C-5 a combined thrust of 7,500,000 lb, equivalent to close to 150 million standard horse power!

Needless to say, in order to deliver this power a prodigious amount of fuel will have to be expended. While its engines burn, the first stage of Saturn C-5 will consume 15 tons of fuel (consisting of a mixture of two parts of kerosene to one part of liquid oxygen) per second of a flight lasting approximately $2\frac{1}{2}$ minutes—the total of 2,250 tons being large enough to drive an average-size family car outside the confines of the solar system! After the first stage has lifted the Saturn C-5 off the ground, a second stage equipped with five J-2 hydrogen-burning engines (of 1 million lb total thrust) will take over. The combined action of the first two stages should be capable of putting a 240,000 lb payload in an orbit around the Earth at an altitude of approximately 200 km. The third stage of the giant rocket, powered by a single J-2 engine, will then be capable of accelerating a payload of 90,000 lb to the Earth escape velocity and delivering its cargo to the Moon. It takes approximately 230,000 horse power to lift to the Moon a man weighing 150 lb.

According to the present schedules, no complete C-5 system is to take off into space before the year 1965; and the first one that goes to the Moon may not attempt actual landing, but go into orbit around it for reconnaisance of its surface at a closer range before returning back to Earth. Eventually, however,

before the end of President Kennedy's promised decade the time should come to reach the supreme goal. The Moon-bound space-craft, weighing about 85,000 lb, will consist of three parts: the command module housing a three-man crew (two of whom should be trained astronauts, and the third a scientist); the service module with supplies, engines and propellants; and the small landing 'bug' (frontispiece) in which two men—a scientist and an astronaut—should eventually descend to the lunar surface.

During the three-day voyage to the Moon the crew will have an opportunity to burn fuel to correct their course. After arriving in the vicinity of the Moon, they will fire additional retrorockets to place their ship in a circum-lunar orbit about 100 miles above the lunar surface. Then two of the crew men will crawl into the bug through an airlock and detach it. The bug will have its own small rocket engines; and by firing these briefly the crew will be able to put their ship into an elliptical orbit which, at peri-selenium, should approach the lunar surface within ten miles.

If anything has gone wrong, the astronauts will still have a chance to rejoin the mother ship and return to Earth without landing. But if all is well, at their next close approach to the Moon they will attempt to land and, by burning sufficient fuel they will decelerate the motion of the bug making it slowly descend on the surface. They will be able to hover for a few minutes in quest of a suitable landing place; and finally the bug will come down, steadying itself on four spidery legs at the end of the first part of its long and perilous journey.

At a later stage the astronauts may spend days exploring the Moon; but the first men to land will probably take off again as soon as their mother ship has re-appeared overhead. At the right moment determined by their flight schedule they will ignite their rockets for a vertical rise, leaving their landing gear behind. Because of the absence of any atmosphere and relatively low lunar gravity, take-off from the Moon should be comparatively easy. NASA planners believe that the finding of

the mother ship and joining it in its circum-lunar orbit should be no more difficult than the rendezvous manoeuvres previously practised with the same equipment in orbit around the Earth. After the lunar rendezvous has thus been accomplished, the bug will be abandoned to revolve for ever around the Moon, and the reunited crew of three men will head back for the Earth.

This, in brief, is an outline of what to expect in the early days of manned exploration of our satellite. Much work remains obviously to be done before this bold scheme has become a part of the history of the human race; and its costs in terms of the material as well as human resources will be enormous. Before the necessary credits are granted, the legislators as well as their constituents have every right to inquire into the wisdom of so ambitious an undertaking, and about the benefits which could be derived from its success. What can we say in reply? Why, indeed, do we wish to go to the Moon at all?

There are many answers to such questions which we can attempt to give at this time, and all of them would embody but a part of the whole story. But in order to confine our attention at first to possible material benefits which could result from such a venture, let us consider a theoretical possibility of replenishing from the Moon our supplies of such raw materials as may one day become scarce on the Earth on account of their intensive exploitation. The ores of heavy elements (such as precious metals, or naturally radioactive substances) come readily to mind in this connection. Can astronomy help us to assess the prospects of such a possibility?

All that we know (and have already related) of cosmochemistry, coupled with the mean density of the lunar globe, does not encourage any particular hopes that the crust of the Moon may contain an appreciably higher proportion of heavy elements—particularly of such sought-after heavy metals as gold and uranium, which are both terrestrially and cosmically so scarce. As far as the bulk of the lunar mass is concerned, its five most abundant constituents are probably oxygen, silicon,

iron, magnesium, and aluminium or calcium—mostly in compounds and approximately in that order—followed by other elements (both heavy and light) in diminishing proportion.

What is the likelihood that some of the scarce and possibly valuable elements may be found on the Moon—as on the Earth—in local concentration as ore deposits which could possibly be mined? Is there, in fact, anything we might expect to find in equal or greater abundance on the Moon than on the Earth?

If we consult the geologists specializing in terrestrial ore deposits, we learn that there are four or five kinds of processes which may bring about localized enrichment of certain elements. They are the processes involving magnetic differentiation, the hydro-thermal processes, weathering, sedimentation, or biological processes. Most of these—and this is significant—can be discounted, for reasons already given in previous chapters—as having played any major role in the long history of the Moon.

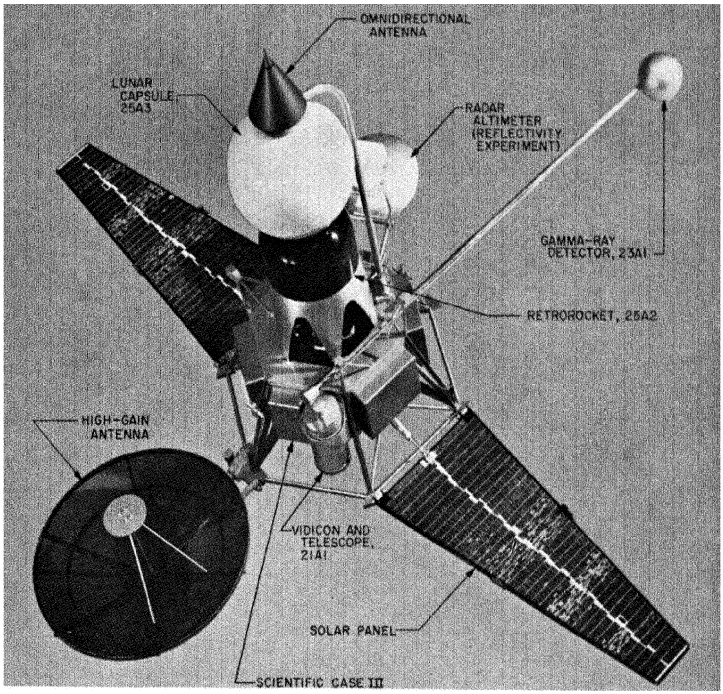
The only two metals which are economically important and may be present on the lunar surface or in its crust in relatively high abundance are iron and nickel due to meteorite impacts; and conceivably these could be mined and exploited. But—quite apart from questions of economics or transport—mining operations on the Moon would be both facilitated and hampered, in comparison with the corresponding terrestrial work, by the prevailing conditions. The factors in our favour would be low gravity on the Moon, and also a virtually unlimited supply of energy coming from the Sun—if it can be suitably trapped and stored. Coming down to practicalities, however, any mining engineer would tell us how difficult it would be to carry out any extensive drilling, mining, or chemical-extraction processes in the absence of an adequate supply of air and water; for one must have some kind of medium in which chemical reactions can take place; and the running of a jack hammer or drill under near-vacuum conditions (coupled with the low thermal conductivity of lunar rocks) might lead to excessive heating of the tools.

Now as we already stressed earlier in this book (pp. 24 and 50)

there is no doubt water on the Moon—possibly as much as in all seas and oceans on the Earth—though not in liquid form. The molecules of H_2O are, instead, built into the crystal lattice of many minerals (such as the silicates, or volcanic glasses) which we expect to find on the Moon. This water is probably primordial (i.e., not acquired at any later stage of mineralization) and can, in principle, be extracted back by heating. If we admit that there are even traces of volcanism on the Moon, we should seek to identify them at a distance as potential beds of volcanic glasses—such as pitchstones or serpentines. Pitchstone contains, for instance, about 5 per cent of water by weight; and serpentine (or kimberlite) as much as 10 per cent. Moreover, one group of meteorites—the carbonaceous chondrites (probably present in some abundance on the surface of the Moon)—are known to contain from 10 to 20 per cent of water. Their dehydration should, in turn, constitute no difficult process; one could just shovel such rocks into a furnace at about 500–1,000°C to release the water by heat and then condense the escaping vapour into liquid water. Some problems may arise in connection with its condensation; yet it could be done —and, to this extent, the incipient lunar base could make itself self-sufficient—provided that the requisite temperatures could be locally produced.

The only source of energy which could be readily used for this purpose is, of course, that incident from the Sun. The amount of this energy is indeed tremendous: when the Sun stands over our head, each square kilometre of lunar surface receives an amount of heat equal to 2×10^{10} calories, or $4.18 \times 2 \times 10^{17}$ ergs, per minute. This energy, if converted into electricity, would correspond to 5.0×10^9 kilowatts per hour. Compare with this the hydroelectric energy generated by the largest terrestrial installations—such as 1.25×10^6 kilowatts per hour produced by the Hoover dam in the United States, or 9×10^5 kilowatts of the Dnieprostroi in the U.S.S.R.

There should, therefore, certainly be no shortage of energy on the sunlit face of the Moon for running solar furnaces of



A schematic view of the Ranger 3, 4, and 5 spacecraft, which was launched to the Moon in January, April, and October 1962 from the United States

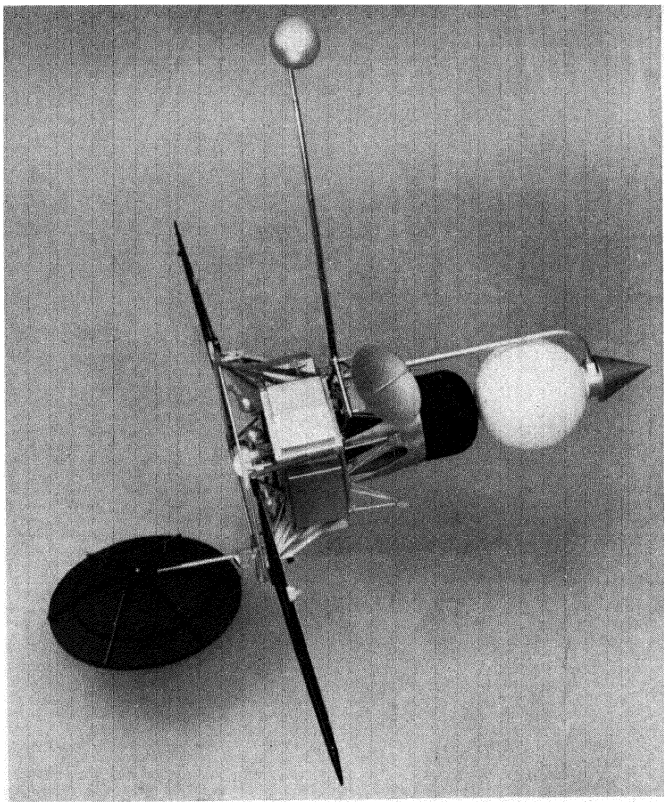
The spacecraft is approximately 10 feet high, 5 feet wide at base, weighing 727 pounds, and its solar-panel batteries should supply a power of 160 watts

For the selenographers, the most important part of the scientific packet carried aboard this spacecraft was a 7-inch Cassegrain reflector of 40 inches focal length, forming an image 0.44 inch square in size, to be picked up by a television vidicon tube and telemetered down to the Earth The transmission was to commence in the last 15 minutes of the flight, and about 70 frames transmitted (at an interval of 13 seconds) while the spacecraft descended from approximately 4,000 km to 24 km above the lunar surface A 2° field of view of the telescope would image some 40 km^2 of lunar ground at the commencement of the transmission, and about 350 m^2 near the end, 200 lines per picture would have corresponded to a ground resolution of 200 metres at the commencement—i.e., comparable with the best telescopic resolution attainable from the Earth—and 2 metres towards the end

These goals were, unfortunately, fulfilled so far only to a very limited extent. The television system itself functioned satisfactorily on Ranger 3; but the orientation of the vehicle at the time of its closest approach to the Moon was largely out of control, so that no pictures of the lunar surface were actually transmitted, while on Ranger 4 and 5 the functioning of the TV system was paralyzed by the apparent failure of the solar batteries to supply the necessary power

Courtesy of the Jet Propulsion Laboratory, California Institute of Technology

PLATE XIX

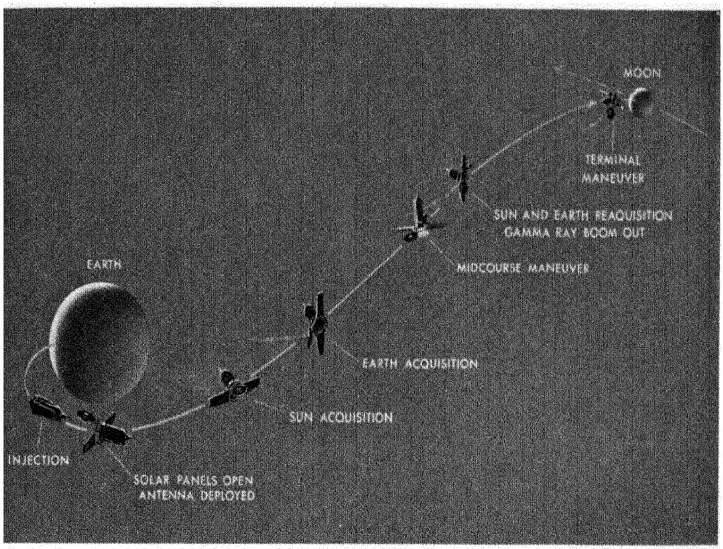


A capsule carried by the Ranger spacecraft (see Plate XIX) containing a seismometer to be ejected from the moving vehicle in the final stages of its approach to the Moon (Plate XXI) and deposited on the lunar surface to supply information on the seismicity of the lunar globe as a whole

The protective sphere of balsa wood on top surrounds a compact single-axis seismometer designed by F. Press of the California Institute of Technology—a cylinder 4 by 5 inches in size and weighing but little more than 8 pounds—of sufficiently rugged construction to withstand an impact with a velocity of 100 m sec (i.e., a deceleration of the order of 500 g), and to continue transmitting any indication of seismic disturbances on the Moon (caused by tectonic processes or meteoritic impacts) for approximately one month, using its own auxiliary antenna and power supply. The tiny battery necessary for this purpose was the only power element aboard Ranger 5 which continued to function after all other sources failed

Courtesy of the Jet Propulsion Laboratory, California Institute of Technology

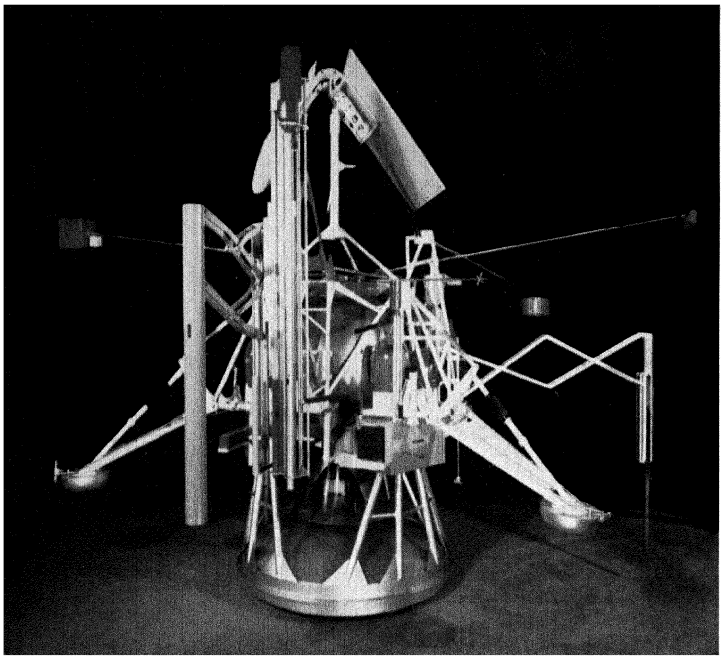
PLATE XX



The flight plan for the Ranger 3, 4, and 5 spacecraft launched in 1962. The main lines of this plan were actually fulfilled by all three missiles. The Rangers 3 and 5 missed the Moon by a small margin eventually to become artificial satellites of the Sun, while Ranger 4 crash-landed on the far side of the Moon

Courtesy of the Jet Propulsion Laboratory, California Institute of Technology

PLATE XXI



A soft-landing spacecraft of the Surveyor class, a series of which are to be landed on the Moon during the second half of the present decade. As it is to be propelled by a more powerful booster—the Centaur—than the Ranger-carrying Atlas, it can transport to the Moon much larger packages of scientific instruments (including more powerful telescopes and better TV cameras) for intensive exploration of the landing site. Some of these instruments should be capable of penetrating a few feet under ground and measuring the chemical composition as well as the temperature profile of the lunar crust in the course of a month. Its own retro-rockets (fired in succession by radar control aboard the moving craft) should enable the Surveyors to lower these instruments (weighing altogether several hundred pounds) on to the lunar surface with a velocity not exceeding 3 m/sec, and expose thus the entire cargo to a landing deceleration of not more than 20 terrestrial g's

Courtesy of the Jet Propulsion Laboratory, California Institute of Technology

PLATE XXII

almost any size; and unlike on the Earth (receiving approximately equal amounts), its utilization is not hampered by any atmosphere. Four types of devices can, in principle, be proposed for capturing solar power: the lens, the parabolic mirror, the flat-plate collector, and the solar battery. The operation of the first three on the Moon should be greatly facilitated by both the low gravity (lessening flexures of large constructions) as well as the absence of any winds or tarnishing effects. On corresponding terrestrial structures it is, in particular, the wind-loading which makes them inordinately expensive; but as there are absolutely no winds on the Moon, and no stirred dust to foul the surface of our mirrors or lenses, the whole structure could be made very light.

One of the tasks on which we would put the heat so collected to work is to melt the silicon dioxide (SiO_2). Silicon is a very useful substance; and on the Moon it could be used for both silicon solar batteries, and thermocouples. We mentioned already that one other common metal likely to be abundant on the Moon is iron. If we now were to construct a thermocouple, one element of which is iron and the other silicon (contaminated, for best results, with approximately 6 per cent of aluminium), approximately 10 metres high, one metre wide, and 1 cm thick, the heating of their contact to 1,000° should produce a direct current of approximately 1 kilowatt at around 50 volts. This d.c. power could, in turn, be used for electrolysis of the magnesium oxide to produce oxygen in gas form.

This all could, of course, proceed only as long as the Sun is above the horizon; and a suitable storage of heat would have to be devised if the operations were to continue during the long lunar nights. Flat-plate collectors suitably insulated, or latent heat of solid materials heated to a high temperature during day-time, could possibly do the job—facilitated as it is by the fact that practically the only way by which a body suspended in vacuum can lose heat is by radiation; and a large part of it can be returned by suitable reflectors. It goes also without saying that the whole problem of storing energy would be eliminated

for any settlement at, or near, either one of the poles of the Moon, where the Sun hovers continuously near the horizon and never completely sets.

As far as the actual habitations of the personnel manning lunar exploratory stations are concerned, the temperature variation inside any solid structure—such as an inter-planetary rocket—exposed on the lunar surface to the conditions of outer space should depend very much on the reflectivity or absorbing power of its surface. In spite of the low temperature prevailing in interplanetary space, the Sun's radiation during day-time is sufficiently strong even at a distance of 149 million kilometres to raise to intolerable levels the temperature of any solid object absorbing the Sun's energy and not re-radiating it away rapidly enough. Ordinary materials of construction can differ widely in their behaviour. Polished aluminium, for instance, absorbs well and radiates poorly in infra-red. A rocket or vehicle having a skin of aluminium would reach 350° to 400°C if exposed to sunlight in space for a protracted period. By contrast, a coating of white-pigmented paint would make the vehicle reflect so well that its temperature would stabilize at some 50°C below zero. It should be possible, of course, to select a material (or combination of materials) that would maintain a comfortable balance of temperatures during day-time. But this balance could be easily upset. At night, the temperature would drop precipitously; or if for any reason the white coating should peel off and expose polished aluminium, the inside of the spaceship could become a crematory for its inhabitants.

There exists, however, one safe way in which all risks connected with the temperature variations during day or night could be safely set aside: and that is by placing our rocket (or more elaborate lunar exploratory station) underground—or at least, to cover it up by a foot or so of lunar dust or surface debris. Such a move would serve two eminently useful purposes. It would protect the underground quarters from chance impacts of small meteorites and, in addition, would provide an almost ideal heat insulation. We learned earlier in this book

that the thermal conductivity of lunar dust is sufficiently low for the temperature at a depth of a yard or so to be virtually constant day and night. The temperature prevailing there would be rather too low for our comfort (about −30°C), so that heating would be essential. However, by placing at most a few feet of highly insulating dust between ourselves and the open space, we should almost entirely escape both the full blast of heat during the day, and the deadly cold of lunar nights out in the open. This operation would, moreover, have to be undertaken almost immediately after the landing of the first party. The prospect of having to deal with dust rather than rock should be welcomed by those who do not like physical exertions in strange surroundings; and the low gravity should also be helpful.

Besides, it may also prove possible to adapt some of the natural features of the Moon's surface to lunar bases. The most appealing features are those which suggest the presence of lava flows. There is indeed evidence for such flows on the Moon, and better photographs may reveal more. Now a characteristic feature of basaltic flows on the Earth are the so-called 'lava tubes'. These can become long underground caverns, sometimes with very smooth walls. Should they occur on the Moon, it should perhaps not be too much of an engineering job to seal them off to provide the living and working quarters for a lunar base.

If the foregoing remarks have perhaps not deterred the reader from keeping our company in the contemplated lunar base with all its risks and vicissitudes, let us return again to more mercenary aspects of its possible exploitation. We mentioned already that the lunar crust is unlikely to contain an essentially higher proportion of such sought-after heavy elements as gold, or uranium, which are terrestrially (and cosmically) so scarce. The prospects might, to be sure, be slightly more hopeful for light metals, such as lithium or beryllium, of great technical importance in metallurgy or the aircraft industry—particularly so if Urey is right in his view that the formation

of the Moon antedated that of the Earth, and if lunar matter was less exposed, in pre-lunar past, to high temperatures prevalent in stellar interiors than that forming the terrestrial crust. But, in a realistic estimate of present prospects, one should expect to find most of these elements—light or heavy—on the Moon in about the same relative abundances as on the Earth.

Should these views leave the cosmic prospectors of the future undeterred in their determination, how could they go about establishing the locations of any such ores on the Moon—if possible—in advance of any actual expedition? Their surface beds could, of course, give some indication of their presence by specific reflecting properties or—as we discussed already in the preceding chapter—by their luminiscence spectra excited by solar corpuscular radiation. It may also be mentioned that—at least in theory—the location of ore beds even at some depth beneath the lunar surface could be detected from the Earth by means of radio-telescopes working at sufficiently long wave lengths. Long wavelength would be necessary to effect penetration; but, unfortunately, it would also entail such a loss of resolving power that (unless new and radically different techniques can be developed in the future) this kind of prospecting at a distance of 380,000 kilometres would call for conventional radio-telescopes of impractically large size.

Even if at least a certain amount of prospecting could thus be done at a distance, the actual mining and transport operations would require, of course, the presence of human operators on the spot; and this would imply the setting up and maintenance of manned bases on the Moon of no small size. Suppose that this will, in time, be accomplished; what about the problems of actual transport? Here the difficulties connected with it may perhaps be less than a lay mind may at first anticipate; for the relatively small mass and size of the Moon would make it possible to lift a given mass of material from the lunar surface to the 'level of no gravity' between the Moon and the Earth at the expenditure of a little more than 3 per cent of the energy needed to transport the same mass from the Earth

to the Moon—in point of fact, for about 99 per cent of the length of the journey from the Moon to the Earth the material would be in 'free fall'.

A free fall from this level would, to be sure, imply a landing velocity of some 11 km/sec just outside our terrestrial atmosphere; but air resistance in the last stage of the journey could be relied upon to slow it down to a very large extent. As is well known, this atmospheric resistance depends vitally on the size and mass of the falling particles, as well as on their velocity. Large rocks would penetrate the whole atmosphere essentially without deceleration; and their sudden stopping on impact might produce enough heat to volatilize completely the whole lump. Fine dust may, on the other hand, be actually stopped by the atmosphere before reaching the surface and float in air —like volcanic dust spread by large eruptions—for a long time before eventually settling down over a large fraction of the globe.

In actual transport of lunar matter to the Earth the material would, therefore, first have to be ground to an optimum size to allow enough atmospheric deceleration before impact to escape volatilization by heat, but to avoid again too much dispersal. The material so ground would then be sent (or 'thrown') down on the Earth, along 'gravitational pipelines' governed by inexorable and precise laws of celestial mechanics, and maintained—without need of repair—by the combined gravitational attraction of the Earth, the Moon, and the Sun, landing in regions presumably like the Sahara or Gobi deserts (where an error of a few miles in the target would cause no great inconvenience). In point of fact, this whole process could be regarded as a gravitational transfer of lunar ore beds to selected regions of the Earth, where they could later be mined by more conventional methods.

Will it, however, ever have to be put into effect? As against this we should keep in mind that the total terrestrial reserves of any element or raw material remain still enormous. Of course the law of diminishing returns in mineral processing is operative

all over the world, and as high-grade ore deposits are used up, we must resort to the exploitation of less rewarding deposits. However, the ocean water covering the globe contains (in highly diluted solution) vastly more gold or uranium than has so far been unearthed anywhere on the surface; and an extraction of these (or other) rare elements from sea water—expensive as it may be, and certainly not rewarding economically at this time—may represent a much more economic process than any import from the Moon. Therefore, should you one day be tempted by stocks of companies organized to exploit the natural wealth of the Moon, it would pay to take good professional advice before investing your family's savings in such a venture!

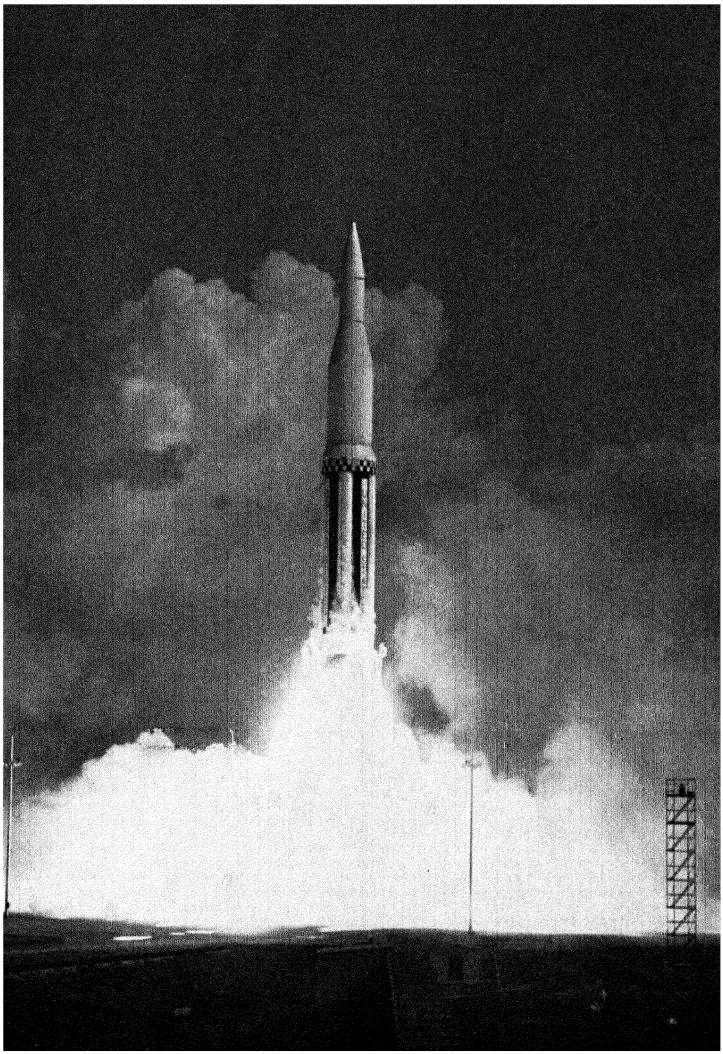
Quite apart from these hypothetical possibilities there are, of course, other and more practicable aspects of space-travel which, as we shall attempt to show, should make an effort to establish a manned base on the Moon not only desirable, but a superlatively worthwhile object. In fact, the principal use of the Moon which we can foresee in this connection is to provide a solid basis for an *observing station* in space, unhampered by any atmosphere. In order to survey the benefits which could be derived from the possession of such a station, let us first stop to consider what could be seen on the Earth from the Moon with the aid of such telescopes as we now possess. Looking at the Moon from the Earth, we can distinguish at best objects down to a size of 300–400 yds in length—this limit being imposed, not by the optical performance of our telescopes, but rather by atmospheric disturbances commonly called the 'seeing' and caused mainly by a turbulent layer of air some miles above our heads. In viewing the Earth from the Moon we must still look at our object through the same disturbing layer, but this time the turbulent air is relatively very close to the object rather than to the telescope—which makes all the difference: so much, in fact, that under ordinary conditions objects four or five times as small could be seen on the Earth from the Moon than in the opposite direction.

Just think what this would imply! Street maps of all major cities of the world could be drawn from such observations, almost as good as those which we now possess; and details of landscape of comparable order of magnitude. The courses of all major surface ships could be followed—in peace or war—through the seven seas; with the whole surface of the terrestrial globe (not covered by clouds) being exposed to view every 24 hrs; and the instantaneous position of any object could be radioed down to the Earth with a delay of only 1.28 sec on the way. If we had such an observing station on the Moon to-day, the location (or layout) of the Russian Atomgrad, or of the launching sites of their cosmic rockets, would no longer be a secret—neither would all similar remote installations of other Great Powers—with all the advantages of a perfect 'open skies' programme at our disposal.

On the economic front, continuous observations from a permanent lunar station would, for instance, enable us to track many aspects of important weather developments over large inaccessible areas of our globe—such as the Pacific Ocean or the Antarctic, where individual weather stations yield but fragmentary records. The growth and motion of 'warm fronts' constitutes a case in point; for their developments could be easily tracked from the corresponding motions of the clouds. Contributions to the weather forecasting along the western shores of the Pacific Ocean, with their extensive plantations from British Columbia to Southern California so often at the mercy of unexpected cold air currents, would alone represent a major economic item. To be sure, we do have now meteorological satellites for similar purposes daily circling the Earth; but the horizon their cameras can survey at any one time is vastly smaller than an entire hemisphere visible from the Moon. The access to so extensive an ensemble of simultaneous weather data may yet render one day the terrestrial weather forecaster a honest man; and with his predictions approaching automatic reliability the Englishmen may lose their last safe topic of conversation.

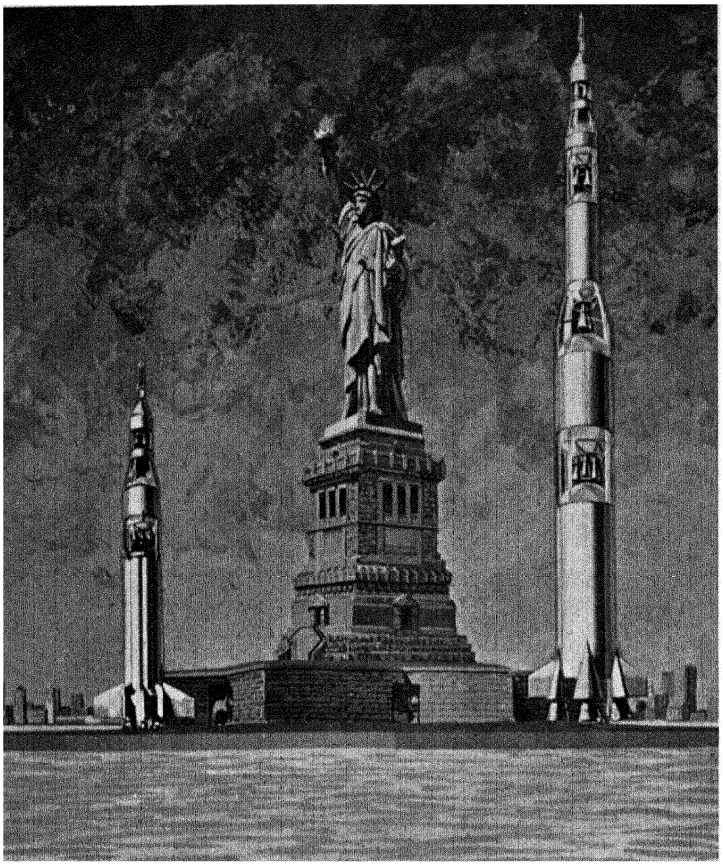
Turning our eyes (or instruments) from the Earth to the Sun and the stars, a lunar observing station would truly represent the astronomer's dream of a paradise. In order to explain this, let us admit that the atmospheric ocean, at the bottom of which we happen to live on the surface of the Earth, may perform many useful functions and be in fact indispensable for our living; but from an astronomical point of view it constitutes an unmitigated nuisance—not only by spoiling our 'seeing', but mainly by cutting off from us the major part of light from outer space. In more specific terms, our atmosphere happens to be reasonably transparent only in two relatively narrow (and well-separated) ranges of wave lengths. One is in the optical part of the spectrum ($\lambda\lambda$ 2,900 to 11,000 Å), limited at its ultraviolet end by the absorption of ozone in the upper atmosphere (mainly between 20–40 miles above sea level); while, in the infra red, an interlocking of the absorption bands of water vapour and of carbon dioxide represents an almost equally effective barrier to light of wave lengths between a few μ's to about 1 mm—beyond which celestial bodies come through once more to be seen (or heard) on radio-waves of frequencies between 300,000–300 megacycles per second; still lower frequencies being again debarred from us by reflection into outer space from our ionosphere. With the exception of these two relatively narrow 'windows' through which we can look at outer space—one in the optical part of the spectrum, the other in the radio-spectrum—all other radiation (i.e., most part of it) is irretrievably gobbled up by our atmosphere with all the information which it carried. Moreover, the scattering of sunlight by air molecules (and dust particles) of our atmosphere limits the effective visibility of all celestial bodies to a few hours of night-time.

How different this would all be on the Moon! As our satellite possesses no atmosphere to speak of, the stars would remain perfectly visible regardless of whether the Sun is above the horizon or below it—and nights for astronomers would thus last without limit. Much more important still, the whole



The first Saturn C-1 rocket—direct forerunner of the vehicles which are to transport men to the Moon—taking into space from Cape Canaveral, U.S.A., on October 27th, 1961

Courtesy of the George C. Marshall Space Flight Centre, Huntsville, Alabama



The artist's view of the Saturn C-1 rocket (left; see also Plate XXIII) side by side with the advanced Saturn C-5 – destined for transport of men to the Moon – together with the Statue of Liberty in New York Harbour placed in between for comparison in size. The giant Saturn C-5 on the right will be 337 feet in height, weigh close to 3,000 tons at take-off, and develop 150 million horse powers to transport a 40-ton cargo from the Earth to the Moon

Courtesy of the George C. Marshall Space Flight Centre, Huntsville, Alabama

PLATE XXIV

extent of the spectra of all celestial bodies—from the X-rays to the longest radio-waves—would be accessible without interruption; and its high-energy part (hidden from us by ozone absorption) would, in particular, reveal a story of greatest interest to the astronomer and physicist alike. Different solar phenomena manifesting themselves at short waves, invisible from the Earth, are largely responsible for phenomena falling into the domain of that part of astrophysical engineering known as the 'solar-terrestrial relations', which include phenomena of such practical interest as ionospheric transmission conditions and radio fadeouts. In point of fact, the information on various celestial bodies, forthcoming from a lunar observing station, would revolutionize in a short time the whole structure of astronomical science, and induce our more fortunate colleagues of that time to dismiss all knowledge painstakingly accumulated by countless previous generations on the Earth as a pre-history of their subject!

For the physicist, or electronic engineer, the surface of the Moon would again constitute an extremely hard high-vacuum laboratory of unsurpassed dimensions. To mention only one of the more important applications for which such a laboratory might become invaluable, consider the high-energy accelerators of elementary particles and the role they have played in contemporary physics. Most of our recent knowledge about the structure and various properties of the atomic nuclei has come about by accelerating elementary particles—or whole nuclei—to very high speeds in 'atom-smashing' machines and allowing them to collide with other nuclei. In order to do this, however, the whole apparatus must be carefully evacuated, so that the particles picking up speed will not lose it again by collisions with atoms which make up the atmosphere.

The difficulties involved in this task can be estimated from the fact that the largest nuclear accelerators of this type, currently built near Moscow, Geneva or Brookhaven, contain evacuated tunnels forming a ring almost half a mile in diameter. The necessity of making so large a structure leak-proof and

removing almost all atoms from it represents a task so difficult as to render it one of the principal factors which limit the construction of even larger machines (capable of producing particles of energies in excess of, say, 100 BeV).

On the Moon, any atom-smashing machine could be built and operated completely in the open. The low value of surface gravity would, moreover, facilitate the mounting and positioning of heavy parts whose weight might prove prohibitive on Earth. For example, a magnet weighing 50,000 tons on Earth (which would require quite elaborate mounting to hold it accurately in position) would weigh only about 8,000 tons on the Moon—a much more manageable burden. Is it too much to expect that lunar research laboratories of the future may, one day, house accelerators which will dwarf anything that could possibly be built 'down here'? And we hope that the power for operating such machines will be obtained by a suitable conversion and storage of the most common Nature-made kind of energy—sunlight—which, unshielded by any atmosphere, beats down on the Moon's surface without let up during the long hours of its day?

Giant particle accelerators represent, moreover, only one aspect of the scientific work which could one day flourish in lunar laboratories. Another one would be studies of the nature and characteristics of the primary cosmic rays, whose origin represents one of the greatest outstanding puzzles of the Universe, and of which only indirect intelligence (consisting mostly of secondary radiation, due to the collisions between primary cosmic rays and atoms of gases in our upper atmosphere) can be obtained on the surface of the Earth. What are the maximum energies attained by the primary cosmic rays, and what is their chemical composition? Are heavy nuclei more abundant in them than they appear to be in the stars, or interstellar matter, at this time? Attempts to answer these questions are being made with the aid of flights of high-altitude rockets carrying appropriate instruments in their war-heads or of the astronomical satellites now circling the Earth; but how much

more completely (and shall we say safely?) would the answers emerge from lunar laboratories, where the physicists would not have to count the precious minutes which their fast-flying little laboratory hidden in the rocket's war-head will spend above the atmosphere or be limited by the transmission problems?

Or consider again the facilities which would be open to electronic engineers on the Moon working in the field of high-vacuum techniques. In terrestrial laboratories, if any such technique is to be tested, the experimenter has to enclose the apparatus in glass, to seal and evacuate it, and see or measure what happens. Should, moreover, any modification be desired, the container must be broken, the change made, and the apparatus re-sealed and evacuated again each time. On the Moon, on the contrary, high vacuum is available on an unlimited scale everywhere around, and all experiments requiring it could go on in the open; it is the experimenter who would have to be enclosed in his space suit, in which suitable air pressure would have to be maintained; or his gadgets may be operated from underground laboratories by remote control.

Are all these possibilities—and many other vistas which can be conjured up if we pursue them further with our imaginations—sufficiently attractive and worth-while the unprecedented effort which would have to precede their realization? Perhaps, fortunately for us, the answer which any of us as individuals might wish to give for the issues appear to have already been decided: the lid to a new Pandora's box has been lifted, and there is no turning back any more. We have indeed been assured by recent statements of highest spokesmen both in the United States as well as the Soviet Union that rockets capable of 'soft' landing on the Moon are already in design—if not production—stage; and backed as they are by the available scientific talent, unlimited financial means, and national prestige of the two greatest powers of this Earth, they will undoubtedly reach the Moon within our lifetime; and the first man who will set his foot there is now probably past his school age.

There are some among us who maintain that large funds committed for this purpose could be used to better advantage for the advancement of science, and of astronomy in particular, from terrestrial bases than for the rather hazardous effort of acquiring new ones. This view can, however, scarcely withstand closer scrutiny, and reflects but backward thinking. There were, to be sure, days when terrestrial science languished from dearth of support; and when advances of historical significance were often made by dedicated amateurs working in their back yard. While new ideas and results continue to be eagerly welcome from wherever they may come, it is also true that adequate support through various channels is now available for most part of research that is really worth while. The emphasis on needs has, moreover, significantly shifted: for our principal shortage, controlling the progress of science to-day is not one of funds, but rather of scientific manpower and talent. A crash-programme of space-flight, which we may see developing in front of us from several sides, may not constitute an unmixed blessing if it continues to claim such a fraction of our scientific manpower that other sectors of the farflung front of scientific progress may be depleted to temporary stagnation. But this has already happened many times in the history of science without any permanent adverse results; and it is up to the scientists to make their own choice.

An increasing number of them have already done so. There is, indeed, every expectation that the problems and attractions of space-flight will, in the coming decades, exert a profound impact on the human mind and imagination—even greater perhaps than the one which the production of energy from atomic nuclei has made in the past 20 years. The comparison is indeed apposite: for since about 1940, great nations of this world have spent enormous sums on nuclear energy release—quite unprecedented in the history of science—and have done so readily in spite of the fact that these enormous investments have brought so far but very limited tangible dividends: nuclear power stations producing as yet only a tiny

fraction of the total energy consumed by mankind; and nuclear weapons, whose gruesome effectiveness nobody has in doubt, but which all their makers profess should never be used. Enormous effort and sums were needed to bring about these achievements—and the parliaments of the world voted funds for this purpose with the readiness formerly reserved for war budgets alone. This money was spent in due course; yet is anyone really poorer for it?

Comparable sums of the taxpayer's money are now being spent on work preparatory to space travel—with the Moon as the first destination outside the gravitational confines of our terrestrial abode—and the nations of this Earth are willingly putting them up. At present, space research absorbs already the equivalent in production of about twenty minutes in every American's working week; and this may be trebled or quadrupled before the Moon is reached. Both the American and the Russian nations, at this juncture of human history, are making their passage to the Moon and beyond by working when they need not. Whether rockets are preferable to leisure is a question which sociologists rather than astronomers should be called upon to answer; for a nation like the United States may find it both more expedient and inspiring to spend some of its wealth on space rather than indulging in social experiments of a four- or three-day week—perhaps for some of the reasons outlined earlier in this chapter—but mainly because *the Moon is there*—as a challenge and inspiration ever present to unparalleled achievement now technically within our reach. Such an achievement can unite all mankind in sharing in its pride, and by eclipsing—at least temporarily—the issues which divide the principal Earth-bound protagonists of spaceflight.

The scientists will, in turn, have more concrete concepts and hopes in their minds, which they are only too glad to share with all their fellow-inhabitants of this Earth. While the specific impact on science of the advances which could be expected to originate in lunar research stations may still be a subject for some debate, one of the strongest lessons derived

from the history of science is the realization that all important advances in pure science have full repercussions in applied science as well as in technology; and that all technological revolutions which have repeatedly transformed human civilizations originated as new conquests in the domain of pure science. There is, in fact, but little doubt that the pure gold of new knowledge constantly emanating from the laboratories and observing outposts stationed on the Moon would, through their eventual impact on technology, outweigh overwhelmingly all the material gold which the conquistadores of new worlds once saw in the Americas from the shores of Spain.

And if we try to look farther beyond the immediate future—when colonies of human beings may have established themselves on the Moon with the aid of spaceships that, fifty years from now, may bear as much resemblance to Saturn C-5 or its 'bug' as did the caravels of Columbus to Cunard Queens—what may the crystal ball in contemporary hands reveal about their eventual fate? This question is, perhaps, more than of idle interest; for who knows whether the Moon may—in a future not necessarily so distant—become the abode where life may survive in this part of the solar system? I am referring, of course, to the possibility that deliberate action of human beings may render the Earth—at least temporarily—unsuitable to this end. It is, perhaps, a part of the hidden meaning of the trend of events that the two great milestones in the technological development of mankind—the utilization of nuclear energy and space rockets—have both been attained in the same generation? Ever since the first nuclear bombs burst over Hiroshima and Nagasaki in 1945, the world has been living in the shadow of a gruesome possibility that the mass detonation of the rapidly growing stockpiles of nuclear bombs of different nations may poison the entire atmosphere, and oceans, by radioactive fallout to such an extent as to bring about a partial or total extinction of life on this planet. Nobody can say at present how near we may be to this danger point; for nobody knows the total power of the bombs piling up in all the arsenals of different nations; their

chiefs know for certain only their own destructive potential, but at that of their rivals they can only guess.

Suppose, however—and we cannot rule it out—that, at some time in the future, a nervous hand will trigger the fateful button and the world gets engulfed in a nuclear holocaust. When it is over, such life as may have survived its immediate impact may still find itself condemned to a lingering death by induced radioactivity of air and water which may take thousands of years to subside, and against which there is no defence. If so, may not the only chance of the survival of life—that precious creation which took Nature hundreds of millions of years to develop—be to transplant it, at least temporarily, to the Moon before Mother Earth may become habitable again? And is it not symbolic that space rockets—the potential version of Noah's Ark—have come into being at just about the same time as a silent answer to the nuclear threat to life?

Suppose that, under the impact of such a contingency—or even without it—some human beings may be destined to go and live on the Moon for several generations. Would they begin, in time, to differ in some aspects from their Earth-bound confrères? This is indeed an intriguing possibility; and while this is not the place to dwell on a subject which is primarily biological, one aspect of it can perhaps be anticipated with some assurance: and that is increased longevity.

Looking back over the long evolution of life on this Earth from its modest beginnings half a milliard of years ago to its present state of development, we cannot for a minute be in doubt as to the crowning achievement of this process: namely, the human brain. Everything else about us is second-rate. All our senses—sight, hearing, smell, etc.—are easily outclassed by those of many animals at lower levels of the evolutionary ladder, and hopelessly so by instruments which we can conceive and develop. Our arms or legs are relatively poor sources of strength or locomotion—inferior to those of many animals, and insignificant in comparison with what man-made machines can do. Yet one part of our body—the brain—is the veritable marvel, solely

responsible for the ascendancy of our race and all our achievements. The work of our hands, the speed of our legs, are all insignificant in comparison with the machines conceived by the human brain; but all 'mechanical brains' devised so far are still hopelessly behind nature.

The human brain, encased in the narrow confines of our skull, is kept functioning by a constant influx of oxygen-carrying blood pumped up there continuously by the action of our heart; without this supply the brain could not function for many seconds. The circulation of blood prompted by the heart day and night is, therefore, necessary to keep the brain in action; and few of us may clearly realize what a tremendous physical effort this entails. Our heart pumps blood through it continuously at a rate of about a quart per minute; which means that during the average span of human life it pumps up over 3½ million quarts of liquid—an amount sufficient to fill a small dam—and constant lifting of it to the average height of an erect human being represents a continuous struggle against gravity.

No wonder that each human heart gets tired in time and eventually gives up this unequal struggle. With most of the infectious diseases now well under control, the heart and circulatory diseases represent (apart from the unsolved riddle of cancer) perhaps the principal killer of mankind—and worse; for long before finishing us off, the gradual weakening of a tired heart may condemn many of us to semi-invalidity—living under a suspended death sentence while our intellectual powers may not yet be far from their prime.

This process is not only cruel; but even from a completely detached position it represents a sheer waste—one of the limitations which compel Nature to go slow in further perfectioning of the human race—and in this particular case the principal culprit is established beyond any doubt: namely, the terrestrial gravity. There is, unfortunately, nothing we can do about it—on the Earth; but how about on the Moon, where the gravity amounts to less than one-sixth of its terrestrial value?

Few have perhaps stopped to realize how hygienic the conditions of life on the Moon could become for those who have got there after the initial stages of colonization. The intense radiation from the Sun could be relied upon to render these conditions as aseptic as any physician could hope for. As all air to breathe will have to be artificially produced, the air-conditioning can attain the degree of perfection impossible to impose on the Earth. Food, protective clothing, etc. will all have to be scientifically planned to ensure survival with such comfort as may be attainable. And—above all—the much reduced gravitational attraction should greatly lessen the physical strain on any part of our body, including the heart, and thus increase their useful lifetime.

Should these conditions result—as is very likely—in the increased span of an average human life, the probable sociological implications of such a change may well be worth more than a passing thought. Let us compare their implications with some of the basic facts of our daily terrestrial pilgrimage. An average human being spends about twenty years to reach intellectual maturity; and after another 30–40 years which could be termed productive, he declines again into senility as a result of gradual failure of the accessory parts of the human body to maintain our brain in proper working condition. The productive period of the human life, and youth with senility are, on the average, almost equal in the number of years claimed by them.

Suppose, however, that once maturity has been attained, the ageing process could be slowed down by some such factor as low gravity, and the productive period thus extended, perhaps, two or three times. What a profound significance this would have for each individual, and what heights of intellectual activity could be attained by slow but steady accumulation of experience and wisdom. Would not such a long-lived race be bound to overtake us, the ephemeral terrestrial plodders smarting under the yoke of constant gravitational acceleration of 9.8 m/sec^2, in most intellectual activities—and, by virtue of this advantage, eventually even deal with us in much the same

way as we did with other terrestrial creatures at the lower level of the evolutionary ladder?

Many of you may recall the delightful pre-war novel, *The Lost Horizon*, in which the late James Hilton depicted for us the community of a long-lived race of sages at Shangri-La, a remote lofty corner on the surface of this Earth. Is it perhaps not possible that his vision may eventually become a reality—not on the Earth, but on the surface of our nearest celestial neighbour? There are, however, other considerations which may likewise influence the outcome; and another important aspect to be kept in mind is, of course, the genetic radiation hazards to which the inhabitants of the Moon would be exposed in increased measure. It is well known from biology that the priceless heritage of past evolution and accomplishments is being transmitted between successive generations of living organisms through one particular type of agent of the reproductive cells which the biologists call the 'genes'. It is, furthermore, well known from bio-physics that abrupt changes in the structure of the genes—which are passed as permanent 'mutations' of certain characteristics to all subsequent generations—can be artificially invoked by external agents, such as X-ray quanta or corpuscular radiation. The mutations invoked by random encounters of complex and fragile organic molecules constituting the genes with energetic quanta of hard radiation or corpuscles can, in principle, produce any effect—beneficial or harmful. However, the proportion of changes falling into these categories depends vitally on the complexity of the respective living organism; and in advanced creatures random processes can be expected to produce only a vanishingly small proportion of genetic mutations which we should call beneficial.

That this is indeed to be expected can be made clear by the following simile. Suppose that something goes wrong with a simple utensil which we use in our everyday life—such as, for example, a lawn mower or a coffee grinder. Should the handle of this grinder refuse to turn, it is not necessary to pass it on for an expert repair; for almost any move made by an untrained

hand can unjam it. Suppose, however, that a pocket watch refuses to march, or to show the correct time. Should this happen, a recourse to a watchmaker becomes desirable; for a pocket watch contains about a hundred times more movable parts than a coffee grinder; and the chances that an arbitrary intervention by a lay hand could cure the trouble is correspondingly more remote. Indeed, the probability is much greater that an amateurish repair would result in greater damage than the one it attempted to repair—a hypothesis which hardly requires mathematical proof. Lastly, it is entirely obvious that any lay interference in the internal workings of an electronic computer—no matter how well meant—could scarcely be expected to improve its performance.

The same analogy holds good also in the field of the mechanism of heredity. The genes of the organisms at the low level of the evolutionary ladder are relatively simple; and random damage done to them by radiation or other physical causes may produce effects to the good as well as for the worse as far as the future of the race is concerned. The genes transmitting the heritage of the entire human race consist of organic molecules which are, however, so complicated that any outside barbarous intervention—be it by energetic radiation or corpuscles—is almost always apt to result in a change for the worse—as if an untrained hand were to take a chance at improving a complicated electronic computer!

All organisms living on the surface of our Earth since time immemorial have been largely protected from the pernicious effects of cosmic radiation by the atmosphere above our heads, which absorbs its most energetic components and mitigates others; but many biologists entertain the view that the genetic effects of radiation so filtered have been the mainspring of the evolution of species which we know to-day—culminating in the development of the human race which is now about to take off for the Moon. Over there, however, no atmosphere is awaiting to shield us from intense irradiation by cosmic sources; and unless the colonies of lunar humans devise adequate steps to

protect themselves from its hazards, their long-range future might not be so bright from the genetic point of view. Any attempt to foresee it would, however, decidedly overtax the capacity of the crystal ball to which we have resorted repeatedly in the course of this chapter, and which is just about beginning to get obscured by an impenetrable veil.

And, thus, we come to the end of our story and of this book. In bidding farewell to its subject, the time has come to direct our thoughts back to the Earth and to prepare ourselves for another day of our terrestrial pilgrimage. The Moon, which we watched rising at the commencement of our story, has probably set in the meantime; and darkness descended on the glacial lake of the stars. Soon the first touch of the dawn may come to augur a new day; and long before the blissful rays of the Sun will rise to wake up the resting world, high above our heads the vapour-trailing jets—forerunners of the space vehicles which will one day take us to the Moon—glistening in the sunlight may already be scrawling in the deep-blue sky their shorthand of the future. They symbolize the advent of another day of work and thought which will gradually enable us to approach the goals set forth in this chapter until, at last, some of them may come true. How long we may have to wait, only the future can tell. Some of the speculations which have guided us through this last part of our narrative may, in the meantime, prove to be false; but it is thoroughly improbable that we have been entirely led astray by a will-of-the-wisp.

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