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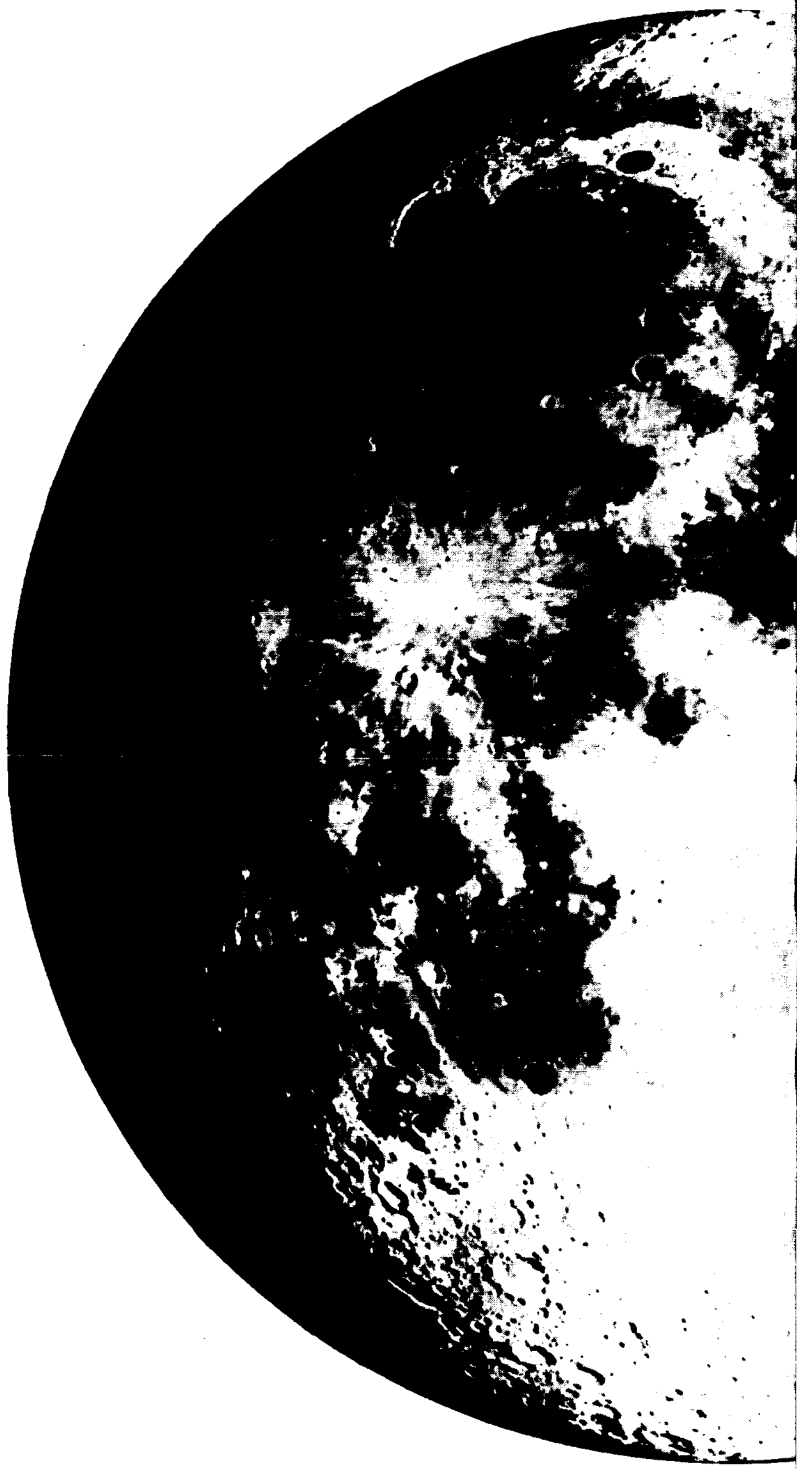

SURVEY OF THE PHYSICAL AND ENVIRONMENTAL PARAMETERS OF 'HE MOON

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SURVEY OF THE PHYSICAL AND ENVIRONMENTAL PARAMETERS OF THE MOON

BY

F. J. Niedz

FEBRUARY 1963

With a Foreword
by
Zdeněk Kopal

[redacted]

Apollo Support Department
General Electric Company
Daytona Beach, Florida

PREFACE

This document presents, in summary, a compilation of the physical and environmental parameters of the moon. A determined attempt has been made to be objective at all times.

Many of the physical sciences are presented in sufficient depth to adequately identify the basic information available.

It is expected that the appropriate references will be consulted when additional detail is required.

It is obvious both from the text and the reference material that divergent opinions prevail and uncertainties exist in almost every phase of lunar science; e.g., the existence of the lunar bulge, the thickness of the dust layer, etc. No pretense is made to resolve these differences, but by bringing together many references, it is hoped that some contribution will be made in lunar science.

The subject index will be of particular value since it relates the reference section by subject.

A glossary of terms used throughout the text is also provided.

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FOREWORD

By

Zdeněk Kopal

This report contains a comprehensive account of the physical and environmental properties of the moon as they are known today. It is not exhaustive, for the literature on this subject is so large that many volumes equal in size to the present one would have been necessary to reference all available sources. Even now, the amount of information submitted in this report is already so extensive that the reader might easily lose sight of the salient fact in the midst of innumerable details. Therefore, it will be the aim of this foreword to give a brief summary of the physical conditions prevalent on the lunar surface, and to place the different avenues of approach to the problem in proper perspective.

First, a few words concerning the methods by which the lunar environment can be studied from the earth at a distance which never becomes less than 364,000 kilometers. Telescopic observations - visual or photographic - can provide direct information concerning lunar topographic relief down to details of a fraction of the kilometer in size. A 24-inch refractor should, under ideal conditions, resolve on the lunar surface details approximately 400 yards in size; and a 40-inch telescope - the largest aperture used so far for systematic lunar studies - may depress this limit down to somewhat more than 200 yards. Below this limit, the outlines of individual lunar objects become blurred in a haze arising from the combination of optical diffraction phenomena, unsteadiness of seeing and photographic plate grain. When the sun stands very low above the lunar horizon, long shadows cast in its rays may enable us, to be sure, to establish the presence of surface uneveness on a scale 10 to 100 times smaller than that necessary for direct resolution; but few results of such studies have been reported so far.

Actual measurements of local deformations of the lunar surface from the shadows cast by such unevenness on the surrounding landscape - carried out in recent years on a large scale - have revealed that the overwhelming part of the lunar surface is smooth and gently sloping, its average inclination to the horizontal does not seem to amount to more than a few degrees. This appears to be not only in the maria, but true also in regions which are ordinarily called "mountainous"; former notions of great ruggedness of the lunar surface, based on telescopic inspection of the shadows along the terminator, failed to take proper account of the low altitude of the illuminating source. This statement does not, to be sure, intend to rule out possible presence of slopes considerably steeper than the average, on a small scale. For instance, as discussed in paragraph 6.4, the inner rims of small craters and crater pits may be considerably more inclined to the horizontal. However - and this should be emphasized - the total area occupied by such slopes represents only a tiny fraction (certainly less than 1 percent) of the entire lunar surface - so that, on the whole, the macroscopic character of the lunar surface must be accepted as smooth. This, on the face of it, does not perhaps seem very unusual, for exactly the same is true of our earth. However, the principal leveling factors operating on the earth - air and water - are totally absent on the moon and have been so from time immemorial; so that the reason why the moon appears to be so similar to the earth in this respect today must be sought along different lines.

Below the limit of direct optical resolution, studies of the microstructure of the lunar surface must rely entirely on indirect methods, based on the measurement and interpretation of the lunar radiation (in the widest range of the spectrum) which remains the sole link between us and the object of our inquiry. With a quite insignificant exception (i.e., thermal radiation of the moon due to its internal radiogenic heat), all moonlight derives its origin from the sun - whether this be sunlight falling directly on the moon, or sunlight scattered towards it through the intermediary of our earth ("earthshine") - and is absorbed or scattered by the lunar surface in accordance with its optical local properties. A small part of the solar radiation (both electromagnetic and corpuscular) may be absorbed and re-emitted by cascade processes to give rise to fluorescence. Energetic corpuscles of the solar wind may even induce the lunar surface to emit an X-ray "bremsstrahlung" the analysis of which could reveal to a terrestrial observer above the atmosphere the atomic chemical composition of the outer lunar crust - just as the studies of lunar luminescent spectra could provide some information about its molecular structure.

At optical frequencies and in the near infrared (up to 4 to 5 microns) scattered sunlight dominates the lunar spectrum; while above 5 microns - i.e., in the deep infrared and in the domain of radio-frequencies - lunar radiation is essentially caused by thermal emission of its globe. The energy sent out as thermal radiation is much greater than that of scattered light, for out of the total incident flux of illuminating sunlight, only about 7 percent gets scattered by the lunar surface, the balance being absorbed and re-emitted.

Even so large a balance of incident flux is insufficient to maintain the outermost layer of the lunar surface at a temperature higher than approximately 400°K at noontime, and about 120°K at night. This means that much of the thermal radiation emitted by it will be absorbed by our own terrestrial atmosphere. Fortunately, our atmosphere is fairly transparent in the 8- to 12-microns band - which should include the maximum of the lunar radiation curve at daylight - but the second atmospheric window through which the thermal radiation of the moon can be observed - between 1 millimeter and 1 meter - is already so far on the descending branch of the intensity distribution of a black-body emitter that the energy flux is quite low. Fortunately, definite measurements are possible approximately to the wavelength of one meter. Their main significance rests on the fact that, inasmuch as such long-wave radiation originates at an increasing depth below the surface, the attenuation of the diurnal heat wave and its lag in phase observed at different wavelengths provide us with the only means we have so far to probe the thermal conductivity of the lunar surface layers down to an appreciable depth - an invaluable piece of information. The emitted and scattered components of lunar radiation can be distinguished also by their polarization properties: for while scattered part of moonlight is distinctly polarized (and its plane of polarization rotates with the phase), thermal emission remains unpolarized. The same distinction exists between the illumination of the moon by the sun and the earth: while the incident sunlight is unpolarized, the earthlight is already partly polarized by the scattering of sunlight in our atmosphere.

These all are passive sources of light, provided by nature. In addition, it has proved possible in recent years to send out radar pulses to the moon and record their echoes which are modified by the reflecting properites of the lunar surface - a very powerful method of exploration - complicated only by the intricate Doppler effects caused by the continuous libration of the lunar surface; and quite recently we witnessed the first use of the laser beams for similar purposes.

The principal results of the measurements of different properties of moonlight and its variation with the phase can be summarized as follows:

a. The intensity of scattered light at optical frequencies changes so rapidly before and after full moon (the full phase being approximately 11 times as bright as the first or last quarter) as to defy analysis in terms of diffuse reflection from the smooth surface of any known substance. The only explanation we can advance is a suggestion that the microstructure of the lunar surface must be highly vesicular, and replete with innumerable pits and irregularities which begin to cast appreciable shadows almost as soon as the sun has ceased to stand directly overhead.

b. The foregoing statement is, moreover, true not only of the integral light of the apparent lunar disc, but of any surface element of it - be it a part of the continents, maria, or even of the bright rays. Each element attains its maximum brightness at full moon - regardless of its relative position or angular distance from the center of the moon. The apparent lunar disc exhibits, therefore, no limb-darkening.

c. The reflectivity (albedo) of the moon varies from place to place within the range of 0.05 to 0.18. The ratio of intensity of illumination of the brightest and darkest spots on the moon exceeds, therefore, scarcely a factor 3; while the mountainous areas are, on the average, not more than 1.8 times as bright as the maria.

d. The light of the moon as a whole is slightly redder than the illuminating sunlight; and locally its color changes but little from spot to spot. In general, the brighter the detail, the redder it seems to be, but the differences in color are small, and the reflectivity of the entire lunar disc is sensibly the same in all frequencies.

e. The scattered moonlight is polarized to the extent of several percent; the maximum polarization being attained roughly at a phase of 90 degrees, and the plane of polarization rotates with the phase. In general, the degree of polarization increases with diminishing albedo; the maximum polarization of dark maria exceeds 15 percent.

f. The thermal radiation of the moon in the 8- to 12-micron domain shows distinct limb-darkening and a phase variation consistent with the conclusion that the local temperature on the lunar surface depends essentially on the angle of incidence of the illuminating sunlight rather than the phase.

g. The intensity of thermal radiation in the 1- to 1000-millimeter domain (wavelengths already too long to permit much angular resolution over the lunar face with the existing telescopes) and its variation with the phase of the day (as well as during lunar eclipses) reveals that the diurnal heat wave on the moon penetrates to a depth of barely half a yard below the surface. Moreover, its phase-lag grows with the depth of penetration in such a way as to correspond to a coefficient of heat conduction of the lunar surface layers deduced in this way far lower than that of any known solid substance - a result explainable only on the assumption that the surface material constitutes loose dust, enabling the propagation of heat only through the corners at which the individual dust grains are in actual contact.

h. The radar echoes at 100 to 3000 Mc per second (10- to 300-centimeter wavelength) reflected from the moon reveal that approximately 50 percent of the echo power arises as a result of a near-specular reflection from a small central region of radius about 0.1 of that of the apparent disc of the moon. The nature of the leading edge of the echo indicates again that the lunar surface must be smoothly undulating, with average gradient of the order of 1 in 10 or 20. On the average, only about 10 percent of it seems covered with small objects which are below the radar limit of resolution (i.e., smaller than 10 centimeters in size).

   From regions near the moon's limb weaker echoes have been observed which obey the Lambert law (necessitating total darkening at limb); but only about one-tenth of the surface appears to give rise to this diffuse reflection.

The foregoing points lend themselves to the following conclusions bearing on the nature of the relief of the visible lunar surface:

a. Direct telescopic observations indicate that, on the scale of 1 kilometer and greater, the lunar surface is essentially smooth; and its average inclination to the horizontal does not exceed one-tenth.
b. Radar echo studies indicate that the same degree of smoothness apparently persists down to a scale-length of the order of 10 centimeters.
c. Photometric observations of the phase-variation of moonlight and absence of limb-darkening at optical frequencies necessitate for their explanation a surface which is again highly vesicular and honeycombed with innumerable pits - probably on a centimeter to millimeter scale.
d. Polarimetric measurements of scattered moonlight suggest that the outermost layer of the lunar surface is covered everywhere with fine dust - of 2- to 3-micron average grain size - which appears to cling equally to all parts of the lunar surface, regardless of their slope.
e. Observed attenuation of the diurnal heat wave and of the increase of its phase-lag with depth indicate that this dust layer must extend down to a depth of at least several centimeters, and probably a foot or so; but how much deeper it it may be in places remains largely conjectural.

What kind of surface should we, therefore, expect to find on the moon once we step out of a spaceship? We must bear in mind that at least its outermost crust must have been largely influenced by external events; and, in particular, should be overlaid by a certain amount of cosmic dust swept up by the moon on its perpetual journey through interplanetary space. By a linear extrapolation of its amount now incident on the earth, it is reasonable to assume that at least 2 to 3 feet of this dust should have accumulated on the surface of our satellite since the time of its formation.

If the whole moon were covered by such a dust, its albedo as well as color should be uniform over its entire face. The color of the lunar landscape is indeed very largely uniform. The albedo is not; varying as it does by a factor 3 between extreme values, but even this is very much less than the differences in reflectivity encountered among common terrestrial rocks. The near-uniformity of the observed lunar albedo suggests, therefore, at least the mitigating influence of cosmic dust intermingled with local "native" debris produced by meteor impacts. At least in regions where impacts were rare (as evidenced by an absence or a small number of craters), the local albedo is indeed more nearly uniform. The heat conduction as well as polarization properties are entirely consistent with an assumption that the medium responsible for the observed phenomena is essentially fine cosmic dust.

The indubitable existence of very rough micro-relief on the moon - probably on the centimeter scale - responsible for the steepness of its observed light changes, can also be naturally explained in this way. A loose layer of fine dust could not, to be sure, maintain indefinitely a static honeycombed surface; for the angle of repose of such a material is not sufficiently large to sustain the requisite roughness. May not, however, its vesicular structure be a simple consequence of a continuous infall of micrometeorites, raining down incessantly on the lunar surface unprotected by any atmospheres and producing their tiny craters on it?

On this picture, the micro-relief responsible for the photometric manifestations of the lunar surface in optical frequencies would not be permanent or immutable, but be all the time destroyed and re-created by an external influence - much as raindrops on earth keep checkering with their pockmarks a dry dusty surface. A powerful argument for an external influence at work is provided by the photometric homogeneity of the lunar surface, demonstrating that the rough micro-relief required to explain the observed light changes is common to all types of ground - whatever their location or albedo. What else but an external influence could impress the same type of micro-relief all over the moon?

Thus, it appears that all essential observed properties of the lunar surface can be explained by different manifestations of a layer of fine dust swept up by the moon from interplanetary space on its perpetual journey with the earth around the sun, overlying in a layer not less than 2 to 3 feet thick the native lunar rocks. Only the observed differences in albedo call for the intermingling of their cosmic dust with underlying "native" debris. Gold's attempt to invoke large-scale transport of dust, along the lunar surface, to account for the albedo differences seems, therefore, superfluous, and dust motion might even run afoul of observed facts if it were actually to denude any appreciable area of rocky surface, for the phase variation of light scattered by such an area would be quite different from that scattered by the dusty lowlands - a fact which would run counter the observed photometric homogeneity of the entire lunar face.

Department of Astronomy,
University of Manchester, England
February 1963.

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CHAPTER 1

LUNAR DATA

1.1 MASS (Based on Earth Mass of 5.977×10^{27} gm)

Mass, gm	Mass, Slugs	Based on $m_{\oplus}/m_{☾}$
7.331×10^{25}	5.024×10^{21}	81.53
7.3544×10^{25}	5.0403×10^{21}	81.271
7.3546×10^{25}	5.0404×10^{21}	81.269
7.3450×10^{25}	5.0338×10^{21}	81.375
7.3466×10^{25}	5.0349×10^{21}	81.357
7.3588×10^{25}	5.0433×10^{21}	81.222
*7.3458×10^{25}	5.0344×10^{21}	81.366

* Recommended. See paragraph 2.2.

1.2 MEAN DIAMETER

The absolute height of any point on the lunar surface, that is, its distance from the center of mass of the moon, necessitates extensive and accurate measurements of the positions of that point at different librations with respect to the neighboring stars, or the lunar limb, Reference 276. Some such determinations are available, Reference 185, for a limited number of fundamental points. The reference discussions reveal that:

a. The deviations of any part of the actual lunar surface from a sphere scarcely exceeds 2000 meters, that is, 0.1 percent of the mean radius of the moon.

b. A sphere offers as good an approximation to the actual form of the moon as a three-axial ellipsoid of any orientation.

The following determinations of the mean diameter of the moon are available:

Statute Miles	Kilometers	References
2159.86 ± 0.08	3475.96	543
2159.9	3476.0	211
2160*	3476	7, 191, 237, 544
2162	3479	47
2163	3481	6

Earth Radius: Equatorial - 6378.388 km (Reference 536)
Polar - 6356.912 km (Reference 536)

* Used by majority of authors.

1.3 SHAPE OF THE MOON AND MOMENTS OF INERTIA

The figure of the moon is complicated. Some investigators argue that its shape is best represented by a triaxial ellipsoid, while others prefer a prolate spheroid. The triaxial ellipsoid, of course, infers the existence of what is called the lunar bulge. Studies of the surface elevations have given evidence for a decreasing lunar radius as the limbs are approached, Reference 552. There is considerable irregularity in the data and the least squares solution cannot be regarded as very conclusive, furthermore, the 0.″1 of arc required to observe any bulge forbids any optical evidence of its existence. Attempts to date to specify the apex of the bulge have also differed widely, Reference 554.

Assuming the triaxial ellipsoid, the following values are given for the semi-major axes.

Semi-Major Axis	Kilometers	References
a	1738.5 ± 0.07	107, 117
	1738.57 ± 0.07	80, 212, 373
b	1738.29 ± 0.07	107
	1738.21 ± 0.07	80, 117, 212, 373
c	1737.49 ± 0.07	80, 107, 117, 212
	1737.58 ± 0.07	373

Where:

a is the axis pointing towards the earth;

b is the axis along the tangent to the moon's orbit;

c is the axis of rotation.

The corresponding moments of inertia are:

Moment of Inertia	kg Meter^2	Reference
I_a	8.797655×10^{34}	326
	$(8.8838 \pm 0.024) \times 10^{34}$	373
I_b	8.798527×10^{34}	326
	$(8.8856 \pm 0.024) \times 10^{34}$	373
I_c	8.803192×10^{34}	326
	$(8.8893 \pm 0.024) \times 10^{34}$	373

1.4 VOLUME

Spheroid:	2.1992×10^{25} cm^3
(2160.0 statute miles diameter)	or
	7.7664×10^{20} ft.^{3}
Ellipsoid:	2.1994×10^{25} cm^3
(based on paragraph 1.3)	or
	7.7671×10^{20} ft.^{3}

1.5 MEAN DENSITY (Mass/Volume)

3.3402 gm/cm^3 = 6.4822 slugs/ft.^{3}

1.6 SURFACE AREA

Ft.^{2}	cm^2	Based on Diameter in Statute Miles
4.0859×10^{14}	3.7959×10^{17}	2159.9
4.087×10^{14}	3.797×10^{17}	2160
4.094×10^{14}	3.803×10^{17}	2162
4.098×10^{14}	3.807×10^{17}	2163

1.7 SURFACE ACCELERATION CAUSED BY GRAVITY, $a = G\frac{m_{☾}}{r^2}$

161.9 cm/sec.^{2} or 5.311 ft./sec.^{2}	based on minimal tolerance
162.2 cm/sec.^{2} or 5.321 ft./sec.^{2}	based on nominal values
162.5 cm/sec.^{2} or 5.330 ft./sec.^{2}	based on maximum tolerance

Where:

$G = (6.670 \pm 0.005) \times 10^{-8}\ cm^3/gm\ sec.^2$ - Reference 212

$\frac{m_{\oplus}}{m_{☾}} = 81.366 \pm 0.029$ - Reference 553

$m_{\oplus} = (5.977 \pm 0.004) \times 10^{27}$ gms - Reference 536

$r_{☾}$ = 1080.0 statute miles

1.8 <u>LINE OF SIGHT</u>: See Figure 1-1.

1.9 INCLINATION OF LUNAR EQUATOR TO ECLIPTIC

Value (deg., min., sec.)	Reference
*1°32' ± 1'	18, 191
1°32'20"	181, 294
1°31'10" ± 22"	597
1°32' 0" ± 14"	505
1°33'48" ± 17"	598
1°33'50" ± 19"	438

* Recommended: See Chapter 5.

1.10 SIDEREAL MONTH FOR EPOCH 1900

True period of revolution, varies by more than 7 hours because of perturbations.

Value	References
$27^{d}.3216610$ or $27^{d}\ 07^{h}\ 43^{m}\ 11^{s}.50$	6, 7, 191, 211, 544
$27^{d}.3216605$ or $27^{d}\ 07^{h}\ 43^{m}\ 11^{s}.47$	207, 543

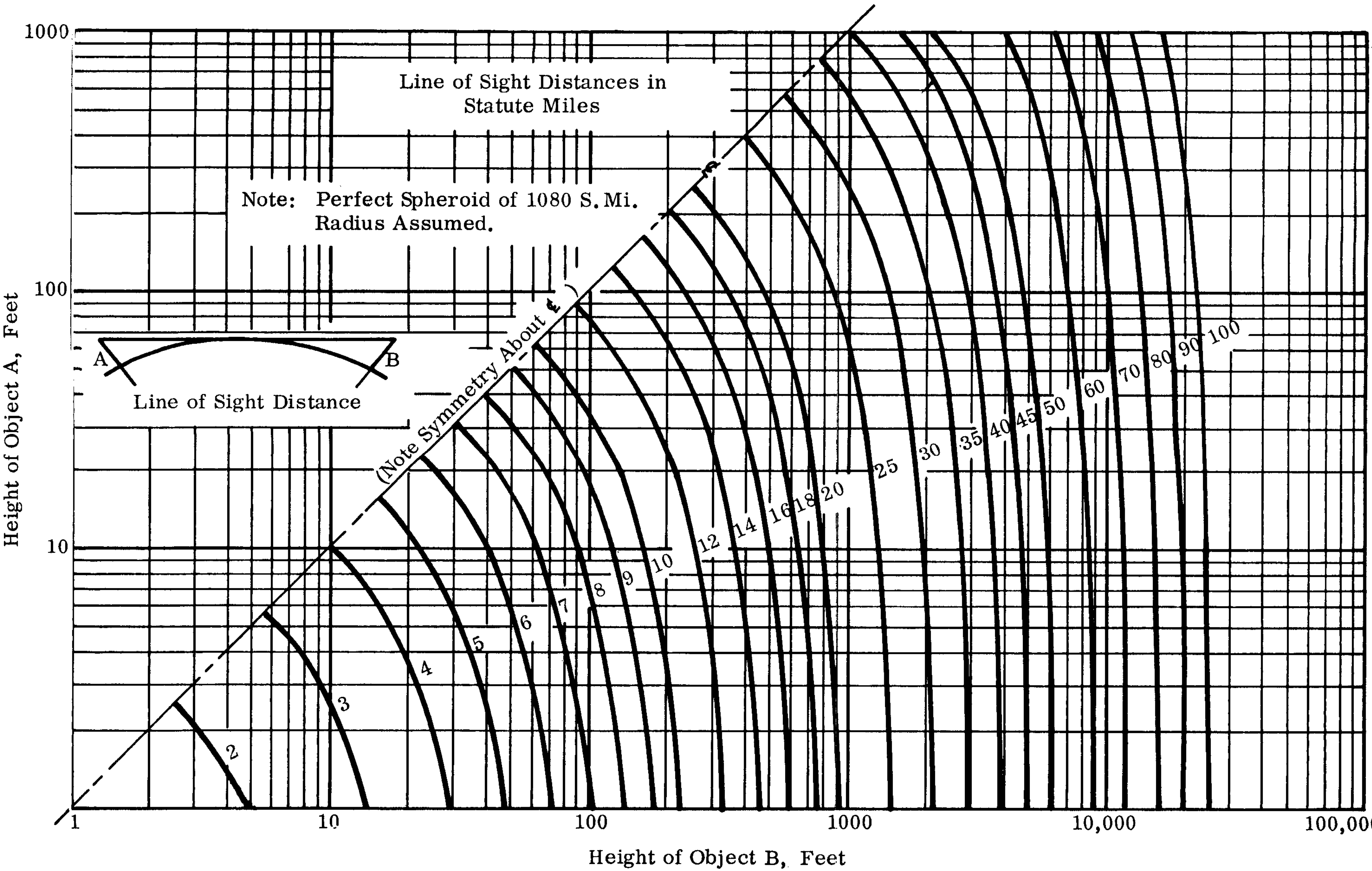

Figure 1-1. Lunar Line of Sight

1.11 LUNAR SATELLITES; Period and Velocity, See Figure 1-2.

1.12 ESCAPE VELOCITY

The escape velocity for a spherical, non-rotating moon is given by $\sqrt{2gR}$ or 2374 m/sec if the earth and sun are absent. In actual fact, however, recourse to appropriate properties of the surface of zero-velocity of the restricted problem of three bodies (i.e., earth, moon, and particle) reveals that a velocity sufficient for the particle to leave the moon is actually only 2322 m/sec, though the particle cannot leave the earth-moon system unless its velocity exceeds 2326 m/sec. The proximity of the earth reduces; therefore, the 2-body problem escape velocity of 2374 m/sec by 52 m/sec. The additional attraction by the sun should, at full moon, reduce the escape velocity by 118 m/sec and increase it by the same amount at new moon, or half a month later.

Therefore, the following lunar surface escape velocities exist:

New moon - 2440 m/sec.

Full moon - 2204 m/sec.

For escape from lunar orbit, one cannot use the $\sqrt{2}$ x circular orbital velocity for the same reasons as stated above.

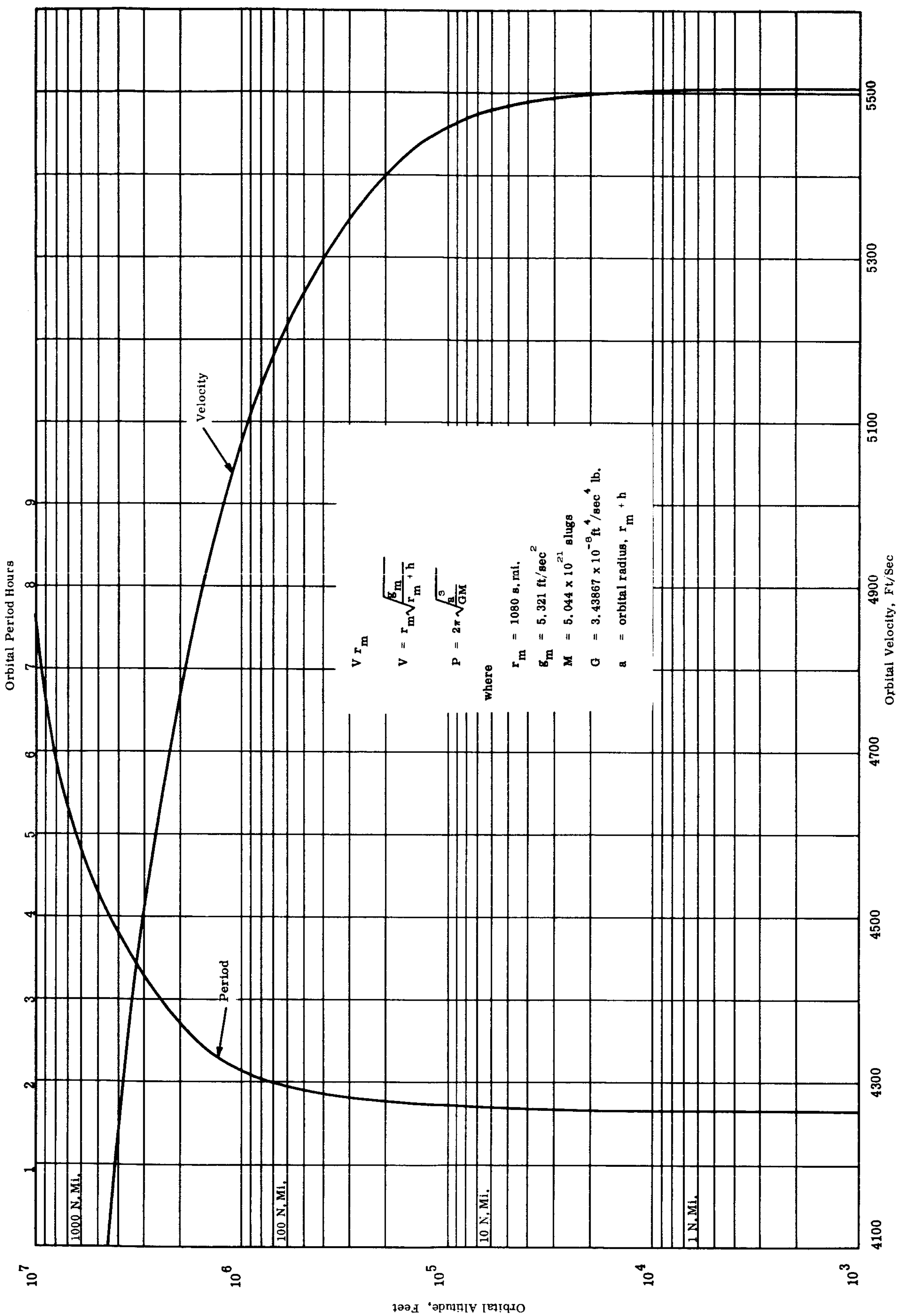

Figure 1-2. Lunar Orbital Velocity and Period Versus Lunar Orbital Altitude

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CHAPTER 2

EARTH-MOON DATA

2.1 ORBITAL ELEMENTS

2.1.1 INTRODUCTION

The moon's orbit about the center of mass of the earth-moon system is subject to continuous perturbations by the sun. As a result of this, all of the necessary six orbital elements to completely define the moon's motion are slowly varying functions of time whose complete formulas are not presented. For the remaining elements, a lunar ephemeris for the time period under consideration must be consulted, e.g., Reference 496.

2.1.2 ECCENTRICITY (Shape of Orbit)

For epoch1900.0, the eccentricity is 0.054900489, References 6, 7 and 496.

2.1.3 INCLINATION OF LUNAR ORBITAL PLANE TO ECLIPTIC (Position of Orbit)

See Figure 2-1.

Value (deg., min., sec.)	Reference
5°.1453964 or 5°8'43".4 for 1963	496
Lower limit 4°59'	543
Upper limit 5°18'	543

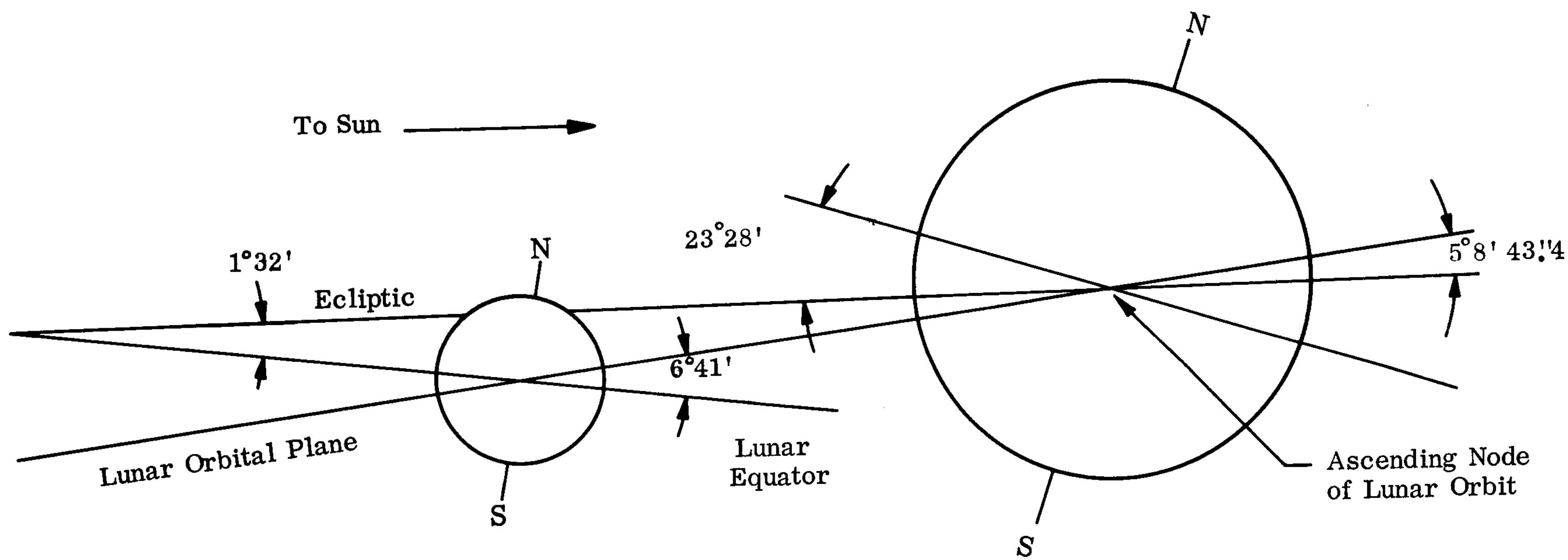

Figure 2-1. Relative Orientation - Moon, Earth, and Ecliptic

2.1.4 SEMI-MAJOR AXIS, "a" (size of orbit).

Statute Miles	Kilometers	Reference
*239,578	*385,565	608
237,293	381,887	6
236,900	381,255	7
237,000	381,416	132
237,086	381,554	237
237,271	381,852	46
238,800	384,313	544
237,087	381,556	207, 543

* Best value.

2.1.4.1 In terms of perigee, mean, and apogee, the following exists:

	Statute Miles	Kilometers	Reference
Perigee	*226,426	*364,397	608
	221,614	356,654	6
	221,800	356,954	7
	221,462	356,410	207, 237, 288, 543, 544
Mean	**238,857 ± 1	**384,402 ± 2	293, 555, 608
	238,840	384,377	6
	238,900	384,474	7
	238,860	384,409	237, 288
Apogee	*252,731	*406,732	608
	252,972	407,120	6
	252,000	405,556	7
	252,710	406,699	207, 237, 288, 543, 544

* Best value (Kopal, Reference 608)

** Best value, Radar Determination...Corrected for earth-to-moon center distance

2.1.4.2 Periods: Nodal and Synodic

Since the period is functionally dependent upon the semi-major axis, "a" by

$$P = \frac{2\pi}{K}\left(\frac{a^3}{M}\right)^{\frac{1}{2}}$$

where k is the gaussian constant and $M = m_{\oplus} + m_{☾}$, knowing the period, "a" can be calculated. Using the value of $27^{d}.212220$ for the nodal month as given below, this corresponds to a semi-major axis of 237,492 statute miles or 382,207 kilometers.

a. Nodal or draconic month for epoch 1900.0 (period from one node back to the same). Period of moon's node is 18.6 tropical years.

Value	References
$27^{d}.212220$ or $27^{d}\ 05^{h}\ 05^{m}\ 35^{s}.8$	46, 211, 237, 563

b. Synodic month for epoch 1900.0. (Period between successive full moons, that is, complete orbital revolution with respect to the sum) varies by more than 13 hours, principally because of eccentricities in the moon's orbit.

Value	References
$29^{d}.530589$ or $29^{d}\ 12^{h}\ 44^{m}\ 02^{s}.9$	6, 7, 46
$29^{d}.530588$ or $29^{d}\ 12^{h}\ 44^{m}\ 02^{s}.8$	211, 544

2.2 EARTH-TO-LUNAR MASS RATIO (See Table 2-1)

2.3 EARTH EQUATORIAL HORIZONTAL PARALLAX (See Figure 2-2 and Table 2-2)

2.4 LUNAR EQUATORIAL HORIZONTAL PARALLAX (Apparent Semidiameter)

See Figure 2-3 and Table 2-3.

Table 2-1

Earth-to-Lunar Mass Ratio

Ratio	Solar Parallax, $\pi_{\odot}$	L, Constant of Lunar Equation	Author, Year, Reference
81.53 ± 0.047	8".806	6".4305 ± 0".0031	Hinks, 1909; DeSitter, 1938; References 518, 519
81.53	--	--	Adopted by 1963 A. E. & N. A.; Reference 519
81.271 ± 0.021	8".790 ± 0".001	6".4390 ± 0".0015	Jones, 1942; Reference 332
81.269 ± 0.025	8".7888 ± 0".0011	6".4378 ± 0".0017	Jeffreys, 1948; Reference 331
81.375 ± 0.026	8".79835 ± 0".00039	6".437 ± 0".002	Rabe, 1945; Reference 327
81.357 ± 0.02	8".7979 ± 0".0002	6".4385 ± 0".0015	DeVaucouleur, 1961; Reference 520
81.222 ± 0.027	8".790	6".4229 ± 0".0015	Delano, 1950; Reference 521
*81.366 ± 0.029	--	6".4378 ± 0".0023	Brouwer and Clemence, 1961; Reference 553; Kopal, 1963, Reference 608

* Recommended by Brouwer and Clemence as the best value when all methods of determination are considered, Reference 553. Also Kopal, 1963, Reference 608.

Table 2-2

Earth Equatorial Horizontal Parallax

	Parallax	Distance	
		Statute Miles	Kilometers
Perigee*	1°1'28".90	226,426	364,397
Mean*	57'1".97	238,857	384,402
Apogee*	53'54".17	252,731	406,732

* Best Values, see paragraph 2.1.4.1.

Table 2-3

Lunar Equátorial Horizontal Parallax

	Parallax	Distance	
		Statute Miles	Kilometers
Perigee*	16'23".84	226,426	364,397
Mean*	15'32".63	238,857	384,402
Apogee*	14'41".44	252,731	406,732

* Best value, see paragraph 2.1.4.1

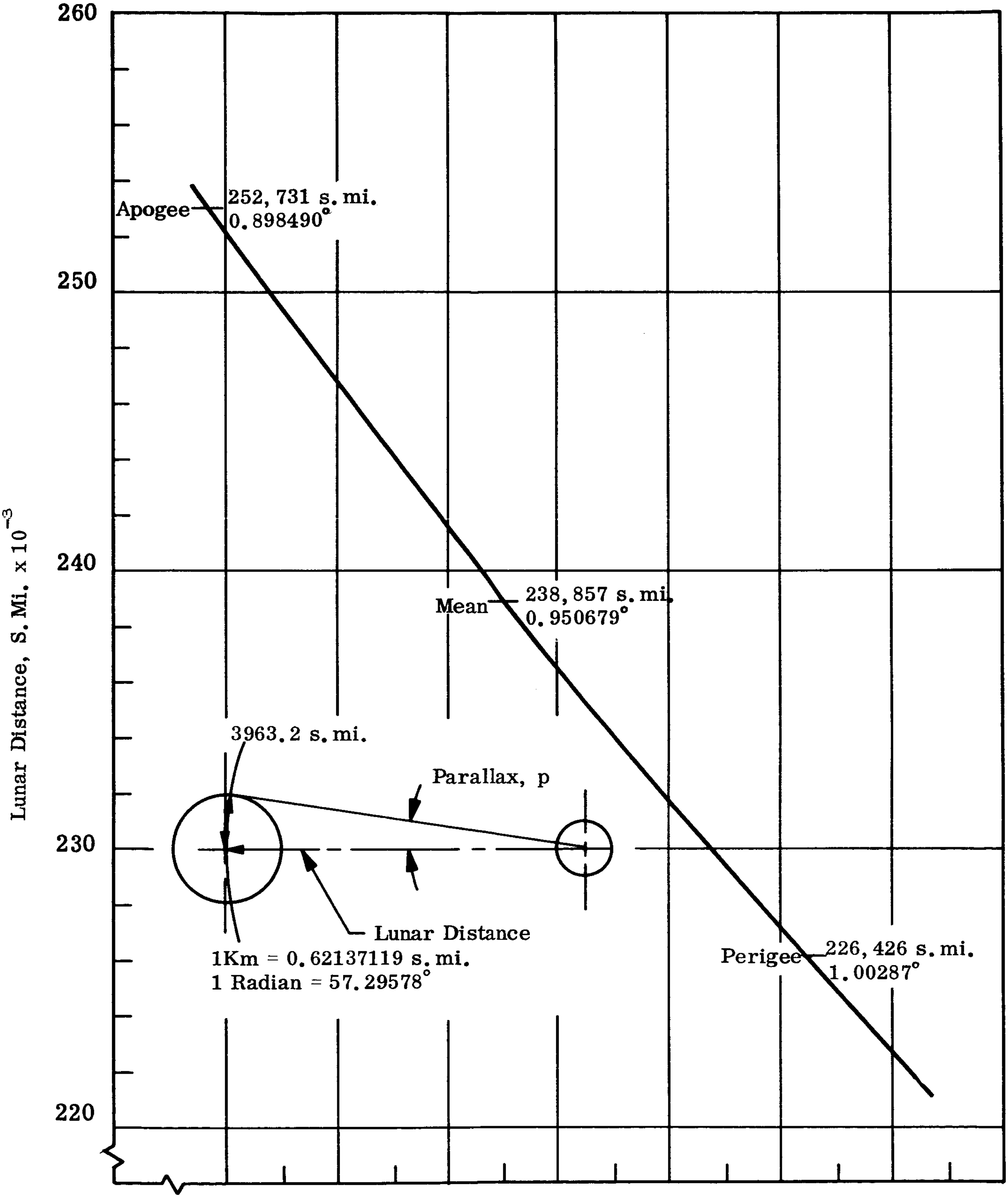

Figure 2-2. Earth Equatorial Horizontal Parallax, p, at Lunar Perigee, Mean and Apogee Distances

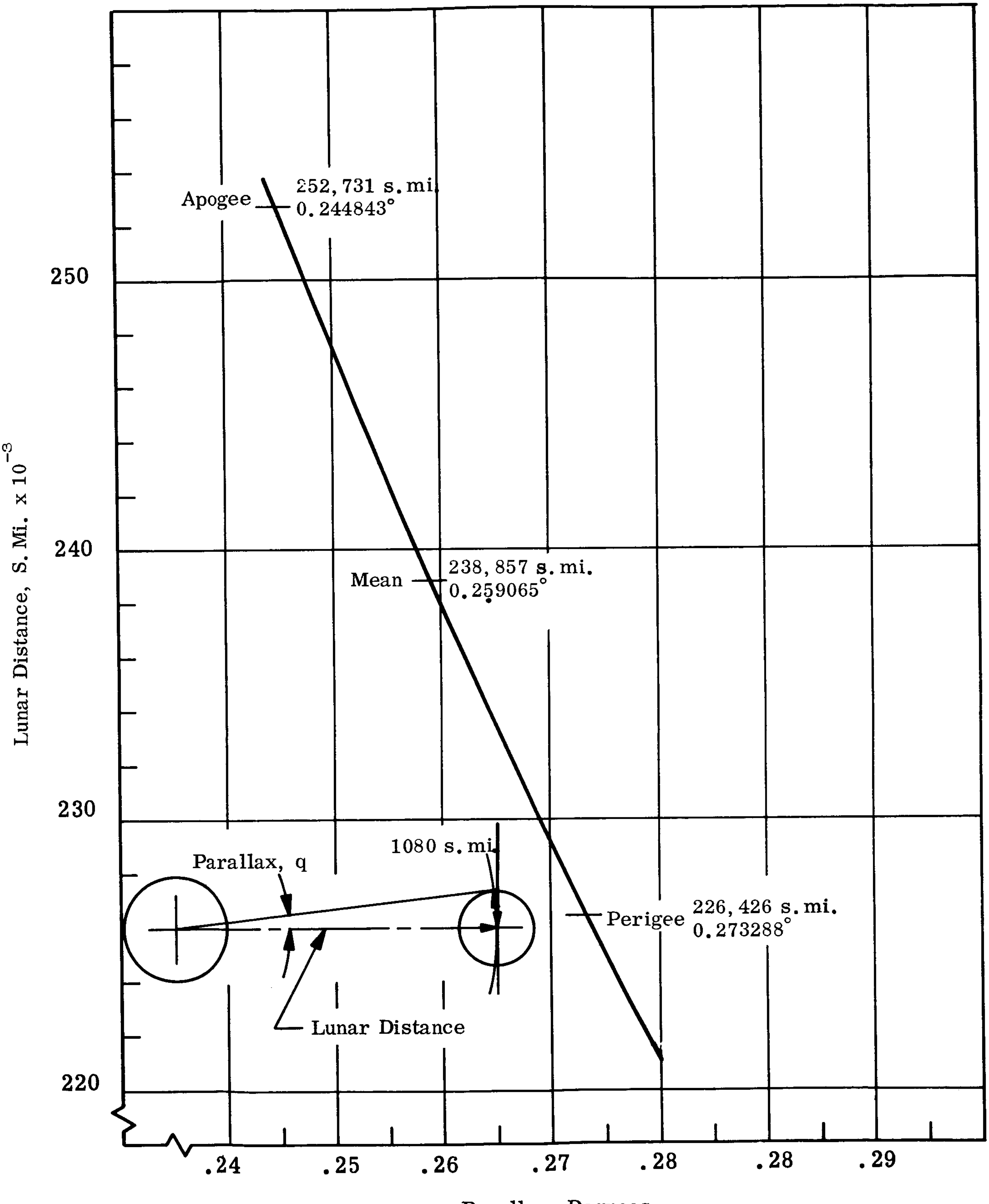

Figure 2-3. Lunar Equatorial Horizontal Parallax, q, at Lunar Perigee, Mean and Apogee Distances

2.5 MOON-TO-EARTH MEAN DENSITY RATIO

$$\frac{7.3458 \times 10^{25}\ \text{gm}/2.1992 \times 10^{25}\ \text{cm}^3}{5.9784 \times 10^{27}\ \text{gm}/1.083 \times 10^{27}\ \text{cm}^3} = 0.6051$$

2.6 MEAN PHOTOGRAPHIC MAGNITUDE OF FULL MOON

As seen from earth

-11.91 stellar magnitudes Reference 346

2.7 MEAN VISUAL MAGNITUDE (5800Å) OF FULL MOON

As seen from earth

Mean Stellar Magnitude	Reference
-12.66	6
-12.5	7, 237
-12.2	132
-12.3	563
-12.70	211

2.8 APPARENT VISUAL MAGNITUDE OF FULL EARTH

As seen from moon

Stellar Magnitude		Reference
Minimum	-17.0	132
Mean	-17.2	132
Maximum	-17.3	132

2.9 BRIGHTNESS OF FULL MOON

As seen from earth (one air mass), optical transmission of atmosphere = 0.70,

Candles/cm^2		Reference
Minimum	0.239	132
Mean	0.247	132
Maximum	0.257	132

2.10 BRIGHTNESS OF FULL EARTH

As seen from moon,

Candles/cm^2		Reference
Minimum	1.70	132
Mean	1.75	132
Maximum	1.81	132

2.11 BRIGHTNESS OF DARK MOON

Illuminated by full earth (earth light) as seen from earth (0.70 of incident light transmitted).

Candles/cm^2		Reference
Minimum	2.11×10^{-5}	132
Mean	2.47×10^{-5}	132
Maximum	2.96×10^{-5}	132

2.12 BRIGHTNESS OF THE LUNAR AUREOLE (Candle/cm^2, See Figure 2-4)

2.13 ILLUMINATION OF EARTH BY FULL MOON (one air mass),

Lumens/cm^2		Reference
Minimum	1.37×10^{-5}	132
Mean	1.58×10^{-5}	132
Maximum	1.92×10^{-5}	132

2.14 ILLUMINATION OF MOON BY FULL EARTH

Lumens/cm^2		Reference
Minimum	1.30×10^{-3}	132
Mean	1.52×10^{-3}	132
Maximum	1.82×10^{-3}	132

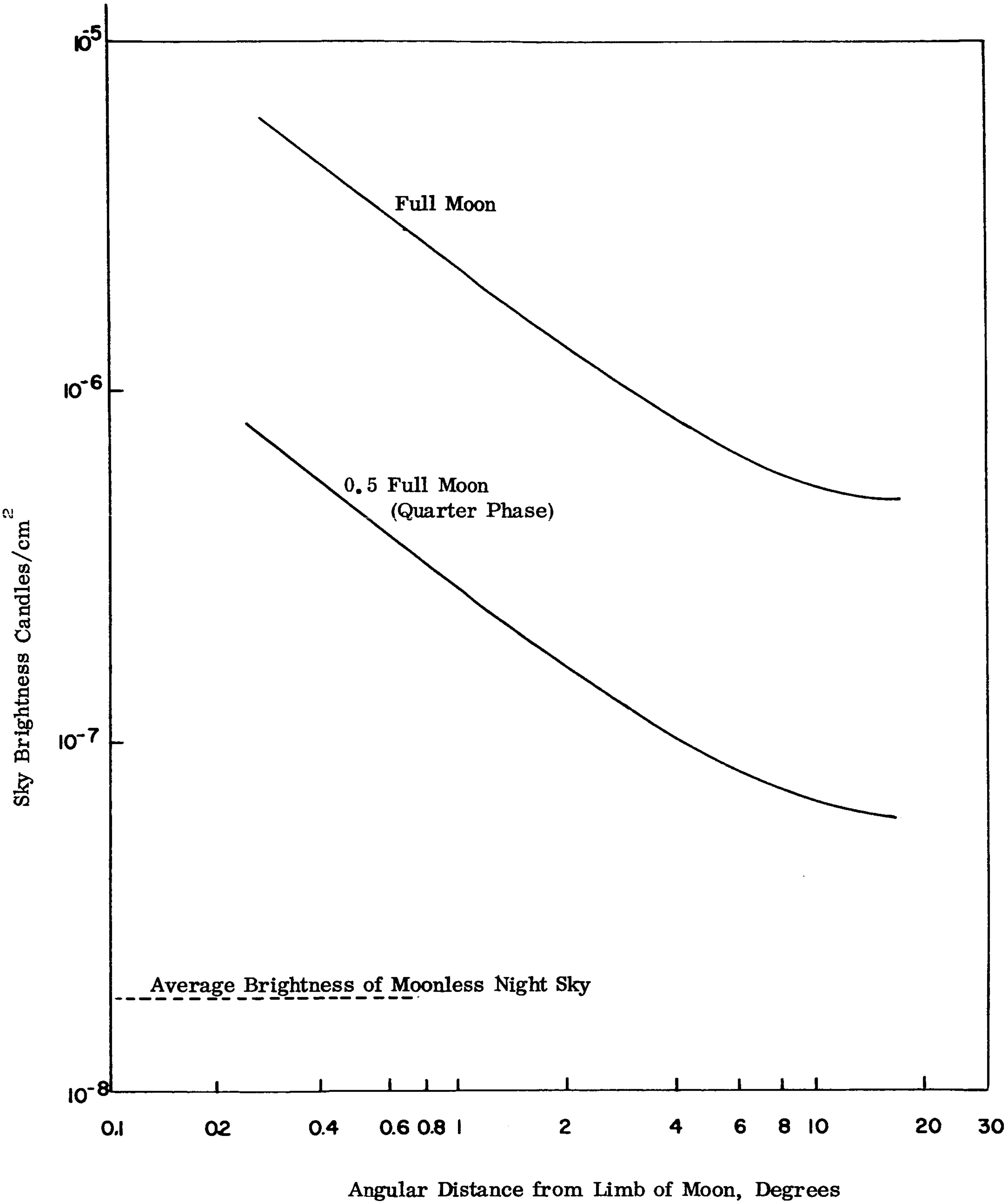

Figure 2-4. Brightness of the Lunar Aureole, Reference 132

2.15 VISUAL DETECTION OF OBJECTS ON OR NEAR THE MOON

2.15.1 FULL MOON BACKGROUND, Reference 132

Telescope Aperture, in.	Diameter, Ft.	
	White Spot	Plane Mirror
20	401	2.22
30	257	1.48
40	200	1.11
100	80	0.44

2.15.2 DARK HALF OF QUARTER PHASE MOON AS BACKGROUND, Reference 132

Telescope Aperture, in.	Fixed Light Intensity, Candle	Single Flash Energy, Candle-Sec.
20	2.25×10^{6}	1.45×10^{7}
30	1.00×10^{6}	6.46×10^{6}
40	*5.63×10^{5}	**3.63×10^{6}
100	9.02×10^{4}	5.81×10^{5}

* Approximately equivalent to the candlepower of 12 strong automobile headlights.

** About 2.6 pounds of low-altitude illuminant.

2.15.3 LUNAR SATELLITE AT 0.75 DEGREE FROM LIMB OF MOON

(3000 miles altitude), Reference 132

Telescope Aperture, in.	White Spherical Lunar Satellite, Diameter, Ft.	Stellar Magnitude
20	25.4	13.7
30	16.9	14.6
40	12.7	15.2
100	5.1	17.2

2.16 PHOTOGRAPHIC DETECTION OF OBJECTS ON OR NEAR THE MOON

2.16.1 DARK MOON BACKGROUND

Telescope	Non-Trailing Satellite Image				Trailing Satellite Image			
	ϕ = 90°		ϕ = 135°		ϕ = 90°		ϕ = 135°	
	Plus X	Royal X	Plus X	Royal X	Plus X	Royal X	Plus X	Royal X
Simple 4" Reflector	---	80	---	27.9	---	---	21.6	---
Baken-Nunn (20")	128	222	44.6	77.5	---	---	---	---
60" Astronomical	---	15.1	---	5.3	---	---	4.1	---
200" Astronomical	6.5	11.7	---	4.1	---	---	---	---
40" Yerkes Refractor	---	10.1	---	---	10.3	---	4.9	4.4

Minimum diameter in feet of a spherical diffusely reflecting satellite that can be detected photographically against the dark side of the moon. ϕ is phase of moon. Where assumptions on which calculations were based are invalid, spaces have been left in the table. Reference 504.

2.16.2 SUNLIT MOON BACKGROUND

Telescope	Non-Trailing Satellite Image			
	ϕ = 90°		ϕ = 135°	
	Plus X	Royal X	Plus X	Royal X
60" Astronomical	932	1620	840	1460
200" Astronomical	715	1250	647	1115
40" Yerkes Refractor	625	1082	561	980

Minimum diameter in feet of a spherical diffusely reflecting satellite that can be detected photographically against the sunlit side of the moon. Trailing images not valid. ϕ is phase of moon. Reference 504.

2.17 LIBRATIONS OF THE MOON

2.17.1 INTRODUCTION

There are four kinds of apparent oscillations of the moon. They are, in descending order of magnitude, libration in longitude, libration in latitude, diurnal libration, and physical libration. The first three phenomena are referred to as the optical librations of the moon. The physical libration is the summation of small periodical variations in the moon's rotation. The amount of total libration is the vector sum of these quantities and requires digital computer techniques for accuracy necessary for radar studies, Reference 462. A maximum of 10°54' is stated in Reference 6.

2.17.2 LIBRATION IN LONGITUDE

Since the angular motion of the moon in its orbit is variable while the rotational motion is essentially uniform, the two motions are out of phase during the month and an observer can see alternately around the "edges" of the moon. This libration changes the longitude of the apparent center of the lunar disc by ± 7° 53' 51".

2.17.3 LIBRATION IN LATITUDE

As a result of the inclination of the moon's equator to its orbital plane, at one time during the month the north pole is tipped toward, the observer and approximately two weeks later the south pole is inclined toward the observer. This variation in latitude of the apparent center of the lunar disk is within the limits of ± 6° 50' 45".

2.17.4 DIURNAL LIBRATION (PARALLATIC)

This libration is simply that caused by the earth's rotation. In just 12 hours, an earth observer can view the moon from positions far enough apart to show slightly different hemispheres. The maximum value is equal to the horizontal equatorial parallax of the moon, i.e., ± 57'.

2.17.5 PHYSICAL LIBRATIONS

While these librations are negligible when compared to the optical librations, it is, nevertheless, necessary to consider them for accurate location on the lunar surface. Two minutes of arc (selenocentrically) can result in a displacement of one kilometer on the lunar surface. The physical libration in longitude has a period of one year and in latitude, approximately six years, References 326, 442, and 598. Reference 326 shows approximately ± 0.04 degree for the latitude component and ± 0.02 degree for the longitude component, having the six and one year periods, respectively.

2.18 PERCENT OF LUNAR SURFACE VISIBLE FROM EARTH

Always	41
Never	41
Sometimes	18 (30-year interval required)

2.19 ANGULAR VELOCITY OF EARTH-MOON SYSTEM, (rad/sec)

2.6616995×10^{-6} Reference 288, 496

2.20 MEAN ORBITAL SPEED FOR EPOCH 1900.0 $\frac{2\pi \times 384,402 \text{ km}}{27.212220 \text{ day}}$

38,822.0 n. mi./day	= 1617.58 n. mi./hr.	= 26.9597 n. mi./min.	= 0.449329 n. mi./sec.
55,150.8 s. mi./day	= 2297.95 s. mi./hr.	= 38.2992 s. mi./min.	= 0.638320 s. mi./sec.
88,756.8 km/day	= 3698.20 km/hr.	= 61.6367 km/min.	= 1.02728 km/sec.
2.91196×10^{8} ft/day	= 1.21332×10^{3} ft/hr.	= 2.02220×10^{5} ft/min.	= 3370.33 ft/sec.

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CHAPTER 3

SUN-MOON DATA

3.1 SOLAR-TO-LUNAR MASS RATIO

Based on solar mass of 1.991×10^{33} gm, Reference 569.

2.710×10^{7}

using recommended lunar mass of

7.3458×10^{25} gm

3.2 LUNAR DISTANCE FROM SUN

At full moon, statute miles, References 46 and 132.

Minimum	January	91.5×10^{6}
Mean	April and October	93.1×10^{6}
Maximum	July	94.8×10^{6}

3.3 ANGULAR SEMIDIAMETER OF SUN AS SEEN FROM FULL MOON

Radians, Reference 132.

Minimum	0.00456
Mean	0.00464
Maximum	0.00472

3.4 ILLUMINATION OF FULL MOON BY SUN ON A SURFACE NORMAL TO RADIATION

Lumens/cm^{2}, Reference 132.

Minimum	14.7
Mean	15.2
Maximum	15.8

3.5 SUN'S APPARENT VISUAL MAGNITUDE AS SEEN FROM MOON

Stellar Magnitude, Reference 132, -27.15.

3.6 SUN'S RADIATION INTERCEPT, Reference 46

Arc:	4"8
Billionths of Total:	0.453

3.7 TOTAL SOLAR INPUT DURING LUNAR DAY (per cm^2), Reference 233

Lunar Latitude (degrees)	Ergs	Calories
0	1.11×10^{12}	2.65×10^{4}
15	1.07×10^{12}	2.65×10^{4}
30	0.96×10^{12}	2.29×10^{4}
45	0.78×10^{12}	1.86×10^{4}
60	0.56×10^{12}	1.34×10^{4}
75	0.29×10^{12}	0.69×10^{4}
85	0.097×10^{12}	0.23×10^{4}

3.8 OTHER SOLAR DATA

a. Solar radius

$(6.960 \pm 0.001) \times 10^{8}$ meters	Reference 569
6.953×10^{8} meters	Reference 543

b. Solar mass

$(1.991 \pm 0.002) \times 10^{33}$ gm	Reference 569
1.993×10^{33} gm	Reference 73
1.983×10^{33} gm	Reference 543

c. Mean solar density, Reference 569

$1.41\ gm/cm^3$

d. Escape velocity at solar surface, Reference 569

6.18×10^{5} m/sec

e. Total electromagnetic radiation emitted from entire sun, Reference 569

$(3.86 \pm 0.03) \times 10^{26}$ joules/sec

f. Mean solar constant, energy flux of electromagnetic radiation of earth's orbit,

2.00 cal/cm^2/min	Reference 569
1.94 cal/cm^2/min	Reference 132

g. Inclination of solar equator from ecliptic, Reference 427, 7° 15'

h. Rotational period, Reference 569, 24.6 days

i. Brightness, Reference 132, 225,000 candles/cm^2

NOTE: Section 3.8, except where noted from Handbook of Astronautical Engineering, Reference 569, edited by H. H. Koelle (c) 1961. McGraw-Hill Book Company. Used by Permission.

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CHAPTER 4

OBSERVATION AND TOPOGRAPHY

4.1 OBSERVING THE MOON

The most detailed information accumulated about the moon comes from telescopic observations of the reflected sunlight, which eventually reaches us after passing through an ocean of atmosphere. Even a perfect telescope when used by an expert observer is limited by this insuperable handicap, the earth's atmosphere. Refraction in this atmosphere bends the light rays through a small angle. However, as winds and currents of warm and cool air circulate overhead, each ray of light is bent in a slightly different manner. The degree of this turbulence of the atmosphere is called the "seeing," which may be good or bad.

The turbulence produces a "spread" and a "jiggle," the spread being caused by small differences in atmospheric refraction, and the jiggle, or motion of the image as a whole, being caused by gross air movements above the telescope which results in a constant change of the air's index of refraction. In visual observations, the eye can compensate for the movement of the image. But in photographic observations which require exposures of the order of a number of seconds, the jiggle is superimposed on the spread. Techniques are now being developed whereby the motion of the image is "tracked" and corrected electromechanically such that the detail in astronomical photographs will approach that seen in visual observations. On average clear nights, images of a celestial point at the prime focus of a telescope are spread out by turbulence to a diameter equivalent to three seconds of arc. On nights of good seeing, the spread is equivalent to one second of arc, while really exceptional seeing, which occurs only rarely, results in an image spread equivalent to twenty-five one hundredth seconds of arc. At the moon's mean distance from the earth, these angles correspond to the following linear distances:

3 seconds of arc - equivalent to 3.48 statute miles
1 second of arc - equivalent to 1.16 statute miles
0.25 second of arc - equivalent to 0.29 statute mile (1530 feet)

The bad "seeing" sets an insurmountable barrier to observing fine detail, either visually or photographically.

Separate and distinct from the "seeing" is the limiting role of diffraction depending solely on the aperture of the optics employed and the wavelength of observation. It is found that the diffraction pattern of a circular aperture consists of a bright circular disc surrounded by a series of dark and bright rings. The angular half-width of the central disc of the diffraction pattern is given by the expression $1.22\left(\frac{\lambda}{d}\right)$, where λ is the wavelength and d is the diameter of the circular aperture. The value of the radius is less than one second of arc for telescopes greater than 5-inch aperture radius. It is thus only for instruments of under 5-inches aperture that the size of the theoretical optical image determines the resolving power. For telescopes over 60 inches, the theoretical resolving power is hardly ever realized, since the "seeing" is then the limiting factor.

Below a certain angular limit of about a tenth of a second of arc, neither the eye nor the photographic plate can register any detail.

A large telescope will enable an observer to discern finer details than a small telescope, only if the "seeing" permits it. When the "seeing" is bad, the image of the moon in a large telescope may be even poorer than in a small one, because of the larger area which allows a greater variation of the air conditions. Hence, telescopes of moderate aperture, that is, six to twenty inches, are the most effective for direct visual studies. The large reflectors are used almost exclusively for photographic work, in which their tremendous light-gathering power is of the utmost value. The magnifying power for any telescope may be chosen at will, by a change of eyepieces. A high power is used when the "seeing" is good and a lower power when it is poor.

The requirements of good "seeing" are so severe that the best photographs taken with the one-hundred-inch telescope fail to reveal craters less than one mile in diameter. The photographs taken with the two-hundred-inch reflector do not come up in sharpness or crispness of detail to photographs taken with the one-hundred-inch or even sixty-inch telescopes. It is doubtful that the displacement, appearance, or disappearance of a spherical mass of one mile in diameter on some lunar mountain ridge could be seen on the best photographs of the moon. Therefore, visual observation has been and will always be the primary source of information of the small details of the lunar surface.

The human eye has the remarkable ability of recognizing, in the moments of good "seeing" by means of a telescope, very narrow lines on the surface of the moon which are completely invisible on the best photographs taken with the largest reflectors. Knowledge of these rills or cracks on the surface of the moon is, therefore, almost wholly based on visual observations with all their attendant uncertainties.

Also, knowledge of the rapid changes in the color and brightness of the various details on the moon have been gained primarily through visual means. The existence of such changes seems to be beyond doubt in spite of the fact that they have never been recorded on photographs.

4.2 TOPOGRAPHIC FEATURES

4.2.1 INTRODUCTION

On the face of the moon, there is a landscape that is strikingly different from that of the earth. Craters are a dominant topographic form, ranging in diameter from huge circular basins 100 miles across down to the limit of resolution for telescopic observation of about one-half mile. By extrapolating below this resolution limit, it is believed that the number of craters increases rapidly with decreasing diameters and that the entire surface of the moon is peppered with uncounted millions of small craters too small to be observed visually. The number of craters exceeding 1-mile in diameter on the visible side alone is greater than 300,000.

Topographic terminology for the moon is many times inconsistent and unscientific because of the prescientific era observers. The surface features fall into several major categories.

4.2.2 SEAS

4.2.2.1 General

Seas occupy about 40 percent of the visible lunar disc. The Latin name mare, plural maria, is always used for a general notation of this feature, despite the fact that they are definitely plains without water. They are large, essentially circular, areas enclosed by ranges of mountains or hills that, in many cases are themselves made up of portions of smaller circular structures. Most of the maria are interconnected and bear a strong geographical resemblance to the ocean basins on earth. They are dark in color and are characterized by a relatively level and only infrequently interrupted surface.

4.2.2.2 Seas proper, such as Mare Imbrium (Sea of Showers) and Oceanus Procellarum (the Ocean of Storms), the largest sea on the moon.

4.2.2.3 Lakes (Lacus) or formations analogous to maria but of smaller extent, such as Lacus Mortis (Lake of Death) connected with Lacus Somniorum (Lake of Sleepers), which, in turn, is connected with Mare Serenitatis (Sea of Serenity).

4.2.2.4 Bays (Sinus) in the seas, such as Sinus Iridum (Bay of Rainbows) in Mare Imbrium.

4.2.2.5 Marshes (Palus), regions intermediate in coloration between continents and seas, such as Palus Somnii to the east of Mare Crisium.

4.2.3 CONTINENTS

These are the brighter portions that occupy about 60 percent of the visible surface of the moon. They are characterized by extensive rough areas that display great concentrations of ringed plains and craters and are analogous to continents on earth.

4.2.4 WALLED OR RINGED PLAINS

Walled or ringed plains are often confused with craters. They are really formations intermediate between seas and craters with diameters from 80 to almost 300 kilometers (50 to 185 miles). The main difference between walled plains and craters is in size (craters are smaller), shape (craters are more nearly circular, whereas walled plains are mostly polygonal), and coloration of the floor (walled plains having a darker coloration). The rims are either low or almost absent above the surrounding terrain. Two kinds of plains can be distinguished:

a. Those with a central mountain formation; e.g., Clavius.
b. Those without a central formation; e.g., Walter.

At the present time, something like 700 walled plains and craters have names attached to them.

4.2.5 CRATERS

Craters are the most characteristic feature on the surface of the moon. The demarcation between walled plains and craters occurs at a diameter of about 65 kilometers (40 miles). The number of craters increases very rapidly with the decrease in size and runs into many thousands if craters of one mile or less in diameter are included, see Reference 172. Large craters are known by individual names, and the smaller craters are named after the larger ones in their vicinity with a capital Latin letter, such as Vendelinus C. The varieties of craters are as follows:

a. Large well-defined craters, such as Copernicus or Kepler, with central peaks or swelling of the floor and of the size 15 to 65 kilometers (10 to 40 miles) in diameter.
b. Same as above, but without a central peak, for example, Aristarchus.
c. Submerged large craters obviously of a more ancient origin, Stadius, for instance, between Copernicus and Eratosthenes.
d. Partially filled up large craters, such as Wargentin.
e. Smaller craters between 8 and 15 kilometers (5 to 10 miles) in diameter often parasitic, that is, occurring on the rims or in the interiors of larger craters.
f. Craterlets smaller than 5 miles in diameter without a central section. Over 1000 of these are known in the region of Copernicus alone.
g. Blow holes or pits a fraction of a mile in diameter.
h. Confluent craters or two or more craters merging together. Hundreds of these are known, such as Thebit, a triple crater formation.
i. Chains of craters well separated from each other. Such as those on the floor of the great crater Bullialdus.

4.2.6 MOUNTAINS

Mountains on the moon are named mostly after terrestrial mountains. More recently discovered mountain ranges bear the names of scientists, such as the Doerfel Mountains. The highest mountains found on the moon are the Leibnitz and Doerfel Mountains, located in the limb region near the south pole. Their altitudes have recently been determined by Watts to be 5970 (19,580 ft.) and 5600 meters respectively, Reference 18. The following types of mountains can be distinguished:

a. Mountain ranges, such as the Apennines or the Alps bordering on the seas and analogous to the mountain ramparts of the walled plains.

b. Mountain ranges not connected with the present seas; for example, Altai Mountains.
c. Isolated mountain peaks, such as Pico in Mare Imbrium.
d. Small rounded mounds of which many thousands are known.
e. Wrinkle ridges, or smooth low-altitude undulations appearing at low sun as twisted ropes, common on sea floors.
f. Domes, or small rounded slight elevations very difficult to see under any conditions, and producing an impression of blisters on the surface of the moon. Minute vents on the summits of some domes suggest that they may be degassing blisters, or they may be areas of serpentinized rocks which have undergone expansion and possibly subsequent contraction.

4.2.7 FRACTURES

Fractures involving large vertical movements are common on the surface of the moon. Several thousands of them have been listed. They are usually denoted by Greek letters accompanying the name of the crater with which they are associated. The following types are known:

a. Mountain valleys, such as the great gorge in the Alps.
b. Valleys not connected with mountain ranges, such as Rheita Valley.
c. Cracks consisting of a large number of small craters joined together; for example, the crack running through crater Hyginus.
d. Scarps: Scarps have been mentioned as forming the faulted borders of the maria. The most famous scarp is the Straight Wall, a fault 130 kilometers long and about 250 meters high, dotted with minute craters along its length and running northwest to southeast in western Mare Nubium. Since no evidence of horizontal movement along this fracture can be seen in photographs, it is provisionally classed as a normal or gravity fault. This type of structure may be indicative of crustal tension, normal to the trace of the fault, or it may be the surface expression of the deeper seated shear. It is an important clue to the crustal processes on the moon and should rank high on the list of features for early examination.
e. Clefts or surface cracks abound on the floor and in the neighborhood of almost every large crater or walled plain. Some are detectable along the inner margins of craters and give the appearance of being tension fractures caused by subsidence of the crater floor.

f. Rills: These surface cracks are finer in detail than clefts and considerably shallower. Two of the most prominent and best known are the Hyginus and Ariadaeus rills. In general, rills are like trenches, sometimes 200 to 300 kilometers long, a few kilometers wide, and in depth frequently about a third of their widths. In many cases, ridges run along their bottoms.

g. Ridges: The maria surfaces display long, wave-like ridges some of which are roughly parallel to the maria borders. They are generally discontinuous with the individual elements frequently in echelon arrangement. Although the appearance is that of ripples in a liquid, they are more likely to be wrinkles in the surface caused by subsidence and a shortening of the crust. Some of the ridge crusts have longitudinal cracks.

4.2.8 RAYS

These are white streaks issuing more or less from craters, the Tycho system of rays being the largest and most prominent. Over 100 of such systems are known. This is the only feature that is best visible at full moon. Some rays are radial to the various crater centers while others are tangential to the crater rims. Actually, it has been observed that the tangential rays, upon close examination, are found to consist of many "fine" lines which are, in fact, radial to the crater, Reference 488. In some areas, namely the craters Messier and Proclus, rays exist only in certain directions.

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CHAPTER 5: COORDINATES

CHAPTER 5

COORDINATES

5.1 LUNAR LONGITUDE AND LATITUDE

In order to describe or determine uniquely the position of any point on the surface of the moon, it is necessary to define a suitable system of angular lunar coordinates, β, λ, which are analogous to the terrestrial latitudes and longitudes, Reference 18. The two great circles on the lunar surface from which such coordinates are conventionally measured are, respectively, the lunar equator (i.e., the circle in which the equatorial plane intersects the surface of the moon) and the principal meridian, perpendicular to the equator, defined as a plane in which the radius vector joining the centers of the earth and the moon is situated at the time of nodal passage (i.e., when the moon's mean longitude is equal to that of the ascending node of its orbit). The selenographic latitude is measured from the lunar equator, positive to the north; i.e., in the hemisphere containing Mare Serenitatis and Mare Imbrium. The selenographic longitude is measured along the lunar equator positive toward the west; i.e., Mare Crisium.

A word should be said about the astronomical convention of placing lunar maps with south up (corresponding to the telescopic view in the Northern Hemisphere), and the terrestrial convention of using north up on charts. The two conventions might be termed astronomical and astronautical, respectively. It is recommended, Reference 34, that the astronomical lunar maps, showing south up, do not use the terms east and west since they refer to directions in the sky and are opposite to those on a rotating globe; and that instead, when necessary, the terms preceding and following are used in their usual astronomical meaning. Astronautical maps, however, showing north up, will show east and west.

5.2 ASPECTS OF 0° EAST, 0° NORTH

5.2.1 INTRODUCTION

The intersection of the equator and the principal meridian from which the lunar latitudes β and longitudes λ are reckoned cannot be measured directly on the moon, and their localization is inextricably connected with the determination of the orbital elements of the moon, its shape, as well as libration, Reference 18.

5.2.2 LUNAR EQUATOR

In assessing the degree of internal consistency of the measurements of the position of the moon's axis of rotation in space, paragraph 1.9, it should be noted that an error of 1 minute in the determination of the position of the lunar equator entails effects of the order of 0."25 as observable from the earth. As this is close to the actual resolving power of any terrestrial telescopes, it should be sufficient, for topographic purposes, to adopt the value of $I = 1° 32' \pm 1'$ consistent with all existing determinations of this quantity, and to round off the determination of all lunar latitudes to ± 1 minute (corresponding, on the lunar surface, to a distance of ± 506 meters at the center of the apparent lunar disc), Reference 18.

5.2.3 PRINCIPAL MERIDIAN

The determination of the position of the principal meridian on the moon, from which the longitudes λ can be reckoned, cannot likewise be attempted directly, but only as a by-product of a grand solution for all the libration constants, from careful measurements of selected reference points on the lunar surface with respect to the limb of the moon (by heliometer), or to the neighboring stars (by photographic methods).

5.3 FUNDAMENTAL REFERENCE POINTS

5.3.1 INTRODUCTION

Tobias Mayer - the father of selenographic positional measurements - chose the central mountain of the crater Manilius as his fundamental reference point (a choice in which he was followed by Bouvard and Nicollet), but all more modern observers have adopted for this purpose a small crater Mösting A (on the slopes of Flammarion), not quite on the principal meridian, but situated sufficiently near the center of the apparent lunar disc. Its longitude λ and latitude β were found to be:

λ	β	Authority
-5°10'26" ± 25"	-3°10'32" ± 2"	Hartwig (1880)
-5°10'19" ± 8"	-3°11'24" ± 5"	Franz (1889, 1901)
-5°10'10" ± 20"	-3°11'15" ± 14"	Hayn (1902-14)

On the basis of an ensemble of these measurements Hayn (1914) adopted $\lambda = -5^{\circ}10'7'' \pm 9''$ and $\beta = -3^{\circ}11'2'' \pm 7''$ for the mean position of Mösting A; while the efforts of the subsequent investigators led to:

λ	β	h	
-5°11'50" ± 12"	-3°10'27" ± 17"	15'32".88 ± 0".56	Koziel (1948-49)
-5°11'16" ± 13"	-3° 9'56" ± 18"	15'33".81 ± 0".58	
-5° 9'20" ± 9"	-3°10'41" ± 7"	15'32".80 ± 0".32	Belkovich (1949)
-5°10'13" ± 14"	-3°11'46" ± 9"	15'33".90 ± 0".45	Nefedjev (1950)
-5°11'13" ± 14"	-3°13'11" ± 11"	15'34".52 ± 0".60	Yakovkin (1950)
-5°10'19" ± 7".9	-3°11'24" ± 5".5		Army Map Serv. (1960) (Ref. 481)

where h denotes the radius-vector to Mösting A in angular units (i.e., the angular distance of its floor from the center of the moon, as seen at its mean distance from the earth). Franz used, besides Mösting A, the positions of the craters Aristarchus, Byrgius A, Fabricius K, Gassendi, Macrobius A, Nicollet A, Proclus, and Sharp A as a system of nine fundamental reference points on the surface of the moon, while Hayn used only five (i.e., Egede A, Kepler A, Messier A, Mösting A, and Tycho).

The close constancy of the selenographic longitude of Mösting A, as deduced from the heliometric observations of the past hundred years, reveals, incidentally, that the axial rotation of the moon is synchronized with the period of its revolution around the earth within ± 0.1 second of time (i.e., about one part in 20 to 30 millions; Banachiewicz, 1955).

With the aid of the system of lunar coordinates as determined by the measured positions of the crater Mösting A or other fundamental points, it should be possible to localize a greater number of reference points on the lunar surface for detailed topographic work. This has been done, References 185, 338, and 581.

Are the available reference points of known coordinates on the surface of the moon sufficient for detailed local topographic measurements of long-focus plates? The density of such points per unit area would indeed be sufficient if it were not for the difficulties in identification. Most points measured by the investigators referred to hills or mountains having no well-defined summits, and their exact locations are too vaguely defined to be identifiable without ambiguity on photographs taken at different angles of illumination with the requisite precision. The same is all the more true of several of the fundamental points (Tycho, for example) measured by Franz or Hayn.

In order to remove these difficulties and to meet the current needs of lunar topography, Kopal suggests, References 18 and 276, that a new homogeneous set of control points (harmonized as far as possible with the existing systems of Franz and Saunder) be set up based on the positions, not of any mountains (because of their ill-defined nature), but rather of small craters, 1 to 3 kilometers in diameter, the adoption of which should have the following advantages:

a. Because of their ubiquitous nature, a sufficient number of them could be located in any small segment of the lunar surface.
b. Their shallow depths would make their positions largely independent of the direction of incident sunlight.

In Kopal's opinion, Reference 18, the deficiencies inherent in the present systems of selenographic coordinates (as reflected in the Blagg-Wesley I.A.U. Atlas, 1935) are probably displacing whole lunar regions by several kilometers relative to others; and their uncertainty constitutes also the principal source of error in the determination of the heights of the lunar mountains from the measured lengths of their shadows.

5.3.2 LUNAR ATLAS PROJECT HEADED BY G. P. KUIPER OF YERKES OBSERVATORY

The Orthographic Atlas of the Moon, Reference 34, edited by G. Kuiper is an attempt to produce a completely objective representation of the lunar surface with the highest possible positional accuracy commensurate with a reasonable expenditure of effort. The control grid of Reference 34 rests on the network of the precisely positioned points established by Franz and Saunder, and where these points proved inadequate, points determined by Arthur, Reference 581, were used. Arthur has very carefully examined all of the classic literature relating to selenographic positions and has produced a corrected supplemented catalog of 4510 selenographic positions, Reference 581. The purpose of this catalog is cartographic and in cartography relative accuracy is in some measure more important than absolute accuracy.

The positions of this catalog are termed selenographic (and not selenodetic), because they have all been computed as if the observed points were on a smooth sphere. Therefore, it will be appreciated that the positions are subject to certain errors. These errors are very small in the central regions of the disc but may be appreciable near the limb.

This lunar Atlas, as well as all major maps of the lunar surface, show the moon in orthographic projection on a plane tangent to the selenocentric sphere at the intersection of the lunar first meridian and equator.

In the older selenographic literature, positions were stated as longitudes and latitudes. Saunder introduced the more convenient standard direction - cosines ξ, η, and ζ, where:

$$\xi = \cos\beta \sin\lambda,$$

$$\eta = \sin\beta,$$

$$\zeta = \cos\beta \cos\lambda.$$

For a point at a distance R from the center of the sphere, at longitude λ and latitude β, the orthographic map coordinates are

$$X = R\xi = R\cos\beta \sin\lambda,$$

$$Y = R\eta = R\sin\beta.$$

Now the uncertainty of R in the Franz-Saunder net is of the same order as the errors of measurement and it has been usual up to the present to treat all points as having the same value of R. The orthographic map coordinates in units of the moon's mean radius are then merely ξ and η.

Reference 34 shows the curves of ξ = constant and η = constant at intervals of 0.01 of the radius.

The applications of this Atlas are:

a. The direct determination of standard direction-cosines of a point.
b. The angular or the linear distance between points.
c. The determination of solar altitude.
d. The determination of lunar slopes.
e. The determination of relative lunar altitudes.

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CHAPTER 6
SURFACE

6.1 GENERAL

6.1.1 INTRODUCTION

The nature of the moon's surface, its composition, and properties, have been the subject of study for many scientists and investigators with, needless to say, many opinions and descriptions as is illustrated in Table 6-1. The moon has been studied by visual, photographic, spectrographic, polarimetric, radiometric, and radar techniques.

Basic unknowns, such as the effect of millions of years of electromagnetic and corpuscular solar radiation, cosmic rays, and collisions with particulate bodies ranging in size from cosmic dust to large meteoroids, leave a void for sound basic scientific premise. Furthermore, chemical and petrographic properties are not known, and the easily changeable optical characteristics, such as albedo and color of minerals, limits observational conclusions.

These factors, however, do not by any means preclude or forbid scientific investigation; in fact, it is the extension of present day efforts that will enable man to perform the exacting analysis and observations necessary to determine fully the nature of the moon when he arrives there.

In spite of the limitations, theories have been developed regarding the nature of the moon's surface. Basic to these theories are albedo, color, and polarization, a discussion of which follows.

6.1.2 ALBEDO

The albedo or whiteness shows how much less a given surface reflects light in a given portion of the spectrum or in the entire spectrum relative to an absolutely white surface; e.g., a surface which reflects all of the light falling on it. Since lunar albedos are dependent upon the solar elevation, it is desirable to eliminate this variable. To obtain an albedo that is independent of the conditions of illumination, the concept of the so-called spherical albedo is introduced. The spherical albedo designates the ratio between the light of the sun scattered in all directions by a hemisphere to the total

Table 6-1

Summary of Some Lunar Surface Investigations

Conclusions/Material	Method/Remarks	Investigator
Lavalike porous material in the maria and sandlike or foamlike material in the bright areas.	Polarimetric studies.	Barabascheff, Reference 182, 1926
Pumiceous substances high in silica to powders of transparent substances and to quartz porphyries and possibly trachytes and granites. No rocks low in silica, such as basalts, peridotites, serpentines, gabbros, etc. No iron, glassy obsidians, or powders of basic rocks.	Polarization studies.	Wright, Reference 339, 1927
If silica or silicates are present; in a finely divided or porous state.	Reflections of 8 to 14 μ solar radiations.	Pettit and Nicholson, Reference 353, 1930
Surface must be very rough.	Brightness observations.	Bennett, Reference 463, 1938
Most important constituent probably lava or pumice of 2.6 cm thickness.	Eclipse temperature measurements.	Pettit, Reference 329, 1940
Pulverized rock, dust, pumice or volcanic ash. No granite rock.	Temperature changes.	Whipple, Reference 207, 1947
No pumice. Surface layer of dust with grains smaller than 0.1 mm diameter.	Temperature measurements.	Wesselink, Reference 342, 1948
Thin dust layer of about 1 mm over a solid crust.	Microwave thermal radiation observations.	Piddington and Minnett, Reference 437, 1948
Granular matter interspersed with dust with a 2 mm dust layer on top.	Microwave temperature variations.	Jaeger and Harper, Reference 354, 1950

Closest agreement to basalt; very tentative. $\mu = 2.9\ cm^2\ gm^{-1}$.	Mass absorption coefficient comparisons.	Sinton, Reference 430, 1955
Strongly torn porous mass, similar to slags of spongy structure.	Brightness measurements (albedo).	Orlova, Reference 456, 1955
A very fine powder with average depths of 1 km. Extremely smooth in fine detail. Top few feet loosely packed but quite solid at depths.	Theoretical based upon thermal, visual, and radar studies.	Gold, Reference 317, 1959
Surface enriched with heavy metal atoms.	Sputtering theory and experimental results.	Wehner, Reference 358, 1961
20 to 100 cm thick dust layer.	Meteoric impact and electrostatic transport phenomena.	Singer and Walker, Reference 537, 1962
A top powdery layer formed by small agglomerated opaque grains, very similar to an irregular deposit of small volcanic ashes.	Polarimetric investigation.	Dollfus, Reference 341, 1962
Volcanic extrusives exist, some vesicular, some not, of varying types covered in places by varying thicknesses of volcanic dust.	Earth analogies.	Green, Reference 479, 1962
Dust layer covers mountain slopes and plains of 5 cm and 20 to 100 cm, respectively, and it cannot possess any appreciable degree of fluidity.	Experimental thermal studies and meteoric impact theory.	Öpik, Reference 535, 1962

light falling on this hemisphere. The spherical albedo of the moon is 0.073. The spherical albedo as well as other albedos are listed in Table 6-2. Comparing the spherical albedo of 0.073 of the entire moon as a whole with the values of the albedo of different substances, as listed in Table 6-3, it can be seen that only very dark substances, such as basaltic lava, chernozem, and the fusion crust of meteorites, have an albedo approaching that of the moon. Substances, such as snow, ice, and sand, sandstone, clay, and schist, as well as granite and basalt, have too large a brilliance. Table 6-4 shows the different albedos of several lunar features. The continents and mountainous regions are approximately twice as bright as the maria. The lunar marshes and the maria are almost 1.5 times darker than the land. The brightest spot on the moon is the bottom of the crater Aristarchus and its central peak.

Comparing Tables 6-3 and 6-4, it can be said that the albedos of terrestrial volcanic rocks resembling separate regions of the moon are:

Lightest Regions	- basalts and stone meteorites.
Medium Lightness Regions	- trachytic lavas, certain dark tuffs, and volcanic ash and slag.
Darkest Regions	- basaltic lavas, dark volcanic ash and slag, and the fusion crusts of meteorites.

A simple similarity in brilliance (albedo) between terrestrial and lunar rocks, however, is entirely insufficient to determine which is the actual rock existing on the moon, for there exist many rocks almost identical in brilliance, but of very different geological properties. For example, chernozem has a spherical albedo of the order of 0.05 to 0.07; i.e., close to that of the dark regions of the moon, yet it can be said with certainty that none exists on the moon from the geologic structure of the moon, its history, and physical properties.

It is, therefore, impossible to assess the lunar rock make-up on the basis of photometric measurements alone!

It is to be noted that if the hard surface of a celestial body has a high albedo, this is direct proof of the existence of leucocratic (light colored) compounds. On the other hand, a low albedo does not make it possible to make any hypothesis, since a dark color may be caused by both the pressure of melanocratic and leucocratic minerals to which extraneous impurities have given a dark allochromatic color. The fact that the surface of the moon is characterized by a low albedo makes it difficult to study its composition by photometric methods.

Table 6-2

Albedos of the Lunar Disc

Type of Albedo	Value	Reference
Spherical (visible)	0.073	6, 7, 344, 442
Geometric	0.105	344
Radiometric	0.093	353
Radiometric	0.10	517
Photographic	0.54	517

Table 6-3

Spherical Albedo of Various Materials, Reference 442

Material	Spherical Albedo
Snow	0.9 - 0.5
Clouds	0.9 - 0.6
Limestone	0.56
Ice	0.37
Sand	0.34 - 0.29
Water	0.45 - 0.03
Trachyte lava	0.100
Basalt lava	0.06
Sandstone	0.22
Clay, schist	0.25
Granite	0.24
Basalt	0.14
Stone meteorites	0.18
Fusion crust of meteorites	0.05
Chernozem	0.05 - 0.07

Table 6-4

Spherical Albedo of Several Lunar Features, Reference 442

Feature	Latitude (Degrees)	Longitude (Degrees)	Spherical Albedo
Sinus Medii	+ 7	- 8	0.054
Mare Nubium	-23	-14	0.062
Mare Serenitatis	+28	+15	0.070
Mare Nectaris	-15	+33	0.080
Mare Nectaris	- 7	+28	0.089
Palus Somnii	+13	+43	0.095
Ptolemaeus	-44	-53	0.108
Aristoteles	+50	+17	0.110
Copernicus	+10	-20	0.120
Tycho	-43	-12	0.137
Tycho, Ray	-23	+25	0.163
Aristarchus*	+23	-47	0.176

* Brightest known spot on moon

6.1.3 COLOR AND COLOR INDEX

Another essential characteristic of different surfaces is color. Visual observations to determine the colors of specific regions of the moon are almost impossible to photograph and very subjective when observed with the eye. Such observations do not lend themselves to precise scientific measurements. Table 6-5 shows the varied conclusions of some visual color determinations. Avigliano, Reference 502, could not find any of the greens or purples often reported seen. Haas, Reference 330, has noted that some observers can see brown and not greens and vice versa. Radlova and Sharonov, Reference 442, concluded that the moon is almost completely monochromatic and denied the existence of color hues. Barabashov and Bronshten on the other hand have noted completely distinct, though weak, color hues.

Color, however, can be expressed in other ways, either by color indices, or by comparing the distribution of energy in the spectrum of the entire moon and of its individual parts with the distribution of energy in the spectrum of features for which this distribution is known sufficiently well, such as the sun and certain stars. Table 6-6 lists the color indices for the entire moon, the seas, and the continents.

Table 6-5

Summary of Lunar Color Observations

	Avigliano, Reference 502, (1954)	Barabashov, Reference 442, (1960)	Firsoff, Reference 483, (1958)	Miscellaneous, as noted below
Mare Tranquillitatis (Sea of Tranquility)	Brownish tone when sunrise terminator fringe passes; when terminator in center mare; western part yellow-gray. No terminator, gray with areas of yellowish hue.	Bluish.	Since portions are dark in extreme red, presumably green or blue. Has seen olive tone.	Greenish tint, Wilkins, OUR MOON, 1954.
Mare Serenitatis (Sea of Serenity)	Yellow. At full moon, pure yellow. At times, trace brownish hue in the yellow.	Reddish in center, greenish bands on southern and northern shores.	Red and yellow portions. Has seen olive tone.	Green in certain areas, working group for lunar observations headed by F. Kaiser, in Ref. 483. Center redder than edge, Sytinskaya, in Ref. 442.
Mare Imbrium (Sea of Showers)	Yellow-gray. Northwestern portion of mare; tones of yellow, somewhat brownish.	Reddish, greenish and rust-colored regions (<22 Km).	Red and yellow portions. N.E. portion south of Sinus Iridum, dark in extreme red, presumably are green or blue. Large quantity of yellow and red.	Yellowish shade, Klein in Reference 442.
Mare Frigoris (Sea of Cold)	Whitish-brownish yellow.	Reddish.	Distinctly yellowish. Full moon, very pale green and yellow.	Red, Wright in Ref. 483.
Mare Crisium (Sea of Crises)	Yellow-gray, more gray beginning lunation, towards yellow at full moon.	Greenish in southern part. Rust in northern part.		Greenish tint, Wilkins, OUR MOON, 1954.
Mare Foecunditatis (Sea of Fertility)	Yellow-gray like Mare Crisium. N.E. area more gray like Mare Tranquillitatis. Southern end lighter in tone during early phase of lunation.	Rust - southern part. Greenish in northern part.		
Mare Nectaris (Sea of Nectar)	Similar yellow-gray to Mare Crisium and Mare Foecunditatis. Fades into the gray of Mare Tranquillitatis to its north.			
Mare Vaporum (Sea of Vapors)	Yellow-gray in eastern portion and gray in western area.		Has seen green.	
Mare Nubium (Sea of Clouds)	Yellow-gray in eastern portion and gray in western portion.	Reddish with greenish spots.		
Mare Humorum (Sea of Moisture)	Yellow-gray.	Reddish.		Greenish tint, Wilkins, OUR MOON.

Table 6-5

Summary of Lunar Color Observations (Cont.)

	Avigliano, Reference 502, (1954)	Barabashov, Reference 442, (1960)	Firsoff, Reference 483, (1958)	Miscellaneous, as noted below
Oceanus Procellarum (Ocean of Storms)	Yellow-gray but certain areas more tinged with yellow.	Greenish, southern end - brownish.	Large quantity of yellow and red. Full moon - pale green and yellow.	
Sinus Roris (Bay of Dew)	Slightly more yellowish than the yellow-gray of Mare Imbrium.			
Sinus Iridum	Tones of yellow, somewhat brownish.			
Palus Somnii	Whitish-yellow, light yellow.			Brownish-yellow, Klein in Reference 442.
Lacus Somniorum (Lake of Sleepers)	Normally light yellow-gray. Lighter than Mare Serenitatis.			
Sinus Medii	Yellow-gray in eastern portions and gray in western portions.		Has seen green in the dark spots.	
Aristarchus (Diamond-shaped area to northeast.)	Yellow-brown, under best conditions, approaches pure brown tint, somewhat reddish.	Bright yellowish-green near full moon.	Mustard yellow at full moon high in sky.	Yellowish, Kuiper, Reference 30.
Plato Floor	Yellowish-gray, southeast and northeast portions lighter and more yellowish. Many occasions, brownish cast on floors, sometimes neutral gray.	Reddish.		Occasionally brown, working group for lunar observations headed by F. Kaiser, Reference 483.
Tycho	Around crater; yellow tone at full moon, sometimes a brownish cast.	Clear reddish hues near Tycho.		
Schickard Floor	Northeast portion and west edge of southwest portion - brownish. Remainder - grayish-yellow-white.			
Copernicus Floor	Northeast portion, grayish tone at 0° phase; yellowish-brown at 55° phase. Size of color patch seems to vary. Northwest portion - yellow-brown.			
Stevinus	Sunrise shadow unusual shade of orange-brown.			
Apennines (S.W. foothills at point where they touch Haemus range.)			Greenish-khaki at quarter phase.	
Ptolemaeus				Cyclic variation from gray or olive in lunar morning to yellowish tone towards evening, Kaiser in Ref. 483 Greenish tint inside rings, Wilkins, OUR MOON.

Table 6-6

Color Index

	Color Index*	Reference
Entire Moon	$+0^{m}.75$ $+0^{m}.85$	6 409, 440
Seas	$+0^{m}.80$ to $0^{m}.83$	409
Continents	$+0^{m}.80$ to $0^{m}.91$	409

* The limits of the color index are $+0^{m}.76$ to $+0^{m}.97$ if star α Aurigae is taken to be $+0^{m}.82$, Ref. 440.

The work of Barabashov and Chekirda, Reference 439, gives the differences in stellar magnitudes for different portions of the lunar surface relative to a white screen. To compare the distribution of brightness in the spectrum of different portions of the lunar surface with the distribution of the brightness in one spectrum of terrestrial rocks, rocks were placed on a board covered with black velvet. A white screen was placed among these samples for standardization. Thus the rocks and the screen were photographed simultaneously on the same plate with the same filters and with the same exposure. This made it possible to determine directly the distribution of energy in the spectrum of the reflected light from the terrestrial rocks and from the white screen placed among them. The rocks included those selected by Khabakov, the existence of which, in his opinion, most likely existed on the moon.

There is no doubt that if other rocks are selected according to the corresponding geological criteria, some will be found with a color similar to that of lunar formations. However, the number of terrestrial rocks resembling the moon in color is considerably reduced, if their albedo is considered in addition to their color, and still better, their albedo in different portions of the spectrum.

If the coefficient of brightness in visual rays and the color of the rocks studied are considered simultaneously, those most appropriate to the moon are volcanic ash (Armenia), coarse-grained basalt (dolerite, porphyrite, liparitic pitchstone, and Mandelstein basalt), red quartz porphyry, iron quartzite, and tuff (Armenia).

6.1.4 POLARIZATION

Any solid body that reflects and scatters light also polarizes it to one degree or another, depending on the conditions of illumination and reflection. Accordingly, studies of the polarization of the light reflected by different parts of the lunar surface and a comparison of the data thus obtained with the characteristics of the light reflected by terrestrial rocks should also be of a certain assistance in elucidating the question of the structure and the composition of the upper layer of the lunar crust.

Since the degree of polarization is dependent upon the structure of the surface, such studies of the light reflected by lunar features give quantities, the comparison of which, with the analogous quantities obtained in measurements of terrestrial rocks, makes it possible to hope that terrestrial rocks probably existing on the moon can be selected. Up until now, polarization studies were not what they could have been because of the lack of automatic-recording electropolarimeters. This deficiency, however, has been corrected, and in the immediate future improved results can be expected.

If an attempt is now made to estimate the makeup of the upper layer of the lunar crust, with respect to the polarization studies to date, it can be said simply that there should be a fine-grained surface layer on the moon.

6.2 ELEMENTAL ABUNDANCES

Depending upon whether the moon had a hot or cold origin determines whether the lunar rocks have undergone chemical and mineralogical differentiations producing igneous rocks or whether they are composed of an accretion of cosmic material that has been subject to phase transitions in the past, Reference 539.

Investigations of the most probable set of elements give O, Si, Al, Mg, Ca, Na, K, and Ni the abundance of each depending upon the hot or cold origin; i.e., whether volcanic or meteoritic impact mechanisms predominated in the formation of the lunar surface features.

The three principal rock types most likely to be encountered on the lunar surface are acidic, basaltic, and aerolitic (chondrite and achondrite), Reference 539. Table 6-7 summarizes the limiting values of the elemental abundances by weight of the above three principal rock types. Table 6-8 shows the probable elemental abundances characteristic for several authors' hypotheses.

Table 6-7

Limiting Elemental Abundances (Percent by Weight), Reference 539

Element	Maria and Terrae		
	Acidic	Basaltic	Aerolitic
O	47 to 52	43 to 46	33 to 44
Si	31 to 38	21 to 24	17 to 25
Al	5 to 10	3.5 to 9	1 to 6
Fe	1 to 6	6.5 to 10	12 to 22
Mg	0.1 to 2	3 to 14	14 to 18
Ca	0.1 to 3	5 to 8	1 to 7
Na	0.2 to 4	1 to 2.5	0.6 to 0.8
K	1 to 5	0.2 to 1.5	0.1 to 0.2
Ni	--	--	0.1 to 0.7
S	--	--	0.2 to 2
H	0.07 to 0.2	0.1 to 1	0.03 to 0.1

6.3 ICE ON THE MOON

It is frequently argued that volatiles are unstable on the lunar surface, because of the rapid removal of constituents by solar radiation, solar wind, and gravitational escape. As a consequence, it has been assumed that volatile substances, such as water, which possess short relaxation times for escape, do not exist on the moon. Watson, Murray, and Brown, References 198 and 393, however, present a detailed theory of the behavior of volatiles on the lunar surface, based on solid-vapor kinetic relationships, and show that water, in the form of ice, is far more stable there than the noble gases or other possible constituents of any lunar atmosphere. Previous investigations did not consider the fact that the amount of any volatile in the vapor phase is determined by the temperature of the solid phase at the coldest place on the lunar surface! Reference 393 concludes, further, that 0.1 to 1 percent, with a most likely value of 0.5 percent ($4.5 \times 10^{13} cm^2$), of the lunar surface is in permanent shade with an upper temperature limit of approximately 120°K, Reference 353, and that it is in these regions where ice, if it exists on the lunar surface, could be found. The corresponding vapor pressure to this temperature is 1.4×10^{-12} mm of Hg.

Table 6-8

Possible Elemental Abundances (Percent by Weight), Reference 539

Hypothesis

	Gold		Urey		Kuiper		Baldwin		Spurr		Firsoff	
Element	Maria[1]	Terrae[2]	Maria[3]	Terrae[4]	Maria[5]	Terrae[6]	Maria[7]	Terrae[8]	Maria[9]	Terrae[10]	Maria[11]	Terrae[12]
O	20 to 45	33 to 44	43 to 46	33 to 44	47 to 52	47 to 51	43 to 46	48 to 52	44 to 46	48 to 52	48 to 55	48 to 55
Si	10 to 22	17 to 25	21 to 24	17 to 25	32 to 38	31 to 35	21 to 24	31 to 35	22 to 24	33 to 35	33 to 36	33 to 36
Al	0.5 to 2	1 to 6	4 to 9	1 to 6	5 to 9	6 to 10	4 to 9	6 to 10	8 to 10	6 to 9	6 to 9	6 to 9
Fe	15 to 40	12 to 22	8 to 11	12 to 22	1 to 6	1.5 to 4	8 to 10	1 to 5	6 to 9	1 to 3	1 to 3	1 to 3
Mg	8 to 18	14 to 18	3 to 15	14 to 18	0.2 to 2	0.1 to 1	3 to 15	0.1 to 1	3 to 5	0.2 to 0.8	0.2 to 0.8	0.2 to 0.8
Ca	0.2 to 2	1 to 7	5 to 8	1 to 7	0.1 to 2	1 to 3	5 to 8	0.3 to 3	6 to 8	0.2 to 3	0.5 to 2	0.5 to 2
Na	0.3 to 1	0.6 to 0.8	0.5 to 3	0.6 to 0.8	0.2 to 4	2 to 4	0.5 to 3	2 to 4	1.5 to 2.5	2.5 to 4	2 to 4	2 to 4
K	0 to 0.1	0.1 to 0.2	0.2 to 2	0.1 to 0.2	1.5 to 4.5	2 to 4	0.2 to 2	1.5 to 4.5	0.5 to 1.5	2 to 4	2 to 4	2 to 4
H	0.1 to 0.3	<0.3	0.1 to 0.3	0.1 to 0.3	0 to 0.2	0 to 0.2	0.1 to 0.3	<0.2	0.1 to 0.3	0.1 to 0.3	0.5 to 1.2	0.1 to 0.3
C	<1	1 to 5	1 to 3	3 to 11	<1	<1	<1	<1	<3	<3	<3	<3
S	0 to 3	0.2 to 3	<0.5	0.2 to 3	<1	<1	<1	<0.5	0 to 6	0 to 6	<1	<1
Ni	0.1 to 3	0.1 to 2	<0.5	0.1 to 2	---	---	<0.05	<0.5	---	---	---	---

[1]Chondritic dust [2]Chondritic [3]Basaltic [4]Aerolitic [5]Rhyolitic [6]Acidic [7]Basaltic [8]Acidic [9]Basaltic [10]Rhyolitic [11]Rhyolitic [12]Rhyolitic

It has been suggested that sputtering, see Reference 358, might be a significant erosional mechanism acting on the ice in the cold traps. Reference 393 shows, though, that the resulting energy flux is many orders of magnitude lower than the radiative heat transfer from the cold trap surfaces and seems to exclude the possibility of sputtering having an appreciable effect on the mass removal rate of ice from the cold traps.

It is also shown in Reference 393 that, had the primitive lunar material contained an equivalent concentration of water as the earth, the amount of water liberated from the lunar surface would amount to 3×10^4 gm/cm^2 for the entire lunar surface. In the same time period (one billion years), the loss rate from the cold traps is 4 gm/cm^2. Accordingly, it seems reasonable to assert, Reference 193, that there should still be detectable amounts of ice in the permanently shaded areas of the moon if the moon has undergone a bulk chemical differentiation as small as about one one-thousandth that of the earth. It can be concluded then, that the amount of ice present should prove to be a most sensitive mineral indicator of the degree of chemical differentiation of the moon. It should also be pointed out that accretions of meteoritic water upon the moon are probably small when compared with the amount of water liberated from the interior of the moon.

6.4 SLOPES ON THE MOON

6.4.1 INTRODUCTION

The jagged peaks and precipitous lunar landscape that was once believed to exist on the moon has given way to a landscape in favor of very gentle slopes, not exceeding about 10 degrees. The basis for this change of concept is the recent work on photographic analysis of lunar features, which indicates that the larger surface formations do indeed have gentle slopes, despite their rough appearance through the telescope. Unfortunately, this information has been applied to all lunar surface features, resulting in very unconservative specifications for local lunar conditions.

It is the purpose of this discussion, Reference 172, to indicate that the smaller (and more frequently encountered) surface features of the moon may have relatively steep slopes, and that slopes much greater than 15 degrees may be encountered. The argument is based on lunar craters only, since these form a continuous family with features that may be extrapolated below the limit of telescopic resolution. Whether or not other surface features contribute to small-scale roughness is not resolved in this discussion; as a result, the total roughness of the lunar surface may even exceed that contributed by craters alone.

6.4.2 SHAPES OF CRATERS

Baldwin, Reference 67, has plotted crater depth versus crater diameter for lunar craters as well as terrestrial craters and explosion pits. The results are shown in Figure 6-1. The curve is shown dotted for a diameter less than about 5,000 feet, which is the limit of telescopic resolution. It is considered reasonable to extrapolate the curve for lunar craters to the region of D < 5,000 feet, however, even though the craters are not visible. This extrapolation is the basis for the argument that steep slopes do indeed exist on the surface of the moon, as evidenced by the plots on Figure 6-2 of average slope (line from the crater bottom to crater rim) and of maximum slopes for reasonable crater profiles.

Also shown on Figures 6-1 and 6-2 are depth and diameter ratios and slopes taken from sources which disagree with Baldwin's data. Note, however, that these estimates result in slopes higher than Baldwin's. Also note that had the curves been extrapolated back to the region of small crater sizes without using terrestrial craters and explosion pits as a guide, the result would undoubtedly have been estimates of slopes higher than Baldwin's. Thus, on all counts, Baldwin's estimates are low. Figure 6-2 shows, therefore, the slopes that will be encountered on this argument on a local basis on the lunar surface.

Crater Diameter	100 ft.	1000 ft.	10,000 ft.
Average Slope	30°	24°	16°
Maximum Slope	70°	46°	28°

The reader is cautioned at this point, in view of Baldwin's revised data soon to be published, Reference 552.

6.5 LUNAR DUST LAYER

6.5.1 INTRODUCTION

It is agreed by all selenologists and lunar researchers that the surface of the moon must be covered with a layer of very fine dust. However, as to the thickness of this

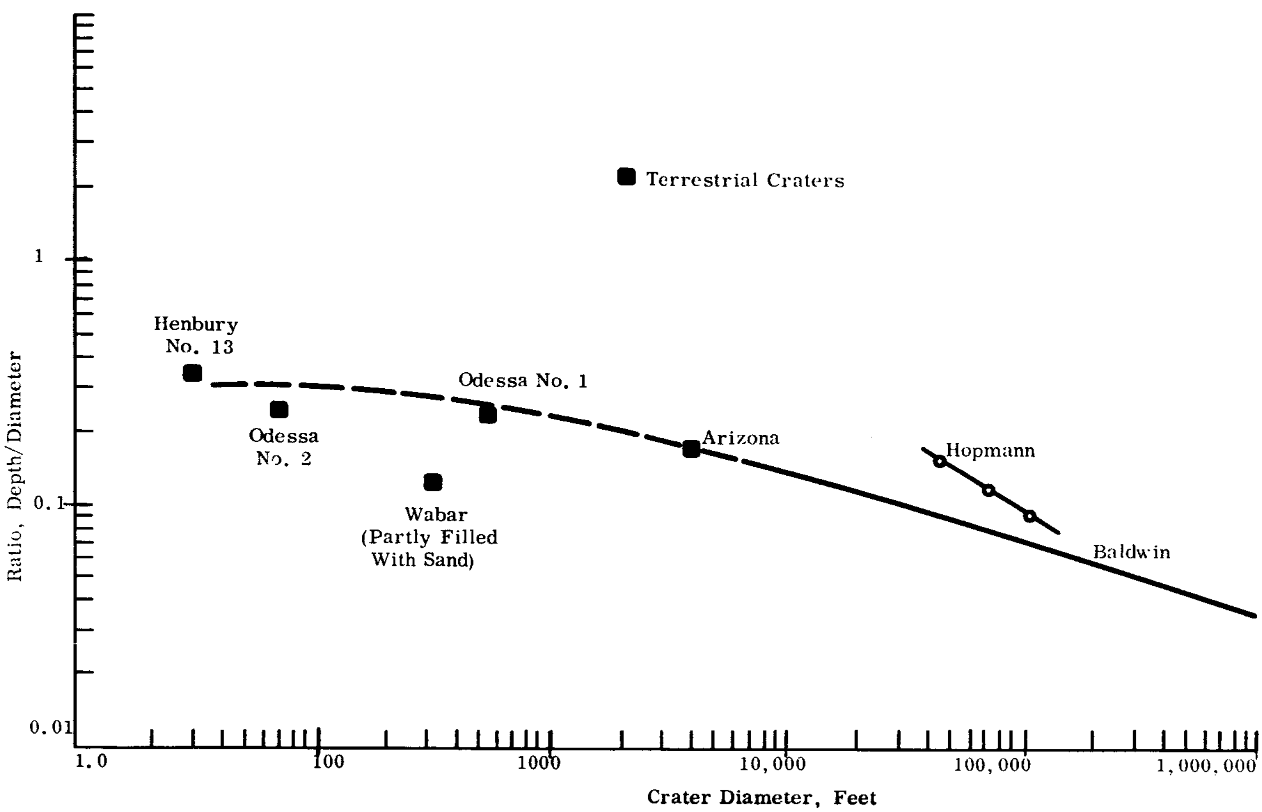

Figure 6-1. Over-all Shapes of Lunar Craters

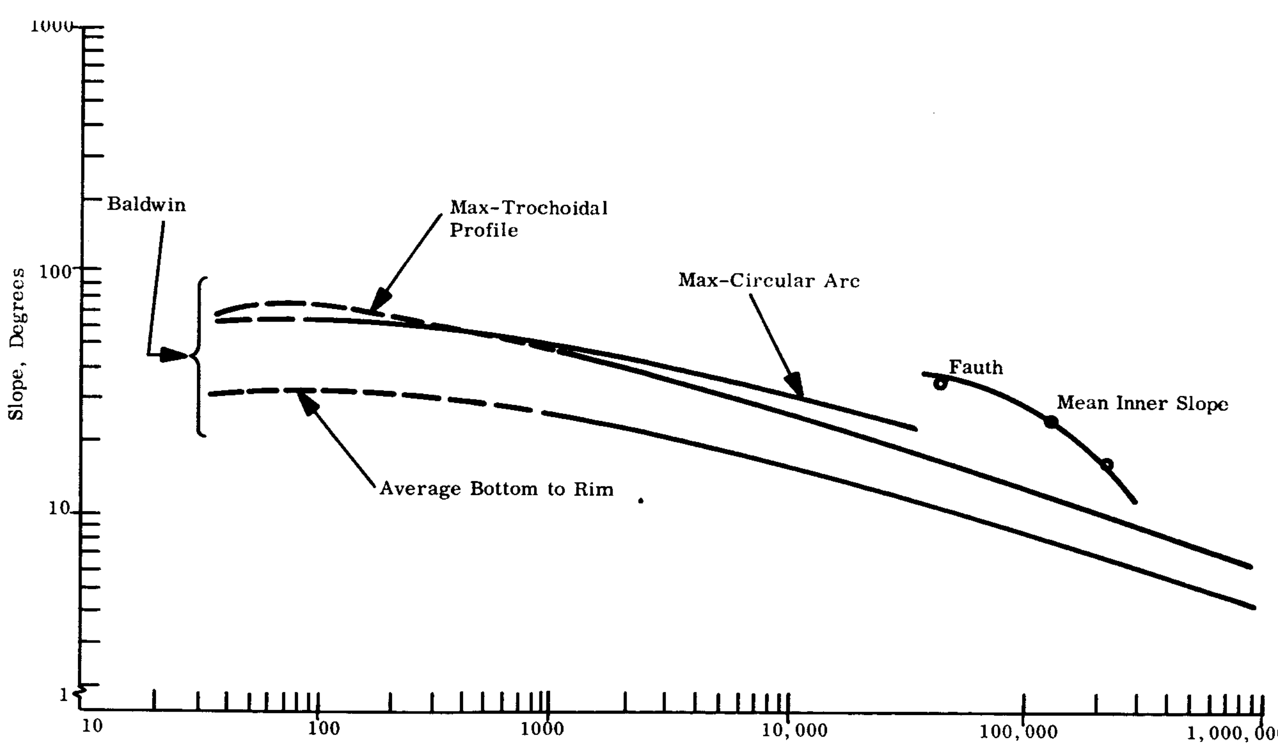

Figure 6-2. Slopes in the Lunar Craters

layer and its material makeup, there has been widespread opinion. The experimental results, to date, give values for the depth, ranging from a few millimeters up to two or three centimeters. It must be emphasized that these values are for gross regions of the moon and give no information whatsoever about possible local accumulations. For local depths, estimates have been made up to a depth of several kilometers.

6.5.2 NATURE OF THE LUNAR DUST

Two major hypotheses have been formulated concerning the nature or existence of lunar dust. Gold, Reference 317, suggests the possibility of a deep loosely packed dust; and Whipple, Reference 316, theorizes a radiation-cemented, weak, porous material.

Gold's theory arises from the observed low rims and flat interiors of the older craters. He suggests that some sort of erosion process could account for such a condition. The action of small particles striking the surface as well as ultraviolet light and the soft X-rays from the sun are all likely to break up the surface into a fine powder. Constituents like oxygen can constantly be liberated from the surface by the radiation, and its loss prevents the "healing" of the crystalline material, with a fine powder resulting.

Furthermore, according to Gold, the transport of this fine powder is conceivably accomplished by the stirring up by small microscopic impacts and electrostatic forces resulting from solar radiation and corpuscular streams.

Whipple's theory, Reference 316, considers the effect of the solar proton flux which produces sputtering, the heavier gases falling at relatively low velocities onto the surface from the interplanetary medium, and gases vaporized from meteoritic impact. He concludes that the lunar dust grains will be "cemented" together by the heterogeneous matter, thus forming a low-density semiporous matrix, weak compared to normal sedimentary rocks on the earth, but strong compared to a layer of dust. He maintains further that electrostatic transport of any dust is not possible because interplanetary space is a surprisingly good conductor ($\sim 10^3$ electrons/cm^3) and thus eliminates any strong surface electric charge. He concludes that loose dust on the lunar surface is practically nonexistent.

Interestingly enough, some considerations show that the dust must exist as a loose powder and others indicate that dust in a vacuum has the tendency to compact itself, Reference 203. Because of this, as both Gold and Whipple point out, the lunar surface must now be investigated directly.

Singer and Walker, Reference 537, investigate the phenomena of lunar dust transport quantitatively and conclude that electrostatic erosion is not valid but that meteoric impact can contribute appreciably to dust production. They believe that lunar dust will preferably settle in shadow areas, such as crevices and on mountain slopes, rather than on the flat mare. They point out too, that many uncertainties exist in dust transport mechanisms and that it is better to have a quantitative estimate, which may have to be amended later, rather than discuss the subject only in qualitative terms. Their estimate of the thickness of the dust layer is about 50 centimeters with an average of 20 to 100 centimeters in the shadow areas.

6.5.3 PARTICLE SIZE

Although there is not too much information available concerning the grain or particle size of the lunar dust, it will be shown that the trend is toward particle sizes from a few microns (μ) to a few hundred.

Grannis, Reference 464, considers the best estimate of the size of individual dust grains to be between 1 and 50μ with a representative size of 5μ.

Wesselink's analysis, Reference 342, which is based upon the observed variations in temperature, concludes a powder size of grains smaller than 100μ with an upper limit of 300μ, the latter figure being derived from theoretical considerations.

This is in agreement with the analysis performed by Siegel, Reference 399, in which it was concluded that the lower bound of the particle sizes to be of the order of 1μ or probably 10μ with an expected range from 30 to 100μ or to be on the safe side, possibly 10 to 300μ.

An indirect measure comes from the collection of particles from the atmosphere which are believed to represent space dust or micrometeorites collected by the moon. For such material, a dominant size range is 5 to 60μ. Based on these same particles, it is probable that the dust grains are spherical or at least partially rounded.

A terminology for pyroclastics, recommended by Green, Reference 361, is listed in Table 6-9 for use when referring to the size of lunar dust which may prove to be volcanic.

Table 6-9

Suggested Pyroclastic Terminology, Reference 361

Uncemented Detritus		Indurated Material	
Name	Size (mm)	Name	Size (mm)
Volcanic Dust	< 1/4	Tuff	< 4
Volcanic Ash	1/4 - 4	Breccia (angular)	> 4
Lapilli (termed cinders if glassy and vesicular)	4 - 32	Agglomerate (rounded)	> 4
Blocks	> 32	---	---

Note: 1 mm = 1000 microns

6.5.4 LUNAR DUST STABILIZATION

The stabilization or bonding of lunar dust, if it in fact exists, might be desirable for landing and launch complexes, roadways, and covering material. The stabilization of individual dust-like particles in a vacuum to create a material possessing a specified load-bearing capacity can be achieved by three different techniques: pressure, thermal, and chemical. Research in this field, References 26, 27, 257, and 478, shows that the problems are insurmountable when pressure and thermal methods are considered. The chemical bond, however, does offer possibilities.

The most promising material for lunar dust stabilization with respect to structural strength and maximum yield per unit volume of cementing agent is the basic aniline-furfural composition supplemented with polyfunctional amines, Reference 478.

Winterkorn, Reference 478, feels too, that taking into account the extremely thin lunar atmosphere and the absence of adsorbed gas films on the dust particles that development of injection methods appears possible.

Important factors, such as the extreme temperature variation, may certainly make the task of stabilization considerably more difficult than it already is, because, over such a temperature range, material properties often vary from soft to brittle. However, it is not necessary that one build or stabilize on the immediate surface, since subsurface treatments are possible and probably preferable.

6.6 RADAR STUDIES

6.6.1 INTRODUCTION

Radar analysis of the moon offers a means by which it may be possible to determine details about the lunar surface too small to be observed telescopically, and which may lead to further knowledge about the composition of the lunar surface material. As yet there is not enough experimental evidence, and radar techniques are not sufficiently refined to supply quantitative facts about the lunar surface, but the experimental results to date have served to initiate and support various theories.

6.6.2 Investigations by Pettengill and Henry, 1961, Reference 359, at the Lincoln Laboratory, MIT, lead to a value of the lunar surface dielectric constant of 2.8, which corresponds approximately to the bulk value for sand. Additionally, the authors deduce that only about five percent of the lunar surface is rough to the scale of 68 centimeters. Measurements of the depolarization of the scattered energy seem to offer further verification of these surface properties.

The radar return in this experiment is made up of two portions, one a sharp, specular smooth-type echo, which rapidly decays. This portion is associated with the near-normal reflection from the center of the lunar disc. After a delay of several milliseconds a weaker, but more slowly varying, diffuse component becomes visible which persists until the region of the limb is reached; this portion is associated with the rough regions of the lunar surface. In relating the measured radar power ratio back to the actual fraction of the lunar surface, which is responsible for each type of scattering, the rough areas are taken to scatter approximately two and one-half times as effectively as the smooth portions when the directivity factor of the specular portion of the surface is taken as unity.

6.6.3 Senior and Siegel, Reference 71, regard the moon's surface as a "quasi-smooth" scatterer at radar frequencies and assume the scattering area nearest to the earth to be the source of a specular echo return. Their analysis leads to the following conclusions:

a. The major sources of scattered energy reflected from the moon are akin to that from a smooth surface; i.e., the surface cannot possess a large number of irregularities whose magnitude is comparable in size with the wavelength. Any rough surface serves to depolarize the incident field, and for a surface with irregularities whose magnitude is on the order of one-half wavelength, the depolarization effect will be almost complete. The study of the moon with polarized waves shows the reflected waves to remain polarized, indicative of a "smooth" surface.

b. The scattering of radar waves on the moon is attributed to a small number of scattering areas distributed over the moon. These areas alone are responsible for the major features of the return waves; their total number is approximately 25.

   These scattering areas are not uniformly distributed over the moon's surface, but are concentrated near the center, and the returns from the portions of the moon far from its center are relatively small. This concentration of scattering areas near the moon's center can be attributed to the distribution of surface slopes on the moon and to the fact that relatively little of the surface is inclined at more than a few degrees to the "mean" lunar sphere which is in accord with observations at optical frequencies. As a result, the portions of the surface which are suitably orientated to reflect energy back to the earth are located near the "front" of the moon. However, it is noted that if the moon were observed from some point in space other than the earth, one would expect to find a similar set of scattering areas distributed around the point on the moon nearest to the new transmitter-receiver location. No statement can yet be made about the physical nature of the scattering areas, and further work remains to be done in this connection.

6.6.4 Hey and Hughes, Reference 444, made radar observations of the moon using ten centimeters wavelength, a pulse length of five microseconds, and transmitter peak power of two milliwatts at the Royal Radar Establishment, Malvern, England.

The results of the radar echo indicate a highly specular reflecting surface in the area of the moon's sphere by the fact that the echo amplitude is reduced to about 50 percent of the initial value at an angle of incidence of 5 degrees. Also indicated are a large number of scatterering areas at distances away from the leading edge by the presence of amplitude peaks of the echo. From the decrease in amplitude of the signal with range, it would appear that the surface of the moon producing the echo consists mainly of almost flat regions, presumably covered by dust, and that the mountains and craters occupy but a small percentage of the total area. It is also concluded by Hey and Hughes that the mean gradient of the lunar surface is about one in twenty.

6.6.5 Yaplee, et al., Reference 352, made a lunar radar study at ten centimeters wavelength at the United States Naval Research Laboratory, Radio Astronomy Branch, Washington. This work was principally directed towards making accurate range measurements between the earth and the moon, and it was reported that the specular-like reflection by the lunar surface was similar to that observed with airborne radar over dry sandy terrestrial deserts at normal incidence.

6.6.6 Evans, Reference 178, has reviewed the experimental results of a number of the outstanding authors in the field of radar study of the moon, and his conclusions concerning these efforts are quoted as follows:

> The results of many experiments carried out in the wavelength range three to one-tenth meters indicate that the surface of the moon is smooth and undulating with average gradients of the order of one in ten, and on the average only about ten percent of the surface is covered with small objects which are below the optical limit of resolution. The reflected signals are in many respects similar to those observed from aircraft over dry sandy terrestrial deserts at normal incidence. The measurement of the reflection coefficient for the surface material is complicated by the fact that the observed signals suffer marked intensity variations due to interference from many scattering regions. If, however, it is assumed that the rms signal level provides a proper measure of the reflection coefficient; the average value obtained from many experiments is ~ 0.06. This corresponds to a dielectric constant, ~ 2.72, which is similar to that observed for dry, sandy soils on the surface of the earth.

6.6.7 CONSTANTS OF THE LUNAR SURFACE

An important result of lunar radar studies is the determination of electromagnetic constants, the thermal conductivity, and the volumetric specific heat of the surface of the moon as seen from earth.

Siegel, Reference 399, believes that the experiments have shown that the electromagnetic constants are typical constants not only for the key scattering centers at the surface of the moon but are probably good average values for the whole lunar surface as seen from the earth.

The constants under discussion are:

ϵ , Permittivity
μ , Permeability
s , Conductivity, mhos/meter

Passive radiation data obtained on earth from the visual spectrum through the infrared and microwave frequencies down to 1000 Mc has been analyzed as to consistency and utility in deriving constants of the lunar surface. It was found that when this data was utilized with the constants obtained from the radar data, the average thermal conductivity and volumetric specific heat of the lunar material could be derived; where:

K, Thermal Conductivity, cal/sec.cm.deg.
c, Volumetric Specific Heat, cal/deg.cm.^{3}

Table 6-10 shows the resultant values for all of the constants under discussion.

where:

ϵ_o, Permittivity of free space
μ_o, Permeability of free space

The analysis involved in obtaining the electromagnetic constants points out, Reference 399, that the values are dependent upon particle size. Reference 399 concludes that the lower bound on particle size is probably 10 microns with an upper bound of 1000 microns. The expected range of particle size is therefore between 30 and 300 microns, or conservatively, 10 to 1000 microns.

Table 6-10

Lunar Surface Constants

Constant	Value	Ref.
ϵ/μ	7.6×10^{-6} mhos^2	71
s/μ	2.7×10^2 mhos/henry	71
ϵ/ϵ_o	$1.0857\ (\mu/\mu_o)$	399
ϵ/ϵ_o	$1.0939\ (\mu/\mu_o)$ if $s = o$	399
s	$2.3301 \times 10^{-4}\ (\mu/\mu_o)$ mhos/meter	399
K	4.8×10^{-6} cal/cm. sec. deg.	399
c	0.22 cal/deg. cm.^{3}	399

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CHAPTER 7

LUNAR TEMPERATURES

7.1 TEMPERATURE VARIATION

Lunar surface temperature variation has been observed to be substantial (see Tables 7-3 through 7-7) as the orientation of the lunar surfaces changes with respect to the sun. It has been shown, Reference 233, that the effect of earthshine on the moon is such that it contributes less than 0.001°K change in the observed lunar temperatures, assuming that the earth re-radiates and reflects energy equal to the solar constant. It is reasonable to expect larger temperature differences between the dark and illuminated hemispheres of the moon than on earth, since it has no appreciable atmosphere to interfere with the radiant interchange between the sun, moon, and space. The maximum temperature which occurs on the surface of the moon occurs at the subsolar point. This maximum temperature is restricted to a band approximately 3 degrees wide, centered on the lunar equator, since the plane of the equator is inclined at 1°32' to the ecliptic plane.

A theoretical maximum value may be calculated from the Stefan Boltzman Law, if the subsolar point is assumed to be in an equilibrium state and the lunar surface emissivity value is taken as unity.

The minimum lunar surface temperature occurs at lunar midnight (opposite side of subsolar point). Some of the deep craters near the poles have permanent shadows on their floors, and in these areas the temperature is constant near the minimum lunar surface temperature of approximately 120°K.

Much lunar temperature information has been obtained through longwave investigation of the light emanating from moon to earth (planetary heat). Although heated bodies emit radiation in all wavelengths, lunar radiation is measured primarily in 8- to 14-microns water-vapor-transmission band (optical methods) and the 0.8- to 1700-centimeter atmospheric-absorption-ionospheric-reflection band (radio astronomy techniques).

7.2 TEMPERATURE DISTRIBUTION AND PLANETARY HEAT

From drift curves, such as shown in Figure 3 of Reference 353, it has been found that the distribution of planetary heat over the lunar disc at full moon follows the formula

$$E = E_o \cos^{2/3}\theta,$$

where

- E is the measured energy,
- E_o is the radiated energy from the subsolar point,
- θ is the angle between the normal to the point and the line of direction to the sun.

If the moon were a smooth sphere, the variation of energy would follow the Lommel-Seeliger formula,

$$E = E_o \cos\theta.$$

Pettit and Nicholson, Reference 353, state that this theoretical distribution is not followed because of the roughness of the lunar surface, although Piddington and Minnett, Reference 437, think that the observed distribution is a directivity effect of the lunar surface in radiating planetary heat. It should be noted that in Reference 353 on pages 102 and 118, the heat radiation is written

$$E = a \cos^{3/2}\theta.$$

This is not in accordance with the data shown in Figure 4, page 118, nor does it agree with the qualitative explanation of the effect the authors give. There is little doubt that the form

$$E = a \cos^{2/3}\theta$$

is intended.

Surface roughness, Reference 209, causes a variation of the effective subsolar temperature. If the subsolar point is in a crater floor or valley (which cannot radiate into space through a complete hemisphere) it becomes warmer than the adjacent peaks. Also, after heating during a lunar eclipse, the valleys cannot cool as rapidly as peaks because of the lower view factor to space. On the other hand, if the line of sight between a valley and the sun is at a large angle to the vertical, the valleys could become partially shaded by the peaks and result in a lower temperature than the surrounding peaks.

Figure 7-1 shows the observed and theoretical temperature distributions as well as planetary heat about the subsolar point as a function of distance from subsolar point in fractions of lunar radius. Shown in Figure 7-2 is a polar diagram giving planetary heat emitted from the subsolar point as a function of the angle from the normal to the surface.

The temperature distribution as a function of lunar radius may also be illustrated by a replot of Figure 7-1 as shown in Figure 7-3, which explains the distribution seen on heat maps of the moon as illustrated in Figure 7-4.

7.3 WAVELENGTH DEPENDENCY

Observations at different wavelengths (frequencies) give different results because of the wavelength dependence of the surface material absorption characteristics. The attenuation into the surface material increases with decreasing wavelength, Reference 350, and therefore, it is reasonable to expect a different temperature for different wavelengths because of the variation in depth of measurement below the lunar surface. The characteristics of lunar radiation in the 1.5 millimeter range are somewhere between the infrared and the microwave behavior. For a long period of variation in insolation, such as throughout a lunation, the apparent temperature variation is large and nearly in phase; while for a rapid variation, as during an eclipse, there is a small lag and the range of variation is reduced from that which is observed at 10 microns. Reference 209 states that published results of eclipse microwave observations have generally shown no change in apparent temperature (Gibson, 1958; Mezger and Strassl, 1959), but Sinton was not able to confirm this during eclipse of 13 March 1960.

It has been speculated, Reference 6, that at wavelengths greater than about 1 centimeter the variations in temperature during a lunation began to die out with mean temperature during a lunation began to die out with mean temperature around 200°K. Also, that for a total eclipse, the temperature variation seems to end at wavelengths 0.86 centimeter and longer.

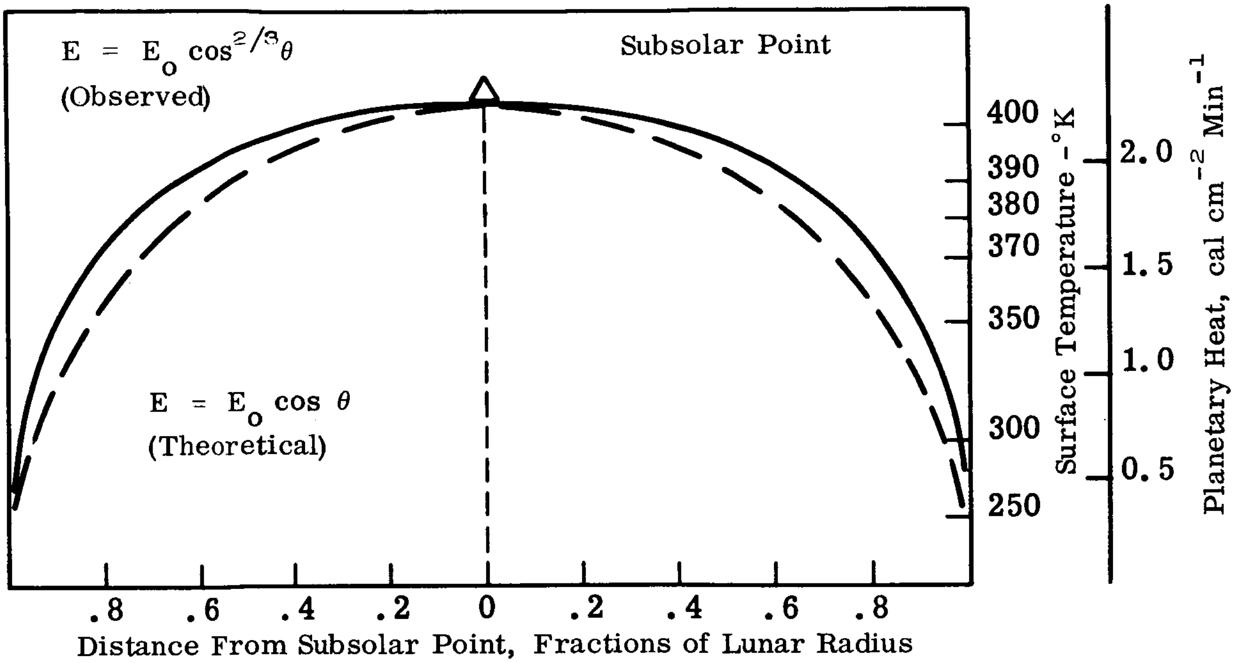


Figure 7-1. Emitted Planetary Heat Distribution About Subsolar Point of Full Moon, Reference 353

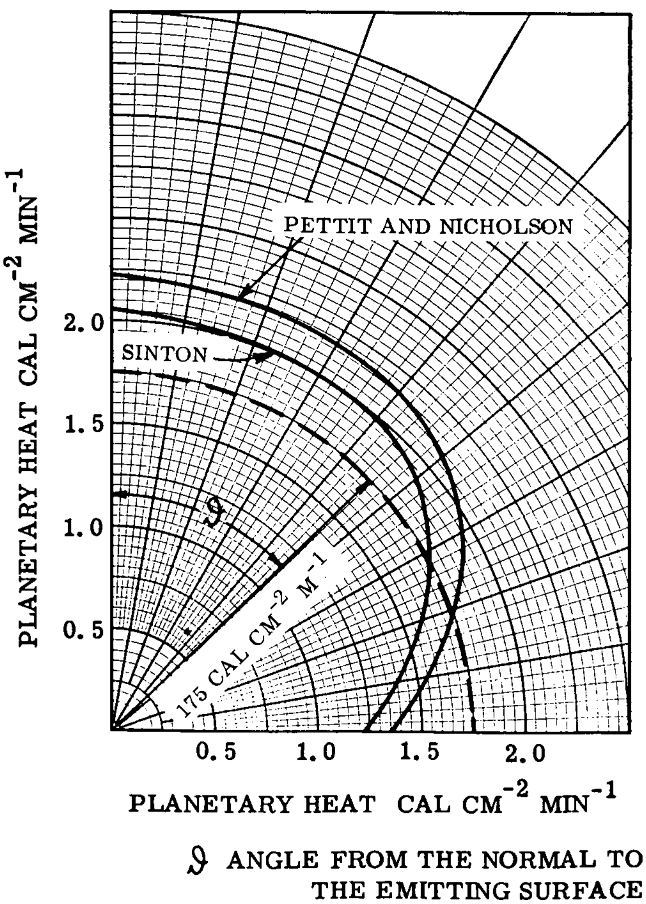


Figure 7-2. Distribution of Emitted Planetary Heat About Subsolar Point of Full Moon, Reference 209

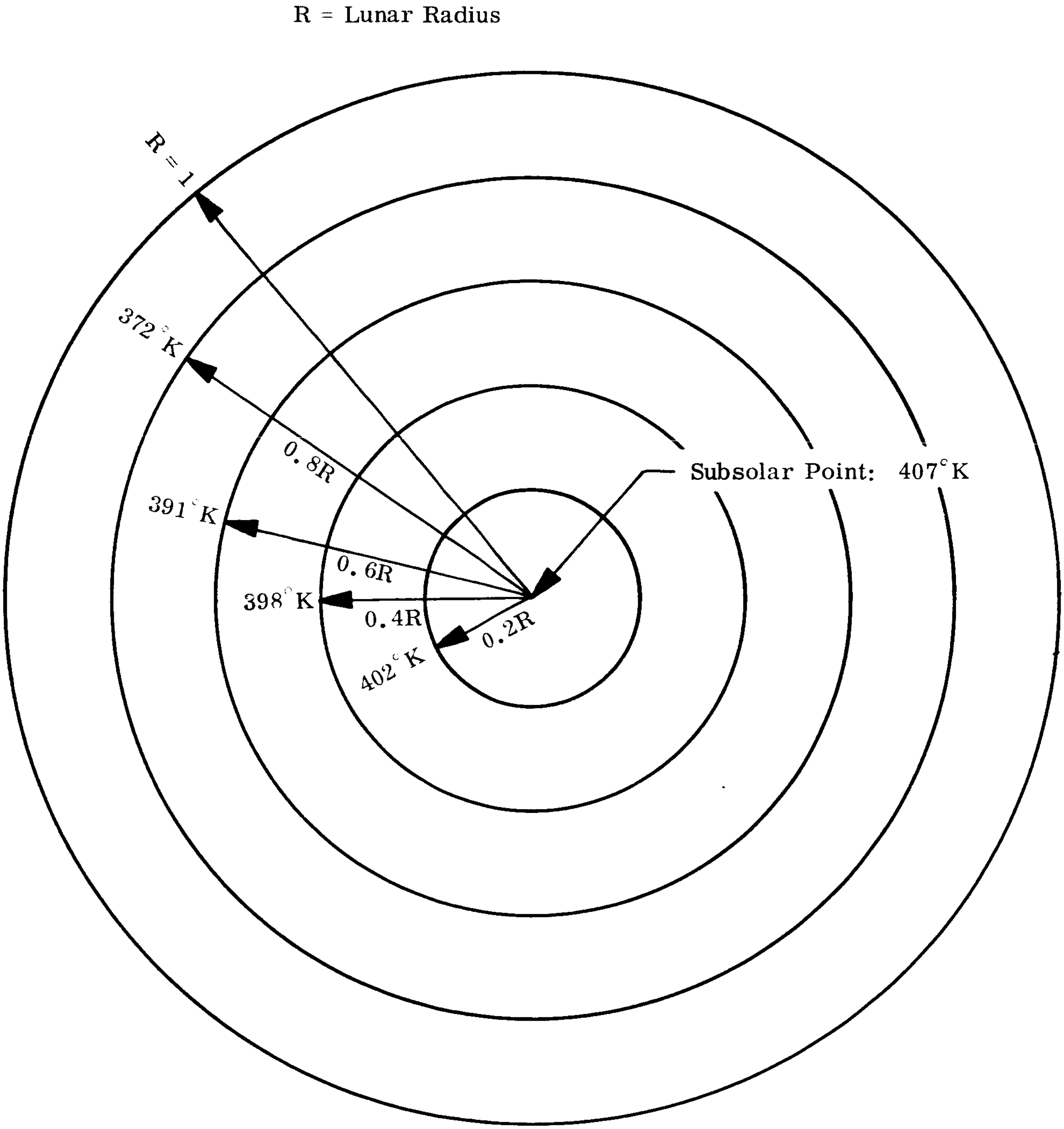


Figure 7-3. Lunar Isotherms

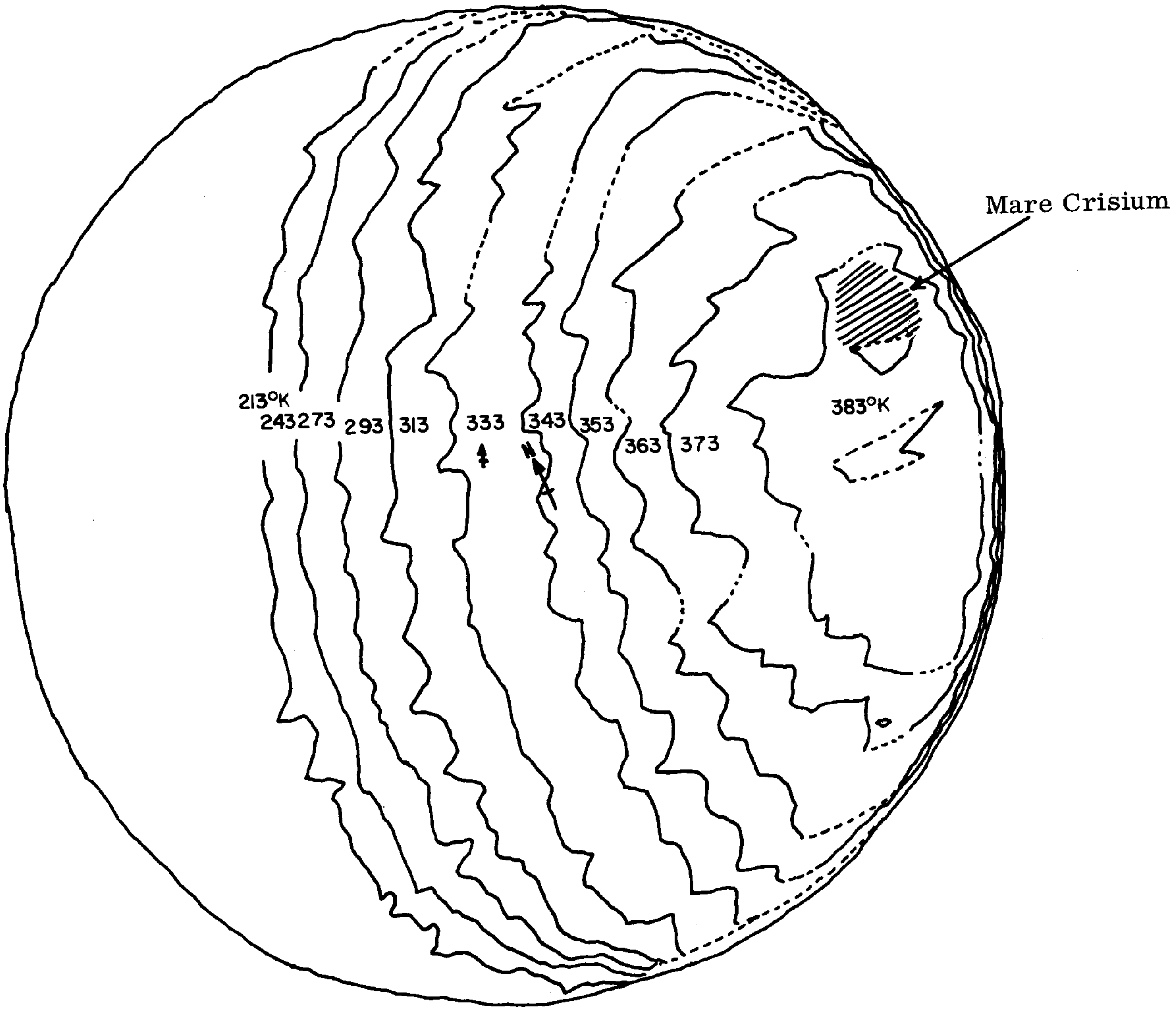


Figure 7-4. Lunar Isotherms on a Simultaneous Photograph of the Moon, Reference 379

Radio measurements of Reference 279 indicate that at wavelengths longer than 20 centimeters the thermal radiation seems to be constant during lunar eclipses and even throughout a complete lunation, Reference 322. These radiations probably come from a region an inch or more below the lunar surface. At shorter wavelengths of 0.8 centimeter, a variation of temperature with phase of the moon is noted, References 435 and 558. Reference 322 states that the mean temperature of radio measurements has been in the neighborhood of 250°K and seems to become less as the longer wavelengths (75 centimeters) are approached.

7.4 SURFACE THERMAL PROPERTIES

Lunar radio observations by Piddington and Minnett (1949) and Gibson (1958) have concluded that the millimeter-wave brightness lags the optical phase, the radiation originates below a surface layer that is a very good thermal insulator. The thickness and composition of this layer is, at this time, quite controversial, References 549 and 559.

It has been shown that variations of lunar surface temperatures are dependent upon a thermal inertia constant $(K\rho c)^{-\frac{1}{2}}$ where K is the thermal conductivity of the material, ρ is the density, and c is the specific heat at constant volume per unit mass. When K is small, the lunar material is a poor conductor and the solar energy absorbed on the surface will not spread very far into the interior. If the influx of the solar radiation is stopped, such as during an eclipse, the temperature drops. Thus a large ρc will work in the same direction as a large K, and the size of the temperature variation is dependent upon the change in $(K\rho c)^{-\frac{1}{2}}$.

Values of this parameter for various materials are shown in Table 7-1. A comparison of the temperatures taken in 1927 and 1939 indicate a value of $(K\rho c)^{-\frac{1}{2}}$ of 1000.

A series of temperature-time depth histories were calculated, Reference 49, for different combinations of surface compositions and thermal properties. Subsolar point surface temperature and dark-side surface temperatures resulting from these calculations are presented in Table 7-2. It will be noted that the subsolar point temperature remains generally at about the same value regardless of dust thickness or conductivity. However, subsolar point temperature is very sensitive to changes in lunar albedo and will drop considerably with an increase in albedo. This may indicate that the dark areas, on the lighted side of the moon, are somewhat hotter than the bright areas. Concerning dark (unlighted) side temperature, it will be noted that this temperature varies considerably with any change in dust thickness or conductivity. The first assumption in the table, which uses Pettit's values for dust thickness and conductivity, results in a calculated subsolar point temperature of 373.9°K, which agrees very closely with his measured temperature of 374°K. However, the calculated dark-side temperature is 165.8°K, which is somewhat higher than his measured value of 120°K. Use of Gilvarry's, Reference 584, much lower value for dust conductivity (Case 4 of Table 7-2) results in a dark-side temperature 124.7°K, which relates more closely with Pettit's measurement, but the resulting subsolar point temperature is calculated to be 378.9°K, which is approximately 5°K higher than that measured by Pettit.

Table 7-1

Thermal Inertia Constant, Reference 6

Material	K (cal/cm^{2}sec)	ρ (gm/cm^3)	c (cal/gm)	$[K\rho c]^{-\frac{1}{2}}$
Copper	0.9	9	0.09	1
Rock	5 x 10^{-3}	3	0.2	20
Pumice	3 x 10^{-4}	0.6	0.2	170
Powder in Vacuum	3-10 x 10^{-6}	2	0.2	500-900

Table 7-2

Calculated Lunar Surface Temperatures, Reference 49

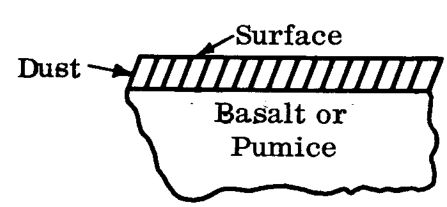
Assumptions		Subsolar Point Temperature	Dark Side Temperature
1.	1.0 cm dust over basaltic rock k dust = 0.004 BTU/hours ft °F k basalt = 1.3 BTU/hours ft °F albedo = 0.125	373.9°K	165.2°K
2.	1.0 cm dust over basaltic rock k dust = 0.004 k basalt = 1.3 albedo = 0.02	384.5°K	165.8°K

Table 7-2

Calculated Lunar Surface Temperatures, Reference 49 (Cont.)

Assumptions		Subsolar Point Temperature	Dark Side Temperature
3.	1.0 cm dust over basaltic rock k dust = 0.004 k basalt = 1.3 albedo = 0.5	323.2°K	163.0°K
4.	1.0 cm dust over basaltic rock k dust = 0.000726 k basalt = 1.3 albedo = 0.125	378.9°K	124.7°K
5.	1.0 cm dust over pumice k dust = 0.004 k pumice = 0.13 albedo = 0.125	377.1°K	138.6°K
6.	2.0 cm dust over basaltic rock k dust = 0.004 k basalt = 1.3 albedo = 0.125	376.8°K	149.1°K
7.	1.0 foot dust over basaltic rock k dust = 0.004 k basalt = 1.3 albedo = 0.125	378.6°K	113.0°K
8.	Conclusions reached by Dr. E. Pettit	373.6°K	119.7°K

Notes:
1. In all cases, surface emissivity = 1.0
2. Solar constant = 430 BTU per hour ft^2
3. Density basalt = 2.8 gm/cm^3
4. Specific heat basalt = 0.2
5. Density pumice = 0.6 gm/cm^3
6. Specific heat pumice = 0.2
7. Density dust = 2.0 gm/cm^3
8. Specific heat dust = 0.2



7.5 LUNATION SURFACE TEMPERATURES

Figure 7-5 shows typical curves for surface temperature variation during one lunation with observed points. Reference 209 presents a curve with Sinton's observed points which closely resemble the $(K\rho c)^{-\frac{1}{2}}$ value of 1000 shown in Figure 7-5. Figure 7-6

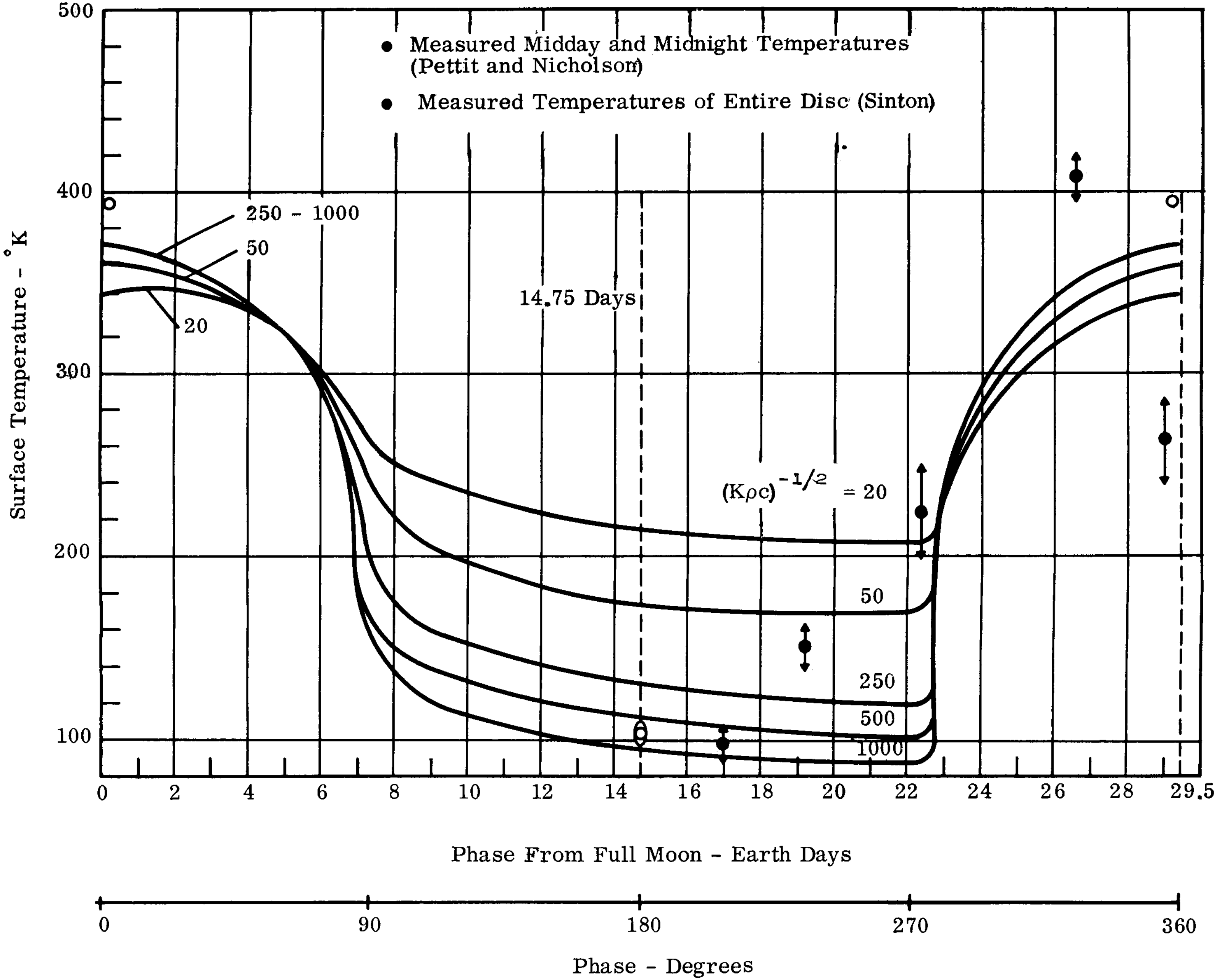


Figure 7-5. Theoretical Lunar Surface Temperature Variation for a Complete Lunation Reference 209

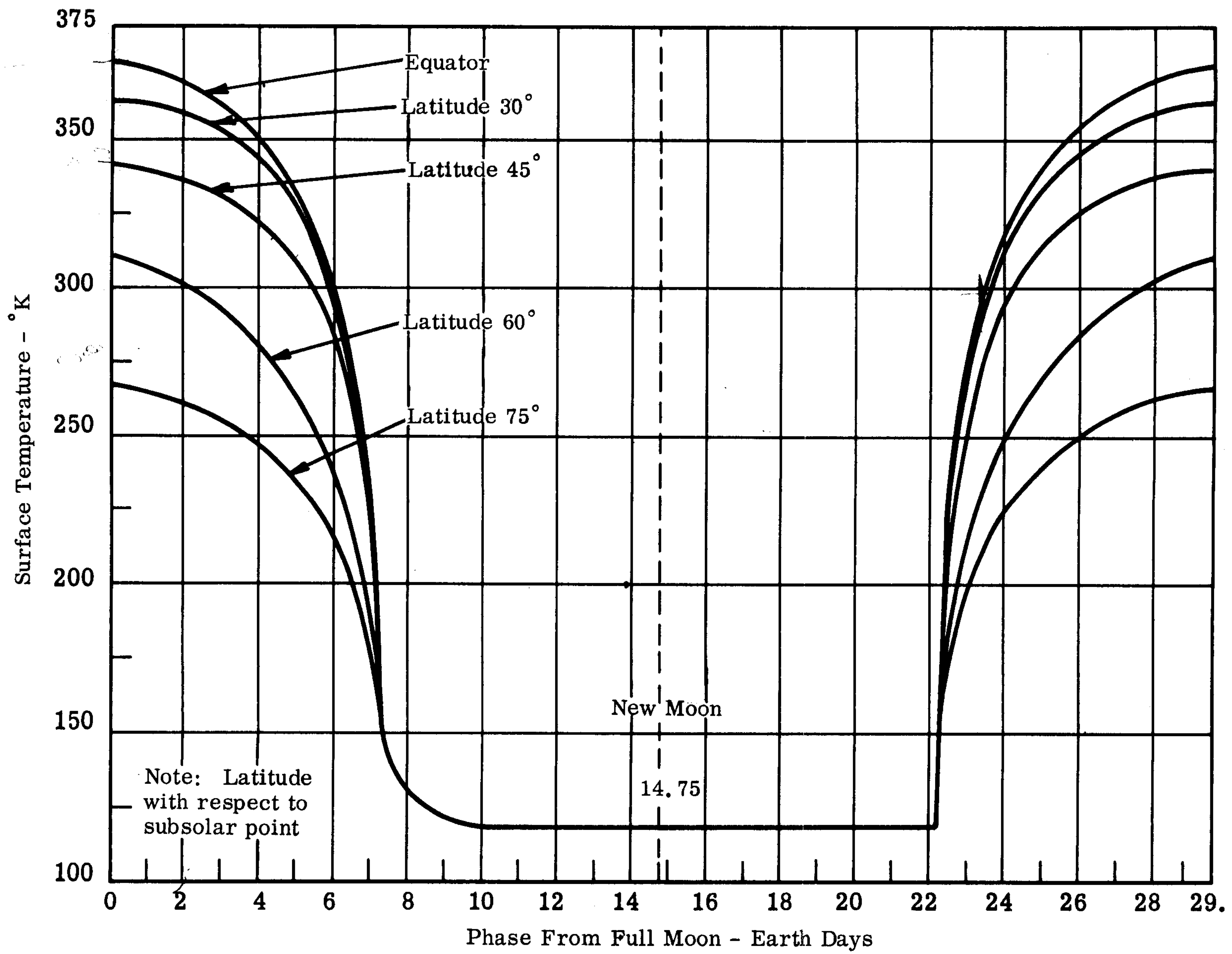


Figure 7-6. Theoretical Lunar Surface Temperature Variation for a Complete Lunation on Lunar Central Meridian

shows the surface temperature variation on the illuminated lunar surface as a function of longitude and latitude during a lunation on the lunar central meridian which follows:

$$T^4 = T_0^4 \cos\theta \cos\psi,$$

where θ equals longitude (relative to the subsolar point) and ψ equals latitude (relative to the subsolar point), the coordinate definitions differing from the selenographic coordinate system as discussed in Chapter 5.

Table 7-3 gives observed values of lunar surface temperatures during a lunation. Also, Table 7-4 presents observed temperatures at various phase angles. The value of 407°K for lunar surface temperature obtained by Pettit and Nicholson for the subsolar point at full moon is in substantial agreement with that found by Menzel, Reference 547, and the water-cell Observations of Colentz.[1]

7.6 LUNATION SUBSURFACE TEMPERATURES

Figure 7-7 shows the microwave (0.86 centimeter) equatorial temperature variation during a lunation. The dotted line represents the theoretical temperature variation for a lunar surface with deep dust. This same reference concludes a minimum dust thickness of 2.5 centimeter. Piddington and Minnett's observations (Table 7-5) show a variation caused by the lunar surface being partially transparent to a wavelength of 1.25 centimeter. They conclude a 1-millimeter depth of dust. The results are shown in Figure 7-8.

Figure 7-9 presents temperatures as a function of time for varying depths beneath the lunar surface, Reference 49.

Assumed conditions are the same as for Case 1 of Table 7-2. It will be noted that the temperature variation from day to night becomes fairly small at a depth of 76.2 centimeters and practically disappears at a depth of 274 centimeters.

[1] Scientific Papers, Bureau of Standards, 18, 535, (No. 438), 1922

Table 7-3

Observed Lunar Surface Temperatures During Complete Lunation

Wave-length (cm)	Region	Temperature (°K) Max.	Temperature (°K) Mean	Temperature (°K) Min.	Mean Depth	Phase Lag to Max. Surf. Temp.	Remarks	Investigator Reference
*8-14μ	Center Disc	374	--	120	--	--	--	Pettit and Nicholson 6, 389
3.2	Whole Disc	170	170	170	--	--	No Temperature phase variation	Troitsky and Zelinskaya 6, 348
21	Whole Disc	170	170	170	--	--	No Temperature variation	Westerhout 6
75	Whole Disc	186	186	186	--	0	No Temperature variation	Seeger, et al, 6, 348
*8-14μ	Center Disc	407	--	120	--	--	--	Pettit and Nicholson 353
*8-14μ	Center Disc	--	--	120 ±5	--	0	This is only direct measure	Troitsky 571
1.25	Center Disc	300	--	200	--	3.4 days	33-45°K measurement variation	Piddington and Minnett 389, 430, 435
10	Center Disc	390 ±50	--	240 ±50	--	3.4 days	--	Akabane 389, 6, 420
3.2	Center Disc	--	--	120	0	2 days	Two day inferred	Troitsky 562
*8-14μ	Subsolar Point	330-390	--	--	--	--	Theoretical and experimental, dependent upon time and albedo	Pettit and Nicholson 353
3.2	Whole Disc	--	--	115	--	--	Surface temperature deduced from 10 centimeter depth	Troitsky 562
21.6	Whole Disc	--	245	--	--	0	No temperature variation	Westerhout 348
33	Whole Disc	208	208	208	--	0	No temperature variation	Denisse and LeRoux 348, 6
--	--	370	--	100	--	--	--	Wesselink and Jaeger 342
*0.3-14μ	--	375	--	125	--	--	Infrared Measurements	Lettau 14
1.25	Whole Disc	--	--	145 ±10%	0	--	--	Piddington and Minnett 437
21.6	Whole Disc	--	250 ±30	--	--	0	--	Mezger and Strassl 279
--	--	--	--	122 ±30	--	--	Lowell Obs. 1959	Sinton 379, 209
--	--	400	--	120	--	--	Lowell Obs. 1960	Geoffrion 209, 568
0.15	Whole Disc	336	--	120	--	--	--	Sinton 209

* Units not centimeters

Note 1: Experimental difficulties in measurements of the 100°K category, Reference 353, easily account for inconsistencies in the lower temperatures that have been observed with vacuum thermocouples.

Note 2: Assumption made that mean depth was zero where reference did not give a value; therefore, included temperatures as surface values.

Table 7-4

Observed Lunar Surface Temperatures for Various Phase Angles

Wave Length (cm)	Region	Phase Angle (Degrees)	Temp. (°K)	Investigator - Reference
0.43	Center Disc	77	182 ±25%	Naval Research Lab. 350
0.43	Center Disc	126	243 ±25%	Naval Research Lab. 350
0.43	Center Disc	280	254 ±25%	Naval Research Lab. 350
*8-14μ	Center Disc	0	407	Pettit and Nicholson 350
*8-14μ	Center Disc	90	358	Pettit and Nicholson 353
1.25	Center Disc	18	**292	Dicke and Beringer 437, 560, 570, 572
--	--	Lunar Sunset	215	-- 47
0.43	Center Disc	100	245	Coates 209
0.43	Center Disc	257	257	Coates 209
0.43	Center Disc	306	306	Coates 209

* Units not centimeter

** Correct to 270°K by Piddington and Minnett

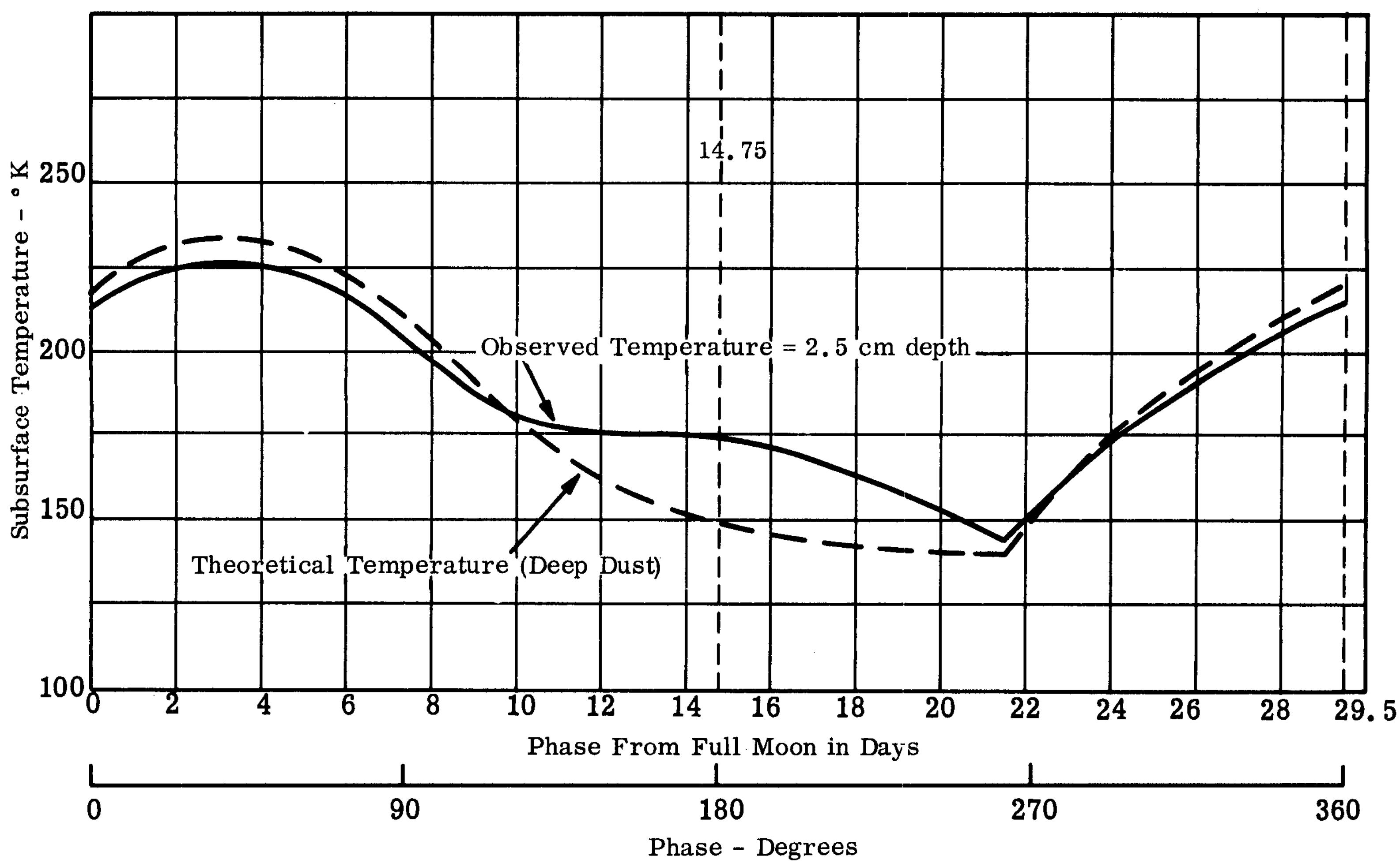


Figure 7-7. Lunar Subsurface Temperature Variation (λ = 0.86 Centimeter) for a Complete Lunation, Reference 435

Table 7-5

Observed Lunar Surface Temperatures During Complete Lunation

Wave-length (cm)	Region	Temperature (°K)			Mean Depth (cm)	Phase Lag (days)	Remarks	Investigator - Reference
		Max.	Mean	Min.				
0.86	Center Disc	255	--	145	2.5	1.8	See Fig. 7-7	Gibson 6, 389 435
1.25	Whole Disc	301 ±15	249	197 ±10	40	3.4	See Fig. 7-8	Piddington and Minnett 6, 437
3.2	Whole Disc	183	--	170 ±10	10	0	--	Seeger, Westerhout, Conway 233, 348
--	--	--	243	--	100	--	--	Paris Observatory 573

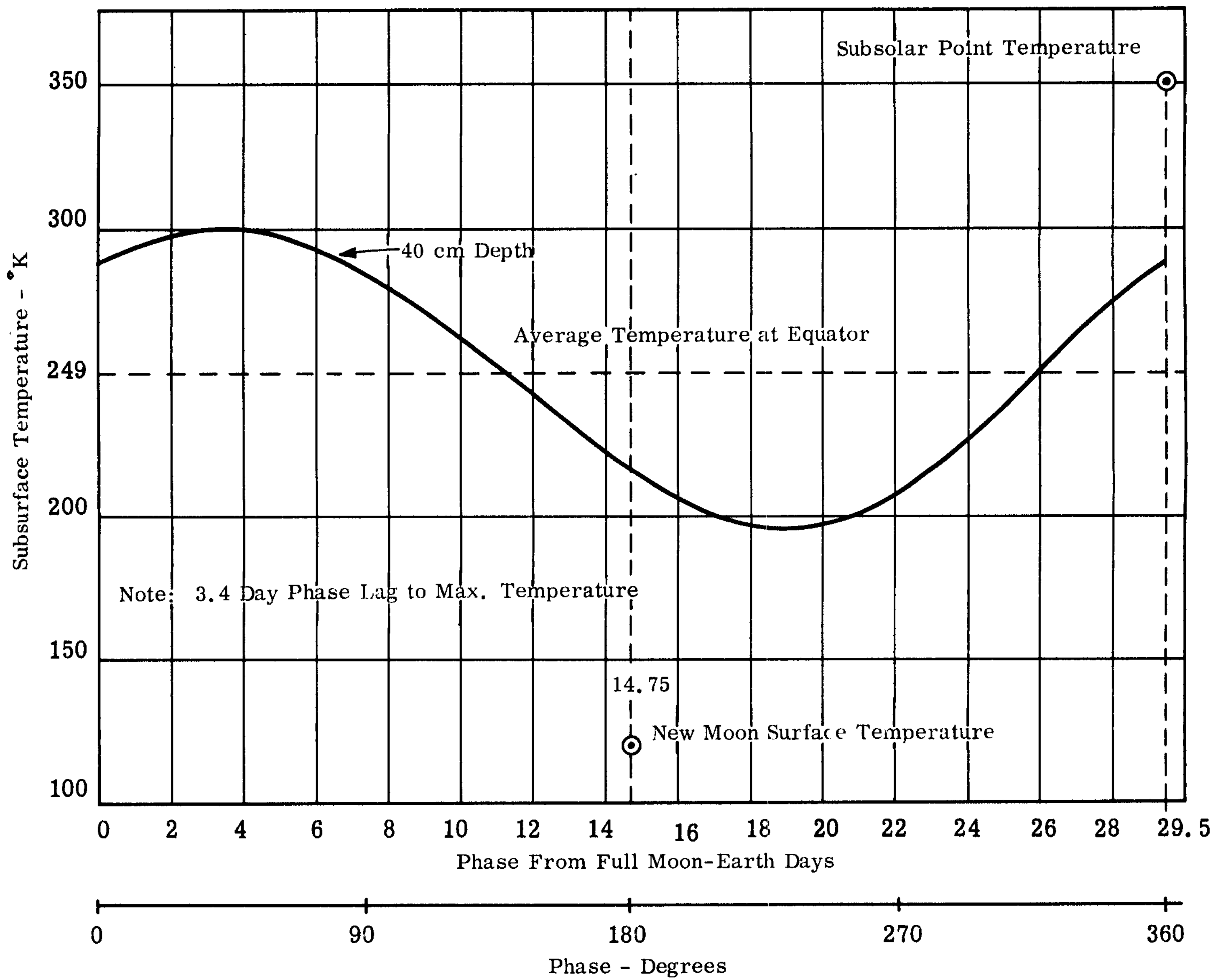


Figure 7-8. Lunar Subsurface Temperature Variation (λ = 1.25 Centimeter) for a Complete Lunation, Reference 437

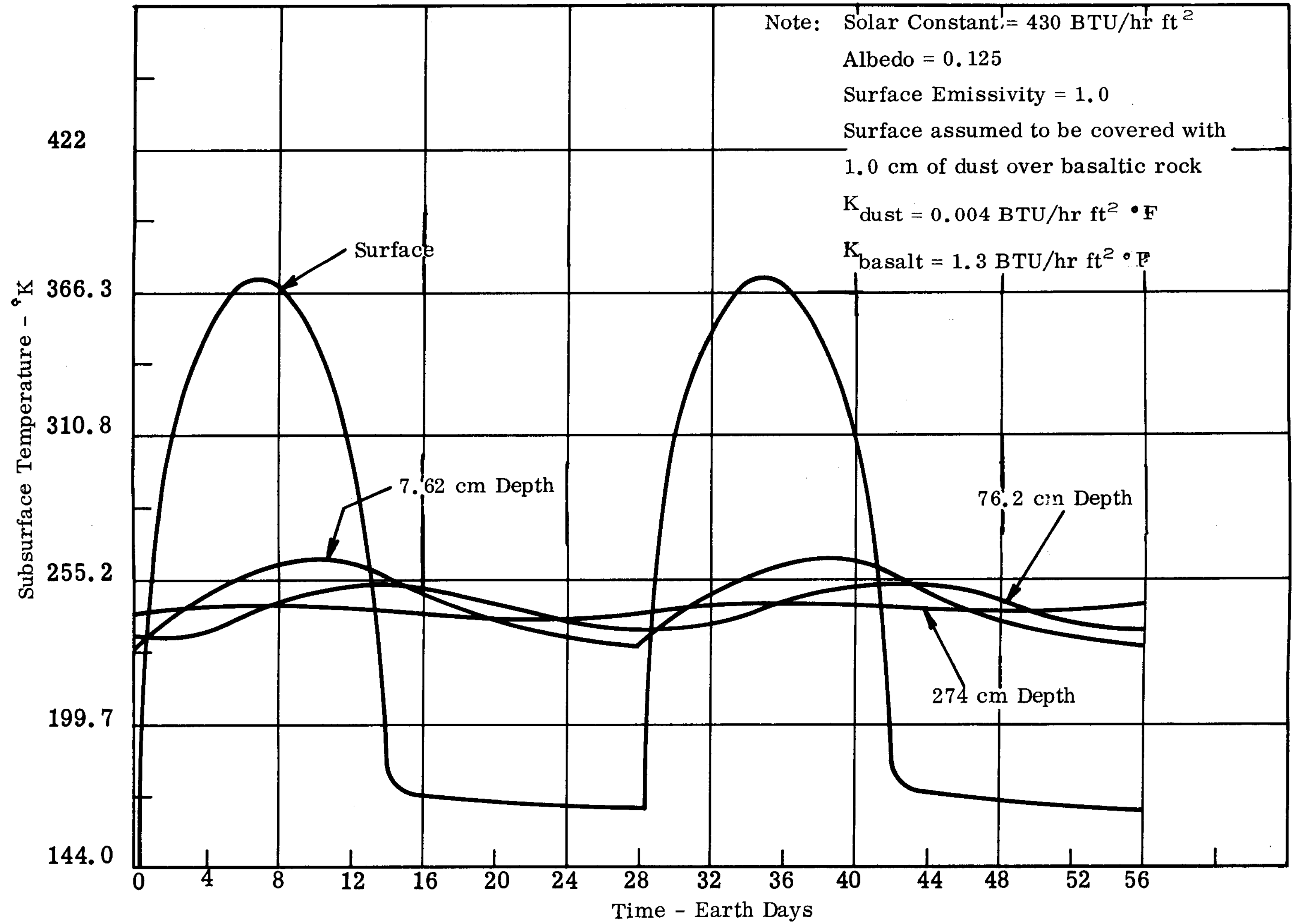


Figure 7-9. Theoretical Lunar Subsurface Temperature Variation for Two Complete Lunations, Reference 49

7.7 ECLIPSE SURFACE TEMPERATURES

It is well known from the work of Pettit and Nicholson that the temperature of the surface of the moon drops rapidly during a total eclipse and recovers almost immediately at the end of the eclipse. Theoretical treatments of this phenomenon have shown the surface of the moon to consist of a material with low thermal conductivity and that the sudden drop in temperature is propagated into the surface but is progressively attenuated beneath the surface, lagging behind the surface variation. A typical curve for surface temperature is shown in Figure 7-10. Table 7-6 presents observed surface temperature during various eclipses.

7.8 ECLIPSE SUBSURFACE TEMPERATURES

Figure 7-11 presents the whole disk temperature of the moon from data taken during a single lunar eclipse, Reference 430. Assuming that all of the radiation was emitted in the dust layer and that the surface is approximated by a semi-infinite solid, a value of the mass absorption coefficient was computed and found to be 2.9, Reference 430. Comparing this with known materials, it is seen that there is a similarity to basalt and obsidian. However, this value is an average over the lunar surface and the comparison with various materials must be considered highly speculative. Table 7-7 gives observed subsurface temperatures.

7.9 CRATER TEMPERATURE DISTRIBUTIONS

In an experiment conducted by Shorthill and Saari, Reference 463, temperatures of the brightest spot known on the moon, the crater Aristarchus and of its dark environment were determined throughout a complete eclipse and are shown in Figure 7-12. It may be noted that the temperature difference is about 30°K. A good relationship between brightness and temperature deviation is discussed in Reference 463. The central crater of Aristarchus appears very bright and the apparent temperature maximum during an eclipse coincides with this area. Copernicus, though, shows a maximum albedo near the rim, and it is in the area of these brightness maxima that the highest temperatures are recorded during an eclipse. Sinton's observations of Figure 7-13 show cool interior and warm sun lit rim of Copernicus. As observed, the penetrated areas, having higher albedo, were actually colder before the eclipse than the unpenetrated dark environs. More observations and more calculations will be needed, but the observed effect could be caused by escape of radiation from layers below the surface.

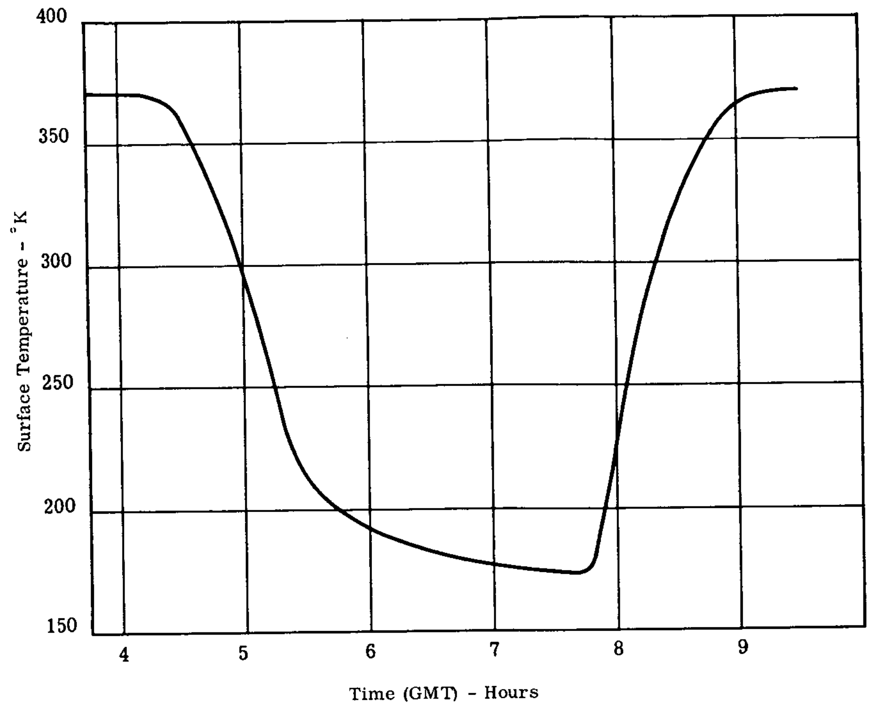


Figure 7-10. Observed Lunar Surface Temperature Variation (λ = 8-14μ) During Total Eclipse of 28 October 1939, Reference 342

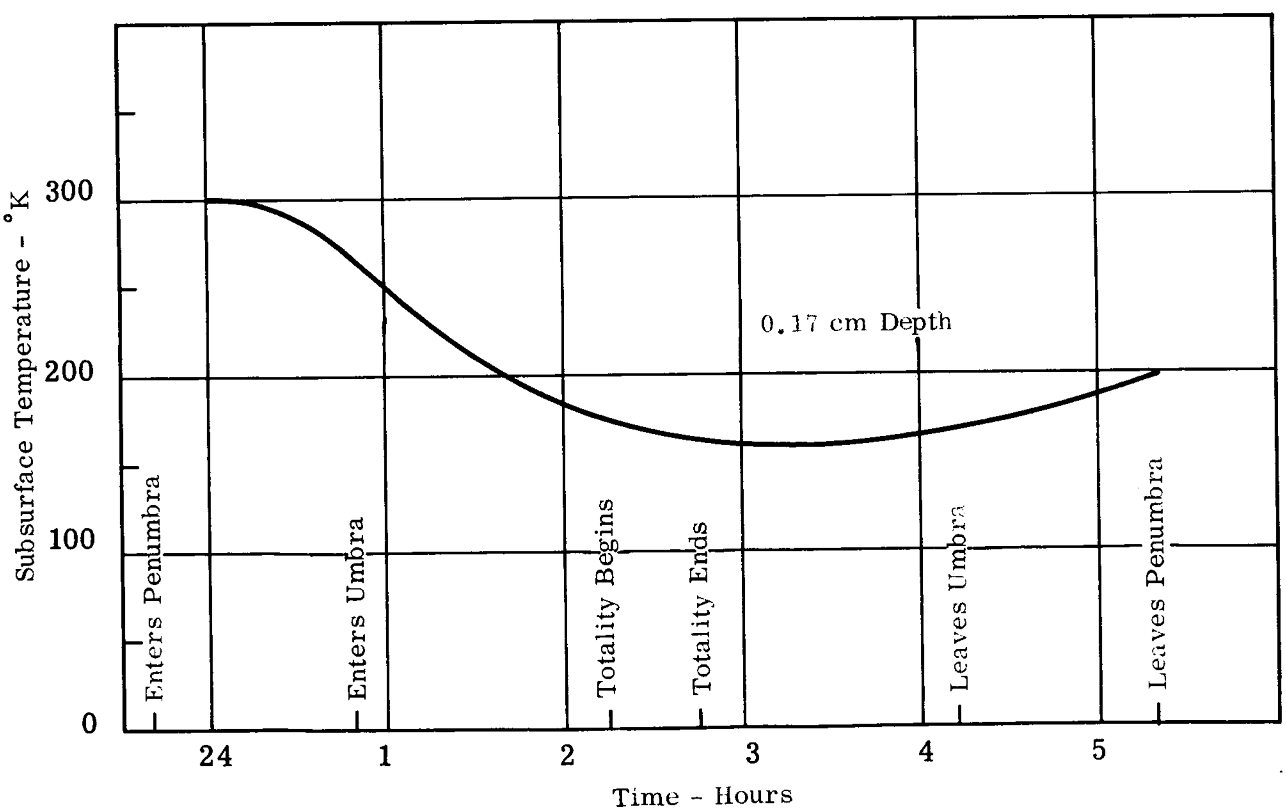


Figure 7-11. Observed Lunar Subsurface Temperature Variation (λ = 0.15 Centimeter) During Total Eclipse of 13-19 January 1954, Reference 430

Table 7-6

Observed Lunar Surface Temperature During Total Eclipse

Wave-length	Region	Temperature (°K) Max.	Mean	Min.	Mean Depth	Phase Lag	Eclipse	Investigator - Reference
8-14μ	Center Disc	371 ±5	--	175 ±5	--	--	10/27/39	Pettit 6, 329, 233, 342
0.86cm	Whole Disc	--	225	--	--	--	--	Gibson 6
8μ	Whole Disc	375	--	160	--	--	3/12/60	Rock 292
8-14μ	--	340	--	170	--	--	--	-- 17
8-14μ	--	342	--	156	--	--	6/14/27	Pettit and Nicholson 353, 442
0.86cm	Center Disc	--	~205	--	--	--	1/29/53 and 1/18/54	Gibson 389

Table 7-7

Observed Lunar Subsurface Temperature During Total Eclipse

Wave-length (cm)	Region	Temperature (°K) Max.	Mean	Min.	Mean Depth (cm)	Phase Lag	Eclipse	Investigator - Reference
0.15	Whole Disc	300	--	170	0.17	1 hour	1/18/54 (See Figure 7-12)	Sinton 6, 430, 233, 442

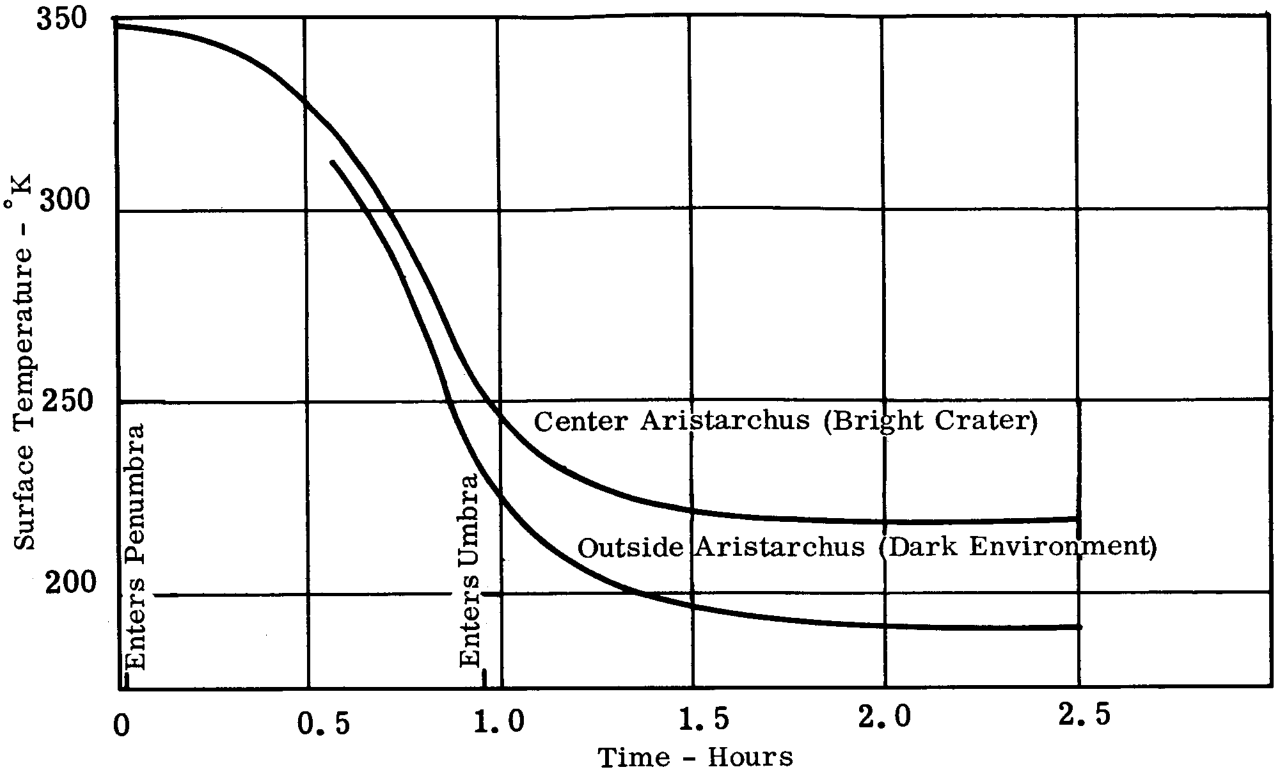


Figure 7-12. Lunar Surface Temperature Variation of Aristarchus During Eclipse, Reference 99

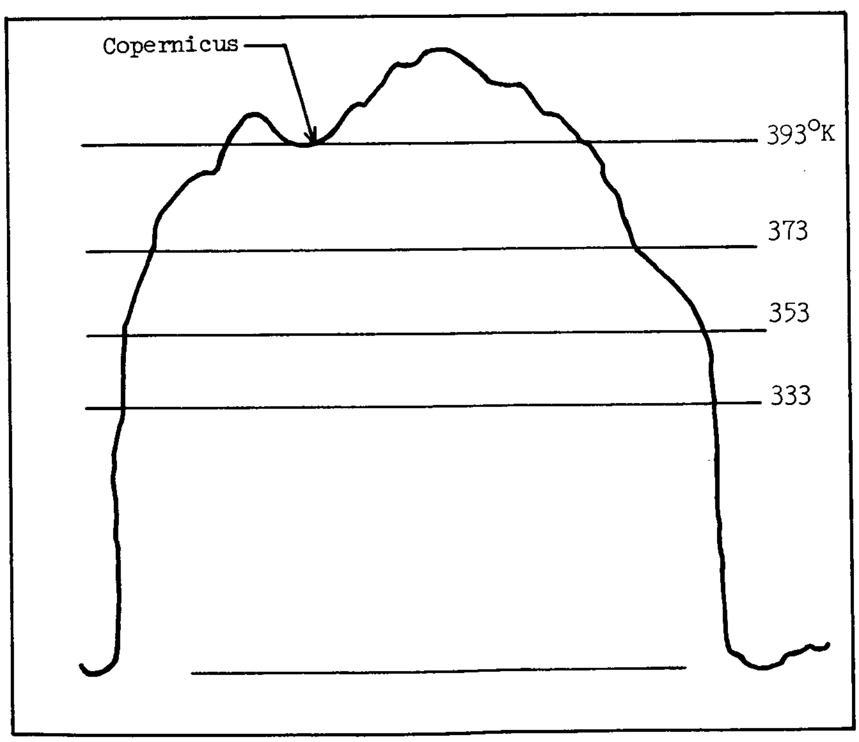
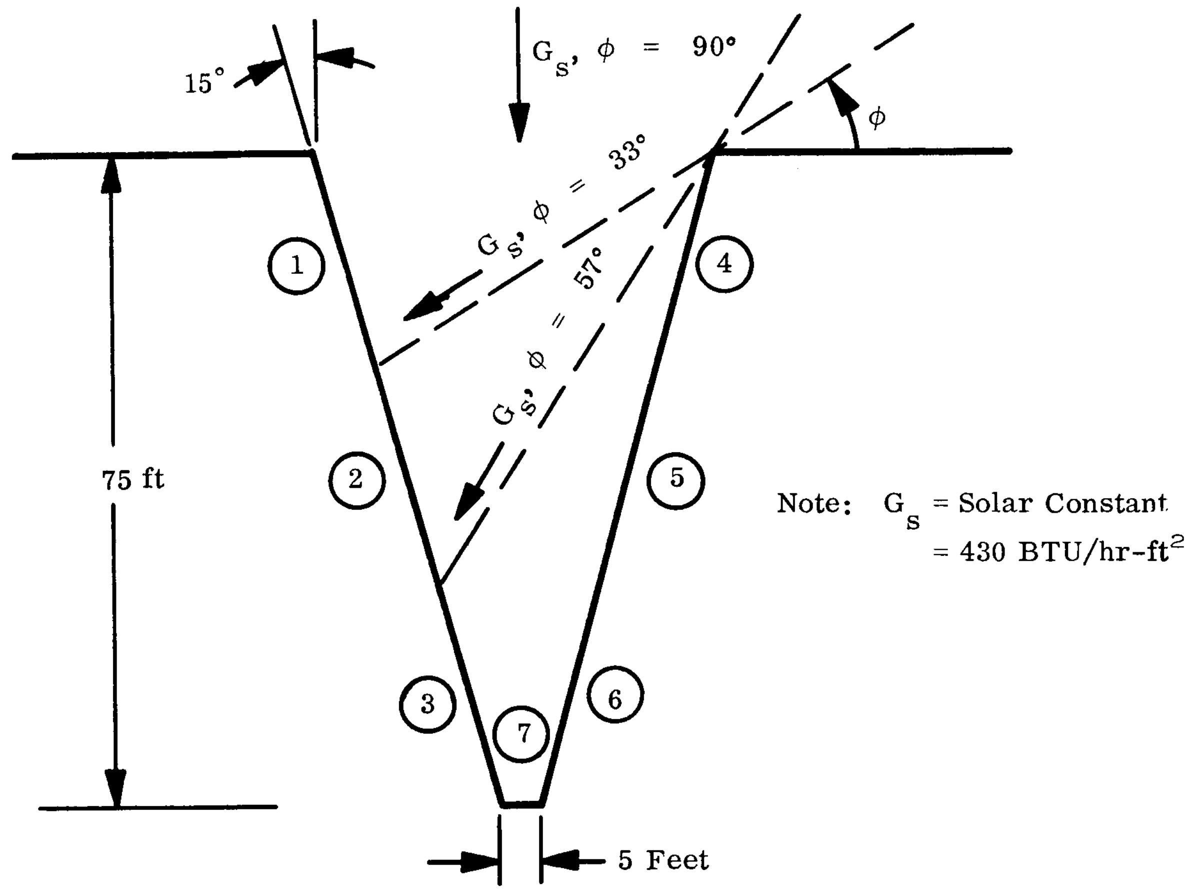


Figure 7-13. Dr. Sinton's Thermal Scan Through the Lunar Crater Copernicus, Reference 379

Saari and Shorthill have also reported infrared observations of the craters Tycho, Copernicus, Aristarchus, and Proclus during the 5 September 1960 eclipse, Reference 549. All except the latter crater showed a retention of brightness temperature 40°K warmer than their environment. Sinton confirmed this during his observations of Tycho (Lowell Observatory Bulletin No. 108). The crater environs are probably covered by a thicker layer of dust than the crater floors. This is also the interpretation of the observations recorded during the 12-13 March 1960 eclipse and stated in Reference 340.

7.10 TEMPERATURE DISTRIBUTION IN A LUNAR FISSURE

Figure 7-14 presents the temperature distribution in a typical lunar fissure for various solar angles. It is evident that the fissure can act as a trap for solar energy and will reach rather high temperatures when the sun is directly overhead. It was assumed in the analysis that there is negligible heat transfer by conduction into the fussure surface. This assumption is based on conclusions drawn by E. Pettit, Reference 353.



Point	Solar Angle, ϕ, Degrees		
	33	57	90
1	338°K	386.3°K	359.1°K
2	278°K	403.6°K	399.1°K
3	273.6° K	342.4° K	438.6°K
4	306.9°K	339.7°K	359.1°K
5	301.3°K	368.6°K	399.1°K
6	275.2°K	350.2°K	438.6°K
7	261.9°K	334.7°K	470.2°K

Figure 7-14. Temperature Distribution in a Lunar Fissure, Reference 49

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CHAPTER 8

CHANGES ON THE MOON

8.1 BACKGROUND

The commonly accepted idea that the moon is a dead world with no changes in it cannot now be seriously maintained, Reference 6.

The decision as to the reality of changes on the moon's surface is made difficult by the variable conditions of visibility of many features of the moon. Visibility depends on the phase and aspect of libration, as well as on the resolving power of the telescope, personal characteristics of the observer, and conditions of the atmosphere of the earth. Much of the evidence for real changes is of a negative character, that is, based on the argument that early observers, such as Schröter and J. Schmidt with their equipment, should have seen certain details whereas they failed to report them. Therefore, such details must be of a recent origin. Or the details that were reported by them and now missing must have been really in existence, with no possibility of these experienced observers making an error.

With the improvement of observational techniques, more and more details are recorded on the surface of the moon that were evidently overlooked by earlier observers or were beyond the power of their telescopes. It is impossible to maintain that such details are recent formations on the surface of the moon developed in the last 50 years or so.

To such details belong the domes, the summit pits of craters to which the attention of observers was directed by the meteoric hypothesis of lunar craters, many rills, bright and dark spots on the floor of various craters, etc. Perhaps the most striking illustration of this point is the discovery, made in 1953 by an amateur, John J. O'Neill, with a 15-inch reflector, of a bridge on the border of Mare Crisium. It has been confirmed by many other observers, Reference 606, and represents a unique feature of the moon. The bridge is some 12 miles long with an open arch of 2 miles and is conspicuous under some conditions of illumination. Yet it was overlooked by dozens of observers who spent thousands of hours studying this portion of the moon.

8.2 CRATER CHANGES

8.2.1 INTRODUCTION

Table 8-1 presents a collection of reports on possible lunar surface changes. The problem of possible changes on the moon is considered in detail in an essay by Markov, Reference 184. The following are remarkable cases.

8.2.2 MESSIER A AND B

Craters Messier A and B (Messier A is now known as Pickering) in Mare Foecunditatis. Between 1829 and 1837, Beer and Madler made over 300 drawings in this area and described Craters A and B as exactly alike. At the present time, they are very different. Moore, Reference 206, made 500 drawings of this pair and found that Pickering generally appears larger than Messier, but sometimes it appears smaller; often the two appear equal, and under high light both appear as white spots.

On the whole, the evidence for any structural change of the craters is very weak, although this region is evidently very active and changes in visibility and color are probable.

8.2.3 HYGINUS N

Somewhat more convincing is the case of Hyginus N which was first seen by Klein in 1877 and described as a rimless depression three miles in diameter, a description fitting its present appearance. It was not recorded on previous maps, and Klein considered it as a new formation. Changes in coloration and mists are frequently observed in this region. There are a dozen more reported cases of such nature equally unconvincing and the most that can be safely said about them is that some local activity of volcanic nature seems to be taking place, with released vapors which change the conditions of visibility.

8.2.4 LINNE'

There is one case of structural change that is accepted by most selenographers as real. This is of the crater Linne' in Mare Serenitatis. Lohrmann in 1834 described it as the second most conspicuous crater in this mare, 6 miles in diameter and very deep. Mädler also referred to it in the same terms, and it appears conspicuous in six drawings of Schmidt, made between 1841 and 1843.

Table 8-1. Reports of Possible Lunar Surface Changes*

Lunar feature	Date of observation	Observer(s)	Size of telescope and location of observatory
Agarum Promontory	ca. 1955	H. P. Wilkins, P. Moore and others	33-inch refractor, Meudon Observatory, France
Wilkins, H. P., and P. Moore (1955), *The Moon:* A Complete Description of the Surface of the Moon, Containing the 300-Inch Wilkins Lunar Map, Faber and Faber, Ltd., London, England, p. 193: "On several occasions, a mist-like appearance has been witnessed near Agarum, especially when the Mare is bisected by the terminator under sunrise illumination. Wilkins has seen a similar effect in the bay to the west."			
Alpetragius	18 Nov. 1958, 22:05 U.T.	R. J. Stein	4-inch refractor, Newark, N. J., Museum
Alter, D., "Obscurations of Lunar Features," unpublished ms. (9 pages), p. 7: "A portion of the shadow vanished and seemed to be replaced by a much lighter shade."			
Alphonsus	26 Oct. 1937	D. Alter	36-inch reflector, Lick Observatory, Mt. Hamilton, Calif.
Alter, D. (1959), "The Alphonsus Story," *Proc. of Lunar and Planet. Explor. Coll.* I(4), p. 19: "One of the Lick pictures, made at the evening half moon on the morning of October 26, 1937, showed the floors of Ptolemaeus, Alphonsus and Herschel as 'milky' under the setting sun. I was then, and am still, uncertain whether the effect was a real one due to a haze, or was an illusion due to a trick of photographic contrast."			
Alphonsus	26 Oct. 1956	D. Alter	60-inch reflector, Mt. Wilson Observatory, Calif.
Alter, D. (1956), "A Suspected Partial Obscuration of the Floor of Alphonsus," *Publ. Astron. Soc. Pac.* 69, p. 160, "In each of these craters [Arzachel and Alphonsus] the infrared reveals a rill in the western side of the floor. In Arzachel the rill shows plainly in all eight photographs. In the crater Alphonsus the result is different. There each blue photograph shows much less detail than can be seen in its infrared mate .... For some reason the blue-violet photographs lose more detail in the west side of the floor of Alphonsus than they do in the floor of Arzachel. This is not true of the infrared ones .... "There is a temptation to interpret these results immediately as being due to a thin atmosphere, either temporary or permanent, over the floor of Alphonsus. The theoretical difficulties in such a hypothesis are, however, strong enough to forbid a wholehearted acceptance of it."			
Alphonsus	Dec. 1958	G. A. Hale	24-inch refractor, Brighton, England
Wilkins, H. P., and P. Moore (1955), *The Moon:* "... reddish spot near central mountain."			
Alphonsus	3 Nov. 1958, 03:00 U.T.	N. A. Kozyrev	50-inch reflector, Crimean Astrophysical Observatory, USSR
Kozyrev, N. A. (1959), "Observation of a Volcanic Process on the Moon," *Sky and Telescope* 18, p. 184: "While I was taking the first spectrogram, at 1h Universal time, and guiding on the image of the central peak, the latter became strongly washed out and of an unusual reddish hue .... The next spectrogram of Alphonsus was made from 3:00 to 3:30 U.T.... Only the central peak of this crater showed on the slit, and I was struck by its unusual brightness and whiteness at the time. "These observations are interpreted as showing that on the morning of November 3, 1958, there occurred a volcanic phenomenon. First there was an ejection of dust—volcanic ash (appearing red in the guiding eyepiece)—and afterward an efflux of gas (causing the emission spectrum). The effusion of gas could come from magma rising to the lunar surface." *Cf.* Kozyrev, N. A. (1959), "Volcanic Activity on the Moon," *Priroda* 48(3): 84-88, in Russian; English translation in *Internat. Geol. Rev.* 1(10): 40-44.			
Alphonsus	18 Nov. 1958, 20:00-20:30	H. F. Poppendiek and W. H. Bond	52-inch focal length 6-inch reflector, San Diego, Calif.
Poppendiek, H. F., and W. H. Bond (1959), "Recent Observations of Possible Volcanic Activity Within the Lunar Crater Alphonsus," *Publ. Astron. Soc. Pac.* 71, p. 233: "While sweeping the moon's surface, we were startled by what we saw within the crater Alphonsus. A large diffuse cloud completely obscured the crater's central mountain peak and its small craterlet. This cloud was about 20 miles in diameter and irregular in shape; ... Two main features attracted our attention: (1) the cloud was large in comparison to the peak that it obscured, and (2) it had a strange diffuse brightness."			
Alphonsus	19 Nov. 1958	J. Wall and F. D. Brewin	12-inch refractor, England
"... dusty patch near central mountain."			
Alphonsus	19 Nov. 1958 and 19 Dec. 1958	H. P. Wilkins	15¼-inch reflector, Dr. Wilkins' observatory, Bexleyheath, Kent, England
Wilkins, H. P. (1959), *Monthly Notices of Roy. Astron. Soc.* 119(4), p. 421: "A reddish patch close to the central peak within the lunar formation of Alphonsus was seen on November 19 and again on December 19; apparent confirmation of Kozyrev's announcement of an eruption."			
Apennine Mountains	ca. 1905	W. H. Pickering	6½-inch reflector, Mandeville, Jamaica
Pickering, W. H. (1905), "Variable Spots on the Moon," *Publ. Astron. Soc. Pac.* 17(105), p. 181: "... certain variable spots on curved ridge attributed to clouds and snow deposits."			
Aristarchus	1948-49	R. Barker	Dr. Barker's observatory, Cheshunt, Hertfordshire, England
Barker, R. (1948-49), *Monthly Notices of Roy. Astron. Soc.* 109(2), p. 176: "Frequent observations of the lunar walled plain Aristarchus have confirmed the dusky markings on the eastern inner wall. These markings have now developed from simple radial bands into complex chequerwork, and this evolution is still proceeding, thus marking what is believed to be the first really definite physical change ever recorded on the moon."			
Aristarchus	ca. 1936	W. H. Haas	6-inch reflector, Las Cruces, N. Mex.
Haas, W. H. (1936), "Lunar Changes in the Crater Aristarchus," *Notices of Mt. Union College Observatory,* p. 135: "The most interesting and most readily observed thing about the bands is their progressive darkening. At a day after sunrise only a discriminating observer sees some very vague bands on the brilliant white wall. Two days later, at full moon, the bands are readily visible; but their darkness is slight, and the brilliant white streaks between them give an impression of great brightness to Aristarchus. A few days later, their darkness is obvious; a little later, and the wall is not bright in any sense; and a little later, the bands, almost like shadows themselves, are covered by the sunset shadow ... "The dark bands are the most interesting changes in Aristarchus, but certain others should be mentioned. "The striking feature of Aristarchus just after full moon is a long, curving, very bright band which has one terminus at a bright spot (a crater or a peak) on the rim of the east inner wall and the other (terminus) at a very bright spot on the inner slope of the south wall. ..."			
Aristarchus	ca. 1945	W. H. Wilkins	
Wilkins, W. H. (1945), "Variation in the Lunar Formation Aristarchus," *J. Brit. Astron. Assoc.* 56(1), p. 12: "... bluish glowing of streaks on floor and on mountain mass delta."			
Bartlett	22 Apr. 1933	H. P. Wilkins and P. Moore	33-inch refractor, Meudon Observatory, France
Wilkins, H. P., and P. Moore (1955), *The Moon,* p. 227: "The 'crosses' recorded by Mädler and Neison remain a mystery. [T. W.] Webb failed to find the main one, but added that Birmingham, a celebrated Irish astronomer, had been more successful; more recently, indications of crosses have been seen by Dr. [J. J.] Bartlett and other American observers. No crosses were visible when the Meudon drawing was made [p. 226], but they may have been masked by shadow. This area will more than repay further study."			

*** Excerpted from Green, J. Geologic Exploration of the Moon, Columbia University Press (in preparation).**

Table 8-1. Reports of Possible Lunar Surface Changes (Cont.)

Lunar feature	Date of observation	Observer(s)	Size of telescope and location of observatory
Copernicus	1939	H. P. Wilkins	
Wilkins, H. P. (1954), *Our Moon,* F. Miller, London, England: Faint glow inside Copernicus lasting 15 minutes.			
Eimmart	Jan.-May 1914	W. H. Pickering	
Pickering, W. H. (1914), "Recent Change in the Lunar Crater Eimmart," *Astron. Nach.* 196, p. 413: "...source of white material spreading from foot of northern interior slope of crater [marked in January and becoming negligible in May]."			
Gassendi	17 May 1951	H. P. Wilkins	15¼-inch reflector, Dr. Wilkins' observatory, Bexleyheath, Kent, England
Moore, P. (1953), *A Guide to the Moon,* p. 118: "A bright speck inside Gassendi was seen by Dr. Wilkins on May 17, 1951; it lasted for one second, and left a glow for perhaps two seconds."			
Godin	ca. 1870	E. L. Trouvelot	6-inch refractor, Cambridge, Mass.
Trouvelot, E. L. (1882), *The Trouvelot Astronomical Drawings Manual,* Scribner's Sons, New York, N. Y., p. 49: "On several occasions, I have seen a purplish light over some parts on the Moon, which prevented well-known objects being as distinctly seen as they were at other times, causing them to appear as if seen through a fog....On one occasion, the great crater Godin, which was entirely involved in the shadow of its western wall, appeared illuminated in its interior by a faint purplish light, which enabled me to recognize the structure of this interior. The phenomenon could not be attributed in this case to reflection, since the Sun, then just rising on the western wall of the crater, had not yet grazed the eastern wall, which was invisible. It is not impossible that a very rare atmosphere composed of such vapors exists in the lower parts of the Moon."			
Graham	11-13 May 1927, 1948	H. P. Wilkins and P. Moore	15¼-inch reflector, Dr. Wilkins' observatory, Bexleyheath, Kent, England
Wilkins, H. P., and P. Moore (1955), *The Moon,* p. 203: "...sometimes not distinguishable near First Quarter."			
Moore, P. (1953), *A Guide to the Moon,* p. 115: "...Dr. Wilkins could see no trace of it [the crater] on May 12, 1927, although it had been normal on May 11 and had reappeared faintly on May 13. Three times in 1948 the writer saw the whole area 'misty gray and devoid of detail,' with the surrounding surface sharp and clear cut. . . ."			
Herodotus Valley "Cobrahead"	1893	W. H. Pickering	6-inch reflector, Arequipa, Peru
Pickering, W. H. (1903), *The Moon,* Doubleday, Page and Co., New York, N. Y.: "So striking, indeed, was the appearance [an active volcano], that...I determined to make a series of careful drawings of the apparent vapour column, in order to determine whether any variations in its outline might be detected from time to time, or whether, like a stain, it was immovably attached to the lunar surface....A casual examination of the sketches shows the great changes that are from time to time undergone by the vapour column...changes that are readily detected by a six-inch telescope under ordinary atmospheric conditions."			
Herodotus Valley "Cobrahead"	10 Feb. 1949	F. H. Thornton	18-inch reflector, Northwich, England
Wilkins, H. P., and P. Moore (1955), *The Moon:* "...puff of whitish vapor obscuring details."			
Hyginus N.	1877	H. J. Klein	Cologne Observatory, Germany
Markov, A. V. (1952), "On the Physical Peculiarities of the Lunar Surface and Its Possible Variation," *Izv. Pulkova* 19(2): 64-80, in Russian: Rimless depression 3 miles in diameter, not recorded on previous maps.			
Kant	4 Jan. 1873	E. L. Trouvelot	6-inch refractor, Cambridge, Mass.
Trouvelot, E. L. (1882), *The Trouvelot Astronomical Drawings Manual,* p. 49: "On several occasions, I have seen a purplish light over some parts of the Moon, which prevented well-known objects being as distinctly seen as they were at other times, causing them to appear as if seen through a fog. One of the most striking of these observations was made on January 4th, 1873, on the crater Kant and its vicinity, which then appeared as if seen through luminous purplish vapors."			
Kepler	2 Feb. 1942	Y. W. I. Fisher	Brussels, Belgium
Wilkins, H. P., and P. Moore (1955), *The Moon:* "...whitish glow near earthlit rim."			
Klein N.	4 Apr. 1944	H. P. Wilkins and others	15¼-inch reflector, Dr. Wilkins' observatory, Bexleyheath, Kent, England
Moore, P. (1953), *A Guide to the Moon,* p. 144: "Moreover, there still seem to be traces of local activity in the region. Mists have been seen from time to time, and on April 4, 1944, Dr. Wilkins saw that [Klein] N. was much darker than usual, while the southern edge of the great Hyginus crater valley was bordered by a narrow dark band for more than eight miles along its length."			
Linné	ca. 1837	W. Beer and J. H. Mädler	3¾-inch refractor, Berlin, Germany
Beer, W., and J. H. Mädler (1837), *Der Mond:* nach seinen Kosmischen und individuellen Verhältnissen, oder Allgemeine vergleichende Selenographie, Simon Schropp, Berlin, Germany, p. 232: Crater is described as deep and 1.4 miles in diameter.			
Linné		W. Huggins	
Alter, D., "Obscuration of Lunar Features," unpublished ms. (9 pages).			
Linné	ca. 1868	Knott, Buckingham and Key	
Alter, D. (1958), "The Crater Linné," *Proc. of Lunar and Planet. Explor. Coll.* I(3), p. 34: "...Knott, Buckingham and Key detected a very shallow circular depression."			
Linné	1834	W. Löhrman	4¼-inch reflector, Dresden, Germany
Linné		A. Secchi	Italy
Alter, D. (1958), "The Crater Linné," *Proc. of Lunar and Planet. Explor. Coll.* I(3), p. 34: "Secchi also detected a shallow depression visible only when Linné was near the terminator."			
Linné	1840-1843, Oct.-Nov. 1866 and 1867	J. Schmidt	7-inch refractor, Athens, Greece
Alter, D. (1958), "The Crater Linné," *Proc. of Lunar and Planet. Explor. Coll.* I(3), p. 34: "Schmidt in 1866 could find no trace of the crater and announced that it had disappeared, although in his earlier observation he had shown the crater as having a diameter of seven miles and had estimated its depth at 1000 feet....Soon after this, Schmidt believed that he saw a mountain in the center of the fairly large bright mound."			
Linné	1951	F. H. Thornton	18-inch reflector, Northwich, England
Wilkins, H. P., and P. Moore (1955), *The Moon:* "...low dome in white nimbus with deep minute summit pit."			

Table 8-1. Reports of Possible Lunar Surface Changes (Cont.)

Lunar feature	Date of observation	Observer(s)	Size of telescope and location of observatory
Macrobius	2 June-8 Nov. 1938	N. W. McLeod	5-inch, Olcott
McLeod, N. W. (1939), "Some Changes in the Lunar Crater Macrobius," *Pop. Astron.* 47, p. 107: "... changes in dark area."			
Messier	1867-77	H. J. Klein	Cologne Observatory, Germany
Wilkins, H. P., and P. Moore (1955), *The Moon:* "... filled with mist, which welled up from the floor and covered the western wall."			
Messier	ca. 1950	P. Moore	
Moore, P. (1953), *A Guide to the Moon*, p. 147: "Several times the writer has found both craters [Messier and Pickering] strangely blurred, and on August 20, 1951, there was a brilliant white patch inside Pickering, so prominent that it could not possibly be overlooked."			
Picard	ca. 1880	W. Goodacre and others	
Goodacre, W. (1931), *The Moon* (with a Description of the Surface Formations), published by the author and printed by Pardy and Son, Bournemouth, England, p. 218: "About two diameters of Picard to the W. is a large white spot (not shown by Schmidt), which is subject to curious alterations in appearance. Capt. Noble and others have seen and described it as an excessively shallow ring, with a diameter about two-thirds that of Picard. It decreases in size as sunset approaches. There is a small craterlet at its centre discovered by Gaudibert in 1874, and subsequently seen by myself and others. This spot seems to be of a similar nature to Linné; it is not easily seen at sunrise, but develops later."			
Picard	ca. 1950	P. Moore	
Moore, P. (1953), *A Guide to the Moon*, p. 115: "One object, a white spot closely west of Picard, seems to be particularly strange. Most 'white spots' are really craterlets, too small to be seen clearly as such. This one, however, was thought by Birt not to be a craterlet at all, but some sort of surface deposit. Now and then it showed haziness and abnormal brilliance, and this has been confirmed in recent years, so that it appears to be able to send out a certain amount of vapor."			
Pickering	20 Aug. 1951	P. Moore	
Moore, P. (1953), *A Guide to the Moon*, p. 147: "Several times the writer has found both craters [Messier and Pickering] strangely blurred, and on August 20, 1951, there was a brilliant white patch inside Pickering, so prominent that it could not possibly be overlooked."			
Plato		D. Alter	60-inch reflector, Mt. Wilson Observatory, Calif.
Alter, D., "Obscurations of Lunar Features," unpublished ms. (9 pages): Occasional haze within ring plain.			
Plato		F. Bianchini	
Wilkins, H. P., and P. Moore (1955), *The Moon:* "... light on floor."			
Plato	1871-72	W. R. Birt	England
Wilkins, H. P., and P. Moore (1955), *The Moon:* Changes in relative intensity and visibility of crater floor.			
Plato	4 Apr. 1952	T. A. Cragg	12½-inch reflector, United States
Wilkins, H. P., and P. Moore (1955), *The Moon:* Obscuration of floor.			
Plato	1869-71	T. G. Elger	8.5-inch reflector, England
Elger, T. G. (1895), *The Moon*, Geo. Philip and Son, London, England, p. 74: "The spots and faint light markings on the floor are of a particularly interesting character.... Among the forty or more spots recorded, six were found to be crater-cones. The remainder—or at least most of them—are extremely delicate objects, which vary in visibility in a way that is clearly independent of libration or solar altitude; and, what is also very suggestive, they are always found closely associated with the light markings—standing either upon the surface of these features or close to their edges ... they tend to show that visible changes have taken place in the aspect of the principal crater-cones and of some of the other spots since they were so carefully ... scrutinized a quarter of a century ago."			
Plato	ca. 1870-80	T. G. Elger and W. Goodacre	England
Goodacre, W. (1931), *The Moon*, p. 246: "Elger shows a line of fault running across the center of the floor NE to SSW and intersecting a crater (No. 1). He states that the feature could easily be one observed at sunrise, if it were not obscured by the shadows of the W wall. Goodacre had not been able to confirm this observation." *Cf.* Elger, T. G. (1891), "The Lunar Walled-Plain Ptolemaeus," *J. Brit. Astron. Assoc.* 1, pp. 305-13 (abstract).			
Plato	1869-97	T. G. Elger and others	England
Goodacre, W. (1931), *The Moon*, pp. 245-46: "The result of these observations [T. G. Elger, Gledhill and Pratt, 1869-71; J. B. Allinson, T. P. Gray and A. S. Williams, 1880; W. H. Pickering, 1892, and P. B. Molesworth, 1896-97] goes to establish that ... the surface [of the floor of Plato] is occasionally subjected to total or partial obscuration due to mist or clouds resting upon it and so blotting out details usually visible. There are numerous well authenticated cases of this phenomena[on] given in Birt's reports. In 1878 Klein several times saw a fog-like appearance on the E. side of the floor. Neison has seen the whole of the interior at sunrise obscured by fog which gradually disappeared. The Rev. W. R. Waugh has seen the interior speckled over with minute points of light as if reflected from flocculent clouds lying near the surface. Mr. R. Hodge observing Plato near sunset, 1904, October 2nd., at 13 hrs. could find no craters on the floor though he had easily seen them two days before under a higher light. I was also observing Plato on the same date but about 3 hrs. later with a 12 inch Telescope, the terminator being one Diameter of Plato to the W. so that sunset was rapidly approaching, but could detect no detail on the floor, apparently a mist was gathering which was obscuring everything."			
Plato		H. J. Klein	Cologne Observatory, Germany
Wilkins, H. P., and P. Moore (1955), *The Moon:* "... fog-like veil on several occasions."			
Plato	1870-80	E. Neison	
Neison, E. (1876), *The Moon* (and the Conditions and Configurations of its Surface), Longmans, Green and Co., London, England, p. 244-46: "...after the solar altitude reaches about 20°, the [crater] floor gradually commences to darken and fall from its cold light yellow grey (3°½), to shortly after Full when it appears a dark steel grey, almost black, and from only 1°¼ to 1° bright. This great change in apparent tint is extremely marked and seems entirely unparalleled by any other portion of the lunar surface." "...so that although numerous circumstances in connection with the phenomena presented by the moon might be advanced as showing the probability of lunar changes still occurring, it cannot be questioned but that the absolute proof of this has still to be brought forward."			
Plato	9 Oct. 1945	F. H. Thornton	18-inch reflector, Northwich, England
Wilkins, H. P., and P. Moore (1955), *The Moon*, p. 235: "Thornton, 9 October 1945, 11h. 23½m., noted a bright flash on the floor close to the west wall, as though the surface had been struck by a meteor."			
Plato	27 Mar. 1882	A. S. Williams	England
Goodacre, W. (1931), *The Moon*, p. 246: "As the sun was rising on the formation and the whole of the floor was in shadow it [the crater Plato] was seen to glow with a curious luminous milky kind of light. This milky appearance extended over the whole of the floor in shadow except about one fourth from the W. wall which appeared quite black, an hour later no trace of this remarkable appearance could be seen."			

Table 8-1. Reports of Possible Lunar Surface Changes (Cont.)

Lunar feature	Date of observation	Observer(s)	Size of telescope and location of observatory
Plato	1936-50	H. P. Wilkins	15¼-inch reflector, Dr. Wilkins' observatory, Bexleyheath, Kent, England
Wilkins, H. P., and P. Moore (1955), *The Moon*, p. 235: "Wilkins has observed the interior, every lunation, since 1936, with apertures of 6 to 15 inches, and noted apparent changes in intensity and visibility among the spots and streaks."			
Plato	3 Apr. 1952	H. P. Wilkins and P. Moore	33-inch refractor, Meudon Observatory, France
Ibid.: "One of the best views ever obtained of Plato was probably that enjoyed by the Authors on 3 April 1952, with the great 33-inch Meudon refractor. On this occasion four perfectly clear and indeed glaring cratercones were seen, with interior shadows, but no trace of any shadows on the outer slopes, thus proving the slight elevation above the level of the floor. Twenty-one light spots were also charted, one surrounded by a light area, while three streaks were seen in the north-east quarter. "The system of light streaks develops as the Sun's altitude increases, and also apparently varies in different lunations."			
Schickard	1933	E. F. Emley	
Emley, E. F. (1937), "Periodic Changes in Brightness of Four Light Spots on the Lunar Crater Schickard," *J. Brit. Astron. Assoc.* 8(2), pp. 76-79: Four light spots in the northern dark area of the crater undergo periodic changes in brightness and size measured from 0° at sunrise to 180° at sunset.			
Schickard	1939, 31 Aug. 1944	P. Moore and H. P. Wilkins	33-inch refractor, Meudon Observatory, France
Moore, P. (1953), *A Guide to the Moon*, p. 113: "In 1939, the writer was lucky enough to witness a particularly dense one [fog]; the whole crater was filled with whitish mist, which concealed all the normal floor detail and even billowed over the lower sections of the wall. Another mist was seen here by Dr. Wilkins on August 31, 1944, though all was normal by the following evening."			
Thales	1892	E. E. Barnard	Lick Observatory, Mt. Hamilton, Calif.
Barnard, E. E. (1892), "The Lunar Craters Alpetragius and Thales," *Astron. Nach.* 130:7.			
Thaetetus	1902	M. Charbonneux	33-inch refractor, Meudon Observatory, France
Moore, P. (1953), *A Guide to the Moon*, p. 114: ". . . and in 1902, Charbonneux, using the Meudon 33-inch telescope with which Dr. Wilkins and the writer made their Plato observations fifty years later, saw a small but unmistakable white cloud form close to Thaetetus."			
Timocharis	1933-53	D. P. Barcroft and others	
Moore, P. (1953), *A Guide to the Moon*, p. 3: "During the last twenty years, Barcroft and others have seen frequent mists inside Timocharis . . . ."			
Tycho		D. P. Barcroft	
Ibid., p. 113: "Barcroft has found the floor [of the crater Tycho] 'strangely ill-defined' at times. . . ."			
Tycho	27 Mar. 1931	R. Barker	Hertfordshire, Cheshunt, England
Ibid., p. 113: ". . . while on March 27, 1931, Barker found the central mountain a curious shade of gray, though the interior of the crater was in full shadow."			
Tycho	1870-80	W. R. Birt	
Ibid., p. 113: "The brilliant ray-crater Tycho is another formation to show similar appearances [frequent mists]. Mistiness was often seen in it by Birt between 1870 and 1880."			
Earthlit portion of the moon	25 Aug. 1950	T. Saheki	Osaka, Japan
Moore, P. (1953), *Guide to the Moon*, p. 97: "On August 25, 1950, Tsuneo Saheki, in Osaka, Japan, saw a stationary yellowish-white flare, lasting for only about a quarter of a second."			
Earthlit portion of the moon	8 Aug. 1948	A. J. Woodward	United States
Wilkins, H. P., and P. Moore (1955), *The Moon*: "A small, bright flash on the earthlit portion, turning from bluish-white to grayish-yellow and similar to the bright sparkle of frost on the ground. . . ."			

On 16 October 1866, Schmidt, while examining this region, found that Linné was gone and in its place only a small whitish patch remained. Modern observations, both visual and photographic, indicate a dome with a perforated top surrounded by a white spot. The whitish spot around Linné is subject to variations in brightness and is one of the few areas on the moon where something like fluorescence is indicated.

According to Moore, Reference 206, to deny real structural changes in Linné is "simply flying in the face of all evidence." Linné is near the center of the lunar disc in a large mare and not in an overcrowded area. It is impossible to imagine such experienced observers as Lohrmann and Mädler describing and drawing a deep crater that was not there. Schmidt, perhaps the best lunar observer of all time, saw Linné before and after its transformation and declared emphatically that a real change had taken place.

In spite of the many reported changes, there is still widespread scepticism. Fauth, in his book Unser Mond, 1936, argues strongly that appearance of Hyginus N and the disappearance of Linné were illusory. On the other hand, contemporaries of Schmidt and Klein accepted the observations as genuine. Kozyrev, Reference 385, states that so far there is not a single scientifically attested proof of any change in the lunar landscape during our epoch.

8.3 ALPHONSUS EMISSION

Several observers have given special interest to hazes which, at times, obscure detail at the bottom of certain lunar craters. Alter was first to objectively approach the possibility. It was speculated that in the western part of the crater Alphonsus a temporary emission of gas took place. Kozyrev, Reference 385, has also observed gases being released on 23 October 1959. He feels that the released gases were of the fumarolic type. Since fumarolic gas emissions on earth have chemical compositions different from erupting volcano gas emissions, the Alphonsus vapors may not have resulted from volcanic action. Urey, Reference 550, feels that the Alphonsus gas was not volcanic but rather cold gas which was trapped beneath the lunar surface. He suggests

$$3C + CaO \rightarrow CaCO_2 + CO$$

$$CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2$$

Also, a report by Poppendiek and Bond that they had visually observed a large gas cloud about 30 kilometers in diameter above the central peak of Alphonsus conflicted with observations of Haas, who saw nothing, Reference 385.

8.4 METEOR STRIKES

It is really remarkable that, with so many people observing the moon, not one observation that could be safely attributed to a meteor striking the lunar surface has been reported. Reports of flashes on the moon are rather common and there is even a claim for photographic record of a flash (Stuart); but these are somewhat different phenomena, caused, in all probability, by specular reflection from certain elements of the lunar surface placed favorably for observations.

Such flashes have been repeatedly seen on the floor of crater Plato, Reference 471, and other places. Once a reddish star-like point was observed near crater Kepler lasting and hour, Reference 585. In 1956 Warner, Reference 465, observed a suddenly appearing bright flare on the slope of crater Cavendish. It fluctuated in brightness and finally disappeared in 10 minutes.

A long list of such observations, sometimes made by experienced observers, is given in Wilkins's book, Reference 585, with a statement that it is only a small sample of the available material. Wilkins himself observed in 1939 a faint glow inside crater Copernicus lasting abount 15 minutes. The group of small hills in the center of the crater appeared to be enveloped in fog. It was not until four hours later that the first ray of direct sunshine reached the tops of these hills. The hills, therefore, were seen from top to bottom while still in the shadow of the crater's wall.

Perhaps an actual observation of a meteorite striking the moon was made by Thornton, Reference 458, on 19 October 1945. It was on the inner west side of crater Plato and is described as a vertiable explosion with no duration at all, as in most other reports. But the observer himself noted many changes on the floor of this crater taking place on two previous nights, and the observed flash may have been in some connection with these changes.

An observation of two lunar meteors on 10 July 1941, was reported by Haas, Reference 330, along with a general review of possible changes on the moon. In contrast to other observations, these were moving bodies, one near Gassendi and the other near

Grimaldi. The first speck was estimated to have a diameter of 0.''1, which results in a linear diameter of 600 feet, and the duration of appearance was about 1 second. The velocity of the object in respect to the surface of the moon was about 63 miles per second, and the apparent stellar magnitude about 8^m.

This observation, however, hardly fits a lunar meteor. In the absence of an appreciable atmosphere, the upper limit of its density being estimated to be 10^{-13} of terrestrial atmosphere, there would be no trail to observe and one would simply see an instantaneous flash.

LaPaz calculated that assuming the same number of meteors per unit area of the moon as for the earth, one should expect to see at least 100 flashes annually on the surface of the moon produced by meteorites exceeding 10 pounds. This figure would be somewhat reduced for fainter meteors, visible only through a telescope because of restriction of the field view.

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CHAPTER 9

METEOROIDS

9.1 GENERAL

The moon, like the earth, is subject to a continuous bombardment by the countless small bodies of extra-terrestrial material called meteoroids, as it orbits through space. The meteoroids encountered can be divided into two classes: sporadic and showers. Sporadic meteoroids, as their name implies, enter the earth-moon system from all, although not random, directions and at irregular intervals, whereas the showers are encountered as concentrated predictable groups. Lovell has estimated that shower meteors contribute not more than 10 to 20 percent of the encountered total meteoric flux, the remainder being sporadic meteoroids.

9.2 UNIQUE LUNAR ASPECTS

When compared to the earth's meteoroid environment, there are two aspects that are peculiar to that of the moon. First of all, the fact that there exists no appreciable lunar atmosphere is of concern since there is no attenuation or energy absorption of any incident particles. In fact, the ejecta from these meteoroid impacts on the lunar surface could possibly be as dangerous to man, contained in his lunar space suit, as the primary bodies themselves. Experimental investigations of impact on metal targets has shown that a small amount of material is indeed ejected with a velocity exceeding that of the impacting projectile, Reference 9.

Secondly, the earth-moon geometry is such that:

a. A slight relative velocity difference exists that is discussed here.

b. The earth's closeness could possibly cause gravitational condensation of encountered meteoritic flux, which is discussed in detail in paragraph 9.3.

A slight difference of 1.03 kilometers per second exists in the relative velocity between an earth observer and a meteoroid traveling in a heliocentric parabolic orbit and a lunar observer and the same meteoroid. The largest possible relative velocity of 73 kilometers per second between a lunar observer and a heliocentric parabolic meteoroid occurs when the moon is full and the inclination of the meteoroid's orbital plane is 180 degrees, as shown in Figure 9-1.

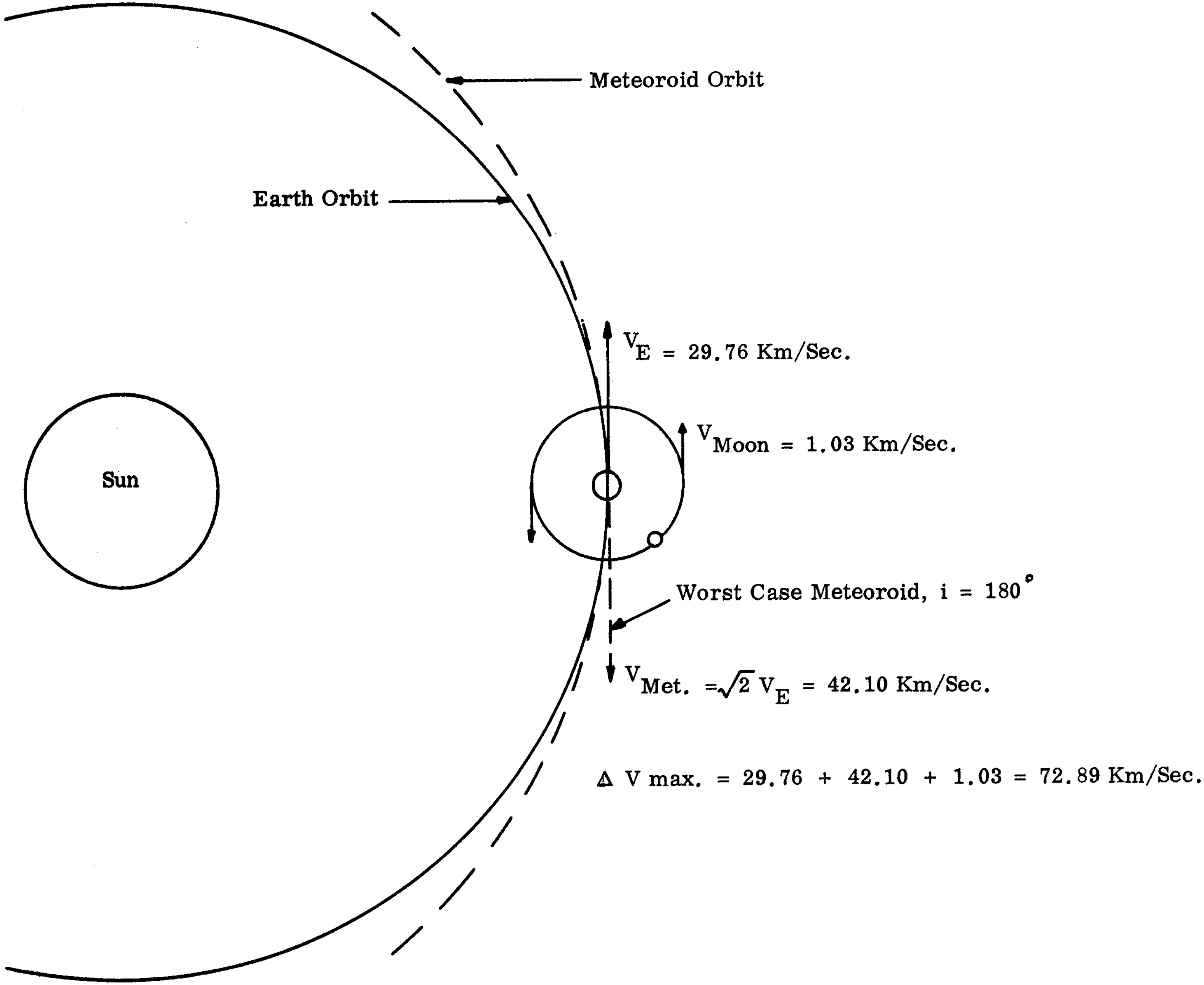

Figure 9-1. Worst Case Relative Velocity Between Lunar Observer and Heliocentric Meteoroid

For impact calculations an average relative velocity of 30 kilometers per second is common in the United States; whereas, 40 kilometers per second is frequently used in the Russian literature.

9.3 LUNAR IMPACT FREQUENCY

At this time it is not possible to estimate the lunar surface meteoroid impact frequency with any high degree of accuracy. At best, such appraisals are very crude. In fact, a variation of five orders of magnitude exists in estimates of the earth's meteoroid environment where relatively greater amounts of information have been obtained.

As in all aspects of lunar science, assessments of the lunar meteoroid environment also vary widely.

It can be argued that since the earth-moon system dimensions are relatively small when compared to those of meteoroid orbital dimensions, both bodies have very similar meteoroid encounters. Whipple's analysis, Reference 590, however, of earth rocket measurements for meteoroid masses greater than 10^{-9} gm shows that the concentration falls off as the inverse 1.4 power of the distance from the earth's surface, while Hibbs, Reference 591, finds that Explorer I measurements, although not statistically significant, indicate a latitude distribution with a peak near the equator. These effects, of course, are masked by the large differences in the estimates made thus far.

Another aspect of the problem is that of the gravitational attraction of the earth on the meteoritic flux encountered by the earth-moon system. Shoemaker, Hackman, and Eggleton, Reference 9, argue that the earth does, in fact, produce a condensation of the meteoritic flux resulting in a focusing effect on the moon. They show that the frequency of impact on the side of the moon facing the earth is increased, the magnitude of which is dependent upon the exact distribution of the meteoroid orbital inclinations and their geocentric velocities. As a result of this effect, the maximum possible increase in the impact frequency on the moon must be less than a factor of 3 with a nominal estimate of 2.15.

An additional affect might be that this focusing results in preferred lunar impact areas; thus affecting the choice of lunar landing sites, bases, etc.

Kornhauser, References 296 and 605, shows (Figure 9-2) a summary of the various estimates of the number of impacts per square meter per second expected to occur with sporadic meteoroids, in the earth's environment, of a given mass or greater. Approximate values of magnitude and depth of penetration in aluminum are included for convenience.

Because of the uncertainties involved in satellite direct readings, it is recommended that the "Hughes-maximum mass" curve of Figure 9-2 be used for conservative calculations. A simple analytic expression for the conservative "Hughes-maximum mass" curve is:

$$N = \frac{10^{-12}}{M},$$

where N is the number of impacts per square meter per second by meteoroids with mass M (grams) or larger.

Because of their high impact frequency, meteoroid showers present a greater hazard to space vehicles than sporadic meteoroids. However, the transitory nature of these showers results in a negligible change to the data in Figure 9-2. The fact that they are predictable gives the advantage of planning lunar activities accordingly.

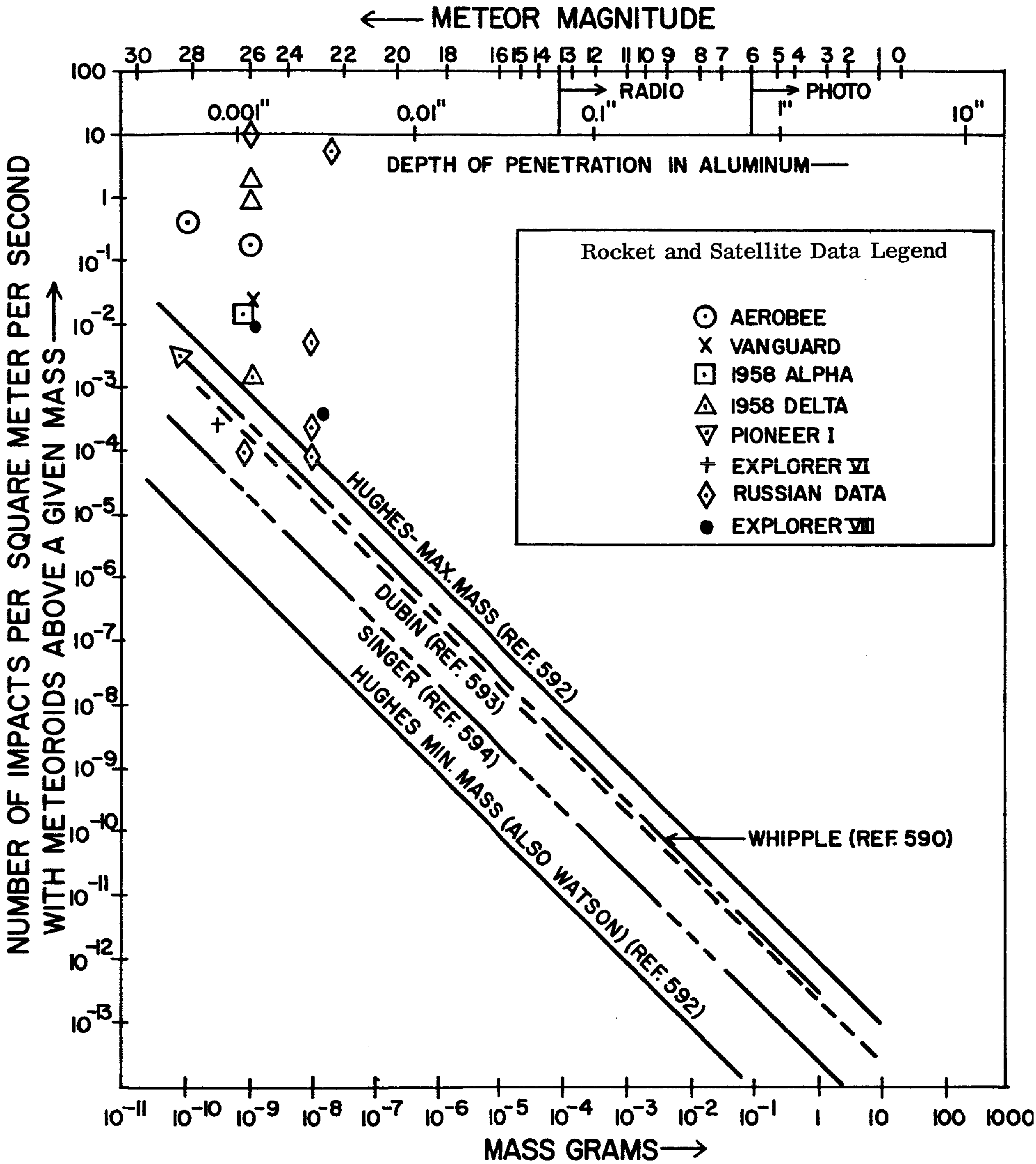

Figure 9-2. Population of Sporadic Meteoroids, References 296 and 605

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CHAPTER 10: THE LUNAR ATMOSPHERE

CHAPTER 10

THE LUNAR ATMOSPHERE

10.1 INTRODUCTION AND SUMMARY

It has been shown by Öpik and Singer, References 13, 45, and 104, that for cogent theoretical reasons, there cannot exist any such thing as a permanent lunar atmosphere.

Any atmosphere of the moon is transitory in nature. The various lunar pseudo-atmospheric phenomena, which are believed to exist, do in fact account for the observed 10^{-13} earth atmosphere's of pressure; i.e., 10^6 atoms or molecules per cm^3.

In dealing with such a tenuous plasma, theoretical approaches are easily misled by analogies with much denser media. In the lunar medium, collisions are rare, so that charged as well as neutral particles can almost freely traverse between the points of emission and destination. Among other things, the concepts of thermal and electric conductivity are no longer valid, the saturation currents depending only on particle density and thermal velocities, Reference 104.

The primary atmospheric activity occurs on the sunlit hemisphere of the moon by photoionization caused by the solar wind. This influx of solar radiation creates a semblance of an ionosphere which exists only on this side of the moon and practically in contact with the surface.

It is concluded by many investigators and most quantitatively by Öpik and Singer that the permanent lunar gaseous envelope is not very different from that of the surrounding interplanetary medium, References 13, 45, and 104.

The problem then is to examine the possible sources of an atmosphere and to balance them against the mechanisms of dissipation, chiefly excape into interplanetary space.

10.2 SOURCES OF A LUNAR ATMOSPHERE

10.2.1 INTRODUCTION

There can be only two sources of a lunar atmosphere: internal and external. The only internal source is that of outgassing of primordial gas, and the external sources are the resultant interactions from the bombardment of the moon by the interplanetary environment. The bombardment interactions consist of photoionization and the photoelectric effect caused by the solar ultraviolet photons and direct sputtering as a result of the solar protons as well as by re-emission not only of absorbed gases, but of gases resulting from radiation damage of the lattice and chemical reactions. Unfortunately the exact nature of the interplanetary gas is to be yet determined, and existing information is often contradictory, Reference 104.

Table 10-1 shows in summary, the results of an analysis by Öpik of the composition, all sources considered, of the lunar atmosphere. Each source is discussed below.

Table 10-1

Composition of the Daytime Lunar Atmosphere, Reference 104

Species	Density, Molecules per cm^3
H_2	0.12×10^5
H_2O	1.4×10^5
CO_2	$1.4 - 3.4 \times 10^5$
Various	0.1×10^5
All	$3 - 5 \times 10^5$

Note: Earth sea level atmospheric density equals about 2.5×10^{19} molecules per cm^3. Reference: Jastrow, R. and Kyle, H., THE EARTH ATMOSPHERE, Chapter 2.1 of Handbook of Astronautical Engineering, McGraw-Hill, 1961.

10.2.2 PRIMORDIAL GAS

On the moon there are only, if any, feeble traces of plutonic activity. It is concluded in Reference 104 that the present lunar atmosphere does not contain primordial components, and whatever traces of gaseous constituents that are found are the products of a short-time equilibrium between accretion and loss. Edwards and Borst, Reference 335, in considering primordial krypton and xenon on an earth-rock analogy show that the lunar rocks could possibly contain more than an adequate number of Kr and Xe atoms to produce the observed 10^{-13} earth atmosphere pressure. It will be shown later that both Kr and Xe are dissipated by solar radiation and cannot be responsible for the observed "atmosphere."

Gas emission from the interior through rifts or cracks appears to be possible, despite the absence of reliable observational records to this effect. Some domes and volcanic cones are definitely present in the maria, but these must have been active mainly during the period of formation of these lunar plains and must have become extinct by now.

In any case, the very limited occurrence of these formations, and the almost complete preservation of the lunar topographic formations obviously undisturbed by volcanic activity would indicate that the crustal(magmatic) turnover and outgassing on the moon must, by several orders of magnitude, be less intense than on earth, Reference 104.

On earth, according to accepted estimates, an average of 1 km^3 of igneous rock is exposed and, apparently, outgassed annually. With the gas proportion as for meteorites, this would yield 6×10^7 CO_2 molecules per cm^2/sec. Plutonic activity on the moon is certainly less than one-thousandth of the terrestrial, whence the injection rate from this source is less than 6×10^4 molecules per cm^2/sec. An upper density limit for this source is 2×10^5 CO_2 molecules with admixtures per cm^3.

10.2.3 SPUTTERING

A semi-empirical theory of sputtering, Reference 104, indicates that for protons of 210 ev with ±100 ev as their energy dispersion, an emission from a silicate lattice of about 0.125 atoms, of an average kinetic energy of some 1-3 ev is produced per impinging proton.

According to Öpik, the 210 ev protons penetrate into the silicate lattice to a depth of about eight atomic layers of 6×10^{-7} gm cm^{-2}; in this layer, they damage the molecules, releasing oxygen atoms, these partly combine with the intruding hydrogen, forming H_2O, the excess of oxygen returning to the Si, Mg bonds. The excess hydrogen combines into H_2. The majority of all of these products is slowly re-emitted into the lunar atmosphere at a temperature of the lunar surface. For the protons of greater energy this leads to a daytime escaping component of O, Mg, Si, and Fe atoms, as well as some molecules of MgO, SiO_2, O_2, and to an appropriate erosion of the surface material. It also is shown by Öpik in Reference 104 that the rate of sputtering is greater than accretion of micrometeoroid material. The time of accretion for eight atomic layers is calculated to be 70 years, and the time to sputter the same layer is only 17 years. Based on the "exhausted" lattice analysis then, for each solar-wind proton, the release is 0.125 atoms and molecules sputtered out and escaping to space. On the sunlit side therefore, the average number of particles leaving the surface is

$$0.125 \times \frac{1}{2} 10^9 = 6 \times 10^7 \text{ cm}^{-1} \text{ sec}^{-2},$$

with an average radial velocity of 3 kilometers per second, the component of surface number density caused by sputtering is then 200 cm^{-3}, or a very low value. This component, therefore, is small and unimportant.

10.2.4 OUTGASSING

If it is assumed that occluded gases exist in the lunar surface material and that similar portions as that of meteorites are present then the release becomes 2×10^4 H_2O molecules per cm^2/sec and 4×10^3 CO_2 molecules per cm^2/sec, Reference 104. The release of H_2O is insignificant as compared with that estimated as being produced directly by the solar wind (see paragraph 10.2.6) and can be disregarded. The release of CO_2 is even smaller, but the cold spots are not absorbing it like the H_2O, Reference 393, hence it may accumulate in greater numbers.

Meteorite outgassing must also be considered. Assuming that 40 times the mass of the meteorite is sufficiently heated to be outgassed, it is estimated that the CO_2 density of the lunar atmosphere is about 1.4×10^5 molecules cm^{-3}, Reference 104.

10.2.5 HYDROGEN EMISSION FROM THE LUNAR SURFACE

Gold suggests, Reference 601, that as a result of the 1000-kilometers-per-second solar wind protons bombarding the sunlit hemisphere of the moon, a substantial, although temporary hydrogen atmosphere is constantly blowing off of the surface. The density of this hydrogen flux is several hundred times greater than that of the solar wind because the protons strike the surface and are evaporated at approximately thermal speeds, which are a few hundred times slower than their initial speed.

Gould, in his paper "Hydrogen Near the Moon," Reference 534, investigates whether this atmosphere is in molecular or atomic form and, based upon a high diffusion rate of the incident particles, concludes that the molecular formation is a minor process only, and that the majority of the outgoing hydrogen is in atomic form. Reference 427 deduces a density of 3.9×10^4 monatomic hydrogen atoms cm^{-3} based on a proton flux of 10^{10} cm^{-2} sec^{-1}. Reference 104, on the other hand, concludes essentially the same numerical density; i.e., 1.2×10^4 particles cm^{-3}, differing, however, in concluding H_2 rather than H. Reference 427 furthermore concludes a dark hemisphere density of 10^5 monatomic hydrogen atoms cm^{-3} based on a very large average path length argument. Figure 5 contained in Reference 425 presents a diminishing distribution for this monatomic hydrogen from the subsolar point.

10.2.6 WATER VAPOR

Reference 104 shows that 0.036 H_2O molecules are released from the lunar surface as a result of each solar wind proton. The possible permanent cold traps on the moon that cover approximately 0.5 percent of the lunar surface, mainly in the polar regions (paragraph 6.3) will serve as collectors of emitted water vapor, removing it from the lunar atmosphere much faster than escape to space.

Also, since the dark side temperature of the moon is about 120°K, Reference 353, it may very well represent a temporary collector of H_2O, sucking it in from the sunlit hemisphere where it is produced, but completely returning it to the atmosphere in daytime. The net balance of this effect is zero; it has no direct effect on the equilibrium number density of the atmosphere, Reference 104. Therefore, for the balance, only removal into the cold spots and escape to space are to be considered. Reference 104 indicates that less than 1 percent of the 9×10^6 water vapor molecules escape, the remaining accumulate in the cold spots at a rate of 7×10^{-14} gm cm^{-2} sec^{-1}. This escape rate to space has an estimated density of 1.4×10^5 molecules cm^{-3}.

10.2.7 COSMIC RAY INDUCED NEUTRON FLUX

It is believed that the interaction of primary cosmic rays with the material of the lunar surface generates a neutron flux at the surface. Lingenfelter, Canfield, and Hess, Reference 392, have calculated the neutron equilibrium leakage spectrums for lunar surface compositions of chondrites, tektites, basalt, and granite. Figure 10-1 shows the spectrums for each of the compositions. To obtain the actual neutron flux leaving the lunar surface, the curves shown must be first integrated over energy.

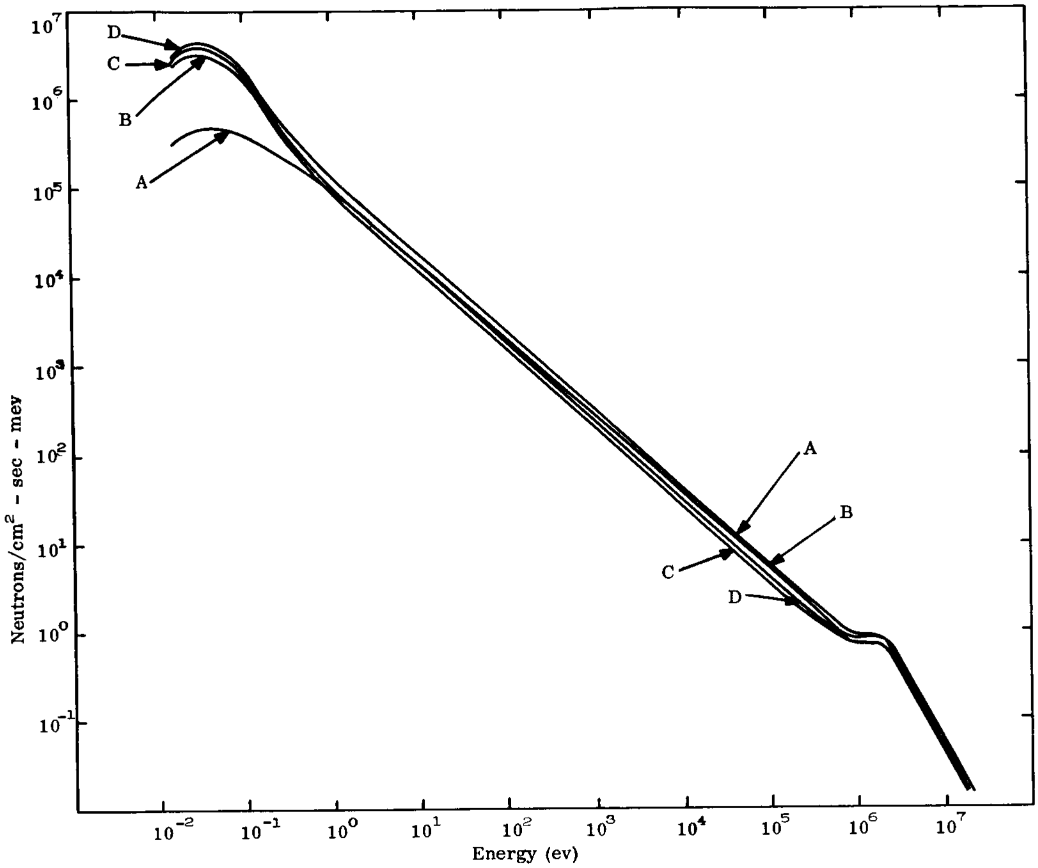

Figure 10-1. The Calculated Neutron Equilibrium Leakage Spectrum for the Lunar Surface for Compositions A, Chondrites; B, Tektites; C, Basalt; and D, Granite

10.2.8 GRAVITATIONAL ACCRETION

The independent consideration of a lunar atmosphere being formed by purely gravitational condensation may not at all correspond to the real situation. Not only has the existence of the lunar magnetic field been neglected but also the existence of a surface electric charge. When these are considered, the picture changes significantly, Reference 306. Considerations by Firsoff, References 302 and 304, and Brandt, References 303 and 305, have either used an invalid barometric equation to derive a density distribution or neglected the effect of the thermalized basis of gravitational accretion of a lunar atmosphere. Detailed studies, however, are not possible until the properties of the interplanetary gas and solar corpuscular streams are known with greater certainty.

10.3 ESCAPE OF GASES FROM THE MOON

10.3.1 INTRODUCTION

Contrary to expectations from the classical theory of an exosphere, it has been shown that even the heaviest gases, for example, the noble gases krypton and xenon, cannot be retained by the moon, Reference 13. It is shown that when all of the escape mechanisms, i.e., thermal, ionic, and interplanetary gas induced collisions, are considered, there is little likelihood that light or heavy gases evolving from the moon will be retained.

10.3.2 THERMAL ESCAPE

The thermal escape mechanism is simply that of a molecule attaining a kinetic energy greater than that of the gravitational potential energy of the moon. Thermal escape is particularly significant for the light gases. Table 10-2 shows the times required for depletion by a factor of e^{-1} for several gases for the hot and cold sides of the moon.

Table 10-2
Thermal Escape Times From Moon to e^{-1} of Initial Concentration
(Compiled from References 13, 45, and 104)

Gas	T = 150°K Cold Side	T = 400°K Hot Side
H	5100 Seconds	3600 Seconds
H_2	10^4 Seconds	4100 Seconds
He	200 Hours	9700 Seconds
O	10^{10} Years	1.4 Years
O_2	10^{26} Years	10^6 Years
H_2O	10^{11} Years	60 Years
CO_2	10^{37} Years	10^{10} Years

It is generally accepted that light atoms and molecules evolving from the lunar surface will escape quite rapidly by the thermal escape mechanism.

Öpik and Singer, Reference 13, have utilized the production rates of krypton and xenon as determined by Edwards and Borst, Reference 335, and show that in the beginning it is possible that a thick atmosphere evolved and that the excape layer of this atmosphere would be separated from the lunar surface and might have a temperature of about 1500°K, similar to that of the base of the earth's exosphere. The thermal escape time from such a thick atmosphere is 170 years and 4×10^6 years for krypton and xenon respectively or very short compared to the lifetime of the moon. However, as the atmosphere thins down sufficiently, this escape level is still above the surface of the moon, but the atmosphere will be sufficiently cooled by contact with the lunar surface so that the temperature is low throughout. Then the atoms will escape with a temperature corresponding to about 400°K. In that case the lifetimes would be 10^{24} years and 10^{41} years for krypton and xenon, respectively, and it would seem, therefore, that such an atmosphere could survive, on the basis of thermal escape alone. For the case of CO_2, a 1500°K thick atmosphere would cause the CO_2 to disappear in about 70 years; hence the absence of a CO_2 envelope on the moon.

10.3.3 IONIC ESCAPE

10.3.3.1 Introduction

Thus far an isolated moon has been considered. Reference 13 presents the effects of solar ultraviolet radiation. The ionic escape is that mechanism whereby photoelectrons are ejected into space, thus creating a small positive potential at the top of the atmosphere, or throughout, if it is thin enough.

Öpik and Singer, Reference 13, consider the situation when the atmosphere of the moon is a true exosphere, that is, when the atoms do not make collisions with each other but describe free orbits under the influence of gravitational and other forces.

The degree of ionization is derived to be 1 in 10^5 and contrary to certain treatments, for example, Reference 427, the effect of a solar corpuscular stream on a krypton and xenon exosphere is to cause additional ionization by about a factor 2.5 by impact ionization or charge exchange. It is shown that any (positive) krypton or xenon ion that happens to be formed within the region where the potential is not screened by the surrounding plasma will be expelled. The theoretical treatment of Reference 13 shows that the lunar potential should be of the order of 20 to 25 volts positive as a result of the electrons escaped by photoionization. The lifetime of the krypton and xenon ions on this basis is calculated to be about 1000 years.

This in turn increases the electron density in the vicinity of the moon and reduces the screening length which in turn increases the lifetime of the krypton-xenon exosphere to about 3000 years. Hence, the exosphere still cannot survive.

10.3.3.2 Surface Electric Charge

In the absence of ionizing photons, a solid surface in contact with a plasma acquires a negative charge sufficient to inhibit efficiently the electron flux to the surface and make the flux equal to that of the much slower ions, Reference 104. This is the case of the nocturnal hemisphere of the moon. However, a plasma is rapidly neutralized there and disappears.

On the daytime hemisphere, the surface charge depends on electron density and the photon flux that reaches the surface practically undiluted, causing emission of photoelectrons. For a given flux, there is a critical electron density, N_c, at which the surface charge is zero. When $N_e < N_c$, the photoelectric effect prevails and the charge is positive. When $N_e > N_c$, the accretion of ambient electrons prevails and the charge is negative. The problem has been considered by Öpik and Singer, References 13, 104, and 554. It is a multifaceted problem with several underlying assumptions, such that the exact nature of the surface charge, that is, whether it is negative, neutral, or positive, cannot be firmly established at this time.

10.3.4 INTERPLANETARY GAS COLLISIONS

In addition to the atoms and molecules sputtered directly into space from the lunar surface, consideration also must be given to the effect of the solar wind on the atmosphere. Using a solar wind model of 10^9 protons per cm^2 sec, Öpik shows that the solar wind as a source of ionization is relatively unimportant and can be neglected, Reference 104. He goes on to show, however, that the direct knocking out time is important for the heavier particles being of the order of 10^6 seconds. Comparing this with ionic escape for the heavier molecules it is found that they are comparable and far more efficient than the thermal mechanism.

Hence, in calculations of the material balance of the lunar atmosphere, it is sufficient only to consider combined ionic escape and solar wind sputtering for the heavier molecules and only thermal escape for hydrogen.

10.4 EXPERIMENTAL OBSERVATIONS OF THE LUNAR ATMOSPHERE

10.4.1 INTRODUCTION

There are two broad methods of experimentally observing the lunar atmosphere, optically and by radio observations. Table 10-3 shows in summary the experimental results of lunar atmosphere observations.

10.4.2 OPTICAL METHODS

The occultation method is that of measuring the refraction of star images. No such refraction has ever been observed, hence giving as an upper limit the limit of resolution of $0''.25$ of arc. This corresponds to a lunar atmosphere of less than 5.5×10^{-4} of the terrestrial.

The twilight arc is the illuminated tangential extension of the cusps toward the dark hemisphere at quarter phase as the result of an existant atmosphere. No such arc has ever been recorded and leads to a probable upper limit of 10^{-8} earth atmosphere, Reference 104.

Dollfus, by his failure to record any trace of polarization, sets the upper limit of the twilight intensity at 10^{-9} of the terrestrial.

10.4.3 RADIO OCCULTATION

10.4.3.1 Introduction

This technique is by far the most accurate experimental method known to date. The density of the lunar atmosphere can be derived from measurements of the refraction of radio waves at the sunlit limb of the moon when a radio star is occulted. The difference between the calculated and observed times of obscuration may be attributed to refraction at the moon's limb. This refraction is interpreted in terms of an electron density near the moon, in excess of that of the surrounding medium, from which is deduced the density of the lunar atmosphere.

Table 10-3

Summary of Experiment Results of Lunar Atmosphere Observations

Value in Earth Atmospheres	Density, Molecules/cm³	Surface Electron Density, No./cm³	Method/Remarks	Investigator/ Reference
$<5.5 \times 10^{-4}$	$<1.7 \times 10^{16}$	----	Optical Refraction (Stellar occultation)	104
$<10^{-6}$	$<3 \times 10^{13}$	----	Surface Brightness	Fesenkov
$<10^{-8}$	$<3 \times 10^{11}$	----	Twilight Arc	Öpik, 104
$<10^{-9}$	$<3 \times 10^{10}$	----	Polarimetric Measurements	Dollfus (1952) 104
$<10^{-12}$	$<3 \times 10^{7}$	$<10^{5}$	Radio Occultation of IC_{443} at 3.7 and 7.9 meters	Elsmore (1955) 347
$<10^{-13}$	$<3 \times 10^{6}$	10^{3} - 10^{4}	Radio Occultation of Crab Nebula at 3.7 and 7.9 meters	Costain, Elsmore, Whitfield (1956) 328, 343, 347

10.4.3.2 Electron Density

The electron density has been assumed, Reference 328, to be caused by the action of solar radiation on the lunar atmosphere. It is extremely difficult to estimate the degree of ionization of the lunar atmosphere by comparison with the terrestrial ionosphere because its composition probably differs from that of the earth's upper atmosphere in composition and temperature. Elsmore, References 328 and 343, estimates that one molecule in a thousand is ionized, and an electron density of approximately 10^{3} - 10^{4} per cm³ is derived.

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CHAPTER 11

LUNAR MAGNETIC FIELD

11.1 INTRODUCTION

The only direct measurements of the lunar magnetic field were made at altitudes down to approximately 1 kilometer by the Lunik II Rocket, which impacted on the sunlit side of the moon on 13 September 1959. Conclusions from this experiment are somewhat limited, References 16 and 404, and as a result, all information about the lunar field is still a theoretical extrapolation or speculation from an earth-based science.

Discussions of the lunar magnetic field in the reference literature are linked with other major scientific questions about the moon; such as, its primordial state and relation to the earth, the density and composition of its atmosphere, and the physical characteristics of its surface. Of greater importance to the measurement and interpretation of lunar magnetic field values are such phenomena as the sun's corona, sun spots, proton streams or tongues, solar flares, and magnetic streams, tongues or storms. Observations and conjectures concerning these phenomena are also earth-based; they are intimately linked to questions about the moon because of the relative proximity of the moon to the earth.

Since the solar electromagnetic and corpuscular fields are position and time dependent, and since the plasma fields would interact with an existant lunar magnetic field, this field is also position and time dependent. The preponderance of opinion appears to indicate that, in fact, a lunar magnetic field does exist, although it may be quite small relative to that of the earth's (0.5 gauss) and is probably masked by solar effects. Values of the lunar magnetic field have been suggested as high as 10^{-2} gauss (1000 gamma).

11.2 VALUES OF THE LUNAR MAGNETIC FIELD

Table 11-1 presents the different values as supported by various investigations. Reference 607 gives a zero magnetic field value for the Lunik II data, although this is not quite correct because the detecting equipment had a lower limit of only 6 x 10^{-4} gauss. Neugebauer points out, Reference 16, the fact that the impact of Lunik II took place on the sunlit surface and, as a result of this, does not necessarily conclude that

Table 11-1

Lunar Magnetic Field Values

Lunar Field (gauss)	Basis	Investigator, Reference
$<6 \times 10^{-4}$	Lunik II data (based on the lowest detectable limit of onboard instrumentation).	USSR 588, 16
$<10^{-2}$	Limiting value of 10^{-2} gauss was based on a calculation of suppression of the lunar magnetic field by a proton stream assuming a proton density and momentum.	Neugebauer 16
$<10^{-2}$	Solar corpuscular radiation cannot reach lunar surface if field greater than 10^{-2} gauss to produce the observed luminescence.	Kopal 215
$<10^{-2}$	Nonobserved deflection of solar protons, same as Kopal and Neugebauer.	Sagan 404
0.14×10^{-5}	Represents a lower bound based on an extrapolation of earth's field of 0.5 gauss at a distance of 386,000 kilometers, i.e., the lunar distance.	Kellogg 136
0	Theory that moon formed from condensed gaseous cloud.	Vestine 135
14×10^{-5} (polar)	Vestine extended the results of Blackett for the earth and sun (theory of the massive rotating body).	Vestine 135
2×10^{-8}	Induction of solar plasma theory considering suppression of the lunar field and obtained distance of penetration of plasma.	Vestine 135
$4\text{–}40 \times 10^{-5}$	Theory that the moon was once a part of the earth and assuming that the earth's field was "frozen" and extrapolatable.	Vestine 135
May exist	Effects of currents in lunar atmosphere.	Vestine 135
10^{-1}	Cosmic intensity at noon would attenuate to the limit of spectrum of higher energy particles present.	Singer 405
1	Cosmic intensity at noon would attenuate to a value corresponding to high altitude earth equivalent intensity (momentum = 1.5 Bev at 50 miles).	Singer 405

Table 11-1

Lunar Magnetic Field Values (Cont.)

Lunar Field (gauss)	Basis	Investigator, Reference
Several hundred gammas*	Primordial Magnetohydrodynamic Model	Vestine 135
Several hundred gammas*	Effect of Transported Solar Fields	Vestine 135

*Note: 1 gamma = 10^{-5} gauss, if the permeability equals unity.

the general lunar magnetic field is weaker than 6×10^{-4} gauss on the surface. She suggests that if a weak magnetic field exists, it would be confined by solar corpuscular radiation, or solar wind, to a thin layer above the sunlit surface and could extend a considerable distance beyond the surface on the side away from the sun. This same compressing effect by the solar wind also could account for the low magnetic intensity at the 21,500-mile distance from Venus on the recent Mariner probe.

The calculations show that the upper limit of the magnetic field strength that can be compressed by the solar wind is approximately 1.4×10^{-2} gauss, which is much greater than that of the Lunik II detection level.

Using a solar wind model, Neugebauer also investigates the magnetic field intensity above the lunar surface with an assumed surface intensity of ~700 gamma. She shows that such a field would drop to 1/e of its surface value at a height of ~500 meters on the sunlit side.

Kopal points out, Reference 215, that the moon's surface magnetic-field strength should be less than 10^{-2} gauss because the observed solar corpuscular-induced surface luminescence would be non-existant if a 10^{-2} gauss field were present.

Reference 16 points out the consistency between the above theories and the Lunik II data, i.e., a lunar surface field strength of 10^{-2} gauss.

11.3 CISLUNAR MAGNETIC FIELD

Although the interplanetary magnetic field (IMF) and the distant geomagnetic field (DGF) may not yet be clearly separated, they are discussed together in Reference 103 as the cislunar field. Comparison of Tables 11-2 and 11-1 shows that the cislunar magnetic field is of the order of 100 times-smaller than that of the moon's.

The DGF is dome-shaped and extends to 10 to 15 earth radii on the solar side. On the dark side, a few percent of the lines of force are not closed within cislunar space but extend as a tail under the control of the interplanetary gas. The tail has an angular extent of some 20 degrees, opening and closing as the flux of solar ions decreases and increases. It may control the position of the gegenschein.

The IMF originates as magnetic "tongues" rooted in sunspot areas and extending beyond the earth's orbit. The outer part of a "tongue" remains at rest and the inner part rotates with the sun to form an intermediate spiral field.

Table 11-2

Cislunar Magnetic Field

Field Value (gauss)	Geocentric Distance R_e	Basis	Investigator, Reference
0.04×10^{-2} 0.003×10^{-2}	10	Pioneer V launched in general direction of the sun during the recovery phase of a magnetic storm.	Piddington, 103, 589
0.032×10^{-2}	21.5 Dipole	Explorer X launched 3/25/61 following a week of low geo-magnetic activity.	Heppner and Piddington, 103, 588
0.016×10^{-2}	36	Explorer X - 3/27/61	103, 588

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CHAPTER 12

RADIATION

12.1 INTRODUCTION

The radiation environment that exists on the lunar surface is believed to be made up of several sources and to be position and time dependent. The sources include the following:

a. Primary cosmic radiation.

b. Solar high-energy particles (SHEPS; after Singer).

c. Induced surface radiation.

d. Decay of naturally occurring radioactive elements.

As might be suspected, little literature exists on this subject. The only quantitative analysis referenced in this document is that work done by Barton, Reference 586, and, in fact, is the basis for this section.

12.2 PRIMARY COSMIC RADIATION

Primary cosmic radiation refers to energetic radiation originating at regions remote from the solar system. For the most part, this radiation consists of stripped nuclei that have been injected into intergalactic space. This radiation is essentially isotropic in space, and its magnitude varies, at most, only a few percent with time.

The primary cosmic radiation incident on the moon will be assumed to be the same as that incident at the top of the earth's atmosphere near the earth's geomagnetic poles. Table 12-1 gives the particle types and the flux of the various components of this radiation under these conditions.

The energy spectrum of this radiation is given in Figure 12-1. This figure also includes the energy spectrum of the prompt solar particle radiation, which will be discussed later. Since it is postulated that the minimum injection energy for the acceleration of charged particles by intergalactic magnetic fields is about one Bev, it is assumed that there is no primary cosmic radiation below this energy.

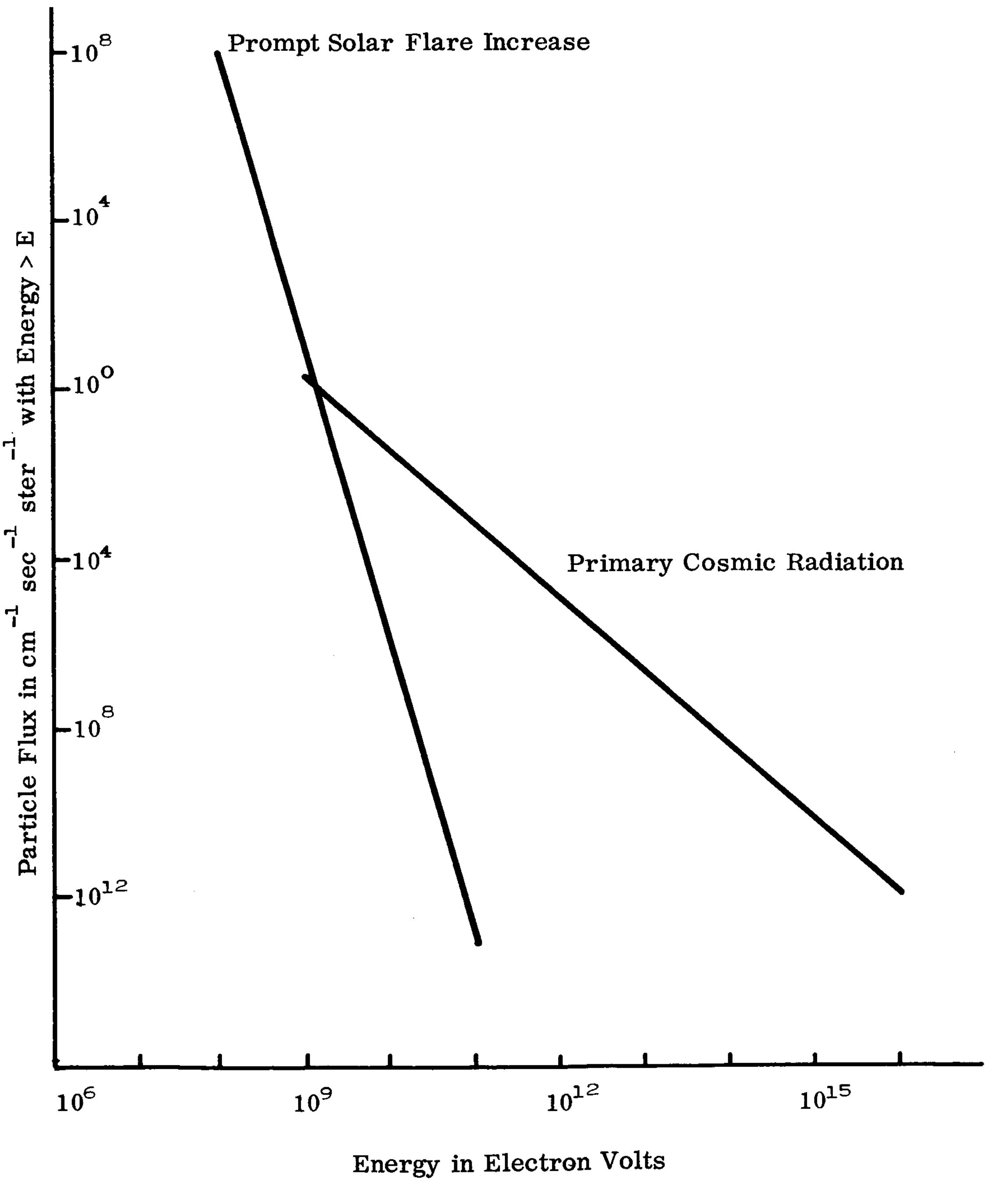

Figure 12-1. Prompt Solar Radiation and Primary Cosmic Radiation Energy Spectra, Reference 586

Table 12-1

Composition and Flux of Primary Cosmic Rays, Reference 586

Component	Percent of Total	Flux $M^{-2}sec^{-1}$ (E > 1 Bev)
Hydrogen nuclei	86.00	10^4
Helium nuclei	13.00	10^3
Li, Be, and B nuclei	0.16	10
C, N, O, and F nuclei	0.54	27
Nuclei with Z > 10	0.19	10
Electrons	Little, if any	--
Gamma rays	1.00	--
Neutrons	None	--
X-rays	1.00	--
Neutrinos	----	Enormous Flux

In the region of the earth there are two types of time variations in radiation intensity that are apparently caused by solar activity. These are the 11-year cycle and the Forbush decrease, which consist of, respectively, a decrease of not more than a factor of 2 during sunspot maximum and a decrease of about 30 percent following a large solar flare. It is reasonable to assume that these variations also apply to the moon.

12.3 SOLAR HIGH ENERGY PARTICLES (SHEPS)

The SHEPS are interesting because the low-energy solar wind flux of 10^{10} protons $cm^{-2}sec^{-1}$ is readily stopped by moderate shielding. The energy spectra of five prompt- or surface-measured increases is given in Figure 12-1, but the energy spectra are not yet well known for the delayed increases. Some measurements on the penetration of this radiation within the earth's atmosphere indicate an energy minimum of about 100 mev. It is evident from the data that the earth's atmosphere and magnetic field have considerable effect on this radiation and that too few data exist to predict with any accuracy the solar corpuscular radiation incident on the moon.

The intensity of this radiation may vary considerably with time, longitude, latitude, and altitude. This is perhaps more true in the case of the prompt radiation than the delayed radiation. Schaefer[1] has estimated the total dose at the top of the atmosphere as a result of the radiation accompanying the +3 class flares of 23 February 1956 and 10 July 1959.

He shows the following radiation doses:

Geomagnetic Latitude (degrees)	Dose in Roentgens
23 February 1956	Class 3^+ Flare
42	0.001
48	0.025
52	0.400
55	1.000
60	130.000
10 July 1959	Class 3^+ Flare
55	6.6
65	50.0
88	110.0

The doses assume that the increase over background is constant over the latitudes. It will tentatively be assumed that these doses are applicable to the moon.

In Barton's study, he assumed that there is no neutron or meson component to solar corpuscular radiation. Mechanisms have been proposed for the production of these particles in the solar corona, but measurements of neutrons and mesons indicate that the flare-induced increases are secondary in nature. This assumption concerning the absence of neutrons, if invalid, could materially affect the results.

12.4 INDUCED SURFACE RADIATION

It is believed that the moon's surface is activated as a result of bombardment by energetic particles. Such activation can result from the processes of spallation,

[1] Schaefer, H.J., Journal of Aviation Medicine, 28, 387, 1957.

fission, fragmentation, and capture. The induced radioactivity is a result of the de-excitation and decay of the resulting nuclei along with leakage of some of the fragments, particularly neutrons. Rigorous treatment of the problem of the interaction of energetic protons with the lunar surface is not possible because of a lack of precise knowledge of the target composition, energy spectra of the impinging particles, and reaction cross sections. As a first approximation, single interactions are considered.

Among the areas of uncertainty is the chemical and elemental composition of the lunar crust. Although the gross induced radioactivity is probably not significantly dependent on the crust model assumed, the characteristics of the secondary radiation are a function of the composition. For these reasons, different illustrative lunar crust models have been employed. Table 12-2 lists the major elemental components of these models.

Table 12-2

Lunar Crust Models (Average Percent), Reference 586

Element	Earth's Crust	Basalt	Meteoric
O	46.60	46.12	32.76
Si	27.72	24.26	16.38
Al	8.13	8.10	---
Fe	5.00	4.97	30.11
Ni	---	---	2.20
Mg	2.09	5.25	12.42
Ca	3.63	5.21	1.53
Cl	---	---	1.35
Na	2.83	2.04	0.59
Mn	---	---	0.22
Co	---	---	0.21
K	2.59	2.08	---
H	---	0.28	---

The meteoric model is used because, subsequent to the formation of the lunar crust, meteoric material had undoubtedly been accumulating on the lunar surface. Assuming that the meteoric influx at the lunar surface is the same as that at the top of the earth's atmosphere, a reasonable influx is approximately 75 tons per day for the moon. This corresponds to a daily buildup of about 6×10^{-11} centimeters in depth if the material density is $3gm/cm^3$. Assuming a residual density of $2gm/cm^3$, a layer of meteoric material of some 64-centimeter average depth has accumulated in 4×10^9 years.

Since the processes most important in the activation of the lunar material are those that give rise to neutrons, reactions of the type X(k, an)Y should be investigated. Here X represents the target nuclei, k the impinging particle, an the ejected particle, and Y the resulting nuclei. Table 12-3 presents the results of a number of reactions producing neutrons.

Table 12-3

Neutron Production in Lunar Surface Material

Reaction	Neutrons ($sec^{-1}cm^{-3}$)
X(p, n)Y	1.1×10^{-2}
X(p, pn)Y	0.6×10^{-2}
X(p, an)Y($a \geq 2$)	3.3×10^{-2}
X(α, n)Y	0.2×10^{-2}
X(x, n)Y	Nil
X(x, an)Y($a \geq 2$)	Nil
Total	5.2×10^{-2}

The crust model used was the average composition of basalt given in Table 12-2, and the particle fluxes used were those given in Table 12-1.

Where cross sections were not available, reasonable values were used based on apparent cross-section trends with Z, the atomic number, and energy.

The following assumptions are made to arrive at the induced radiation leaking out of the lunar surface. The average range of impinging particle radiation is 10 centimeters for the lunar crust material; one-third of the neutrons escape the surface and the remaining two-thirds are scattered in the lunar crust and are eventually captured by atoms of the lunar crust. Further, it is assumed that on the average each neutron capture gives rise to both a capture gamma and a decay gamma, and each initial nuclear reaction gives rise to a gamma ray.

To simplify further, the attenuation of gamma rays and neutrons are neglected and it is assumed that all the alpha and beta particles and other nuclear fragments are completely absorbed by the lunar crust. Then for the leakage of induced neutrons and gamma rays from the lunar surface, the following exists:

$$\frac{10}{3}\,(5.2 \times 10^{-2}) \approx 0.02 \text{ neutrons/cm}^2 \text{ sec}$$

and

$$\frac{10}{2}\left[(5.2 \times 10^{-2}) - \frac{4}{3}\,(5.2 \times 10^{-2})\right] \approx 0.6\gamma/\text{cm}^2 \text{ sec.}$$

In order to convert these fluxes to biological doses, the energy spectra are required. In the absence of this information, if, as a first approximation, a flat energy spectrum for the neutrons is used, 1 mev as the average energy of the decay and reaction gammas, and 8 mev as the average energy of the capture gammas, a neutron dose of 0.12×10^{-3} rem per week and a gamma dose of 0.37×10^{-3} rem per week is obtained.

12.5 NATURAL SURFACE RADIOACTIVITY

Part of the radioactivity at the surface of the moon will be caused by trace quantities of naturally occurring radioactive elements in the surface material. If a distribution of elements of the moon is assumed to be the same as that of the earth, almost all of the radioactivity of the lunar material will be from uranium (both U^{238} and U^{235}); thorium, in equilibrium with their daughter products; and potassium 40.

It is possible that the moon, like the earth, has a so-called crust of more acidic rocks and that natural processes have concentrated these radioactive elements in this crust, Reference 370. Under these conditions, the weekly radiation dose would be in the range of 0.3 to 2mr, as on earth. Based on a nondifferentiated basaltic moon, the radiation dose would be about one-fourth that shown for the more acidic rocks of the earth's crust or from 0.07 to 0.5 mr per week.

Quite probably, certain areas of the lunar surface are covered with appreciable (in the order of centimeters) amounts of meteoritic material. The surface radiation dose in this case would be about one-tenth (0.03-0.2 mr per week) that of the earth crust material, since the uranium, thorium, and potassium content of meteoritic material is correspondingly lower.

12.6 EFFECTS OF LUNAR MAGNETIC FIELD, ATMOSPHERE, AND ELECTRIC FIELD

Magnetic and electric fields will determine the cutoff energies and the trajectories of incident-charged particles on the lunar surface. Also, any atmosphere will attenuate the primary radiation and give rise to secondary radiation. Furthermore, the elemental make-up and the topography will influence the activation and shielding.

If the value of 10^{-2} gauss for the lunar magnetic field is used (see Chapter 11), the proton energy cutoff at the lunar equator will be about 6 mev. It is seen, therefore, that neither the primary cosmic or solar corpuscular radiations will be influenced by the lunar magnetic field.

The 10^{-13} earth atmosphere or 2.5×10^{6} molecules/cm^{3} for the lunar atmosphere, see Chapter 10, is not sufficient to appreciably attenuate the incident radiations.

There is the possibility that local electric fields may exist on the sunlit side of the moon which may affect the low-energy cutoff in the absence of a lunar magnetic field. In the absence of any estimate of the magnitude of this field, and since in all likelihood it will be too small to influence energetic radiation, this effect will be neglected.

12.7 LUNAR SURFACE RADIATION DOSES

The radiation dosages from all sources considered are given in Table 12-4. It is readily seen that by far the greatest dose is from direct solar corpuscular radiation. This dose is time-dependent, present only during the lunar day, and should be absent in the shadows. A much smaller dose develops from induced radioactivity from solar particles bombarding the surface. This should have the same time dependence as the direct radiation but should be a maximum at the subsolar point, diminish toward the limbs, and be completely lacking during the lunar night except for a small fraction whose half is comparable with the lunar period. The primary cosmic ray dose is independent of location on the lunar surface and should have the same time dependence as that at the earth. The radiation induced by cosmic ray bombardment and the radiation from decay of radioactive elements naturally occurring in the lunar surface material are small. The former may be uniform, whereas the latter may vary somewhat over the surface.

In summary, then, pending more rigorous calculating with the limited information at hand or pending the gathering of more experimental data, the nuclear radiation dose at the lunar surface - assuming moderate shielding and proper site selection - is within the AEC tolerance. It should be noted, however, that although the weekly dose is within acceptable limits, the genetic damage will probably be increased.

Table 12-4

Lunar Surface Radiation Doses, Reference 586

Radiation Source	Maximum Weekly Radiation Dose (in millirems)		
	Steady State		Active Sun
Direct corpuscular radiation (Primary cosmic and SHEPS)	Max. Min.	336.0 118.0	100,000.0
Induced radiation (neutrons, gammas, and protons)		0.5	310.0
Lunar crust radioactivity			
Granite		2.0	2.0
Meteoric Material		0.2	0.2
Basalt		0.5	0.5
Total	Max. Min.	339.0 119.0	100,312.0

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CHAPTER 13

SITES

13.1 SITE LOCATION

The criteria for a specific landing or base site location for a given lunar mission will, of course, be constrained by mission objectives; e.g., an observatory will require a relatively high elevation and some latitude restriction because of line-of-sight requirements; whereas, a selenological research station will obviously be situated in a region of maximum geological benefit. The controlling factors in the early phases of lunar exploration, as in the case of trajectory constraints, will be, in all likelihood, different from those in the later phases when things, such as the processing of raw materials, could assume the dominant role. There are, however, many criteria that will influence every lunar landing site or base installation location. They are as follows, although not necessarily complete nor in order of importance:

a. Line of sight for communications (moon-to-moon and earth-to-moon) and observations.
b. Latitude and longitude selection in view of temperature variations, trajectory constraints, guidance limitations, and launch windows.
c. Surface roughness effect on required surface operations.
d. Surface roughness required for covering material.
e. Subsurface structure danger because of near-surface cavity collapse.
f. Subsurface cavities for site emplacement or for storage.
g. Proximity of specific topographic features for use of talus aggregate; mineral deposit, such as ice and sulfur; and internal heat sources.
h. Topographic selection for ease of landing and launch operations, solar ray availability, natural shields from corpuscular radiation, and site camouflage.

13.2 SITE SELECTIONS

13.2.1 INTRODUCTION

Past studies by individual researchers and Government contractors have recommended various lunar landing and base locations, no two of which have been the same. Figure 1 -1 shows the widespread site locations. It does not seem likely that there exists,

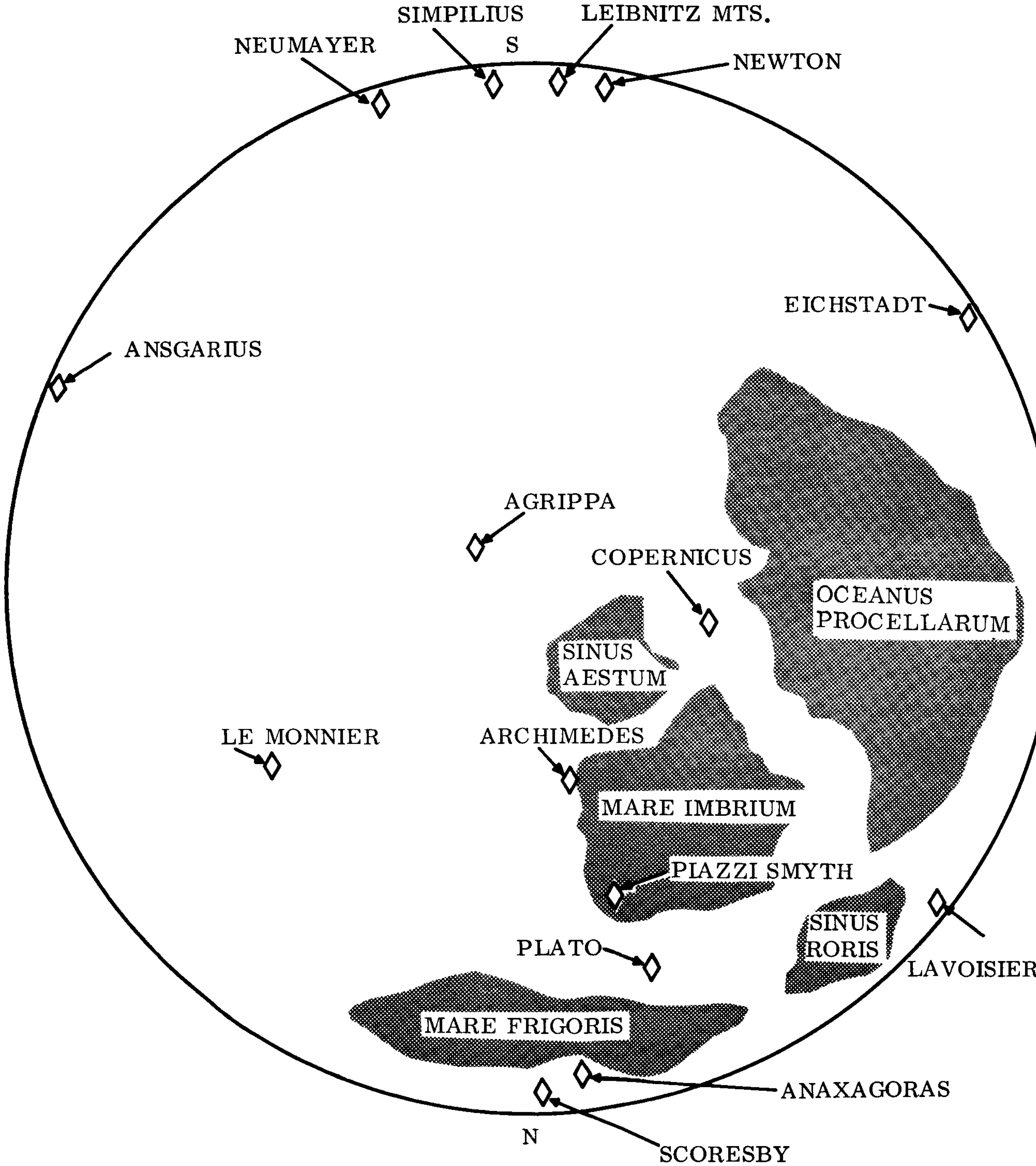

Figure 13-1. Recommended Lunar Landing/Base Sites

a given site, which is best for the particular mission under consideration. There are, however, regions, craters, and the like that have been suggested which merit consideration.

13.2.2 ALPHONSUS CRATER

Green, References 357 and 479, suggests the Alphonsus Crater as a possible non-polar selection for the following reasons:

a. Favorable region from the standpoint of rocket trajectories.
b. Evidences obvious peripheral fracturing of geologic importance.
c. Has internal heat possibilities.
d. Contains possible mineralization.

He cites further that within 12 miles from a nominal touchdown point, the following exploration possibilities exist:

a. Dark spots suggestive of fumarolic activity.
b. Possibility of water, as ice, and volcanic mineralization, such as sulfur in rifts.
c. Possible installation sites.
d. Fracture intersection: possible mineralization.
e. Smooth area for possible landing and launch site.
f. Dark flow of possible basalt.

Within 27 to 117 miles distance from this same nominal touchdown point, there exists:

a. Base of peak of the Kozyrev observation.
b. Basalt or obsidian material.
c. Possible fumarolic complex.
d. Possible access to south floor of Ptolemaeus.
e. Nearest shores of Mare Nubium.
f. Peak of Alpetragius.

13.2.3 POLAR SITE

Green also considers the following polar site locations, References 357 and 479. The criteria for selection in these cases are:

a. Use of sunlight for power generation and ecological facilities.
b. Use of minerals such as sulfur in solar-powered base technologies.

Table 13-1 shows the wall and peak elevations for possible south pole sites, and Table 13-2 shows the wall and peak elevations for north pole sites.

Table 13-1

Wall and Peak Elevations of Possible South Polar Base Sites, Reference 357 or 479

Formation	Wall or Peak Elevation		Diameter	
	Meters	Feet	Kilometers	Miles
*Leibnitz Mountains	4,900 to 10,000	16 to 33,000		
Malapert (overshadowed) by Leibnitz Beta)	4,600	15,000	56	35
Cartes	--	--	--	--
Cabaeus (north wall)	6,100	20,000	97	60
Scott	--	--	106	66
Amundsen	--	--	106	66

*Considered most favorable south pole site.

Table 13-2

Wall and Peak Elevations of Possible North Polar Base Sites, Reference 357 or 479

Formation	Wall or Peak Elevation		Diameter	
	Meters	Feet	Kilometers	Miles
*Shackleton	2,700	9,000		
Delta	2,100	8,000	-	-
Beta, "lofty"	-	-		
Perry			24	15
Hansen				
Beta	3,400	11,000	113	70
Gamma	2,400	8,000		
Main	-	-	48	30
Vairsala	-	-	81	50
Gioja				
(1)	2,700	9,000		
(2)	2,400	8,000		
(3) and (4)	1,100	3,500		
Gamma	2,100	7,000		
Alpha	2,900	9,500		
Beta (1)	2,700	8,800		
Beta (Unspecified)	2,400	8,000		

*Considered most favorable north pole site.

13.2.4 MARE IMBRIUM, PIAZZI SMYTH

Steward, Reference 204, makes the choice of Piazza Smyth in Mare Imbrium for a lunar landing site. His criteria are:

a. The required non-rough region for ease of movement for exploratory teams.

b. Tolerable working conditions because of the cooler latitude.

c. Selenologic factors for investigation of Mare Imbrium.

d. Mount Blanc (12,000 feet), Mount Pico (8,000 feet), and Mount Piton (9,000 feet) offer good possibilities for communication facilities.

e. The entire maria is abundant with exploratory possibilities; namely, the crater Plato, the Lunar Alps, the Alpine Valley, Timocharis with its central vent, and Aristillus with its central mountain.

13.2.5 HIGHLANDS LOCATION NEAR THE CARTER AGRIPPA

Salisbury and Campen, Reference 510, provisionally propose a lunar base location in the highlands just south of the Hyginus Rill, near the crater Agrippa (8°E. longitude, 5°N latitude). Their criteria are:

a. The choice of the highlands area, as opposed to maria area, is based on the meteoritic theory of origin of the major lunar surface features; according to which, the location of the lunar base in the highlands is preferable, because the discontinuous layers of rubble, rock flour, and meteoritic material overlying the highly fractured basement rock does not present a collapse hazard. The maria, on the other hand, are considered to bear near-surface cavities probably twice the size of those predicted under the volcanic theory.

b. The gross topography in the highlands, though quite rugged in appearance, is actually not rugged enough to hinder base location. The microtopography (on a scale of tens of feet) produced by rubble ejected from the craters also should not hinder base location, at least in the case of the meteoritic theory. Under this theory, lunar seismic waves caused by large meteorite impacts have shaken the rubble into a maximum density packing arrangement with low relief. Under the volcanic theory, despite internal seismic disturbances, adjustment should be less complete because of the cementing action of lava flows and atmospheric processes. Both theories predict that the microtopography of the maria should have a relief not exceeding three or four feet, and probably less.

c. It appears that appropriate natural resources could play an even more important part in base location than structure or surface characteristics. Remnants of the lunar atmosphere and gases leaked from the interior are probably present in the shadowed zones of deep polar craters and surface fractures. Such deposits, though common, would probably be small, scattered, and somewhat random in location. It appears, on the other hand, that large concentrations of volatiles should occur near maria margins during solidification of the lava, and that these concentrations may have been tapped by revitalized fractures to form rills, chain craters, domes and wrinkle ridges. Therefore, it is probable that large centralized mineral deposits, composed largely of water, will be found in association with these features.

13.2.6 OTHER

In conjunction with an analysis of translunar trajectories, Reference 107, a study of feasible landing sites were determined. Table 13-3 indicates the preliminary choices:

Table 13-3

Lunar Landing Sites, Reference 107

Landing Site	Region	Desirable Aspects of Area	Undesirable Aspects of Area
Newton Simpelius	South Polar	1. Experience very long days, i.e., six months 2. Moderate day time temperatures	1. Earth appears near horizon 2. Earth is visible for only two weeks in each month 3. Surrounding terrain irregular
Anaxagoras Scoresby	North Polar	1. Experience very long days, i.e., six months 2. Moderate day time temperatures. 3. Surrounding terrain relatively smooth	1. Earth appears near horizon 2. Earth is visible for only about two weeks in each month
Mare Frigori Plato	Far North	1. Experience long days 2. Moderate temperature 3. Earth can always be seen 4. Plato has very smooth floor	1. Earth appears at a 30 degree elevation

Table 13-3

Lunar Landing Sites, Reference 107 (Cont.)

Landing Site	Region	Desirable Aspects of Area	Undesirable Aspects of Area
Oceanus Procell-arum	Far East	1. Minimum fuel requirements for 3.25 day trajectory to reach area 2. Very smooth terrain 3. Earth always visible	1. Extreme temperature 2. Earth appears at 30 degree elevation
Sinus Aestuum	Central	1. Earth can always be seen 2. Earth appears near zenith	1. Extreme temperature

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CHAPTER 14

EXPERIMENTS

14.1 INTRODUCTION

Lunar experimentation is obviously not a part of the physical and environmental parameters of the moon. It is, however, a very important consideration for the future because it provides an immediate means by which lunar technology will make significant progress and will help settle some of the theoretical variations that are identified in other chapters of this document. The several categories of space programs now in full development on an international basis establishes a vast potential for lunar experimentation. Starting with lunar probes, then to orbiters and finally to landers, the full range of scientific disciplines measured through literally thousands of experiments will permit the first significant analysis of extraterrestrial vestiges in the universe. Ultimately, of course, man's landing on the moon becomes a singular objective and it is toward this particular purpose that much of the experimentation must be directed. Experimentation subsequent to man's arrival on the moon will quite naturally develop to the degree of sophistication now available on earth, and it is certainly expected that today's theoretical lunar discrepancies will be resolved.

It is not the intent of this chapter to recommend nor develop experimental programs or experiments. Its purpose is to familiarize the reader with a sampling of some of the various experiments that can be performed and to describe in reasonable detail some of the instrumentation required.

14.2 CLASSES OF EXPERIMENTATION

Major classes of experiments can be listed as follows:

a. Specifics of locale, mass, or geometry:

1. Terrain size, color, formation.
2. Material densities.
3. Dust layer.
4. Elemental make-up.
5. Mineral make-up.

b. Large scale or field effects:

1. Magnetic field.
2. Electric field.
3. Temperature.
4. Gravity.
5. Radiation.
6. Meteoroids.
7. Cosmic dust.
8. Charged particles.

c. The moon as a vantage point:

1. Earth and cislunar survey.
2. Solar observations.
3. Astronomical observations.

d. Life science:

1. Human behavior.
2. Effects on transplanted earth organisms.
3. Search for indigenous organics and life forms.

14.3 TYPES OF EXPERIMENTS

In the following list are a few of the experiments that will provide information in one or more of the previous classes of experiments.

a. Seismic Observations

There are probably two natural sources of motion in the moon's crust:

1. Shifting, sliding, or folding.
2. Impact of meteoroids.

In order for the first to occur, the middle of the moon would have to be plastic or molten. The second source is a definite possibility, and depending on their energies and their distance from the instruments, the impacts would be detected as waves in the crust. Reference 79 states that a single seismic detector capable of recording seismic body and surface waves can reveal the presence or absence of a lunar crust and core.

Rough indications of lunar seismicity can be made with an experiment lasting a few weeks to a few months. For a moon as seismic as the earth, the number of moonquakes recorded per month will greatly exceed 10 to 100, since this number represents only the large tremors with moonwide audibility. In the absence of significant lunar seismic activity, meteoritic impacts offer the possibility of an alternate seismic source for inferring the moon's internal structure.

b. Surface Radioactivity

The background count caused by cosmic radiation is believed to be very high on the moon, and unless the surface radiation were extraordinarily high, the count from natural radioactivity in the soil would be undetectable.

c. Chemical Composition and Physical Analysis of the Surface

Chemical analysis, as performed in the laboratory can be done on small samples scooped up from the lunar surface. The samples can be vaporized by electric arc or concentrated sunlight, whereafter presence or absence of elements can be established by spectrum. The conductivity, density, reflectivity, and other physical characteristics can be measured. Specific characteristics will yield much valuable information, e.g., the amount of ice present in a sample, see paragraph 6.3, should prove to be a most sensitive mineral indicator of the degree of chemical differentiation of the moon.

Another technique proposed for determining the chemical composition or model of the lunar surface is by orbiting a gamma-ray spectrometer about the moon, Reference 362. Since each proposed crust model emits a unique gamma spectra, identification is possible.

d. Biological

It has been concluded, Reference 404, that at a depth of some tens of meters below the present lunar surface, there may be localized a layer of organic material deposited during the period in which the moon possessed a reducing atmosphere opaque in the ultraviolet.

A qualitative analysis of such organic matter would provide important information on the types of molecules produced in prebiological organic syntheses on the earth and elsewhere; it would furnish clues for the laboratory simulation of prebiological organic evolution, and for the reconstruction of pathways which lead to the origin of life. A quantitative analysis would supply evidence on the nature and lifetime of early lunar gaseous envelopes, on current theories of stellar evolution, and on hypotheses concerning the origin and early history of the solar system.

The simplest analytic technique would be to determine the vapor pressure of cores from various depths as a function of temperature. This could identify many of the major categories of organic molecule, and could easily distinguish organic matter from silicates, irons, and residual ices.

e. Measurement of Lunar Mass and Gravity

Present estimates of the moon's mass are only accurate within 0.3 percent. Greater accuracy must be obtained in order to accurately predict space vehicle trajectories near the moon. The precise tracking of a vehicle transiting to the moon could supply the lunar mass to an error considerably less than 0.1 percent.

The measure of the lunar gravity from the surface of the moon can be made directly by a calibrated spring displacement, time of fall of a known body a known distance, or the period of swing of a pendulum. All of these measurements will result in an error of less than one part in a thousand.

f. Hardness and Density of Lunar Surface Layer

A lunar satellite properly instrumented could determine the depth of the outer layer of the surface of the moon as a function of a set of lunar coordinates and of the electromagnetic constants of the inner layers. Thus - based on correlation between electromagnetic constants and physical properties of materials - it is hoped to obtain knowledge of the hardness and density of inner layer materials, References 236 and 399.

14.4 INSTRUMENTATION

By nature of the stringent requirements in compactness, weight, and remote controlability (for the initial lunar experiments), the instrumentation necessary for the various experiments will be extremely advanced and in line with the latest developments in the state of the art.

Table 14-1 is compiled to give an example of the latest thinking in terms of equipment, weights, volume, and power requirements.

Table 14-1

List of Instrumentations

Experiment	Instrumentation	Lbs.	In^3	Watts	Remarks	Source
Solar X-ray	Scintillation detection	12		Power self-confined	Designed to detect bursts of low energy X-ray originating at the sun. Six opaque windows protect against cosmic dust puncture permitting X-rays to the detecting portions of the instruments.	Los Alamos Scient. Lab. J. A. Northrop
Neutral Hydrogen Cloud	Lyman-Alpha Telescope	15		1.4	The Lyman-Alpha detector will detect Lyman-Alpha radiation from sun or reflections from neutral hydrogen in space. Indicates geocorona or other physical characteristics.	Naval Research Lab/JPL T. A. Chubb H. P. Bull
Cosmic Dust	Cosmic Dust Detector	3.55		0.20	Special microphone attached to the sensitive exposed surface. Will detect particles in solar orbit in both clockwise and counterclockwise rotation.	Goddard Space Flight Center W. M. Alexander
Seismic	Seismometer	7.8	100	2.5	Single axis measuring device in the spring-mounted mass with a variable reluctance electromagnetic pick-up (measures one millionth of an inch displacement).	California Institute of Technology
Atmosphere	Mass Spectrometer	12	800	20	Neutral particles to be ionized by an electron beam from a rhenium filament. Permanent magnets are used to conserve weight and power.	Consolidated Systems Corporation, Monrovia, Calif. Bull. 3024, 1960
Detection of Non-Mineral Materials	Lunar Gas Chromatograph (LGC)	12	675	100	A gas chromatograph to prove the absence of terrestrial forms of life in each sample analyzed. Carrier gas is Helium as an additional supply.	Aerojet General JPL M and R, 7 August 1961 Aviation Week, 7 July 1961, p. 66
Chemical Composition of Lunar Crust	Gamma-ray Spectrometer	--	--	--	By measuring the gamma spectro from a lunar orbiter, the distinct radiations from the proposed crust models will permit identification.	Autometric Corp., Reference 362
Solar Plasma	Solar Corpuscular Detector	33	2.74		Six detectors in six different directions measures plasma particle energies with electrostatic analyses. Determine whether these particles are streaming outward from sun as a solar wind or wandering at random through a comparatively stationary plasma cloud.	JPL M. Neugebauer C. W. Snyder
Solar Plasma Cosmic Radiation	Semiconductor Detectors and Thin-Walled Geiger Counters	3.8	.16		Six detectors observe charged particles in an energy range overlapping the low energies of particles in the interplanetary plasma and extending upward toward the high energies of fast-moving cosmic rays. (Insensitive to electrons and X-rays.)	State University of Iowa (Van Allen) University of Chicago (Fan, Meyer and Simpson)
Cosmic Radiation	Ionization Chamber	1.2	0.004		Quartzfiber - Quartzrod integrating type ionization chamber.	California Inst. of Tech. (H. V. Neher)

Table 14-1

List of Instrumentations (Cont.)

Experiment	Instrumentation	Lbs.	In^3	Watts	Remarks	Source
Cosmic Radiation	Triple Coincidence Telescopes	9	0.5		Two triple coincident telescopes each consisting of an assemblage of countertubes.	University of Chicago (Fan, Meyer and Simpson)
Magnetic Field	Rubidium - Vapor Magnetometer	5.75	4.1		Measures strength and direction of magnetic field. The rubidium vapor cell resides at the center of a hollow 13-inch diameter fiberglass spherical shell. This shell is wrapped in the coils of wire through which sequenced currents are sent.	Goddard Space Flight Center J. P. Hepner J. D. Stolarik
Petrological Analysis	Absorption Spectrophotometer	12	1600	4	Lunar surface analyses, quantitatively and qualitatively analyzes by absorbing particular wave lengths of light, measuring the absorption.	Beckman Instruments
Petrological Analysis	Mass Spectrometer	17	400	15	Determine the wave lengths of different radiation characteristics of elements in the periodic table.	Bendix Research Laboratory Detroit
Thermal Diffusivity Density. Hardness Magnetic Susceptibility Sonic Transmission	Geophysical Measurement Instrument				Will obtain data by drilling a 1.25 inch diameter hole.	Texaco Experiment, Inc. AW 8 January 1962
Temperatures	Infrared Radiometer	2-1/2			Two channel infrared photometers with fixed optics.	Barnes Eng. Co. Stamford, Connecticut AW 5 February 1962
Temperatures	Microwave Radiometer	20			Crystal type microwave radiometer, measuring two wave lengths.	Ewen - Knight Corp., East Natich, Mass.
Temperatures	Surface Probe Subsurface Probe Subsurface Probe Reel	1 3 2		1 1 10	Thermal probe to operate night and day.	Planned Rover Experiment (General Electric)
Lithology	Geological Tools TV Camera Drill	50 10-30 50	 200 1700	0 20-7 200	Lunar material formations, strata; selenogical processes and illuminate solar system relationships.	Reference 476
Lunar Elements	Mass Spectrometer X-ray Spectrometer and Diffractometer	10 40	800 72	15 30	Reveals forces acting on moon; indications of surface activity, atmosphere origins, life potential.	Reference 476
Mass and Gravity	Radar Gravimeter	10 35	600 1500	60 12	Of basic celestial interest, will lead to more accurate dimensioning of the entire system.	Reference 476

Atmosphere	Mass Spectrograph Mass-ion Spectrometer	10 8	850 45	15 20	Presence oı lack of reveals lunar origins. Indicates probability of past and present life.	Reference 476
Magnetic Field	Magnetometer	4-6	900	4	Field elucidates lunar interior. Interaction between moon, earth and sun of primary interest.	Reference 476
Subsurface Temperature	Infrared Device-Thermal Probes	10		10	Of fundamental interest in determining origin and make-up of moon.	Reference 476
Solar Plasma and Radiation	Plasma Probe Triple-coincidence Device Med-energy Detectors X-ray Spectrometer	2 9 .6	100	1.5 0.5 .03	Lunar scene allows direct measurement of low-energy (anticipated) solar corpuscular radiation (plasma or wind) and other radiation. Yields insight into sun's metabolism.	Reference 476
Seismic	Seismic Probes Geophones	10 4-20	200 2500	3-10	Few measurements yield greater information than seismic; it may be necessary to activate quakes.	Reference 476
Meteoroids	Electrostatic Detector	3.5	100	2	Lunar surface is ideal to detect meteoroid distribution of mass and energy.	Reference 476
Lunar Life or Potential	Chromatograph ph and Turbidity Tester	12 5	625 40	100 2	Ability of moon to evolve and support life is the prime question for biologists and bio-chemists.	Reference 476
Astronomical	Radio/Optical Telescopes Camera				An unobstructed view of the heavens is obtained; increase seeing power 3 or 5 times.	Reference 476
Engineering Studies	Environmental Test Device	400		200	The gamut of engineering problems connected with space flight; basic testing and design data.	Reference 476

GLOSSARY OF TERMS

AIR MASS (OR OPTICAL AIR MASS) - The ratio of the length of the atmospheric path traversed by the sun's rays in reaching the earth to the length of this path when the sun is at the zenith.

ALBEDO:

SPHERICAL (OR BOND) - The ratio of the whole amount of light scattered in all directions by a hemisphere illuminated by parallel rays to the total amount of light incident on this hemisphere.

GEOMETRIC - The ratio between the average brightness of the disc at phase 0° (total eclipse) and the brightness of a white screen of the same dimensions placed normal to the direction.

ALLOCHROMATIC - Mineralogical term for color obtained by extraneous, or foreign impurities in a mineral.

ASCENDING NODE - The point where a planet's (or moon's) center crosses the ecliptic going north. In only 18.6 years the lunar nodes shift completely around the ecliptic.

ASTRONOMICAL UNIT - The semi-major axis of the orbit of the center of gravity of the earth-moon system around the sun in the year 1900.0, neglecting planetary perturbations, Reference 520.

CANDELA - Unit of luminous intensity. Now defined and internationally accepted candle equal to the luminous intensity of five square millimeters of platinum at its solidification point of 1773.5°C also called the new or international candle.

CANDLE (See Candela) - Unit of luminous intensity. One-sixtieth of the intensity of one square centimeter of a blackbody radiator at the temperature of solidification of platinum (2046°K): A unit about 98.1 percent of the "new" candle or candela. One candle produces one lumen of luminous flux through an area subtending a solid angle of one steradian measure from the source.

CHERNOZEM - A dark colored zonal soil with a deep and rich humos horizon found in temperate to cool subhumid climates.

CISLUNAR - Of or pertaining to phenomena or activity in the space between the earth and the moon.

COLOR INDEX - The algebraic difference between the photographic (4250Å) and visual (5280Å) magnitudes, expressed in stellar magnitude.

CONDUCTIVITY, ELECTRICAL - The quantity of electricity transferred across unit area, per unit potential gradient per unit time. Reciprocal of resistivity, units of $ohm^{-1}\ cm^{-1}$.

CONDUCTIVITY, THERMAL - The rate of transfer of heat by conduction, through unit thickness, across unit area for unit difference of temperature, measured in calories per second per square centimeter for a thickness of one centimeter and a difference of temperature of 1°C.

CUSPS - The points of the crescent moon.

DIRECTIVITY FACTOR - A measure of the amount of energy scattered back towards the radar receiver as compared to the average of that scattered into all directions.

ECLIPTIC - The sun's apparent annual path around the celestial sphere; it is a great circle inclined $23\frac{1}{2}°$ to the terrestrial equator. The ecliptic represents the plane of the earth's orbit, and the celestial equator is in the plane of the earth's equator.

ECOLOGY - Biology dealing with relations between organisms and environment.

EPHEMERIS - A table of calculated coordinates of an object with equidistant dates as arguments.

EQUATORIAL HORIZONTAL PARALLAX - The angle subtended by the earth's equatorial radius at any particular distance from the moon.

EQUINOX:

VERNAL EQUINOX - That point on the celestial sphere (relative to the fixed stars) in the constellation Pisces at which the earth's equator and the ecliptic intersect.

AUTUMNAL EQUINOX - The other intersection of the ecliptic and equator, one hundred and eighty degrees from the vernal equinox.

FOOT-CANDLE - Illuminance of one lumen per square foot.

FUMAROLIC GAS - A hot gas or vapor expelled from a hole or orifice in a volcanic region.

GEGENSCHEIN - The quasi-stable "point" which is one of the straight line solution points of the earth-sun system. It is exactly opposite to the sun with respect to earth and appears as a hazy patch of light. It is believed that numerous infinitesimal dust particles in semi-equilibrium at the point are responsible for the haze.

IDIOCHROMATIC - Mineralogical term meaning natural color.

IGNEOUS ROCKS - Formed by solidification of molten magma.

ILLUMINANCE - Luminous flux incident on unit area, Unit: lux, foot candle.

INDUCTION, MAGNETIC - The magnetic flux per unit area taken normal to the direction of the flux in the cgs unit of gauss.

INSOLATION - Rate of delivery of all direct solar energy per unit of horizontal surface.

INTENSITY, MAGNETIC FIELD - A unit field intensity, the oersted, is that field which exerts a force of one dyne on unit magnetic pole.

LEUCOCRATIC - Mineralogical term meaning light in color.

LIBRATIONS - The apparent oscillations of the moon that exist with respect to an earth observer. There are four kinds of librations. They are in descending order of magnitude: libration in longitude, libration in latitude, diurnal libration, and physical libration. See paragraph 2.17.

LIMB - The outer edge of the lunar sphere.

LUMEN - The unit of luminous flux. It is equal to the luminous flux emitted through a unit solid angle (one steradian) from a uniform point source of one candle; or to the flux on a unit surface all points of which are at unit distance from a uniform point source of one candle.

LUMINANCE (photometric brightness) - Luminous intensity of any surface in a given direction per unit projected area of the surface viewed from that direction. Unit: nit.

LUX, synonym metercandle - An illuminance of one lumen per square meter.

MASS ABSORPTION COEFFICIENT (μ) - A material property given by $\mu = \alpha/\rho$, where α is the absorption coefficient and ρ is the density of the material. The absorption coefficient is a measure of the rate of decrease in intensity of radiation passing through the material.

MELANOCRATIC - Mineralogical term meaning dark in color.

METAMORPHIC ROCK - That rock formed by pressure and heat from igneous or sedimentary rock.

NIT - A luminance of one candle per square meter.

NODAL PASSAGE - The time at which the moon crosses the ecliptic.

NODICAL MONTH - The period of time required for the moon to pass from one node back to the same.

OCCULTATION - The eclipse of a celestial body behind another.

PARALLAX - The arc difference between the direction of a heavenly body as seen by the observer and as seen from some reference point.

HELIOCENTRIC PARALLAX - The angle at an object in the Solar System (star, etc.) subtended by the radius of the earth's orbit.

GEOCENTRIC PARALLAX - The angle at an object in the Solar System subtended by the earth's equatorial radius.

Also see "EQUATORIAL HORIZONTAL PARALLAX."

PERMEABILITY:

ABSOLUTE - The property of a medium given by the ratio of the magnetic flux density (B) to the magnetizing field intensity (H).

RELATIVE - The ratio of the magnetic flux in any element of a medium to the flux that would exist if that element were replaced by a vacuum with the magnetizing force remaining unchanged.

PERMITTIVITY (ϵ) - A physical constant of a dielectric medium defined in the Coulomb Law

$$F = \frac{q_1 q_2}{\epsilon r^2}$$

where the force F is measured in dynes, r is the separation distance in centimeters and q_1 and q_2 are charges (measured in electrostatic units) immersed in the medium.

RELATIVE PERMITTIVITY - Dielectric constant, the ratio of the absolute permittivity of a medium to the permittivity of free space.

SEEING - The turbulence of the earth's atmosphere caused by winds and currents of warm and cool air circulation which results in variable deflections of transient light rays.

SIDEREAL MONTH - The interval between successive identical positions of the moon in relation to the background of fixed stars as seen from the earth's center. Mean value is $27^d.321661$.

SPECULAR - Having qualities of a mirror; a reflector.

SPUTTERING - The removal of atoms and molecules from a surface bombarded by high velocity impinging particles.

STELLAR MAGNITUDE - Equals

$$0.4 \log_{10}\left(\frac{I_0}{I}\right)$$ where I is the

apparent visual brightness of the observed object and I_0 is a standard observed corresponding roughly to the light of Arcturus or Vega.

STERADIAN - A unit solid angle, which encloses a surface on a sphere equivalent to the square of its radius. The total solid angle about a point equals 4π steradians.

SUBSOLAR POINT - That point on the surface of the moon that the sun is directly over at the zenith.

SUN'S RADIATION INTERCEPT -

ARC: The lunar diameter represented as a segment of arc on the circumference of a circle around the sun at lunar distance.

AREA: The area of moon's disc represented as an intercept on the surface of a sphere around the sun with a radius equal to the moon's distance.

SYNODIC MONTH - The period between successive full moons, the mean value being $29^{d}.530588$.

TALUS AGGREGATE - Rock debris at the base of a cliff.

TERMINATOR - The line dividing the illuminated and the unilluminated portion of the lunar disc.

VOLUMETRIC SPECIFIC HEAT - The ratio of a substance's thermal capacity to that of water at 15°C.

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NOTE: It is recommended that item 609, not available at this printing, be consulted for additional information.

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