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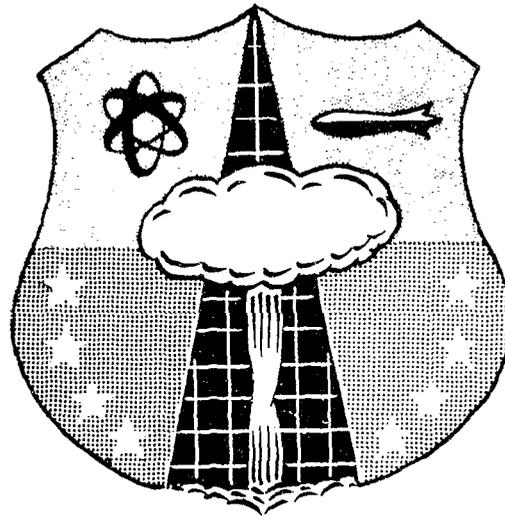
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A STUDY OF LUNAR RESEARCH FLIGHTS

Vol I

by

L. Reiffel

ARMOUR RESEARCH FOUNDATION

of

Illinois Institute of Technology

19 June 1959

TR-59-39

Vol I

HEADQUARTERS  
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Vol I

(Unclassified Title)

A STUDY OF LUNAR RESEARCH FLIGHTS

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With contributions by

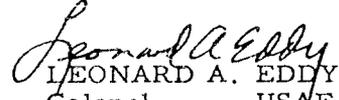
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ABSTRACT

Nuclear detonations in the vicinity of the moon are considered in this report along with scientific information which might be obtained from such explosions. The military aspect is aided by investigation of space environment, detection of nuclear device testing, and capability of weapons in space.

A study was conducted of various theories of the moon's structure and origin, and a description of the probable nature of the lunar surface is given. The areas discussed in some detail are optical lunar studies, seismic observations, lunar surface and magnetic fields, plasma and magnetic field effects, and organic matter on the moon.

PUBLICATION REVIEW

This report has been reviewed and is approved.



CAREY L. O'BRYAN, JR.  
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Deputy Commander

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Chapter I  
INTRODUCTION

## Chapter I

### INTRODUCTION

Rapidly accelerating progress in space technology clearly requires evaluation of the scientific experiments or other human activities which might be carried out in the vicinity of the earth's natural satellite. Among various possibilities, the detonation of a nuclear weapon on or near the moon's surface has often been suggested. The motivation for such a detonation is clearly threefold: scientific, military and political.

The scientific information which might be obtained from such detonations is one of the major subjects of inquiry of the present work. On the other hand, it is quite clear that certain military objectives would be served since information would be supplied concerning the environment of space, concerning detection of nuclear device testing in space and concerning the capability of nuclear weapons for space warfare. The political motivations for and against the detonation of a nuclear weapon are equally clear and are, in reality, outside the scope of the present work. Obviously, however, specific positive effects would accrue to the nation first performing such a feat as a demonstration of advanced technological capability. It is also certain that, unless the climate of world opinion were well-prepared in advance, a considerable negative reaction could be stimulated. Obstacles to detonation of a nuclear weapon on the moon, from a scientific viewpoint, center around environmental disturbances, biological contamination, and

radiological contamination, only the last of which is unique to the nuclear weapon. While the present efforts have been designed to explore scientific aspects of lunar experimentation, including detonation of a nuclear weapon among other possibilities, we nevertheless have felt some obligation to consider the obstacles listed above and at least a beginning has been made in an evaluation of some aspects of the contamination problems.

A central theme, which runs through many of the projected experimental situations, envisions placing of a maximum of three identical instrument packages at arbitrary locations on the visible face of the moon prior to any possible nuclear detonation. These instrument packages would be equipped to make a variety of measurements treated in the following chapters, and, as such, only certain operations would require a nuclear detonation. The instrument packages, in general, would accumulate very valuable information on the way to the moon, while emplaced on the moon before any detonation, as well as during and after a possible nuclear detonation. The location of the instrument packages need not be pre-determined but is presumed to be known by virtue of suitable markers.

Clearly, the landing of three complex instrumentation packages on the lunar surface with "state of the art" techniques, either today or in the near future, must be considered a maximum effort. It is presumed obvious to the reader that many valuable measurements could be performed with only one instrument package, and for certain of the observations to be treated in the present work, only terrestrial observations are required. In no case have we attempted to detail the design of a suitable instrument package

combining the functions necessary to perform the many experiments discussed. Such an effort would have been large and perhaps entirely inappropriate at this early stage of overall planning for possible lunar experimentation.

In conclusion, it should perhaps be emphasized that the course taken has been the exploration of a fairly large number of problems and experimental possibilities without, in any given instance, attempting to be exhaustive. It is evident that many aspects of the problems which are treated here remain untouched or, at best, have been only qualitatively considered. Furthermore, it is almost unnecessary to point out that a vast number of possible experiments, not even mentioned or perhaps not even considered by the present group, should be carefully evaluated. The enormous effort that would be involved in any controlled experiment on or near the moon demands nothing less than an exhaustive evaluation of suggestions by the many qualified persons who have begun to think about this general problem.

CHAPTER II

(See Vol. II of Report)

Chapter III

OPTICAL STUDIES RELATED TO THE LUNAR RESEARCH FLIGHTS

## Chapter III

### OPTICAL STUDIES RELATED TO THE LUNAR RESEARCH FLIGHTS

Optical studies undertaken in this analysis of lunar research flights cover the following three areas: (a) various observational parameters governing the visibility of markers associated with apparatus on its way to the moon, in the vicinity of the moon or on the surface of the moon; (b) stellar spectroscopy and high speed spectroscopy of the lunar blast using available astronomical and high speed photographic equipment and (c) measurements on the thermal conductivity of the lunar surface using infrared emission measurements.

Visibility data has been compiled which would permit the calculation of required target intensity in order that it be visible against a background of known luminance. However, since the moon is not of uniform luminance, the results are not rigorous. Ranging from unresolvable points to large irregular areas and from bright spots to deep shadows, arranged in most irregular fashion, the moon represents a difficult background in which to search for a small area. Therefore, target intensities must be substantially greater than indicated by calculations assuming uniform background. With these considerations in mind, a critical evaluation of various types of markers is presented.

Spectroscopy of the lunar blast area would yield useful information on the composition of material on the moon's surface. Detailed considerations

are given to the dependence of spectral type and high speed spectroscopic parameters on the visible light emission by the blast. The influence of atmospheric absorption and turbulence on the spectrographic information yield by existing stellar spectrographs is presented in a tabulated form. Balloon carried telescope and spectrograph up to an altitude of approximately 150,000 feet is considered. Whereas, a number of practical problems are known to exist in high altitude balloon telescoping, it is clear that an extension of the UV spectra, as well as freedom from atmospheric turbulences, will be achieved by going above, say, 130 - 140,000 feet.

In the past, thermal conductivity of the lunar surface has been calculated by measurements in variation of temperature on the moon's surface during a lunar eclipse. With the nuclear detonation acting as a strong heat source and with the availability of highly sensitive infrared detectors, it seems possible to calculate thermal conductivity of lunar surface to a high degree of accuracy. The influence of atmospheric absorption and turbulence on these measurements is tabulated for various existing telescopes and infrared receptors.

## Section One

### Marker Visibility

The problem of sending a vehicle to the moon and of landing an instrument package on the moon raises the question of tracking in flight and accurate location on the surface of the moon. Visual optical approaches to the problem are preferred because of the great sensitivity of the human eye

and the high precision in location possible in modern optics. Of prime interest is the visibility and detectability of various possible markers. These fall naturally into two classes, those that are self-luminous by virtue of consumption of self-contained fuel or stored energy and those that are luminous by virtue of reflected sunlight. The need for keeping weight and size to a minimum restricts the optical problem to threshold or as near threshold conditions as possible.

It is generally known that threshold illumination from a point source detectable by the eye depends upon background brightness, color and adaption level of the eye. Three such background levels, full moon, dark moon, and night sky 3000 miles distance from full moon are considered in detail.

#### A. Visual Thresholds of Disks of Light

Two investigations of visual thresholds of disks of various brightnesses in uniform fields of various brightness levels by Blackwell<sup>1</sup> and by Tousey<sup>2</sup> are of importance and form the basis of most visibility studies. Their results agree remarkably well, although their experimental conditions were quite different. Fig. 1 presents their data in graphical form. It displays threshold illumination from a point source which is detectable at different background brightness levels. A point source is defined as one which subtends less than one minute of arc at the eye. Based on observations of Tousey and Hulbert<sup>3</sup> a point source is very difficult to find when the illumination is just threshold or even twice the value. Up to five times

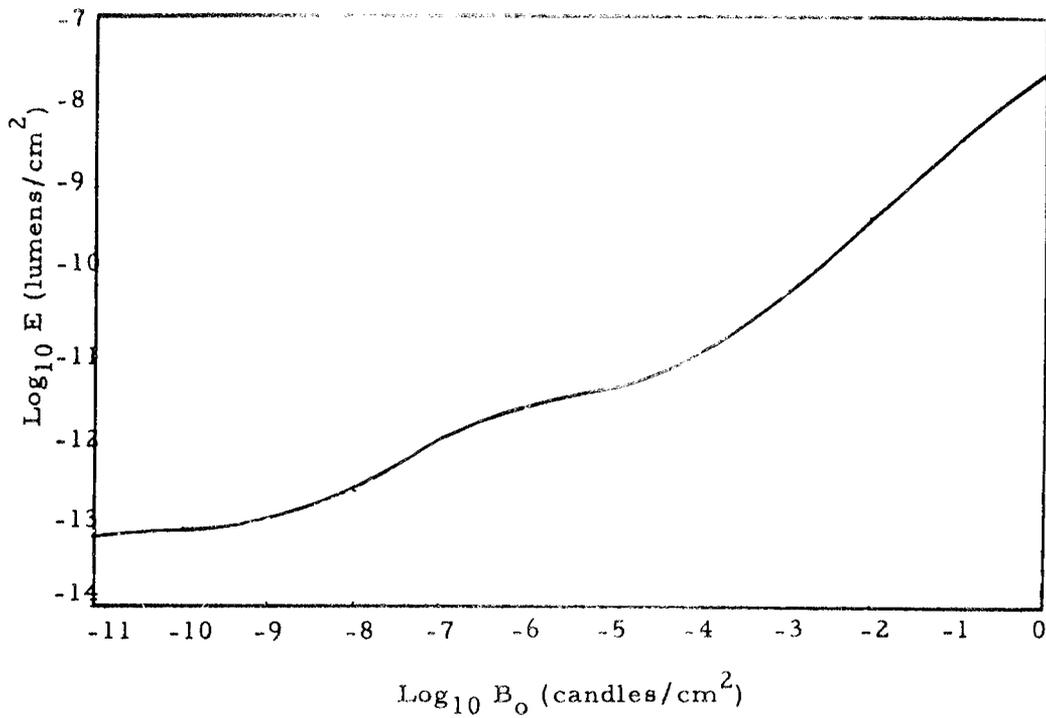


FIG. 1 - THRESHOLD ILLUMINATION FROM POINT SOURCE  
DETECTABLE BY NAKED EYE AS FUNCTION OF  
BACKGROUND BRIGHTNESS

threshold value is moderately hard to find. To convert threshold illumination (vertical axis) of Fig. 1 to source intensity necessary for detection, one has only to multiply  $E$  by the square of the distance, which in this case is 240,000 miles, expressed in centimeters. The intensity values shown in Fig. 2 were obtained in this way

Fig. 2(a) presents average brightness values of light and dark moon and of night sky 3000 miles from the moon's surface at full moon. The source intensities necessary for detection with the naked eye against these backgrounds are also indicated.

#### B. Telescopes and Improvement of Visual Thresholds by Magnification

A telescope increases illumination from a point source relative to the brightness of a uniform background and therefore makes it possible to see some sources which are below the limit of the naked eye. Tousey and Hulbert<sup>3</sup> derive an expression for the gain by the use of telescopes which can be written as

$$f' = \left(\frac{D}{P}\right)^{0.92} (M)^{1.68} (t)^{0.10} \quad (1)$$

in which  $D$  = diameter of objective lens,

$P$  = diameter of eye pupil,

$M$  = magnification,

$t$  = transmission factor of telescope,

$i$  = illumination on objective lens when point source appears at threshold,

$i'$  = unaided eye threshold,

$(i'/i)$  = improvement in threshold due to telescope.

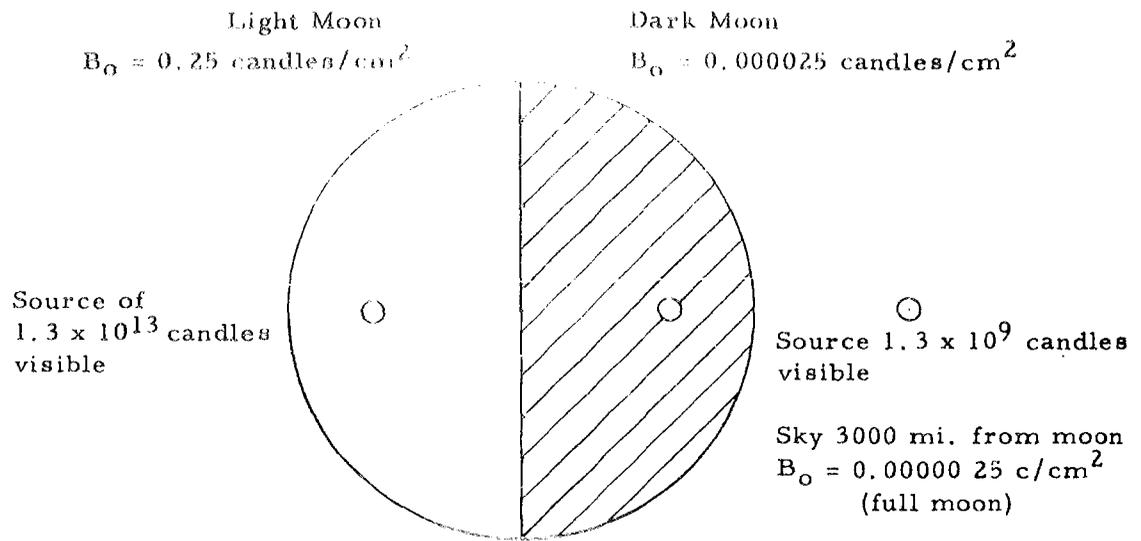


FIG. 2(a) - SOURCES VISIBLE TO NAKED EYE AGAINST LUNAR BACKGROUNDS

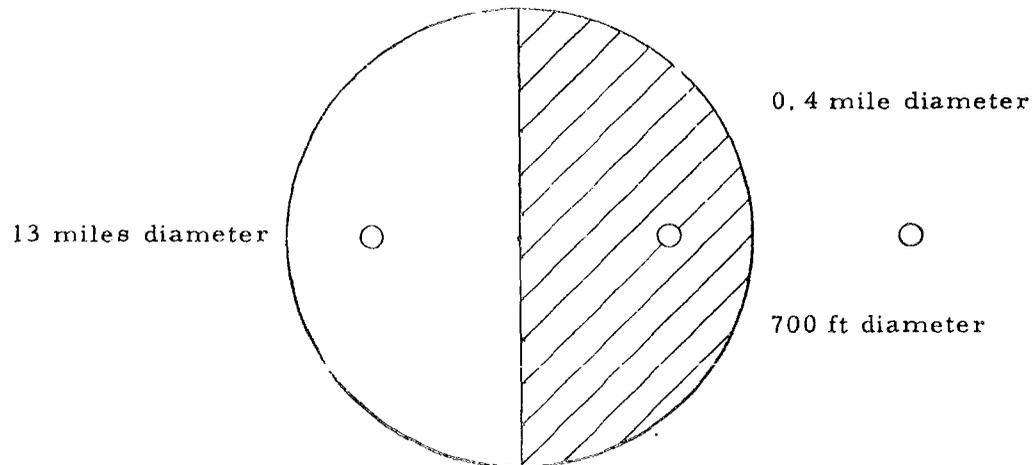


FIG. 2(b) - WHITE SPHERES VISIBLE TO NAKED EYE

This formula was used to make the calculations shown in Table I. In deriving this formula certain assumptions had to be made with respect to the relative size of eye pupil and exit pupil of the telescope. Since the size of the pupil varies with adaptation level, the assumption is not strictly true, and therefore the formula must be regarded only as an approximation. Table I shows the advantage to be gained with the use of telescopes in the visibility of point sources against full moon background.

Table I

Telescope with  $M = 16D(\text{in.})$   
 $t = 85\%$

D(in.)	M	$1/i$	Candles for Detection Against Avg Full Moon		
Eye	1	1	13,000,000	mega-candles	
1	16	172	75,000	"	"
2	32	630	20,600	"	"
8	128	11,000	1,200	"	"
20	320	68,000	190	"	"
40	640	274,000	50	"	"
100	1000	790,000	16.5	"	"
200	1000	900,000	14.5	"	"

### C. Visibility of Diffuse and Specular Spheres

Tousey<sup>1</sup> has considered this problem in connection with earth satellites but his findings can be easily extended to moon orbiters. The angular distribution of luminosity of a sphere illuminated by the sun was considered for two special cases; a perfect specular reflector, and a perfect diffuse reflector which obeys Lambert's Law. The expressions for luminous intensity,  $I$ , measured at a distance which is large compared to

the radius, R, are

$$\text{Specular: } I = \rho \frac{R^2}{r^2} E \quad (2)$$

$$\text{Diffuse: } I = \rho \frac{R^2}{3r^2} (\sin \theta + (r-\theta) \cos \theta) E \quad (3)$$

Where  $\theta$  is the angle between the directions to the sun and the observer,  $E$  is the solar illumination, and  $\rho$  is the reflectivity factor of the sphere material. The specular sphere has a constant luminosity in all directions since the expression for  $I$  does not contain  $\theta$ . The diffuse sphere goes through phases like the moon and is brighter than the specular when viewed "full" but dimmer when "new." The two types are equally bright when viewed at 83.7 degrees. Fig. 3 shows the angular distribution of luminosity in the two cases.

The visibility conditions may be computed approximately by making use of formula (2) or (3) to calculate the luminous intensity for the appropriate conditions of illumination and viewing. Reference to Fig. 2 will determine its visibility status for three different background brightness conditions. If it is not visible to the naked eye, Table I may be used to determine the appropriate telescope to make it visible.

Formulas (2) and (3) apply strictly to ideal specular and diffuse spheres, respectively. Clearly, no practical sphere will be ideal, either specular or diffuse, so a decision must be made as to which is the more appropriate formula. In general, this is not a difficult decision to make; a polished metal sphere approximates the specular case unless it is badly

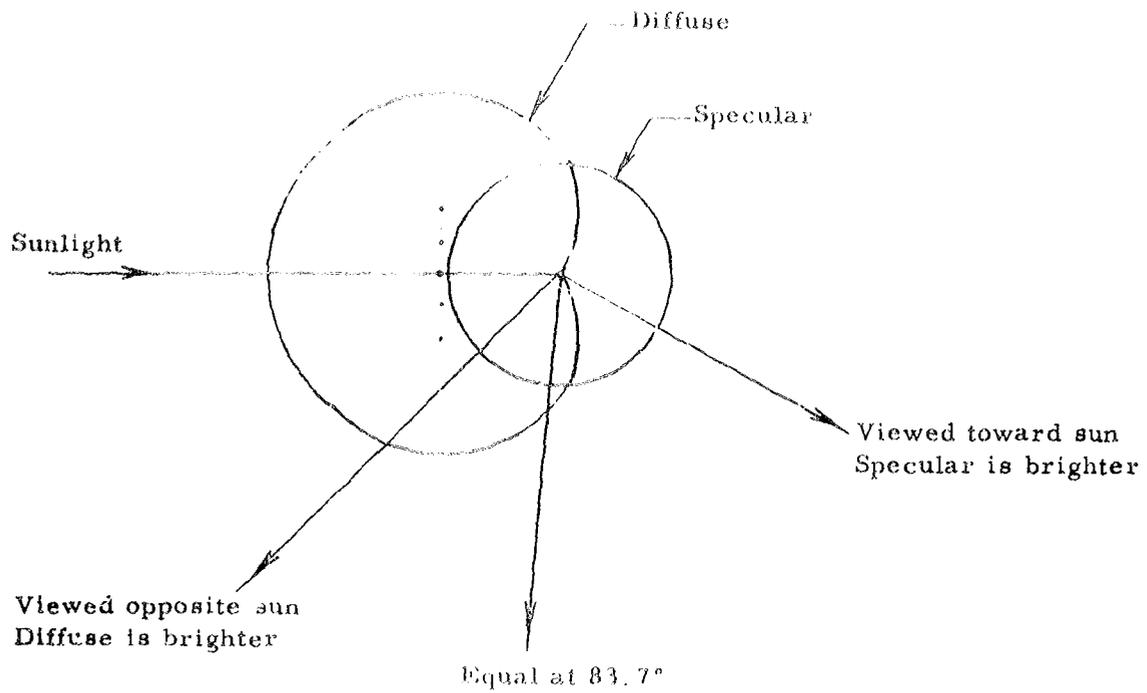


FIG. 3 .. ANGULAR DISTRIBUTION OF LUMINOSITY OF DIFFUSE AND SPECULAR SPHERICAL REFLECTORS ILLUMINATED BY SUNLIGHT

oxidized or corroded and a sphere covered with a mat white paint approximates the diffuse case. Exceptional surfaces could make the decision more difficult; for example, a metal foil which is inflated in flight. If such a balloon were to present an uneven surface consisting of a large number of small facets, it would probably approximate the diffuse case even if individual facets are specular.

Fig. 2(b) shows the size of white diffusely reflecting spheres necessary for detection with the naked eye when they are fully illuminated by the sun and appear against the backgrounds of Fig. 2(a). Fig. 4 shows the corresponding size of spheres necessary for visibility with a 40-inch telescope. However, the values given in Figs. 2 and 4 are based on average background brightness and do not take into consideration the irregular background that the moon actually presents. The values are therefore optimistic for those cases in which the light moon forms the background. Although the average albedo (reflectivity) of the moon is approximately seven per cent, the reflectivity of individual areas varies from about 4 per cent to 30 per cent or by a factor of seven. This, coupled with the wide range of sizes and shapes of individual areas, makes the problem most difficult.

It should be recalled, furthermore, that the detectability data are given for approximately threshold situations. This corresponds to the detection of a sixth magnitude star which is just visible to the average eye only when other conditions, such as the earth's atmosphere, are ideal. It should also be noted that, although telescopes offer a tremendous advantage

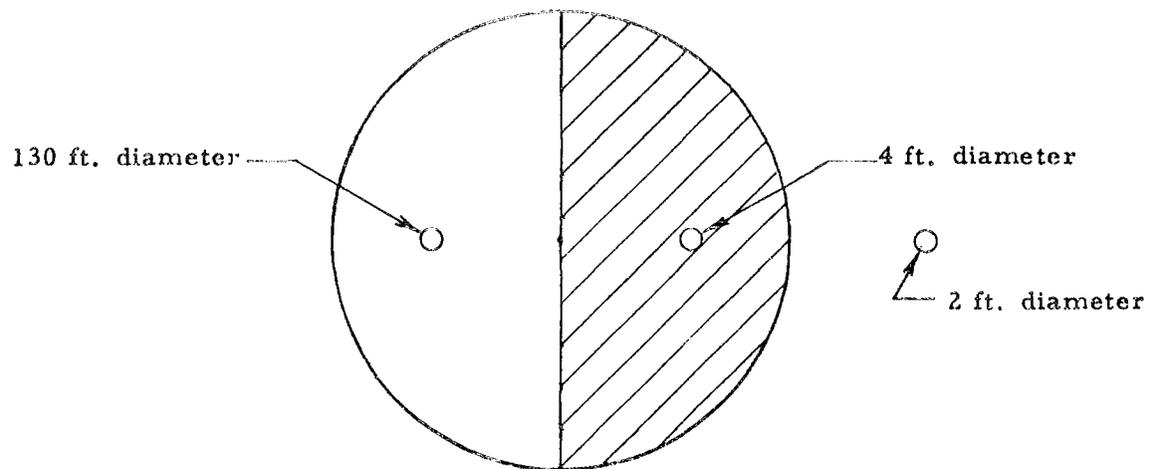


FIG. 4 - WHITE SPHERES VISIBLE WITH 40-INCH TELESCOPE

in visibility once an object is located, but their restricted field of view makes the problem of detection tracking more difficult.

#### D. Identification of Markers

One of the problems associated with markers on the moon is that of positive identification. The discussion thus far has dealt with visibility based on brightness contrast between an object and its background. The values given have been threshold or just visible values and were based on data obtained with uniform backgrounds. With the moon as a background, a number of possible solutions of this problem will be discussed here.

##### 1. Intense Source

One obvious method of insuring positive identification is to increase the intensity of source to well above that specified by threshold requirements. The associated disadvantage is, of course, greater quantities and size requirements.

##### 2. Color

Inasmuch as the contrasts present on the surface of the moon are those of brightness (white, gray, black), it seems reasonable that a colored object or source could be positively identified. Certain pyrotechniques produce brilliant chromatic emission and fluorescent paints are available in brilliant colors. Most likely the luminous efficiency achieved with colored materials would be lower than with white materials but some efficiency could advantageously be sacrificed in the interests of positive identification. Unfortunately, not enough is known about the subject of color contrast against irregular background in connection with point sources.

### 3. Intermittent Sources

Obviously, a source would be positively identified if it emitted intermittently at a known frequency. Presumably, a frequency could be chosen which would suffer a minimum confusion with those arising from natural phenomena. Eye response to pulsed sources must be considered. Hudson<sup>5</sup> gives the sensitivity of the eye for square pulse of light  $t$  seconds long by the equation

$$I = I_0 \left( \frac{t + t_c}{t} \right) \quad (4)$$

in which  $I_0$  is the threshold source intensity for steady light,  $I$  is the threshold intensity for the pulse under the same conditions, and  $t_c$  is called the critical duration or retinal action time. Various authors give values of  $t_c$  from 0.1 to 0.2 sec. If short duration pulses are used, the source intensity requirements may become prohibitive.

#### E. Marker Configuration

The effect of size, shape, and contrast in detection of targets has been investigated by Lamar and Associates.<sup>6</sup> Their work was done at two background levels, daylight and twilight. The average brightness of a full moon lies within their range of operation but dark moon and night sky levels fall far below so that their findings are applicable only in part. In addition, their investigation was restricted to uniform backgrounds which further limits its applicability. Nevertheless, their results with fine line targets suggest a promising approach to the lunar marker problem. They found that a line target whose width subtends only three seconds of arc is

detectable at a contrast of 1.0 to 2.0 (Contrast =  $\frac{DB}{B_0}$ ). The advantage of a line target against a non-uniform background like the moon is obvious since it would generally embrace a range of background levels whereas a point source is restricted to one level which may or may not be propitious.

#### F. Sodium Vapor

In 1955 U.S. experiments with sodium vaporization in atmosphere up to an altitude of 30 - 40 kilometers were begun for studying winds at these altitudes and the chemical reactions of gases in these atmospheric layers with sodium. On January 3, 1959, the Russians set a cloud formed of the sodium vapors in an atomic state. The sodium cloud is discharged at a specified moment and it glows because of resonance fluorescence emitting the sodium lines. The yellow light is preferred from the point of view of visual sensitivity. Furthermore, use of narrow band interference filters can enhance the contrast.

The brilliance of sodium cloud containing one kilogram of sodium and discharged 113,000 kms away from the earth is equal to a sixth magnitude star which is at the threshold of naked eye visibility against average sky background. These figures seem to agree closely with calculations based on experience with sodium emission in flame photometry. Using these figures it can be concluded that for detectability with naked eye at lunar distance, the amount of sodium required is:

against sky background - 10 Kgms  
against dark side of the moon -  $10^2$  Kgms  
and against bright side of the moon -  $10^5$  Kgms.

The sodium requirements are substantially reduced when appropriate telescope magnification is employed as discussed before.

One might envision a dual purpose use of solid propellant rocket motors as (1) retrodirective devices and (2) marking flares in the present context. The propellant, containing sodium, would be released on firing the rockets near the moon. It is quite likely that a known formulation can be used, thus precluding the costly development of a new special propellant formulation. Most likely, formulations currently undergoing development at NOTS will be applicable. These formulations include metal additives such as aluminum, boron, and magnesium.

Several factors would bear on the amount of light detectable such as missile configuration, spinning or tumbling and angle of viewing.

## Section Two

### Spectrographic Studies

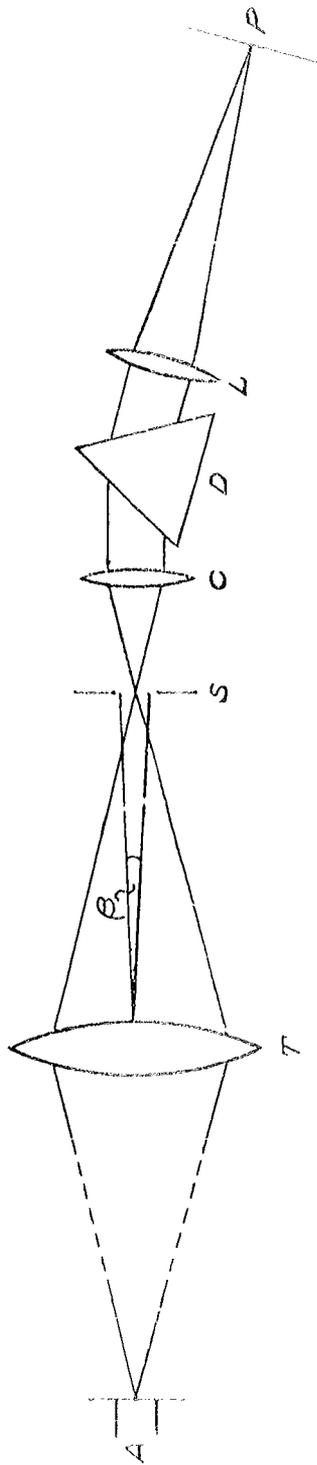
The performance of a given stellar spectrograph system examining emission spectra of the lunar blast depends primarily on two factors: (1) the amount of energy (in ergs/sec) radiated in each of the emission lines; (2) the separation and width in angstroms of the closest lines that need to be resolved. With these quantities known either the optimum exposure time can be computed or a calculated compromise can be made so that the desired exposure time is used for spectroscopy or high speed spectroscopy at the expense of over or under-exposing some of the lines. Tables relating the exposure time to the equivalent stellar magnitude of a lunar explosion are

therefore compiled. It should be emphasized at the outset that the spectrographic recording apparatus now in existence is unlikely to be substantially improved in the next few years and that this study is therefore restricted to discussing the capabilities of apparatus already in existence at various observatories. This study is divided into the following three parts: first, to derive an expression for the speed of a given telescope-spectrograph system; secondly, to substitute existing values for the various parameters and, thirdly, to present the results in tabulated form.

Consider a telescope focusing an image of a point source at the entrance slit of a dispersing system as in Fig. 5. The formation of the point image at S is not diffraction limited, due mainly to atmospheric turbulences, and to a lesser degree, to aberrations and imperfections in the telescope system. The size of the image is dependent on the seeing conditions at the time of observation. Thus, with  $\beta = 0.5 \times 10^{-5}$  ( $= 1$  sec of arc) the seeing is said to be good and with  $\beta = 1.0 \times 10^{-5}$  the seeing is said to be fair. The size of the image in the plane of the narrow slit is  $\beta F_1$  and, if this is unobstructed by the slit, the size of the image at the photographic plate is

$$S = \beta \frac{F_1 F_3}{F_2} = \beta \frac{D_1 F_3}{D_2} \quad (5)$$

This is the width of the spectrum that results from the seeing conditions and instrumental parameters alone and is denoted by  $S_{\perp}$  to differentiate it from  $S_{\parallel}$ , the image size parallel to the direction of dispersion. The slit width



A represents the unresolvable area of the nuclear detonation on the lunar surface.

T is the telescope objective of diameter  $D_1$  and focal length  $F_1$ .

$\beta$  is the angle subtended by the image at the objective T and specified the seeing condition (see text).

S is the spectrograph entrance slit.

C is the collimator lens of diameter  $D_2$  and focal length  $F_2$ .

D is the dispersing element of the spectrograph.

L is the spectrograph camera lens of diameter  $D_3$  and focal length  $F_3$ .

P is the photographic plate.

FIG. 5 - THE GENERAL LAYOUT OF STELLAR SPECTROGRAPH

$S_{11}$  corresponding to the linear resolution limit,  $\lambda$ , of the photographic plate is given by

$$S_{11} = \frac{F_2 \cos \rho}{F_3 \cos i} \lambda$$

where  $i$  and  $\rho$  are the incident and the refracted angles.

The fraction of the flux transmitted,  $T$ , by the slit is dependent on slit width and image intensity distribution. In order to derive a simple expression, we assume a uniformly bright square image for simplicity. In fact, of course, the intensity distribution in a star image generally follows a bell-shaped curve. It is then given by

$$T = \frac{S}{\beta F_1} = \frac{F_2 \cos \rho}{\beta F_1 F_3 \cos i} \lambda = \frac{D_2 \cos \rho \lambda}{\beta D_1 F_3 \cos i} \quad (6)$$

The effective resolving power  $R = \frac{\lambda}{\delta \lambda}$ , of the spectrograph is limited by  $\lambda$  when the aperture ratio of the camera is greater than  $f/40$ . Under such conditions

$$R = \frac{F_3}{\lambda} \frac{d\rho}{d\lambda} \lambda \quad (7)$$

Substituting (7) in (6) we have

$$T = \frac{D_2}{\beta D_1 R} \frac{d\rho}{d\lambda} \frac{\cos \rho}{\cos i} \lambda$$

Now the factors governing the amount of flux incident on the photographic emulsion are

- (1) the atmospheric transmission  $K_{at}$
- (2) the transmission of the telescope-spectrograph system  $K_{TS}$
- (3) the width of the spectrum  $S_L$
- (4) the linear dispersion of the spectrograph  $\frac{d\rho}{d\lambda} = \frac{\lambda}{AR}$

Combined, these expressions reduce the flux emitted by the point source  $B_0$  (in the solid angle subtended by the telescope aperture to the point source) to  $B_T$  the energy incident on the photographic plate per resolution area of the emulsion.

$$B_T = \frac{B_0}{\lambda S_L} \left( \frac{D_2}{\beta D_1 R} \frac{d\tau}{d\lambda} \frac{\cos \nu}{\cos \nu'} \lambda \right) (K_{\lambda\epsilon}) (K_{TS}) \left( \frac{l}{S_L} \right) \left( \frac{\lambda}{\mu R} \right)$$

ergs/resolution area

Dunham<sup>7</sup> suggests that the minimum density for recording an emission line on a photographic plate is 0.6. Eastman Kodak<sup>8</sup> quote a figure of  $3.0 \times 10^{-2}$  erg/cm<sup>2</sup> as the energy required to produce this density in the visible spectrum on 103a-0 emulsion, the usual emulsion used in stellar spectroscopy. For photographic resolution this corresponds to  $6.0 \times 10^{-6}$  ergs/resolution area; for 103a-0 emulsion the resolution area is  $1.0 \times \lambda^2$  sq mm where  $\lambda = 20\mu$ . It should be noted that equation (5) indicates that only for poor seeing conditions ( $\beta = 4$  sec of arc) and with the 200-inch telescope working at high resolution ( $F_3 = 2600$  mm, see equation (7)) does the spectrum width  $S_L$  exceed 1 mm. In all other cases, including those considered below,  $S_L$  is assumed constant at 1 mm. This can be achieved by using such techniques as Kapany's<sup>9</sup> Light Funnel or Bowen's<sup>10</sup> Image Slicer.

Table II lists the exposure times required to record a density of 0.6 on 103a-0 emulsion as a function of stellar magnitudes and spectrographic resolving powers. The quantities assumed constant are: the width of the

Table II

Stellar Magnitude	EXPOSURE TIME IN SECONDS		
	Resolving Power of 80,000	Resolving Power of 20,000	Resolving Power of 5,000
-21	$4.0 \times 10^{-7}$	$2.5 \times 10^{-8}$	$1.6 \times 10^{-9}$
-19	$2.5 \times 10^{-6}$	$1.6 \times 10^{-7}$	$1.0 \times 10^{-8}$
-17	$1.6 \times 10^{-5}$	$1.0 \times 10^{-6}$	$6.2 \times 10^{-8}$
-15	$1.0 \times 10^{-4}$	$6.2 \times 10^{-6}$	$4.0 \times 10^{-7}$
-13	$6.2 \times 10^{-4}$	$4.0 \times 10^{-5}$	$2.5 \times 10^{-6}$
-11	$4.0 \times 10^{-3}$	$2.5 \times 10^{-4}$	$1.6 \times 10^{-5}$
-9	$2.5 \times 10^{-2}$	$1.6 \times 10^{-3}$	$1.0 \times 10^{-4}$
-7	$1.6 \times 10^{-1}$	$1.0 \times 10^{-2}$	$6.2 \times 10^{-4}$
-5	1.0	$6.2 \times 10^{-2}$	$4.0 \times 10^{-3}$
-3	6.2	$4.0 \times 10^{-1}$	$2.5 \times 10^{-2}$
-1	$4.0 \times 10^1$	2.5	$1.6 \times 10^{-1}$
1	$2.5 \times 10^2$	16	1.0
3	$1.6 \times 10^3$	$10^2$	6.2
5	$1.0 \times 10^4$	$6.2 \times 10^2$	$4.0 \times 10^1$
7	$6.2 \times 10^4$	$4.0 \times 10^3$	$2.5 \times 10^2$
9	$4.0 \times 10^5$	$2.5 \times 10^4$	$1.6 \times 10^3$
11	$2.5 \times 10^6$	$1.6 \times 10^5$	$1.0 \times 10^4$

spectrum,  $S_{\lambda}$ , at 1 mm, the resolution limit,  $\lambda$ , of the 103a-0 emulsion at  $20\mu$ ; the diameter of the collimator objective at 200 mm; the angular dispersion of the grating (of 15,000 lines per inch and used in the second order) at 1.26 radians/ $\text{\AA}$ ; the transmission factor of the telescope-spectrograph system  $K_{TS}$  assumed to be 10 per cent and fair seeing conditions ( $\beta = 1.0 \times 10^{-5}$  radian). In order to calculate the flux required to produce a photographic density of 0.6, the measurements of Pettit and Nicholson<sup>11</sup> at the Mount Wilson Observatory were used. They found that 0.244 ergs/sec of radiation were incident over the aperture of the 100-inch telescope from a 1.0 magnitude star in the zenith for a mean wavelength of 5000  $\text{\AA}$ . The relationship between stellar luminosity and magnitude is given as follows:

$$m_2 - m_1 = 2.5 \log_{10} \frac{l_1}{l_2}$$

where  $m_1$  and  $m_2$  are the stellar magnitudes and  $l_1$  and  $l_2$  are their relative apparent luminosities.

The exposure times listed in Table II apply to three different spectrograph systems attached to the 100-inch Mount Wilson telescope; they can be converted to the exposure times for a 25, 50 or 200-inch aperture telescope by multiplying the exposure times by 4, 2, or 0.5 respectively. Similarly, for good and poor seeing conditions with the 100-inch telescope, the exposure times are respectively halved and doubled.

Table II does not include the variations in atmospheric transmission ( $K_{at}$ ) which are functions of wavelength and zenith angle. Stebbins and Whitford<sup>12</sup> have published some observed values of atmospheric spectral

transmission about the Moon with an Observatory. These observed values are of importance because they include not only molecular scattering effects but also transmission losses due to haze and the selective absorption of the atmosphere. These results have been used to determine the variation of atmospheric transmission with zenith angle and are shown in Table III for zenith angles of 0°, 20° and 40°.

Table III

Wavelength	0°	20°	40°
3530 A	64%	62%	56%
4220	78%	77%	73%
4880	86%	85%	82%
5700	89%	88%	86%
7190	95%	95%	94%
10300	97%	97%	97%

High speed spectroscopy of the lunar blast and infrared measurements of the moon in the vicinity of the blast would yield information regarding: (a) composition of lunar materials, (b) thermal properties of lunar materials, and (c) the associated exciting phenomenon. High speed spectrographs, using various types of image dissectors and rotating drums have been developed. Some of these instruments have been used for high speed photography and spectroscopy of explosions on earth using speeds of the order of  $10^7$  to  $10^9$  frames per second. However, due to the complex image dissecting systems used, the spatial resolution and light efficiency of these systems is, in general, poor. Need for development of efficient high speed cameras in conjunction with astronomical telescopes is therefore indicated. Furthermore, with

the recent emphasis on balloon carried telescopes, it would seem that more efficient high speed photography systems with wider spectral range in the UV and IR will have to be developed.

#### A. Stellar Spectroscopy Above the Ozone Layer

The point of interest in high altitude spectroscopy is whether the recording range can be extended from the visible into the atmospheric attenuated ultra-violet as well as infrared regions of the spectrum. The main problem here is to lift a telescope-spectrograph by balloon to a height of 150,000 ft., i.e., above the ozone layer, to stabilize the motion of the balloon and to direct the telescope so that the image of the detonation lies across the entrance slit of the spectrograph. This presents a large number of practical problems in precision tracking and stabilizing instrumentation as well as development of large payload balloons.

Assuming this problem is solved, then the telescope-spectrograph system is working under ideal conditions and the size of the primary image is that of a diffraction-limited system. That is, the seeing condition  $\beta$ , taken as  $10^{-5}$  radians in Table II is substantially reduced. Consider a 24-inch telescope, the value for  $\beta$  in the diffraction-limited case is given by

$$\beta = \frac{1.22 \lambda}{D} \text{ radian}$$

where  $\lambda$  is the wavelength used and D is the diameter of the aperture.

Putting  $\lambda = 5000 \text{ \AA}$  and  $D = 24''$  we then have  $\beta = 10^{-6}$  radians. If, in equation (8) the ratio of  $\frac{D_2}{D_1}$  is kept constant and the same values for the resolution, etc., are used as for the 100-inch telescope, then the speed

will be altered in the ratio

$$\frac{D_{24''}}{B_{24''}} \bigg/ \frac{D_{100''}}{B_{100''}} = \left(\frac{24}{100}\right) \left(\frac{10^{-5}}{10^{-6}}\right) = 2.4$$

Hence, the 24-inch telescope, working under ideal conditions, will be 2.4 times as fast as the 100-inch telescope at Mount Wilson working under fair seeing conditions. If a 12-inch telescope is substituted for the above 24-inch telescope, then the speed is 0.6 times that of the 100-inch telescope.

If a telescope 12 inches or more in diameter could be carried to a height of 150,000 feet with a spectrographic system attached to it (it should be noted that for a resolution of 80,000, 20,000, or 5,000 the focal length of the camera would be 2,600 mm or 160 mm respectively for a 15,000 lines/inch grating in the second order) then the spectral range would be limited by the reflectivity of the different components of the system. Aluminum is the usual reflection coating used through the visible spectrum; it has a reflection coefficient of over 85 per cent through the visible spectrum and down to about 2000 Å, but then the reflectivity falls nearly linearly to 10 per cent at 1000 Å.

### Section Three

#### Infrared Measurements for Determination of Lunar Thermal Conductivity

The infrared measurements of the moon's surface temperature being considered consist of collecting the radiant flux from a one square mile area centered about ground zero, and obtaining a complete time vs

temperature record of this region. The information obtained from such a measurement would enable one to estimate the thermal conductivity on the basis of the rate of cooling, and would yield the same type of information previously obtained by infrared measurements during total lunar eclipses<sup>13</sup> except that information could now be obtained at very much higher temperatures, and with the additional advantage that more sensitive measurements are possible now due to the development of highly sensitive photoconductive detectors such as the lead sulfide cell.

The measurements made during lunar eclipses have indicated a rapid cooling rate showing that the conduction of heat into or out of the interior of the moon is very slow. This very poor thermal conductivity could be attributed to the layer of highly porous, dust-like material thought to be blanketing the moon's surface. Infrared measurements made during a lunar detonation might yield radically different results, since if a surface burst is employed, a very large amount of thermal energy would be deposited in the lunar material beneath this porous covering, and the thermal conductivity of this material may be considerably greater. Thus, one might anticipate a slower rate of cooling to be measured under these conditions than has previously been measured during the lunar eclipse measurements.

The sensitivity of measurements of temperature of regions of the moon in the vicinity of the blast is a function of the absolute temperature of the area being compared. For instance, if the area closest to ground zero is at a temperature of 1510°C and the area further from the burst is at a

temperature of 1500°C, the ten-degree difference in temperature would produce a difference in the total radiation collected by a one square meter telescope mirror of  $2 \times 10^{-8}$  watts and in the lead sulfide region (1.0 - 2.8 $\mu$ ) to a difference of  $1.3 \times 10^{-8}$  watts. Since the noise equivalent power of present day lead sulfide detectors is approximately  $10^{-11}$  watts, this signal can be easily detected by such a photoconductive detector. We can see from the very low noise characteristics of these detectors that temperature differences of considerably less than 10°C can be detected at an absolute temperature of 1500°C. At an absolute temperature of 200°C, the same 10°C difference in temperature would produce a difference in the radiation collected by the one square meter mirror of  $0.73 \times 10^{-11}$  watts in the lead sulfide region. This quantity of flux is approximately equal to the noise equivalent power of the cell, however, and would produce a signal-to-noise ratio of one. In order to detect this 10°C difference at 200°C, one could employ a larger telescope mirror so that the signal-to-noise ratio would be increased until the signal could be resolved.

In the above calculations the transmission of the earth's atmosphere was chosen as 30 per cent, and the moon was considered as performing as a perfect blackbody with an emissivity of unity. The total flux collected at the earth's surface from a unit area of the moon's surface is then given by the expression

$$W = \frac{\sigma_0 \epsilon^4}{r^2} T_{00} \cdot A_0$$

where  $a$  = emissivity of the moon

$\sigma$  = Stefan-Boltzman constant

$t$  = temperature in °K

$r$  = moon-earth distance

$T_{at}$  = transmission of the earth's atmosphere

$A_c$  = area of the telescope mirror

The table shown below illustrates the flux collected by a one square meter mirror from one square mile of the moon's surface which is maintained at the six different temperatures listed. The total radiation as well as the radiation in the lead sulfide (1.0 - 2.8 $\mu$ ) and lead selenide (1.0 - 7.0 $\mu$ ) regions is shown.

T °C	Total (watts)	PbS( watts)	PbSe(watts)
200	$4.66 \times 10^{-9}$	$2.35 \times 10^{-11}$	$1.59 \times 10^{-9}$
500	$3.38 \times 10^{-8}$	$3.04 \times 10^{-9}$	$2.30 \times 10^{-8}$
1000	$2.47 \times 10^{-7}$	$9.75 \times 10^{-8}$	$2.19 \times 10^{-7}$
1500	$9.26 \times 10^{-7}$	$5.46 \times 10^{-7}$	$8.43 \times 10^{-7}$
2000	$2.47 \times 10^{-6}$	$1.61 \times 10^{-6}$	$2.10 \times 10^{-6}$
3000	$3.60 \times 10^{-5}$	$2.05 \times 10^{-5}$	$2.34 \times 10^{-5}$

The noise equivalent power for each of the three types of detectors listed above can be taken as  $10^{-7}$  watts for the total radiation detector (bolometer),  $10^{-11}$  watts for the lead sulfide cell and  $10^{-9}$  watts for the lead selenide cell. It can be seen, therefore, that the lead sulfide cell gives the highest signal-to-noise ratios at all temperatures, and at 200°C temperature determinations can only be made with this cell since the total radiation

detector and lead selenide cell yield signal-to-noise ratios of less than two. Thus, a lead sulfide detector is the best suited for this type of measurement. The size of the detector to be employed will be dependent upon the intensity distribution in the diffraction pattern in the image plane of the telescope and will, therefore, be governed by the atmospheric "seeing" conditions and to a lesser extent the diameter of the objective mirror of the telescope.

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Chapter IV  
SEISMIC OBSERVATIONS ON THE MOON

## Chapter IV

### SEISMIC OBSERVATIONS ON THE MOON

Seismic observations on the moon are of great potential interest from the viewpoint of fundamental theories of the development of the solar system and of the moon itself. Determination of the physical structure of both the outer layers and core of the moon would go far in permitting choice between various suggestions as to the origin and early history of our satellite.

It is not certain how much seismic energy will be coupled into the moon by an explosion near its surface, hence one may develop an argument that a large explosion would help ensure success of a first seismic experiment. On the other hand, if one wished to proceed at a more leisurely pace, seismographs could be emplaced upon the moon and the nature of possible interferences determined before selection of the explosive device. Such a course would appear to be the obvious one to pursue from a purely scientific viewpoint.

In the event high sensitivity seismic detectors could be emplaced on the moon and the noise levels were sufficiently low, one might gain valuable information either from the impact of meteorites or of rockets undergoing hard landing on the moon or from natural quakes if such quakes exist.

We shall outline here some general aspects of seismic observations and possible instrumental configurations and also attempt a rough calculation on the detectability of detonations of various magnitudes.

## Section One

### The Nature of Seismic Observations

From the point of view of seismology, observational data indicates that we may consider the earth and presumably the moon as large elastic spheres that are essentially homogeneous and isotropic insofar as local variations in elastic properties are concerned. The mechanical energy involved in any local deformation of such a sphere will be propagated in part in the form of elastic waves moving out from the focus of the deformation to every part of the sphere. Considerations based on an infinitesimal strain theory of elasticity lead to the conclusion that there are two possible types of body waves in such media. One, which is transmitted with the speed  $a = \sqrt{(\lambda + 2\mu)/\rho}$ , is a compressional body wave designated as the P wave in seismology. The second, which travels with a speed  $\beta = \sqrt{\mu/\rho}$ , the S wave of seismology, is a transverse wave. In these equations,  $\lambda$  and  $\mu$  are the Lamé stress constants,  $\mu$  is a measure of the rigidity of the material, and  $\lambda$  is related to the incompressibility of the media,  $k$ , through the equation  $k = \lambda + \frac{2}{3}\mu$ .

When these waves reach the surface they cause that surface to undergo a complex periodic motion. A properly designed seismometer is able to record one or more of the translational components of that motion. The two types of body waves move with distinct velocities, and, therefore, arrive at a distant station at different times. Their arrival is usually recorded as distinct motions in time of the seismic mass relative to the surface.

As a preliminary, we shall first discuss various aspects of terrestrial seismology and then proceed to the main question of seismic observations on the moon. Within the earth's interior, there are regions wherein decided changes in elastic properties occur. Either type of body wave incident upon such regions of discontinuity will, in general, give rise to both reflected waves and refracted waves of both compressional and transverse character. The complex system of waves arising from the reflections and refractions at the several regions of discontinuity ultimately reach the surface to be recorded, in turn, by the seismometer. In addition to the body waves, the typical seismograph records the arrival of various types of surface waves that have travelled through the outermost layers of the crust to the station. The complicated record of the arrival of all of these varied wave pulses constitutes the basic observational data of seismology. Fig. 1 is a representation of the ray paths for a few of the possible types of wave pulses that might reach a station on the earth's surface from a disturbance whose focus is within the mantle. The major zones within the earth, based on seismic data of the variation of velocity with depth, are indicated. The details of this pattern will be discussed in Section Two. For our purposes here we have indicated only the mantle which extends to a depth of 2900 km and beneath this layer core of the earth. Within the core a further subdivision occurs at a depth of about 5100 km. This central portion of the earth is called the inner core. The notation used to identify the various types of rays is the following: For compressional waves within the mantle, P is used. Shear waves within the mantle are designated by S. For compressional waves within the core, we

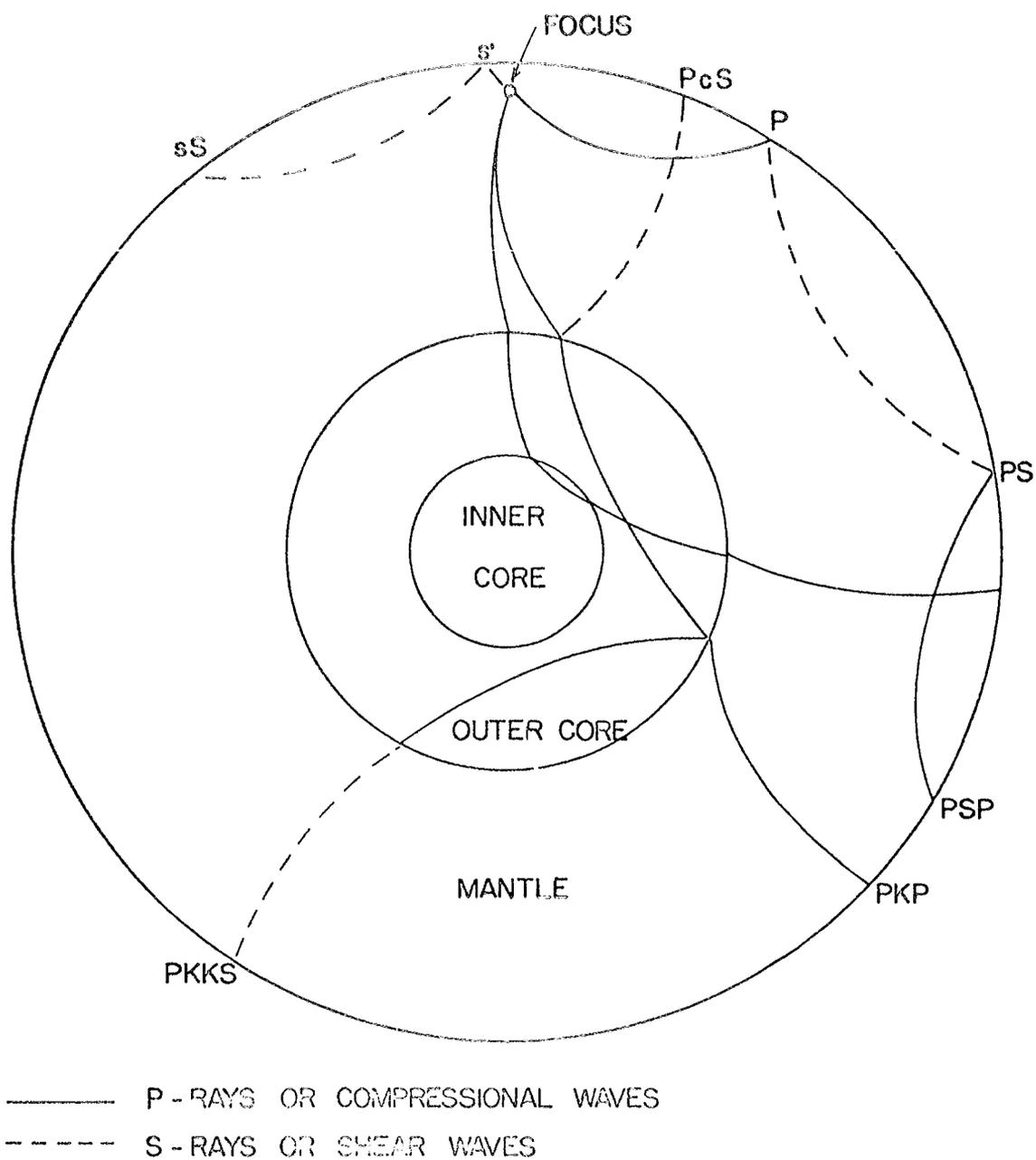


FIG. 1 - PATHS OF SEISMIC RAYS WITHIN THE EARTH.

use K. No shear waves have been observed within the core so that no symbol need be specified for such a ray. To indicate that a reflection has occurred at the core a small letter c is placed between the capital letters designating the incident ray and the reflected ray in this manner, PcP.

The short rays moving upward to the surface from the focus are designated by small letter s or p, depending upon whether the wave is a shear wave or compressional wave.

In the seismographs taken at stations some distance from the focal point of a disturbance within the earth, it is possible to determine the time of arrival of many of the waves described above. A knowledge of the locus of the focal point of the disturbance, the time of occurrence of the disturbance, and the time of arrival of a given wave pulse at various stations enables one to construct a travel timetable giving the time required for a given pulse to travel the distance from the focus to the point of observation. The most comprehensive data of this type for the earth have been compiled by Gutenberg and Richter and by Jeffreys and Bullen. Travel time curves for several of the types of wave paths occurring within the earth are illustrated in Fig. 2.

These tables are the basic tools for the interpretation of seismic data for the earth. With their use it has been possible to obtain an accurate knowledge of the variation of velocity of both shear and compressional body waves with depth within the earth. In terms of their variation, together with some further assumptions and known properties of the earth, it has been

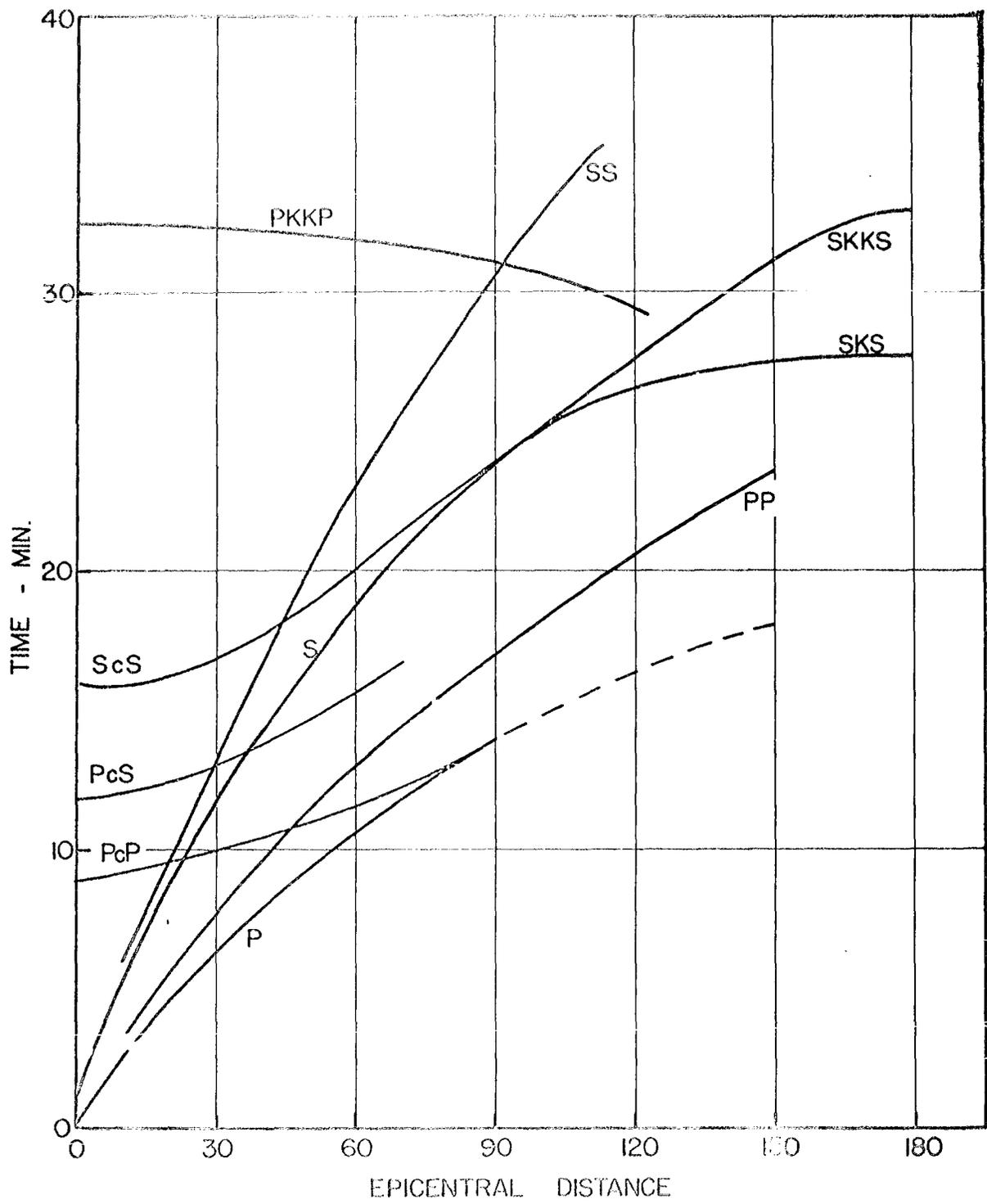


FIG. 2 - TRAVEL TIME CURVES FOR SEISMIC WAVES IN THE EARTH.

possible to determine the variation with depth of such quantities as density, pressure, and the elastic constants of the earth's interior.

## Section Two

### The Structure of the Earth's Interior

If we consider the variation of velocity of seismic waves with depth, we can distinguish three major zones within the earth's interior. The first zone is the crustal layer varying in depth between 30 and 40 km over the large continental land masses and between 5 - 6 km under the large ocean areas. This region is heterogeneous in those properties which relate to the movement of seismic waves, and velocities of both P and S waves within it are very variable. From the lower surface of the crust, the Mohorovicic discontinuity, to a depth of approximately 2900 km lies the mantle. This region is characterized by steadily increasing velocity of seismic waves with depth and is believed to consist of dunite, a hard, dense rock made up largely of the mineral olivine, a silicate of magnesium and iron  $(Mg, Fe)_2SO_4$ .

At the surface olivine has a density of about  $3.3 \text{ gm/cm}^3$ . Since the density of the earth as a whole is of the order of  $5.52 \text{ gm/cm}^3$  this implies that the interior of the earth beneath the mantle must have a very high density. Seismic evidence indicates for the core of the earth a density of the order of 10 to  $12 \text{ gm/cm}^3$ , a very low rigidity, and a marked decrease in the velocity of compressional waves. The most reasonable assumptions appear to be that the core consists largely of iron or of an iron nickel mass in the molten state and under very high pressures.

A more careful analysis of the velocity depth curves reveals a still finer subdivision of the three major zones mentioned above into regions wherein marked changes either in velocity or velocity gradient occur. These subdivisions are presented in Table I taken from Bullen<sup>1</sup> whose analysis is based on the velocity depth curves of Jeffreys. In addition, we have included Fig. 3 which gives the velocity depth curves for the earth as developed by Bullen. It will be observed that the curve for S waves does not continue beyond the lower surface of the mantle at a depth of 2900 km. The absence of data revealing the passage of a shear wave through the core of the earth is one of the major facts of seismology and attests to the molten state or at least very low rigidity of the earth's core.

This discontinuity is further marked by the drastic drop in the velocity of P waves at this same level. The minor variation in the velocity of P waves at a depth 5121 kms attests to the existence of an inner core within the core.

If we know the variation of the velocity of shear waves and compressional waves and, therefore, the variation of the Lamé constants  $\lambda$  and  $\mu$  with depth, then the assumption that the stress within the earth's interior is essentially equivalent to a hydrostatic pressure leads to the following differential equation relating density and the distance  $r$  from the center of the earth.

$$dp/dr = -\gamma m \rho / r^2 \phi$$

$\gamma$  = gravitational constant

$m$  = mass of earth in a sphere of radius  $r$

$\rho$  = density at distance  $r$

$$\phi = a^2 - 2/3 \rho^2$$

Table 1

DIMENSIONS AND DESCRIPTIONS OF INTERNAL LAYERS OF  
THE EARTH

		Depth to Boundaries in Km	Feature of Region
		0	
Crust	A	33	Conditions fairly heterogeneous
	B	413	Probably homogeneous
Mantle	C	984	Transition region
	D		Probably homogeneous
		2898	
	E	4982	Homogeneous fluid
Core	F	5121	Transition layer
	G	6371	Inner core

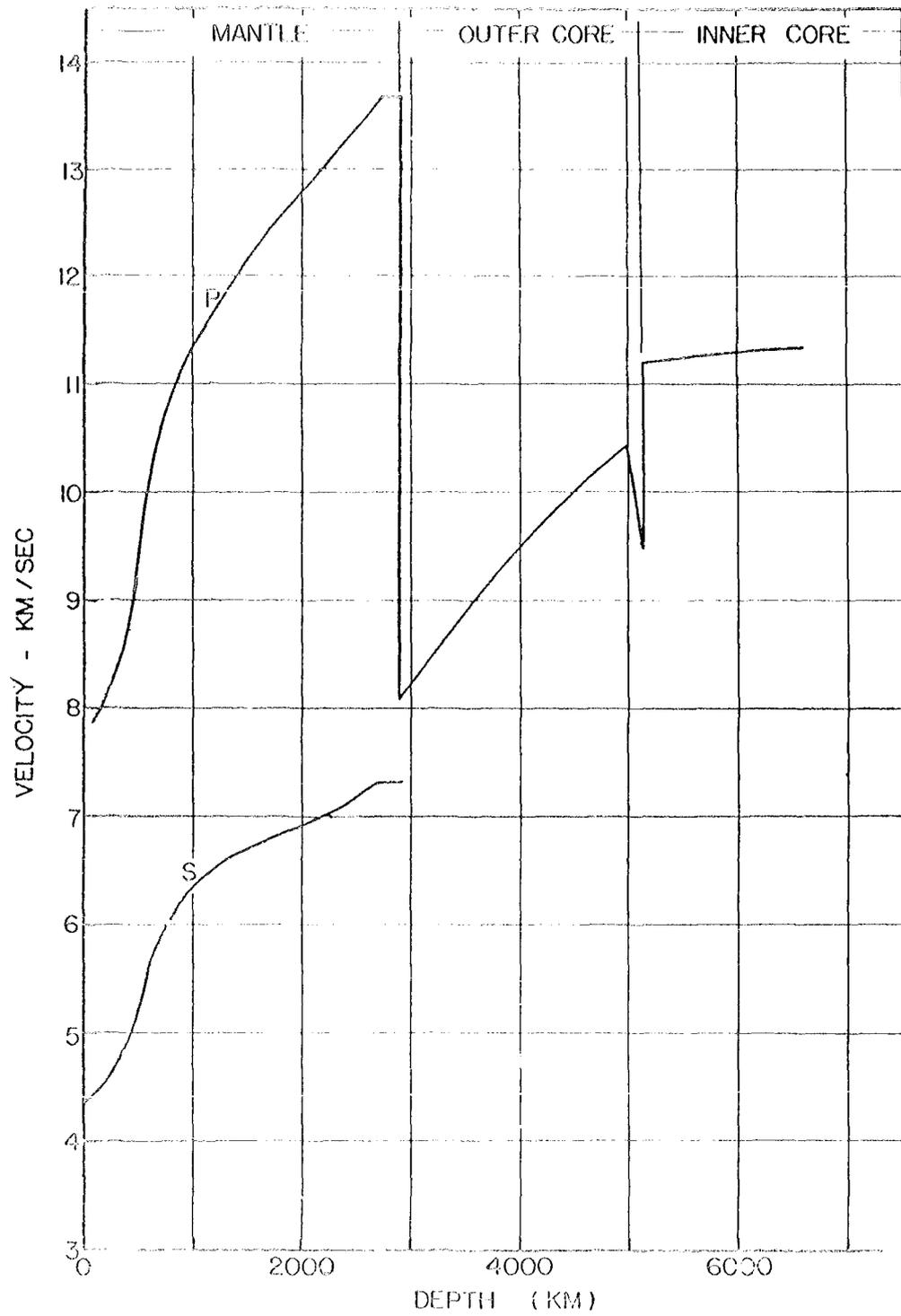


FIG. 3 - VARIATIONS OF P & S WAVE VELOCITIES WITH DEPTH IN THE EARTH.

If we add the boundary conditions implied in the known mass of the earth,  $5.977 \times 10^{27}$  gms, and the known moment of inertia,  $8.104 \times 10^{44}$  gm cm<sup>2</sup>, then by certain reasonable assumptions as to the nature of the material of the core and the lower layers within the mantle the integration of this equation leads to a determination of the variation of density with depth within the earth.

If  $m$  is the mass of the material within a sphere of radius  $r$ , then, since the stress in the earth's interior is essentially equivalent to a hydrostatic pressure

$$dP/dr = -\gamma m\rho/r^2$$

and a knowledge of the density variation with depth allows the evaluation of the variation of pressure with depth. Finally, since the velocities of the compressional wave,  $P$ , and the shear wave,  $S$ , are known in terms of the density and the values of  $\lambda$  and  $\mu$ , then the variation of  $\lambda$  and  $\mu$  with depth can be established. In terms of these, such elastic properties as the bulk modulus of the earth's interior is obtainable.

Table II is a compilation of the density, gravity, and pressure distribution in the earth due to Bullen.

### Section Three

#### Why A Seismological Investigation of the Moon?

One of the fundamental problems of the seismology of the moon that needs to be investigated is the level of background noise or seismic activity. This investigation would involve only the placement of a single seismometer at a single location upon the moon's surface. For the earth there is a

Table II

## DENSITY, GRAVITY AND PRESSURE DISTRIBUTION WITHIN THE EARTH

Depth km	Density gm/cm <sup>3</sup>	Gravity cm/sec <sup>2</sup>	Pressure x 10 <sup>12</sup> dynes/cm <sup>2</sup>
33	3.32	985	0.009
100	3.38	989	0.031
200	3.47	992	0.065
300	3.55	995	0.100
400	3.63	997	0.136
413	3.64	998	0.141
500	3.89	1000	0.173
600	4.13	1001	0.213
700	4.33	1000	0.256
800	4.49	999	0.300
900	4.60	997	0.346
1000	4.68	995	0.392
1200	4.80	991	0.49
1400	4.91	988	0.58
1600	5.03	986	0.68
1800	5.13	985	0.78
2000	5.24	986	0.88
2200	5.34	990	0.99
2400	5.44	998	1.09
2600	5.54	1009	1.20
2800	5.63	1026	1.32
2898	5.68	1037	1.37
2898	0.43	1037	1.37
3000	9.57	1019	1.47
3200	9.85	979	1.67
3400	10.11	934	1.85
3600	10.35	892	2.04
3800	10.56	848	2.22
4000	10.76	803	2.40
4200	10.94	758	2.57
4400	11.11	716	2.73
4600	11.27	677	2.88
4800	11.41	646	3.03
4982	11.54	626	3.17
5121	14.2	585	3.27
5400	-	460	3.41
5700	-	320	3.53
6000	-	177	3.60
6371	17.2	0	3.64

considerable background of seismic noise. This is due to such factors as the activity associated with civilization, the movement of trees with the wind, the movement of atmospheric storms over the surface, and possibly the pounding of the surf along the shores of the oceans. Upon the moon all such activity will be absent. Dr. Jack Oliver, a seismologist of the Lamont Geophysical Laboratory of Columbia University, New York City, has expressed the opinion to us that, as a consequence, the moon would be expected to be seismically very quiet. The only probable sources of background seismic noise within the moon would be the natural vibrations induced in it as an elastic solid in response to uneven gravitational pulls of the earth and possibly other planets within the solar system, together with the "creaking noise" associated with the adjustment of large masses of rock to the resulting uneven stresses. The periods associated with the natural frequencies of an elastic sphere of the size of the moon are much larger than the periods of the usual seismic waves of interest in seismology or those associated with explosions. Special design of instrumentation is required to achieve the ability to record such waves. A program for the development of such instrumentation to measure the corresponding periods for the earth are even now being carried out at Lamont Geophysical Laboratories. The required long period seismometers have not yet been devised. On the earth the seismic noise background, usually called microseisms, is of the amplitude level of 0.1 to 10.0 microns. That background noise on the moon attributable to the constant re-adjustment of large rock strata to the uneven stresses due

to the gravitational pull of the earth would then be expected to be no larger in amplitude and is probably much lower. It will be of importance to monitor this background level for a period of time to determine its absolute value, the nature of its variation with time, and the characteristics it exhibits. The accomplishment of this phase of the investigation, assuming that a single functioning instrument package can be landed on the moon, requires the minimum of equipment that would be involved in any seismic investigation.

Upon the basis of the current hypothesis of the structure of the moon's interior, one would anticipate no large amount of moonquake activity.

This hypothesis assumes the moon has no liquid core and that it consists of a layer of mantle-type rock overlying a small solid core of iron or nickel-iron. Upon the earth the great majority of earthquakes arise within the crustal layer as the result of volcanic activity or the adjustment of excessive strains along fault lines. Only a small proportion have been recorded as originating in the underlying mantle rock and these only in the shallowest layer.

In the absence of volcanic activity and a crustal layer for the moon, we must anticipate that a moonquake can be only a very rare occurrence. Yet this is all hypothesis and the recording of none or little moonquake activity is an important experimental fact with which to judge any theory of the structure and the formation of the moon. Upon the earth although a major earthquake is fortunately rare, yet an earthquake of low intensity is very common. This is against a relatively high background activity. Thus,

if for any reason there should be moonquakes, then since the background noise will be low, one would expect a considerable amount of interpretable data from a single seismometer.

What has been said so far envisages the placement of a single seismometer upon the moon and does not involve even the explosion of a single bomb whether of a nuclear or chemical type.

If we enlarge the scope of planned instrumentation to include the possibility of placing three widely-spaced instrument packages, we can expect to gain additional information. The presence of three recording seismometers increases the possibility of obtaining usable records, increases the possibility of verification and cross-checking of instruments and, in addition, allows for the construction of elementary travel timetables.

It is to be remembered that the travel timetables for the earth are the result of a long and continuous statistical analysis of a large body of seismic data taken by a wide coverage of instruments.

Our moon tables can be only a crude beginning, yet can offer a wealth of information relative to its interior and surface layers. Assuming some seismic activity whether due to moonquakes, or the collision of meteorites with the surface, or for whatever causes, we could immediately obtain some general and far reaching conclusions for the structure of the moon, its surface layers, and its history. The velocity of body waves and, therefore, the elasticity of the medium, at least within its mantle, would be an immediate result. The existence or non-existence of a layered structure

within the immediate sub-surface areas of the moon could be established. If we are fortunate the existence of a core and the absence of a liquid core can be confirmed. Some ray paths are shown in Fig. 4.

If we have some approximation to the variation with depth, we can obtain an idea as to density variation and pressure variation with depth. In short, the path laid out by the analysis of the structure of the earth's interior from seismic data becomes at least partially available for the moon. This has hypothecated observable seismic activity upon the moon.

If we further hypothecate the explosion of a nuclear or even chemical bomb, we then have the possibility of certain determination of at least the immediate sub-surface structure of the moon. The existence of any pronounced sub-surface discontinuities will certainly be revealed. The elasticity, density, and pressures within these layers will have been determined. The certain occurrence of surface waves will add to the information obtainable.

#### Section Four

##### The Nature of the Requirement for Instrumentation

As ordinarily constructed, a seismometer would ideally record some component of the relative motion of the earth's surface with respect to its quiescent state. In seismology the components normally measured are one or more of the three translational components of that relative motion. The rotational components are so small at all observational points except within the immediate vicinity of the focal point of the disturbance that they are not recorded. To measure this component of displacement would

- P ——— COMPRESSION WAVE IN MANTLE
- S - - - - SHEAR WAVE IN MANTLE
- K ——— COMPRESSION WAVE IN CORE
- S' - - - - SHEAR WAVE IN CORE
- c ——— REFLECTION OF CORE SURFACE

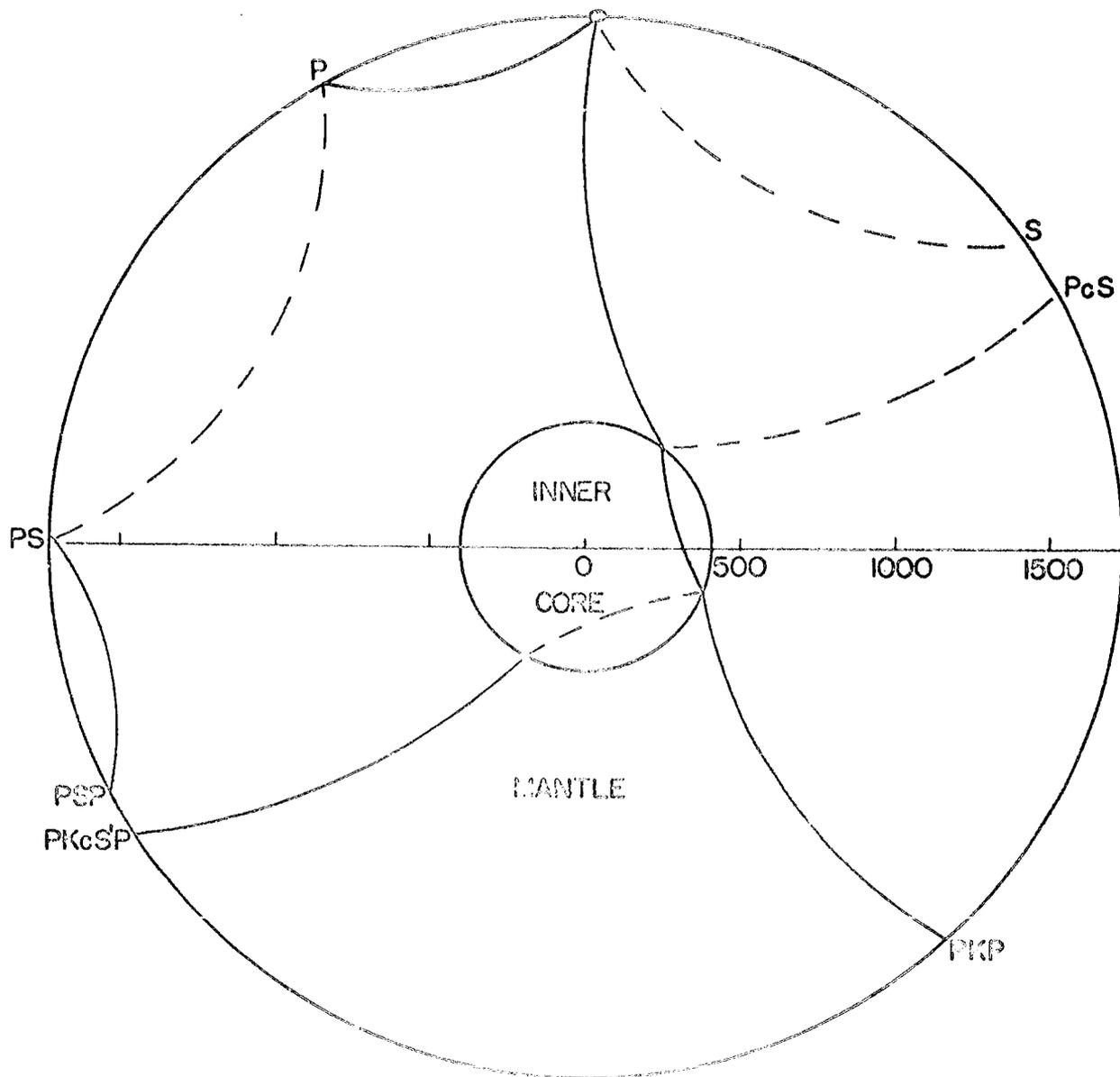


FIG. 4 - POSSIBLE SE. PATHS OF THE EARTH'S INTERIOR AND RESULTING SEISMIC WAVE PATTERNS.

some point of a material body that remains fixed in space as the earth's surface undergoes its motion under the influence of the passing seismic wave. One way of providing such a point is to suspend or support a mass on a spring from a rigid frame that moves with the earth. The softer the suspension and consequently the longer the period of such a mass, the more nearly does its motion relative to the frame and thus the earth represent the quantity we wish to measure. An alternative is to use a pendulum, in the usual case for seismological observations, a horizontal one. For a pendulum, we also require that some point relative to the pendulum mass remains fixed in space if the point of suspension moves with the rapid motion of the earth. If the period of the earth's motion, normally less than 30 seconds, is much less than the free period of the pendulum, the center of oscillation of the pendulum system is such a point. For a physical pendulum this is that point at which all mass may be conceived to be concentrated so that a simple pendulum whose length is the distance from this point to the point of suspension and with the same mass would have the same period. For seismic instruments designed as permanent installations at observatories on the earth, these principles have resulted in typically large installations with relatively large masses and long beams. The instruments are firmly anchored to large concrete pillars resting on bedrock if possible. Major problems have involved those associated with obtaining a recording without undue reaction by the recording mechanism upon the instrument in the form of resistance or the coupling of the material oscillations of the recorder.

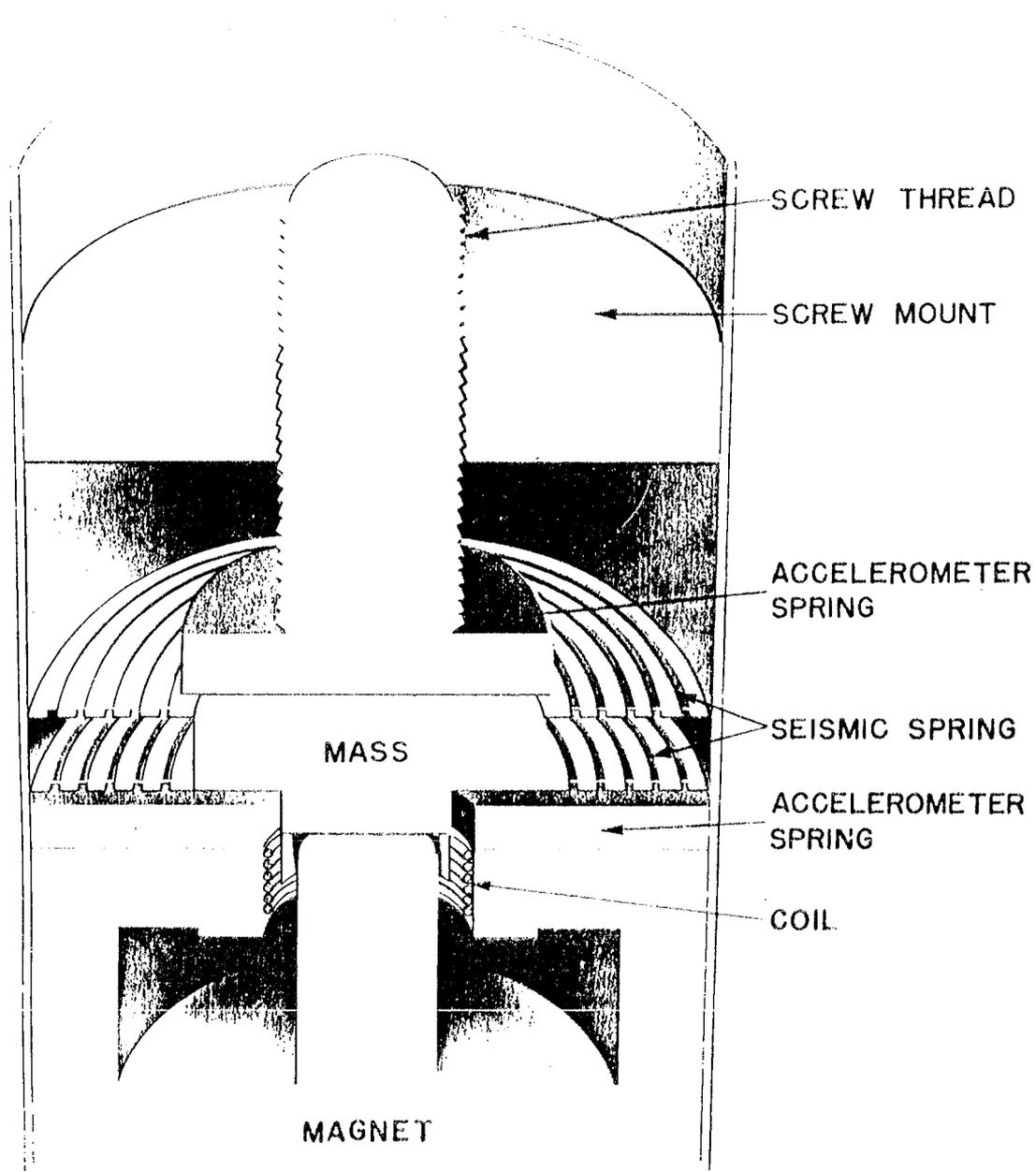
The chief methods of solution thus far developed have involved either mechanical linkages to pen or paper, optical lever arrangements, or coupling to electrical systems through coils moving in a magnetic field. Recent developments in the field have been connected with such problems as obtaining records from seismometers placed in remote inaccessible locations. At Columbia University, for example, they have been interested in obtaining records from seismometers dropped to the ocean bottom from the surface. The Air Force as part of the IGY program has been interested in obtaining records from seismometers parachuted to the Greenland ice cap from the air. These programs have met some, if not all, of the problems likely to confront the development of instrumentation for the present program. The problem of size and weight of the instrument is simply one of design and the people at Columbia feel that a maximum of 20 pounds for the total instrumentation is not unrealistic. Whether this can be bettered will depend upon the interplay of size and weight of such components as coils, electronics, and so forth.

The problem of coupling of instrumentation to the ground does not appear too severe. Assuming no very thick layer of dust or debris above the basic rock of the surface layers we need not even contemplate the necessity of anchoring the instrument to the ground. If it but rests solidly on the ground, adequate coupling is assured. This is, in particular, true for the case of the long surface waves which would be an important component of the seismic activity created by the detonation of a large bomb. The largest difference

in performance would be associated with the higher frequency body waves.

Leveling of the instrument after landing is not expected to be a major problem. The requirement for exact and delicate leveling is connected with the recording of the horizontal components of long period earthquake waves. For seismometers used to measure the vertical component of motion and for the high frequency waves associated with explosive detonations near the recorder the requirements as to leveling are much less severe.

A sketch incorporating those features that would be desirable in a seismometer for exploration of the moon is included as Fig. 5. A mass is coupled to the frame of the seismometer through the corrugated diaphragm providing a weak spring constant. This is to be so selected as to provide a natural period of the mass very large in comparison to the range of periods of seismic motion of the moon to be studied. The motion of the seismic mass relative to the frame and also the moon is transduced by the motion of the attached coils in a magnetic field. To protect the seismometer during the high accelerations encountered during its flight to the moon and at impact, blocks have been provided between the seismic mass and the frame. These blocks are chosen so as to provide a high spring constant and the resulting combination of seismic mass and blocks constitute an accelerometer which can provide a record of the character of the impact of the instrument with the surface of the moon. After impact the blocks are removed by a suitable mechanism and the instrument capsule assumes its role as a seismometer.



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FIG. 5 - MODEL OF AN ACCELEROMETER-SEISMOMETER

An estimate of the distance from the focal point of a nuclear blast on the moon to which the resulting seismic signal can be detected can be made as follows. There have been several underground nuclear blasts that were recorded seismically on the earth. These include detonations of Blanca, 23 kilotons; Logan, 5 kilotons; Rainier, 1.7 kilotons; and Tomalpais, 0.1 kilotons.

The amplitude of the seismic waves resulting from these shots was approximately proportional to the first power of the kiloton equivalent yield of the bomb. The coupling of the energy of the detonation to the earth was such that the resulting seismic signal for the Rainier shot was equivalent to that observed from an earthquake with a scale value of 4.6 on the Gutenberg-Richter scale.<sup>2</sup> This scale is given by the empirical formula

$$M = \frac{1}{18} \log_{10} \frac{E}{E_0}, \text{ where } E_0 = 10^{12} \text{ ergs}$$

is approximately the energy involved in the smallest detectable earthquake on earth.  $E$  is the estimated seismic energy in ergs involved in a given disturbance. On this scale the Logan shot would correspond to a scale value of 4.9 and the Blanca shot to a scale value of 5.2. The efficiency of energy transfer into seismic energy will not be so large for a bomb exploded above ground as for one which has been buried. In the field of seismic exploration for oil bearing strata, for example, it has been noted that the transfer of energy can be increased a hundred fold by burying the charge in a water logged strata over that for a surface explosion. In a high energy nuclear explosion above the surface of the moon, it has been estimated that the effective agency of energy transfer to the surface of the moon will be x-rays

produced by the explosion. The energy of the bomb converted into this form is of the order of one-half its total energy of which less than one-half again will be directed toward the surface of the moon. The exact mechanism by which seismic energy is generated by an atomic explosion is not known. But of the total energy reaching the surface a considerable fraction must be expended in heating and vaporization of the surface layers of rock. A crude estimate would be that energy transfer into seismic energy is 0.1 as large for an above surface detonation as for the detonation of the same bomb when buried underground. However, we have the additional factor that the moon is expected to be seismically quieter than the earth. If we assume that instrumentation is noise limited then we have a gain in the signal-to-noise ratio due to this factor. A decrease in the noise level of the moon over that of the earth of the order of 100 to 1 seems reasonable but we shall assume a gain of only 10 to 1. The net result should then be that a nuclear bomb detonated above the surface of the moon should be the equivalent as a source of detectable seismic activity on the moon as the same bomb exploded underground upon the earth. Under these assumptions a kiloton bomb exploded just above the surface of the moon would be the equivalent (insofar as seismic detonation on the moon) of an earthquake upon the earth of magnitude

*M<sup>2</sup> 4.5 on the Gutenberg-Richter scale.*

Similarly, a megaton bomb so detonated would be the equivalent of an earthquake of magnitude

$$M = 4.5 + \frac{1}{18} \log_{10} \frac{10^6}{10^3} = 6.2 .$$

The kiloton bomb would be detectable at a distance of 300 - 400 miles, while the megaton bomb would be detectable anywhere on the moon. Table III is presented as a resume of the Gutenberg-Richter scale of earthquake intensity and the predicted equivalent seismic intensity for nuclear explosions above the surface of the moon.

Table III

DETECTABILITY OF MOON TREMORS

Earthquake Category	TNT Equivalent (kilotons)	Seismographic Equivalent of Nuclear Weapon	Lunar Radius of Detection
Great	$>10^6$		
Major	$10^4 - 10^6$		
Destructive	$10^2 - 10^4$	1 MT	Anywhere
Damaging	$1 - 10^2$		
Minor Strong	$10^{-2} - 1$	1 kT	400 Miles
Generally Felt, Small	$10^{-4} - 10^{-2}$		

## REFERENCES

1. Bullen, Introduction to the Theory of Seismology, Cambridge (1953).
2. Rainier, The Underground Nuclear Detonation of Sept. 19, 1957, Univ. of California Radiation Laboratory, Livermore, California.

Chapter V

THE HIGH ENERGY RADIATION ENVIRONMENT OF THE MOON

## Chapter V

### THE HIGH ENERGY RADIATION ENVIRONMENT OF THE MOON

The landing of one or more instrument packages on the moon will offer, in addition to other possibilities envisaged in other parts of this program, the challenge of obtaining information about radiation in space and on the moon.

At present, the high energy cosmic radiation, say above 100 Mev, is fairly well understood through measurements from the ground and in the upper atmosphere. However, as a result of the shielding and particle trapping due to the earth's magnetic field, we know little about the intensity and composition of the low energy radiation in outer space, and no consistent correlation can be drawn between solar phenomena and the variation in intensity and the spectral distribution of cosmic radiation. Because of the moon's absence of atmosphere and its possibly low magnetic field, instruments on the moon will be in an excellent position for the gathering of reliable information on low energy cosmic radiation.

Measurement of the intensity of cosmic radiation at different points of the moon's surface could provide information on which to base an estimate of the magnitude of a possible magnetic field of the moon.

Measurement of the radioactivity of the moon's crust may give useful

information about the past history of the moon. This data together with a knowledge of the chemical composition of the crust could contribute to a solution of the controversial problems of the age, origin, and process of accretion of the moon.

The schedule and the technical facilities available will suggest what emphasis could and should be placed upon the whole problem of radiation. There is always the possibility that some of the problems involved may be solved in the near future through measurements performed by instruments carried by outer-space vehicles. Therefore, in view of the survey nature of this project, this chapter is strictly limited to a feasibility study of certain measurements involving radiation that may contribute to a better knowledge of the earth's natural satellite.

## Section One

### Cosmic Ray Latitude Effect and Moon's Magnetic Field

The magnetic field of the earth is of a magnitude not comparable with the fields used in the laboratory for the deflection or the focusing of fast charged particles. It extends, however, to an enormous distance and its effect on the trajectories of the primary cosmic radiation is conspicuous and determines an energy selection of the particles that enter the atmosphere at different latitudes.

The solution of the equation of motion of a charged particle in the field of a magnetic dipole extending to infinity presents great analytic difficulties. A simple approximate solution is given by the theory of the Stoermer cone.<sup>1</sup>

This theory shows that for any definite geomagnetic latitude there exists a minimum critical energy that a particle must possess in order to reach the earth. At the same latitude and for an energy greater than the critical energy, particles can reach the ground only from a region of the sky which is contained in a cone having its apex at the point of impact and its axis perpendicular to the meridian plane through that point. Particles not admitted are reflected back into space and eventually trapped by the magnetic field around the earth.

At the geomagnetic equator the critical energy for protons is 9.3 Bev. Neglecting the interaction of the primary cosmic radiation with the atmosphere, protons of this energy can hit the ground only at a grazing angle from the West horizon. Protons of energy greater than 9.3 Bev, up to 14 Bev, which is the magnetic cut-off for vertical incidence, are allowed only from the Western sky. The minimum energy for the grazing incidence from the East horizon is about 58.5 Bev. Since this is the least favorable direction, protons of energy greater than 58.5 Bev are admitted from all points of the sky.

At higher latitudes the situation is quite similar but the critical energies are lower in value. Thus, the intensity of the cosmic radiation varies with the geomagnetic latitude and increases as it moves from the equator to the pole. A similar latitude effect is to be expected on the moon's surface if the moon has any appreciable magnetic field.

More than one instrument package will probably be landed on the moon in order to take care of other suggested measurements. Detectors for

the monitoring of natural or man-induced radioactivity may be included in the packages. These detectors could be designed and switched for intervals of their service in order to measure the cosmic ray intensities. In view of this eventuality, it would be worthwhile to investigate the feasibility of making an estimate of the magnetic field of the moon by using the cosmic radiation intensity as a probe.

Since the orientation of the hypothetical magnetic dipole is unknown, it would be necessary to use at least two detectors landed at different latitudes on the moon. We assume that the instrument packages will be scattered on the moon either by chance or by design so that results will be obtained for different latitudes. The two latitudes of  $20^\circ$  and  $60^\circ$  have been chosen for a comparison of two expected intensities and for an evaluation of the sensitivity of this method.

For the magnitude of the magnetic field of the moon, we may assume as an hypothesis, a value determined by a dipole of a moment smaller than that of the earth by a factor of 80 which is the ratio of the two masses of the earth and its satellite.

Although the more correct Vallarta-Lemaitre theory<sup>2</sup> of the cosmic ray trajectories will be required for a precise treatment of this problem, the Stoermer cone theory is adequate for a feasibility study.

The simple theory of Stoermer gives for the minimum kinetic energy of a particle of rest-mass  $m_0c^2$ , incident on a spherical body of radius  $a$  and magnetic moment  $M$  the expression:

$$E = m_0 c^2 \left[ \sqrt{(e^2 M^2 K^2 / m_0^2 c^4 a^4) + 1} - 1 \right] \quad (1)$$

as a function of a variable

$$K = \cos^3 \lambda / (1 + \sqrt{1 - \sin^2 \theta \cos^2 \lambda})$$

This parameter depends on  $\lambda$ , the magnetic latitude, and on  $\theta$ , the angle of incidence of the particle with the meridian plane at the point of impact. It can be shown that an estimate of the cosmic ray intensity at each latitude can be obtained by using, as an average energy cut-off, the cut-off for the vertical incidence. Values of the parameter K and the corresponding energy cut-offs are shown in Table I.

Table I

Latitude	K	E(Bev)
20°	0.441	2.05
60°	0.125	0.023

It is reasonable to assume that the instruments will be enclosed in a convenient casing determining an instrumental cut-off on the low side of the cosmic ray energy spectrum. This is not, however, an inconvenience since the measurements will then be independent of the contribution of the low energy particles whose intensity, as has already been pointed out, is not yet well known and is affected by temporal variations induced by solar activities.

Table I shows that at a 60° latitude a convenient instrumental cut-off of the order of 300 Mev for protons will be the only limitation on the

primary cosmic ray spectrum, however, at a low latitude the limitation is due to magnetic cut-off.

For the intensity of protons of energy greater than  $E$  (in Bev) we can use the expression<sup>3</sup>

$$N = \frac{9800}{E^2} \text{ m}^2 \text{ sec}^{-1} \text{ sterad}^{-1}$$

By using the calculated energy cut-offs, the expected intensities will be:

$$N_{20} = 1250 \text{ m}^2 \text{ sec}^{-1} \text{ sterad}^{-1}$$

$$N_{60} = 2900 \text{ m}^2 \text{ sec}^{-1} \text{ sterad}^{-1}$$

The contribution of  $\alpha$  particles and heavy ions will not change significantly the picture of the phenomenon. These particles represent only about 10 per cent of the total number of primaries and because of their momenta distribution they will show a latitude effect quite similar to that of the protons.

As a conclusion, a latitude effect:

$$L = \frac{2(N_{60} - N_{20})}{(N_{60} + N_{20})} = 80\%$$

should be obtained. This may indicate that it is possible to measure a magnetic field even weaker than that hypothesized. However, the sensitivity of the method and the reliability of the results drop rapidly with the intensity of the magnetic field.

The use of energy insensitive detectors was assumed in this treatment of the problem. The case of scintillation counters was also considered. A proper choice in the thickness of the detectors and a pulse amplitude discrimination could restrict the measurements to the non-relativistic

part of the proton spectrum leading to an improvement in the sensitivity of the method. With this kind of detector, however, measurements of a latitude effect will be possible only in a limited range and for low values of a magnetic field.

From the above considerations it seems that the analysis of the cosmic ray latitude effects can lead to an estimate of a possible lunar magnetic dipole as two orders of magnitude lower than that of the earth. At lower values severe limitations upon the possibility of this method are imposed by the need of a very high accuracy in the phenomenological and instrumental factors involved in the measurements.

A special feature of this method should be emphasized in conclusion: the latitude effect on cosmic ray intensity is due to an integrated effect over an infinite distance from a hypothetical lunar dipole; it is not affected by local distortion due to ferromagnetic materials (such as iron meteorites) which would invalidate a field determination given by magnetometers. Both types of measurements would appear desirable.

## Section Two

### Radioactivity on the Moon

Valuable information in regard to the history of the moon may be furnished by a study of its radioactivity.

In view of the present lack of evidence as to the nature, origin, thickness, and localization of the material deposited on the moon's surface, it is considered desirable to make measurements at different

depths of the moon's surface could help in solving the problem of the moon's history.

Two different types of radioactivity can be expected on the moon. One will be a natural, whose level depends essentially on the content of the  $K^{40}$  and of U and Th families. The other type will be induced by cosmic radiation and be due to unstable evaporation fragments, fission products and neutron activated isotopes produced by primary cosmic radiation and by its secondary originated in the moon's crust.

For an evaluation of the radioactivity of the moon's crust we may take into consideration the fact that, whatever moon theory we accept,<sup>5,6</sup> the moon's surface is believed to be covered by meteoric materials whose natural and induced radioactivity will appear at the surface and down to a certain depth of the moon's crust. We can assume for the moon's surface the average measured radioactivity of meteorites found on earth; this assumption is also supported by the fact that the determination of age from the break-up of same meteoric material indicates their lunar provenience.<sup>7</sup>

It was recognized that meteoric material does not show a radioactivity directly measurable with the standard techniques.<sup>8,9</sup> However, chemical separation and special low level counting techniques proved the existence in meteorites of a natural and of an induced radioactivity.<sup>9,10</sup>

Neutron fission and nuclear emulsion techniques were also used recently for the detection of the natural radioactive elements in meteorites.<sup>11,12</sup> From the experimental results it seems reasonable to assume that the

average content of the U-Th families element is of the order of  $10^{-9}$  grams per gram of material, with an activity of  $2 \cdot 10^{-3}$  disint  $\text{min}^{-1} \text{g}^{-1}$ . For the  $\text{K}^{40}$ , an activity of the order of 2 disint  $\text{min}^{-1} \text{g}^{-1}$  can be assumed.<sup>13</sup>

Measurement on different meteoric materials of recent fall or unknown terrestrial age proved that, according to the evaporation theory,<sup>14</sup> the low Z evaporation products are the more abundant, the  $\text{H}^3$  being the main source of induced radioactivity in meteorites.<sup>15, 16</sup>

For short-lived isotopes, the activity at equilibrium, under cosmic ray irradiation in space or at the moon's surface must be evaluated by the relative yields obtained with artificially produced high energy particles.<sup>17</sup>

Some contribution in the total induced radioactivity is due to neutron activation. Fission products due to the possible content of uranium mentioned above will give a negligible contribution in the overall radioactivity.

In Table II is reported a list of radioactive isotopes expected on the moon's crust with their average activity per gram of material.

Table II

Isotope	Mean Life	Activity	Disint/Min g
$\text{H}^3$	12.2 y	$\beta$	0.5
$\text{Be}^7$	53 d	$\gamma$	0.06
$\text{Be}^{10}$	$2.7 \times 10^6$ y	$\beta$	0.005
$\text{Al}^{26}$	$10^6$ y	$\beta, \gamma$	0.05
$\text{Cl}^{36}$	$3 \times 10^5$ y	$\beta$	0.01
$\text{Co}^{60}$	5.2 y	$\beta, \gamma$	0.02
-	-	-	-
$\text{K}^{40}$	$1.2 \times 10^{11}$ y	$\beta$ (89%), $\gamma$	2
U, Th	-	$\alpha, \beta, \gamma$	0.002

As is shown in Table II, most of the isotopes are  $\beta$ -emitters. An estimate of the counting rate in a thin counter of a unit of cross-sectional area and 100 per cent detection efficiency may be made assuming that one-third of the disintegrations gives  $\gamma$ 's of average energy  $E = 1$  Mev. With a total of natural and induced  $\gamma$  radioactivity  $D \sim 1$  disint  $\text{min}^{-1} \text{g}^{-1}$  the expected counting rate in a medium of average atomic number  $Z = 11$  will be:

$$N \int_0^{\infty} F(D, Z, V) dV \sim 5 \text{ counts } \text{cm}^{-2} \text{min}^{-1}$$

It will be of special interest to compare this level of counting rate with that expected by artificial activity induced by detonation of a nuclear weapon on or near the moon.

The measurement of the above figure of  $\sim 5$  counts  $\text{cm}^{-2} \text{min}^{-1}$  is quite low and a measurement would require at least a special low level counting technique. A measurement of this kind could be a serious problem on the moon because of the high background due to the cosmic radiation.

### Section Three

#### Cosmic Ray Intensity on the Moon

In considering the feasibility of radioactivity measurements on the moon, we found that the cosmic ray background may be a serious obstacle in the measurements.

We attempted an evaluation of the cosmic ray flux at the surface of the moon and under its crust, due to the absorption of the primary radiation and to the secondary particles that will be produced in penetrating the lunar crust.

For the intensity of the cosmic radiation at the moon's surface, we may assume the value measured at the top of the atmosphere at high latitude. For an instrumental cut-off of the order of 300 Mev for protons, the primary cosmic ray intensity is  $0.25 \text{ particles cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$ .

In the absence of an atmosphere, this is the omnidirectional intensity and it gives a flux:

$$\phi \int_0^{2\pi} I d\Omega = 0.77 \text{ particles cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

and a counting rate of  $47 \text{ counts min}^{-1} \text{ cm}^{-2}$ .

A comparison of this value with the radioactivity level of  $5 \text{ counts min}^{-1} \text{ cm}^{-2}$  evaluated above shows that some system of anti-coincidence or background discrimination must be used.

An appreciable amount of albedo radiation is expected at the moon's surface. An evaluation of this contribution for the wide energy distribution of the cosmic ray is not so obvious. Measurements made in our upper atmosphere<sup>18, 19</sup> may suggest that the backward flux of radiation is of the order of 25 per cent of the incident flux. This radiation is mostly composed of electrons and gamma rays of energy below 100 Mev.

The presence of the albedo radiation will exclude the possibility of measuring the radioactivity by placing on the moon's surface a detector shielded by a simple system of anti-coincidence in all the directions except toward the moon's surface.

The relatively high flux of the primary and albedo radiation may lead us to the conclusion that a very efficient shielding and a  $4\pi$  anti-coincidence

system with an efficiency of the order of 95 per cent will be necessary in order to measure the radioactivity of a moon sample. It is very doubtful, however, if such efficiency can be obtained because of all the ionizing and non-ionizing secondary radiation produced by the cosmic rays in the apparatus itself.

For measurement of the radioactivity at some depth inside the moon crust the conditions are somewhat better because of the absorption and degradation in energy of the primary particles.

The absorption of the primary cosmic ray cannot be described with a simple absorption process. What happens inside the moon crust may be represented with a simplified scheme. High energy primary particles strike the moon's surface from all directions and in their first collision with the matter they produce showers. Proton, neutron and  $\pi$  mesons are emitted in such collisions. Some of these particles have energy sufficient to produce secondary showers and through several generations the energy of the primary flux is distributed and absorbed.

A cosmic ray cascade is expected to develop through the moon's crust, quite similar to that produced in our atmosphere. There is, however, one great difference. In the atmosphere most of the  $\pi$  mesons, because of their short mean life, decay into  $\mu$  mesons before a nuclear interaction. In the dense material of the moon they contribute with protons and neutrons to the development of a nucleonic cascade.

Due to the large proportion of  $\pi$  mesons in the showers, a transition effect is expected for the nucleonic component in the moon's crust, while in the atmosphere the nucleonic component is exponentially absorbed. Gamma rays produced in the decay of neutral pions give origin to an electro-photonic cascade. Due to extremely short mean life of the  $\pi^0$ , the gross behavior of this cascade does not depend on the concentration of the matter and is expected to be the same in our atmosphere and inside the lunar crust. The intensity should first increase, and after a broad maximum at the depth of about  $150 \text{ g/cm}^2$ , it should fall off exponentially with increasing depth.

As a consequence of these transition effects, the flux of the cosmic ray through the lunar crust will be down a certain depth, even greater than at the surface.

The intensity distribution of the cosmic ray cascade through the lunar crust can be described by equations of absorption, rate of interaction and yield of shower particles for several generations on the development of the cascade. With some assumptions, the problem can be treated in a simple way for an approximate solution adequate for our purpose.

We can assume equal absorption and interaction length and that high energy particles lose their energy only by nuclear interactions. In a uni-dimensional treatment of the problem, the intensity of the primary radiation will fall off with the law:

$$I = I_0 e^{-\mu x}$$

with an interaction rate expressed by:

$$I_1 = \mu I_0 e^{-\mu x} S_1$$

The yield of secondary particles will be,

$$Y_1 = \mu I_0 e^{-\mu x} S_1$$

where  $S_1$  is the yield of shower particles per interaction.

The secondaries will go through the same process and the flux of the first generation will be:

$$\frac{dI_2}{dx} = \mu I_1 e^{-\mu x} S_1 = \mu^2 I_0 e^{-2\mu x} S_1^2$$

which integrated gives:

$$I_2 = I_0 S_1^2 \mu x e^{-2\mu x}$$

These particles will proceed with a rate of interaction

$$I_2 = \mu I_2 = I_0 S_1^2 \mu^2 x e^{-2\mu x}$$

producing the number of secondaries

$$Y_2 = I_0 S_1^2 S_2 \mu^2 x e^{-2\mu x}$$

and so on. The intensity of the  $n$ th generation at a depth  $x$  will be:

$$I_n = \frac{1}{(n-1)!} I_0 \mu^{n-1} x^{n-1} e^{-\mu n x} S_1^{n-1} S_2 \dots S_n$$

From experiment with nuclear emulsions we know that the spectrum of

secondaries is independent of the energy of the primary.<sup>20</sup> Then

$S_2 = S_3 = \dots = S_n$ . The intensity at a depth  $x$  is given by the summation of the intensities of all the generations.

$$I = \sum_0^n I_n = I_0 e^{-\mu x} \left[ 1 + \frac{S_1}{S_n} (e^{\mu x S_n} - 1) \right]$$

With experimental values of  $S_1$  and  $S_D$  and for an intensity at the surface of 0.25 particles/cm<sup>2</sup> sec sterad, we obtain:

$$I = 0.25 e^{-0.105 x} / [1 + 0.105 x (e^{-0.004 x} - 1)]$$

The values of the intensity  $I$  of the nucleonic component at different depth on the lunar crust are shown in Table III. About 20 per cent of the particles are protons, 20 per cent neutrons and 60 per cent charged  $\pi$  mesons. The yield of low energy evaporation particles was neglected in this computation. Because of their short range they do not contribute appreciably to the flux.

Table III

* Depth (cm)	Intensity (particles/cm <sup>2</sup> sec sterad)
0	0.25
10	0.32
20	0.35
30	0.35
40	0.33
50	0.31
70	0.26
100	0.16
200	0.025
300	0.0034

In evaluating cosmic radiation as background when measuring radioactivity it is necessary also to take into account the electrophotonic cascade. An approximate distribution of the electrons through the moon's crust was evaluated from the behavior of the electrophotonic cascade in our

\* Assuming a density of 3.3 g/cm<sup>-3</sup>

atmosphere<sup>20</sup> and the total intensity was then integrated over a solid angle  $2\pi$  at different depths to account for the different path length of the cascade due to primaries of different angles of incidence.

Angular spread of the cosmic ray cascade was not included in the computation. An appreciable contribution to the flux is expected from scattered radiation. We already pointed out that albedo radiation on the surface of the moon may account for a contribution of the order of 25 per cent of primary flux. We assume that this correction can be applied at all the depths on the moon's crust. The final values of the flux are plotted in Fig. 1.

We can see that the flux, even at great depth, is quite large as compared with the expected radioactivity. Measurement of the radioactivity inside the lunar crust will require protection by background rejection techniques. Even at a depth of several feet, the shielding provided by the lunar crust alone will be insufficient to allow a low level measurement.

The embedding of complex and delicate instrumentation at a depth of several feet could be a rather difficult problem.

#### Section Four

##### Cosmic Ray and Age Determination

It may be interesting to consider if the cosmic ray effects on the lunar crust can be used for an age of deposition determination.

We can take into consideration one particular process extensively used for age determination in meteorites.<sup>22</sup> The  $H^3$  produced in the evaporating

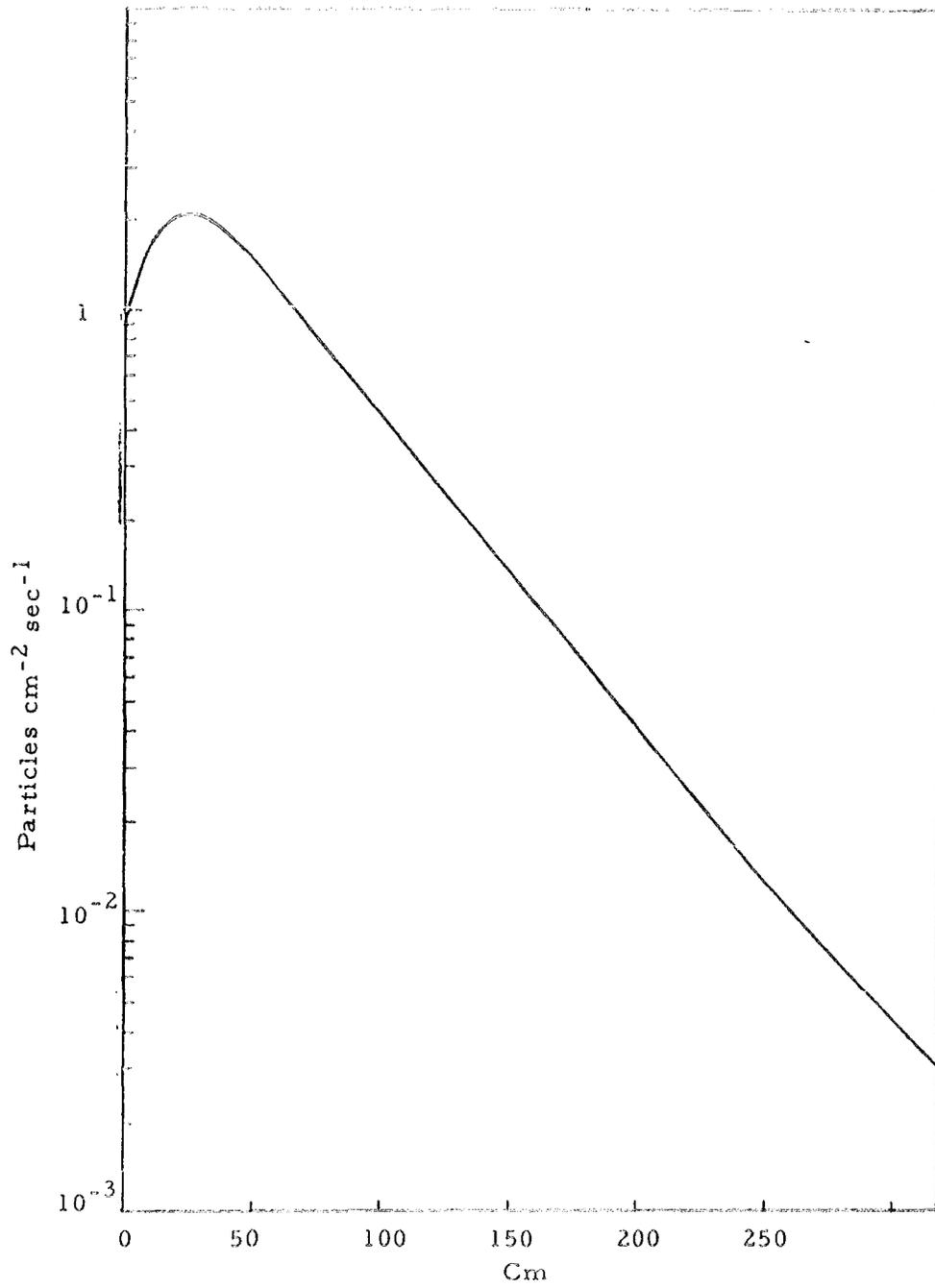


FIG. 1 - COSMIC RAY FLUX THROUGH THE LUNAR CRUST

processes has a mean life of approximately 10 days in  $\text{He}^3$ . The  $\text{He}^3$  does not diffuse out of the materials and the amount produced through the time can give a cosmic ray age if one assumes that the cosmic ray intensity did not change through the ages. For the moon's crust this method may give an estimate of the age of deposition. However, the meteoric material of which the moon's crust may be formed is irradiated in outer space by the same flux of cosmic rays present on the moon's crust. Not all the meteoric material has size sufficient for an efficient production of  $\text{H}^3$  by cosmic rays. However, the flux in outer space is integrated over a solid angle of  $4\pi$ , twice the angle at the moon's surface, and this may compensate for the lack of  $\text{H}^3$  production in small-sized meteorites.

In addition, the transition effect of the nucleonic component on the moon's crust can account for a possible lack of  $\text{He}^3$  concentration gradient on the moon's crust over a quite large thickness. These circumstances may suggest that the production of  $\text{H}^3$  in meteorites proceeds at the moon's surface at about the same rate as in space, thus invalidating this type of age of deposition determination.

## Section Five

### The Question of Lunar Contamination

Having at least roughly established the magnitude of the cosmic ray and natural radioactivity background of the moon, it is of interest to discuss in this same context the radioactivity which might be produced by detonation of a nuclear device. The simplest approach to this problem is to treat

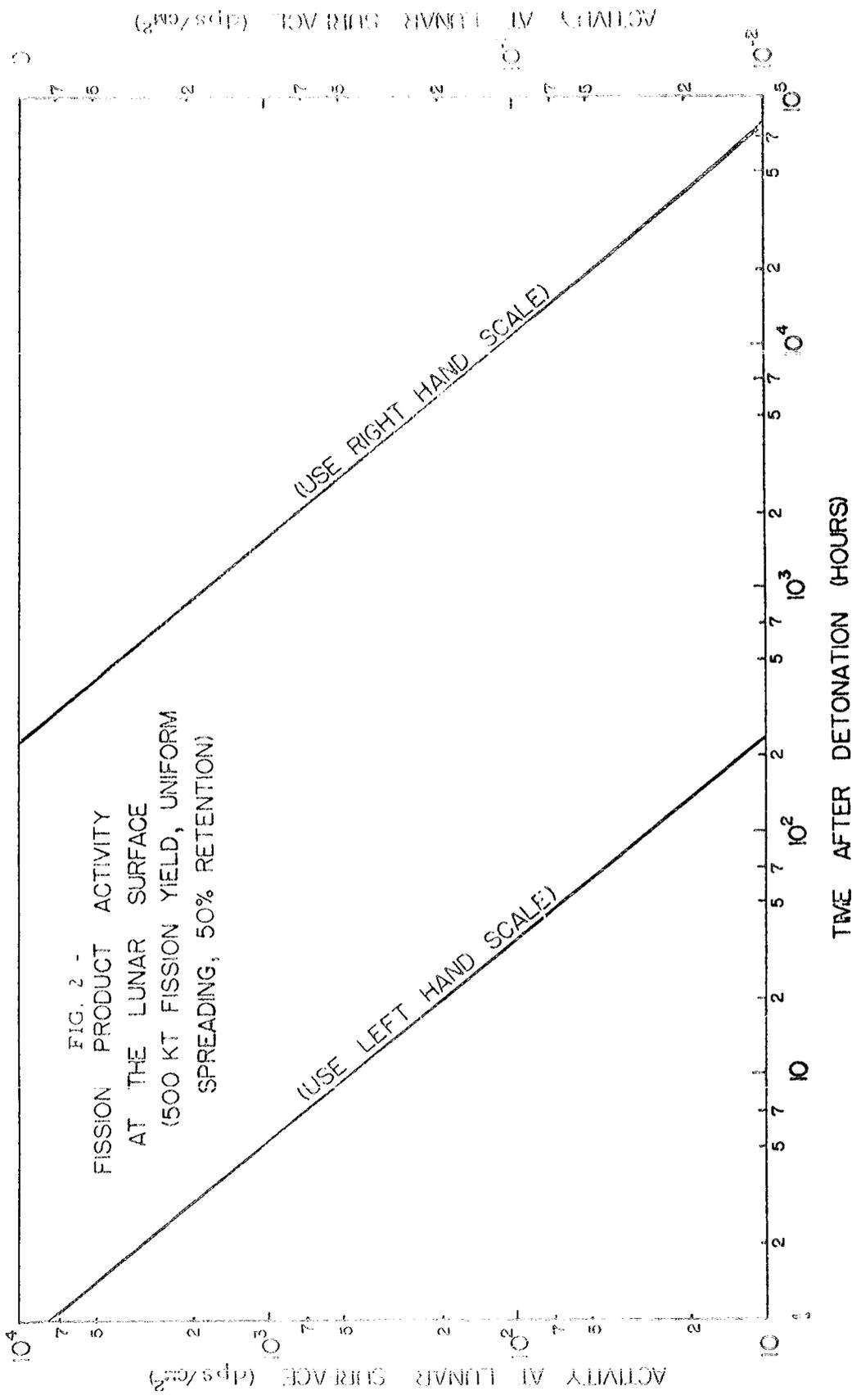
detonation of a one megaton bomb above the surface of the moon with the following assumptions:

- (1) The fission yield is 500 kilotons
- (2) One-half of the fission products are retained by the moon and one-half are lost in outer space
- (3) Uniform spreading of the fission products occurs over the entire lunar surface

Assumptions (1) and (2) are readily justifiable. The latter, in particular, is conservative in view of the very high kinetic energies given to the fragments relative to lunar escape requirements. It may be argued that the third assumption is also conservative because non-uniform spreading over the lunar surface would imply regions of less contamination than will be calculated here.

Using the known decay characteristics of mixed fission products, it is very simple to calculate activity deposited in disintegrations per  $\text{cm}^2/\text{sec}$ . This is shown in Fig. 2. From this curve one may make the observation that by a month or two, for the detonation of a one megaton weapon, the decay rate is down to roughly the order of the primary cosmic ray background.

This calculation represents an upper limit because of at least two effects: first of all, we have assumed 100 per cent retention of one-half the fission fragments. In actual fact, however, the phenomenology will probably work to reduce this retained fraction very considerably. Consider a burst occurring at about one kilometer above the lunar surface. At the time of detonation the x-rays from the bomb will proceed to the surface of the moon



and raise the temperature of a thin layer to very high values as treated in another chapter of this report. This lunar gas will rarefy outward from the lunar surface and there will be a general transfer of random thermal energy to the directed outward velocity of the cloud.

The problem of expansion of an ideal gas into a vacuum has been treated in detail for ideal adiabatic expansions by various investigators. Essentially what occurs is that the gas streams out into the vacuum with a maximum velocity given by

$$l_0 = \frac{2}{\gamma-1} C_0$$

where  $C_0$  is sound speed.

A rarefaction wave moves back into the remaining gas at rest and is important in accelerating the quiet gas into a directed motion. The fastest moving fraction of the outward moving gas will have a thermal temperature of absolute zero. Since we can, as a first approximation, consider this to be a one-dimensional flow, we have the picture of the lunar material moving upward as a gaseous piston from the moon. On the other hand, the fission fragments from the bomb are proceeding downward from one kilometer at a velocity of  $10^8$  cm/sec so that they arrive about one millisecond after the x-rays have developed the lunar gas. As a result, the fission fragments collide with the outward moving lunar gas which contains a large fraction of the total momentum of the system because of the relatively high velocity and relatively low total energy content of the fission fragments. The piston effect of the outward moving lunar gas should impart to the downward moving material a velocity component such that a considerable fraction of the

radioactive material is expelled into space. This entire process is shown schematically in Fig. 3. A detailed treatment of this problem is obviously quite complicated and not only momentum transfer and questions of equilibration times must be considered but also calculations on the range of fission fragments through the highly ionized lunar gas plasma and the rarefaction process in such a non-ideal medium should be made. A detailed discussion of such phenomena is beyond the scope of the present work but is clearly indicated for the future because it appears that a marked reduction in contamination could occur by this mechanism.

We can show now, however, the results of calculations on lunar orbits for individual particles corresponding to various effective temperatures of this mixed cloud of radioactive fission fragments and lunar surface material as some indication of what might be expected. We have noted in the chapter describing x-ray energy input calculations what sort of properties might obtain in the lunar vapor. To any such calculations must be added energy contributions resulting from the heating of the rarefying vapor by the interaction and stopping of the fission fragments. Temperatures of the order of  $10^5$ °K do not appear to be out of the question. If we assume, therefore, a gas without an outward directed net velocity but at such temperatures, we may calculate the number of particles of this gas possessing energies corresponding to either parabolic, hyperbolic or elliptic orbits in the gravitation field of the moon under the assumption of a Maxwellian distribution of velocities. The results of such calculations are shown in Fig. 4 for

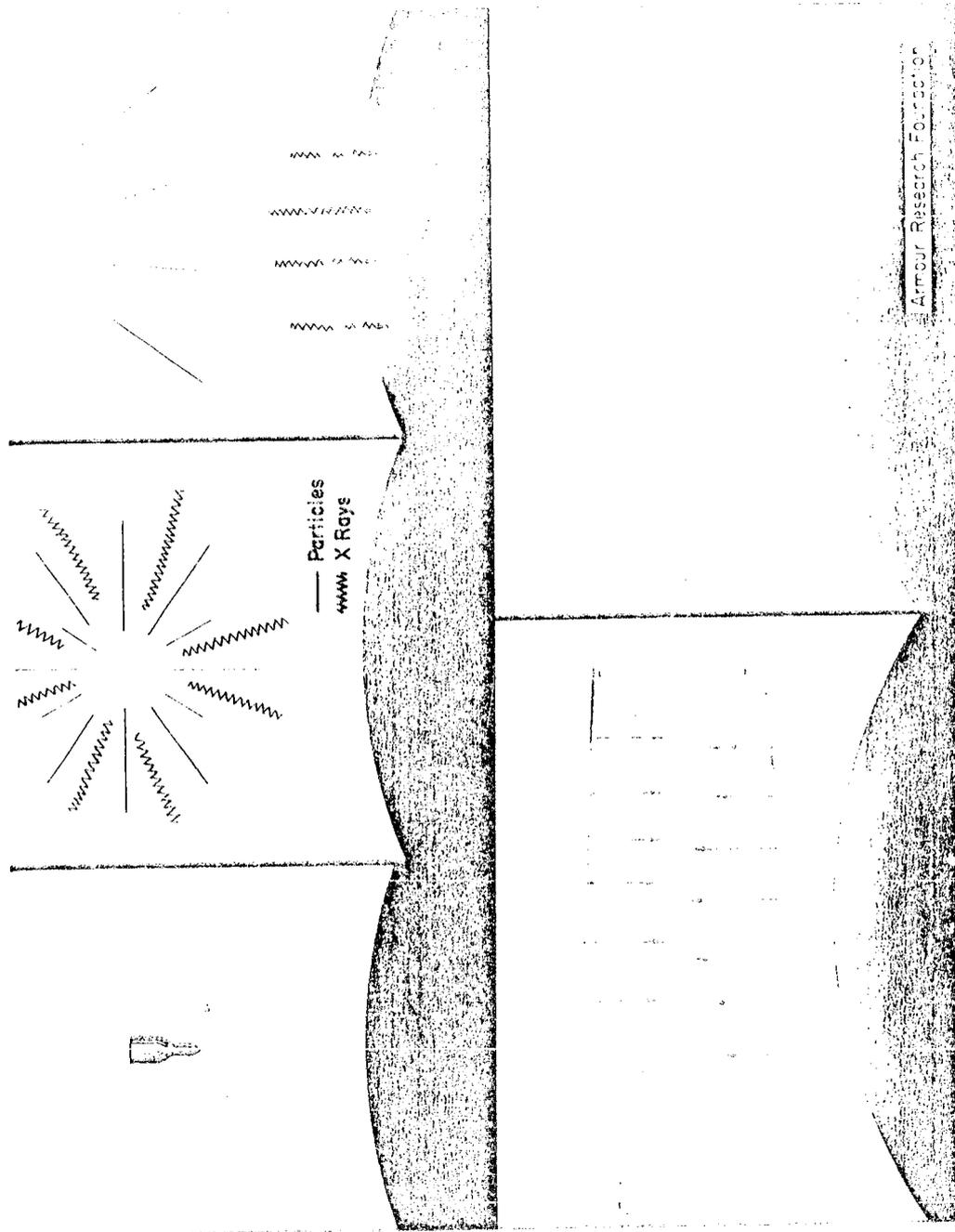
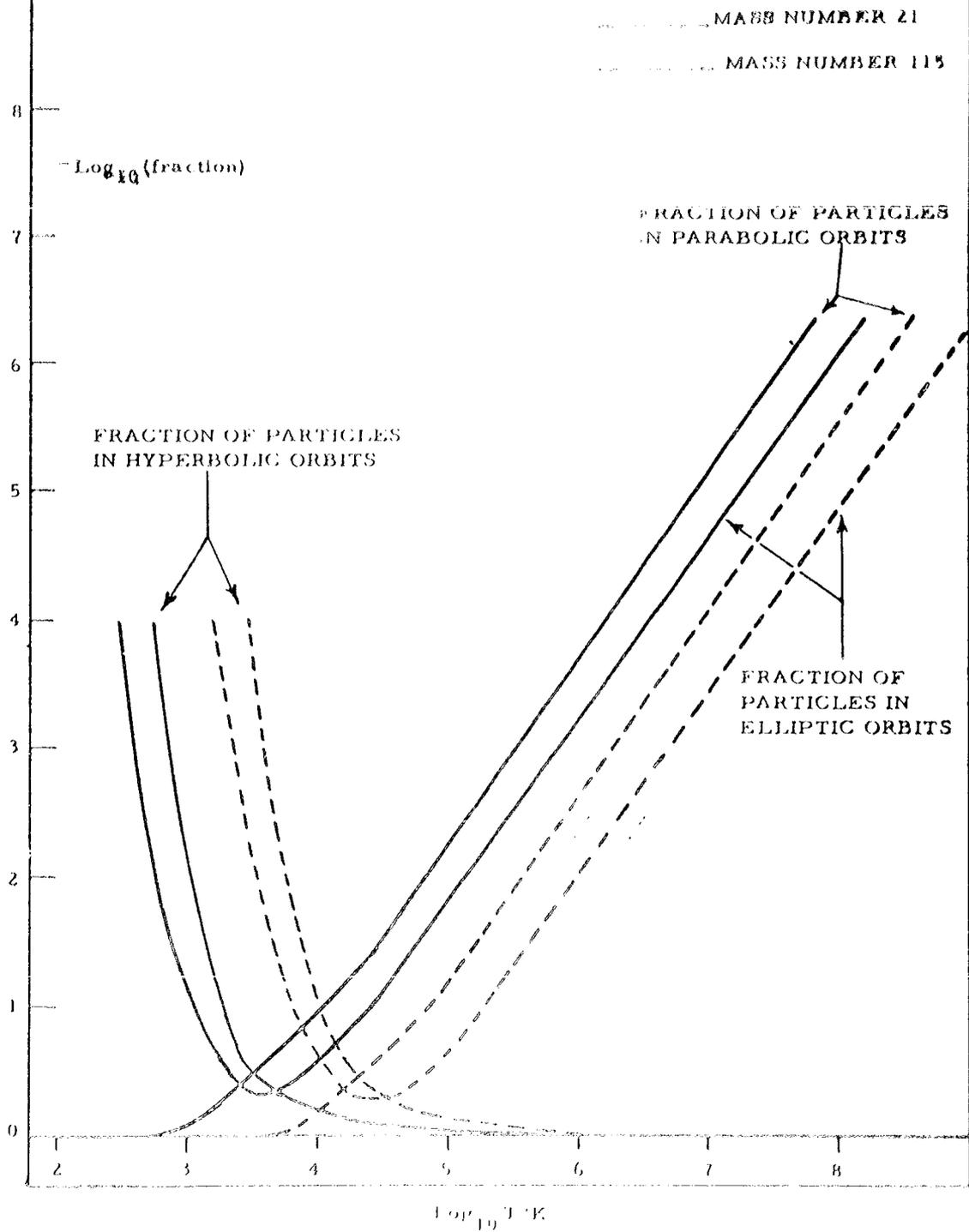


FIG. 3 - SCHEMATIC TIME SEQUENCE OF VAPOR AND FISSION FRAGMENT BEHAVIOR

first row, left to right: approach of weapon to 1 km level;  $T + 10^{-7}$ sec;  $T + 3 \times 10^{-6}$ sec;

bottom row:  $T + 10^{-3}$ sec.

FIG. 3 LUNAR ORBITS OF PARTICLES



both mass 20 particles, corresponding to the olivine, and mass 150 particles, corresponding to some average fission fragment. It is clear from these curves that a very large fraction of the radioactive material would enter into hyperbolic orbits and thereby have an excellent chance of escaping from the moon's surface. This effect, even without consideration of directed velocities as discussed above, can markedly reduce the lunar contamination.

In summary: when one considers the natural radiation at the lunar surface, it appears clear that fairly sophisticated instrumentation will be required to measure lunar radioactivity, for example, in the presence of natural interference. Without adding a great deal of complexity, such apparatus should be able to distinguish the modest lunar contamination produced from a nuclear burst near the moon's surface. Such a conclusion does not, of course, argue for the casual detonation of a nuclear weapon near the moon, but it does appear that with instrumentation emplaced on the moon prior to such a detonation which would, in fact, be capable of making meaningful measurements, the influence of a subsequent nuclear detonation would not be as detrimental to the information content of the moon as is sometimes argued. Clearly, however, it will be to the advantage of any experiment to have data on the natural radiation before detonation of any device producing radioactivity. When such data are available our conclusions here should be reviewed carefully.

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Chapter VI

COMPOSITION OF THE LUNAR SURFACE  
AND THE MAGNETIC FIELD OF THE MOON

COMPOSITION OF THE LUNAR SURFACE  
AND THE MAGNETIC FIELD OF THE MOON

At the present time there are three, not necessarily mutually exclusive, ideas on the composition of the lunar surface material:

- (1) The lunar maria are of lunar composition, being formed by impacts of large bodies of asteroidal mass at a time when the lunar interior was molten at some tens of kilometers beneath the surface. Impact caused lava upflows at the impact site by penetration towards the lava depth and in the neighborhood of the impact site by hydrostatic compensation.<sup>1</sup> On this basis a cloud produced from a lunar mare by detonation of a nuclear device should have a chemical composition comparable with that of terrestrial surface material of density less than about 3.3 gm/cc. Consistent with view (1) is the assumption that the mare-less southern highland area of the moon is the old accreted crust, exhibiting the last pieces of matter to fall on the accreting proto-moon. This material should also be roughly of terrestrial surface composition with perhaps a slight depletion of the heavier elements, especially iron.
- (2) The lunar maria are of meteoritic composition, being formed by impacts of large bodies of asteroidal mass, the energy for melting and the molten material both supplied by the impacting object

itself.<sup>2</sup> On this basis a cloud produced from a lunar mare should have a chemical composition comparable with that of objects of asteroidal mass. The only evidence we have in this regard is from analyses of meteorites, coupled with the probability that meteorites are collision products from the asteroid ring. If the masses producing the maria in view (2) are meteoritic in composition, then the cloud would have a substantially different composition from that of view (1). In particular, more iron should be expected. On the other hand, it is certainly possible that the impacting objects were small bodies accreted in the vicinity of the moon contemporaneously with the formation of the moon; and in this case, it is certainly possible that their composition was identical with that of the southern lunar highlands. (Also consider in this view an unreworked primeval area.)

- (3) At least some of the lunar maria, especially Mare Imbrium, are cometary in origin, being the result of collisions of comets and the moon.<sup>3</sup> In this view a cloud of mare material would possibly contain appreciable proportions of cometary matter; in particular, carbon, nitrogen and oxygen.
- (4) The lunar maria are of meteoritic composition, being deep bowls, filled with micrometeoritic fragments which have fallen on the moon during the last few billion years.<sup>4</sup> The dust may be loosely packed, or, as suggested by Whipple,<sup>5</sup> congealed into a fluffy

matrix in the high vacuum conditions of the lunar surface. In this view, at least the upper regions of the maria would have composition very similar to that of micrometeorites collected in the immediate vicinity of the earth; they would therefore have high iron and nickel abundances.

- (5) The lower regions of maria dust layers are of approximately cometary composition, being formed early in the history of the moon, either by infall from the solar nebula from which the moon was formed<sup>6</sup>, or by infall from the primitive, short-lived, reducing lunar atmosphere.<sup>7</sup> (There may, of course, be no distinction between the early lunar atmosphere and the last stages of the solar nebula in the vicinity of the moon.) The contribution to the cloud from such material would be primarily hydrogen, carbon, nitrogen, and oxygen.
- (6) The lunar maria are of indeterminate composition, being deep bowls, filled with ionized dust particles which have been chipped from lunar surface material by solar electromagnetic and corpuscular radiation.<sup>8</sup> In this view, a cloud of mare material might have any of the above-mentioned compositions, depending on the material from which the dust is chipped. If solar protons have been arriving on the moon's surface at approximately present rates for the last few billion years, the lunar surface material might be expected to retain a saturation amount of hydrogen,

and this might be reflected in the cloud composition.

Although there is considerable overlap in the above views, the following tentative conclusions can be drawn: if the cloud of mare material is substantially of terrestrial surface composition, views (1) and (2) are supported over views (3), (4), and (5). If the cloud has large iron and nickel abundances, views (2) and (4) are supported over views (1) and (3). If the cloud has large carbon, nitrogen, and oxygen abundances, views (3) and (5) would be supported over views (1) and (2). Because of the solar proton flux mentioned in view (6), high hydrogen abundance in the cloud would not necessarily support any of the views over any others. Of course combinations of alternatives are possible. For example, suppose the cloud has essentially terrestrial surface abundances of Si, Mg, Al, Ca, Na, etc., but with appreciable admixture of Fe, Ni, C, N, and O. This might suggest that views (1) or (2) are correct regarding the nature of the maria, but that the maria are overlaid with small amounts of other material, originating as in views (4) and (5).

Spectroscopic observations of the general sort discussed elsewhere in this report could provide data on these questions of composition.

Magnetometric observations, and possible directed motion or trapping of ionized detonation products in the lunar or lunar-terrestrial magnetic field, would give information on the lunar magnetic field and possibly on the interior structure of the moon. It is generally expected that the field will be small but various views will be summarized here. Reference should be

made to the Chapter on the interplanetary environment for very recent comments in the light of Russian reports of lunar eruptions. (See also the translation of N. A. Kozyrev's Prioroda article in Information on Soviet Bloc IGY Cooperation, PB 131632-63 U. S. Dept. of Commerce, April 24, 1959, p. 2.)

If a field of the order of the earth's (0.1 - 1 gauss) is detected, this will be taken as strong a priori evidence for the existence of a liquid iron core. There is some evidence that the earth's magnetic field arises from hydromagnetic motions in a terrestrial liquid iron core,<sup>9</sup> but it should be emphasized that no satisfactory theory for the origin of the terrestrial field exists,<sup>10</sup> there is direct seismological evidence for the existence of a liquid terrestrial core, but of course no present lunar seismological information, and there exist theories for the origin of planetary magnetic fields which do not involve liquid cores.<sup>9</sup> Consequently, conclusions on the structure of the lunar interior proceeding from evidence on the presence or absence of a lunar magnetic field should be treated with some caution.

Since the mean density of the moon is comparable to that of terrestrial surface material, an extensive iron core within the moon would seem to be immediately excluded. However, there is an interesting difference of opinion on the possible existence of a small liquid iron core, hinging on the question of whether the moon was ever molten on a large scale. If there were appreciable melting at some time in the moon's history, a differentiation of irons and silicates would be expected, forming an iron core and a silicate

mantle. This is substantially the view of Kuiper.<sup>11</sup> Urey,<sup>12</sup> on the other hand, believes that neither the earth nor the moon was ever extensively molten.\* The earth's core is attributed to a slow trickle of irons to the terrestrial interior throughout geological time, the earth's gravitational field and some internal heating being the primary causal factors. With a smaller gravitational field, much less internal heating, and a smaller proportion of iron to begin with as is evidenced from the density, Urey anticipates no liquid iron core on the moon. Finally, the Soviet school associated with the name of Schmidt<sup>13</sup> holds that the earth's core is not liquid iron at all, but rather a hypothesized high-pressure modification of

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\* We are indebted to Professor H. C. Urey for the following comments made after review of a draft of this report: "The composition of the old accreted surface, if indeed there is any present on the moon, should be of cosmic composition rather than of the earth's surface. The material of the earth's surface has been highly differentiated by partial melting and flow of material to the surface of the moon. ( . . . ) (Kuiper) has silicates floating on the liquid materials below. The moon accumulated at low temperature but heating in the interior melted the whole interior leaving an accreted crust floating on the surface. We have here the curious situation where a solid floats on its liquid, water being the only common example of this situation. Your statements in regard to my views on this subject are correct if we go back to *The Planets*, but you will find a later discussion of this subject in the *Proceedings of the National Academy of Sciences*, Vol. 41, 127-144, see particularly page 140. The abundance of the radioactive elements in this paper is incorrect and this was corrected in Vol. 42, 889-891." Reference to W. H. Ramsey *MNRAS* 108, 406 (1948), and *MNRAS Geophys. Supp.* 6, 409 (1949) should be made in connection with the high pressure modification of silicate theory of the earth's core.

silicate with about the viscosity of tar. However, it is also believed that the moon was extensively molten, while the earth was not. Hence, if there are any magnetic consequences of a liquid iron core, they would be expected on the moon, but not on the earth. A summary of various views is given in Table I.

Measurement of the magnetic field on the moon may also provide information about fluctuations in spatial magnetic fields due to ionized particle streams from the sun and similar effects due to plasmas originating in a nuclear detonation near the moon. The same instrumentation may be modified to determine residual rock magnetism of the lunar surface which, as indicated above, will be important in theories of the moon's origin.

Table I

LUNAR MAGNETIC FIELD

Source of Field	Magnitude 10 <sup>-5</sup> oersteds	Remarks
Liquid Core <sup>a</sup>	50,000	Considered unlikely Measurable by lunar satellite
-----		
Moon once part of earth <sup>b</sup>	40	Field arises from cooling in earth's field
Moon formed from condensed gas <sup>c</sup>	0	
Moon formed from accumulation of meteoric material <sup>d</sup>	unknown, but small	Intensity of magnetization of existing meteorites hasn't been determined
Mechanical rotation of moon <sup>e</sup>	7	
Thermoelectric origin in early life <sup>c</sup>	100	Field due to cooling in self-field
-----		
Solar Wind <sup>f</sup>	20 (RMS)	Magnetic noise Sets limit of required instrumental sensitivity

- a. S. Chapman and J. Bartels, Geomagnetism, Oxford University Press (1940).
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- e. P. M. S. Blackett, Nature, 159, 658 (1947). and H. A. Wilson, Proc. Royal Soc., 104, 451 (1923). (Blackett is quoted as having abandoned this theory by H. C. Urey, private communication September 4, 1959).
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Although it is likely that the most important question, presence or absence of a substantial lunar field per se, will be at least partially answered by presently contemplated lunar probes in advance of any nuclear detonation experiment, it is worthwhile to consider briefly the entire experiment here.

From Table I we note specifically that in the absence of a present liquid core, a field of the order of 5 to 100 gammas is predicted, depending somewhat on the assumed origin of the moon and conditions during its early history. If a present liquid core exists, the lunar field may be taken to be of the order of the present earth's field, 50,000 gammas.

A special source of magnetic field in the region of the moon and especially germane to the measurement problem is the Solar Wind<sup>14</sup> which is predicted to cause an rms magnetic field fluctuation of the order of 20 gammas. This value appears to be confirmed by indirect experiments<sup>15</sup> and the same measurements also show that the average field in interplanetary space is about one gamma. In the present context, the 20 gamma fluctuation must be considered a noise signal, but obviously measurements confirming this value will be of interest with respect to the solar wind phenomena. A related effect may occur following a nuclear detonation due to the ionized plasma produced. It is obviously of interest to measure this also.

From the above brief summary, it is clear that magnetic field measurements are of considerable importance in determining the present state of the lunar core. A field greater than, say, 500 gammas would imply a liquid center. Careful measurements with an expected magnitude of about

10 gammas may provide information about the moon's origin and the solar wind phenomena. It would be highly desirable to obtain data over a relatively long time interval - of the order of three months - so that temporal effects might be determined. One such effect is that possibly due to electric currents in the lunar atmosphere,<sup>16</sup> which would have a 27-day period.

Measurements taken prior to landing a lunar probe on the moon are likely to be unsatisfactory if the moon's field is below about 50 gammas. Presently contemplated lunar satellites will have an altitude of a few hundred kilometers and may be useful if the field is in the range 200 - 1000 gammas. Thus, to obtain information beyond the primary question of presence or absence of a strong lunar field, it will be necessary to put the instruments on the moon's surface. In order to realize some information concerning the shape of the lunar field, at least three widely separated instrument packages are desirable. If possible, continuous signals during flight should be undertaken in order to compare with present earth satellite magnetometer measurements relating to the earth's field and ring currents near the earth.<sup>17</sup>

The instrumentation required to carry out such measurements must have a sensitivity approaching one gamma and be of small size and lightweight. The proton precession magnetometer<sup>18, 19</sup> is being used for current earth satellite experiments. It has the necessary sensitivity and the considerable advantage of not requiring calibration. Furthermore, the signal is an easily transmitted audio tone whose frequency is a measure of the field. Thus, the precision measuring instrument (a frequency meter) need not be a part of the airborne instrumentation. The instrument has the

disadvantage that it measures the magnitude of the field and provides no directional information. It inherently is not a continuously indicating device, which means short time fluctuations in the field cannot be measured. On the other hand, power requirements are reduced by pulse operation.

Since the frequency of the signal is directly proportional to the field strength, frequencies of the order of 0.4 cps are expected for a lunar field of 10 gammas. This is an inconveniently low frequency to transmit and measure, but probably can be used. However, it may be put into a more suitable range with a small permanent field supplied by a magnet. The accuracy of the instrument is sufficient to easily read a 10 gamma departure from a 10,000 gamma steady field, in which case the signal frequency is in the range of 40 cps.

A more recently developed device, the Rubidium vapor magnetometer<sup>20</sup> also appears to have promise. It, too, requires no calibration and is likely to be lightweight. The signal does not appear to be as convenient, however, and the device has not been miniaturized for satellite applications. In addition, there is some question about its operation in fields as low as 10 gamma.

A rotating coil technique has also been considered<sup>21</sup> and has been employed in rockets for earth's field measurements. In this case a 27,000 turn coil on a mu-metal core generates an a-c voltage when rotated in the field. The rotation is supplied by spin of the vehicle itself and is about 10 cps. In the earth's field a signal of 0.2 volt is observed. In the lunar application a 40 microvolt signal would be generated, which is rather low.

The signal could be increased by greater spin frequencies of the carrier. This technique has the considerable advantage that stray fields generated within the missile do not influence the measurement since they rotate with the coil. Also, the system is inherently simple and lightweight since all that is required is a coil, plus perhaps a transistor amplifier. However, it is incapable of operation from a stationary vehicle as one landed on the moon. Spinning the coil independently of the carrier leads to commutator noise difficulties and is considered less desirable than some of the other techniques available.

The classical earth's field magnetometer is the well-known fluxgate device. Although of sufficient sensitivity, it requires calibration and does not appear attractive on a weight basis. In light of present information, it appears that the precession magnetometer developed for earth satellite use may prove most suitable for the lunar probe if a bias field can be used.

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Chapter VII

SOME ASPECTS OF PLASMA AND MAGNETIC FIELD EFFECTS

## Chapter VII

### SOME ASPECTS OF PLASMA AND MAGNETIC FIELD EFFECTS

In this chapter we shall consider the effect of the environment on the phenomenology of a nuclear device detonation occurring in the vicinity of the moon. The discussion will, at best, be of an exploratory nature since the problems involved are very complicated and, in some cases, insufficient data prevent any analysis in detail. We shall first wish to establish, as best we can, the properties of the interplanetary medium in the vicinity of the earth's orbit where a detonation may be considered to take place. We shall be specifically concerned with the natural particle population in interplanetary space, the magnitude and shape of magnetic fields and the effect of various solar radiations, both electromagnetic and corpuscular, on the material produced in the detonation. In considering the magneto-hydrodynamics of the resulting plasmas (that rarefying off the surface of the moon or coming from the bomb directly) one encounters a problem beyond our capability for detailed consideration in the limited time available. We will therefore concern ourselves with single particle dynamics and a brief discussion of the overall phenomena. Clearly, there are areas here where considerable additional study is necessary to get even relatively crude quantitative information.

We will also consider the effects of solar plasmas on instrumental devices other than the bomb which might be involved in scientific experiments near or on the moon.

## Section One

### The Quiescent Solar Plasma and Solar Streams

There exist a variety of observations which lead to the conclusion that interplanetary space out to somewhat beyond one astronomical unit (1 A.U. =  $1.5 \times 10^{13}$  cm - radius of earth's orbit) of the sun is occupied by a tenuous highly-ionized gas. Details as to the composition, temperature, and the possible presence of non-Maxwellian components are not completely certain and such knowledge must presumably await the results of space probe experiments, some of which are now underway. Strong evidence for the presence of an outward streaming component from the sun has, however, been presented by Biermann<sup>1,2</sup> in early papers and more recently.<sup>3</sup> He shows that the accelerations and radial alignment observed in type I comet tails containing  $\text{CO}^+$ ,  $\text{N}_2^+$  etc. cannot be explained in terms of solar radiation (light) pressure. These accelerations ordinarily appear to be 100 to 200 times as large as solar gravity but may reach 1000 times solar gravity under very active conditions on the sun. A streaming solar hydrogen plasma would produce the observed accelerations because of electric fields set up by the greater stopping power of the cometary material for electrons relative to the protons. Neutral ionized streams having velocities of about 1000 Km/sec and densities of the order of  $10^3 - 10^4$  particles/cm<sup>3</sup> at the orbit of earth were suggested to account for these observations. Biermann points out that the highest accelerations can be related to interactions with individual solar corpuscular beams of still higher density presumably

connected with discrete geomagnetic storms. On occasions of high solar activity, the suggested density of the streams<sup>4</sup> may reach  $10^5$  protons and electrons per  $\text{cm}^3$  at 1 A.U. while velocities might be upwards of 2000 Km/sec. Similar values may be obtained from observations on changes in solar radio noise.<sup>5</sup>

For a quiet sun, Behr and Siedentopf<sup>6</sup> have examined the polarized component of the zodiacal light and find an electron density at 1 A.U. of 700 particles/ $\text{cm}^3$ . Electrical neutrality would then require an equal number density of protons. In a discussion of Biermann's early papers, Kiepenheuer<sup>7</sup> derives a lower limit for the particle density of about six particles/ $\text{cm}^3$  assuming a velocity of 1000 Km/sec for the solar plasma.

Recently, Kuiper has suggested<sup>8</sup> that a reasonable average density for quiet conditions might be about 600 protons/ $\text{cm}^3$ .

In a series of papers,<sup>9</sup> Parker has summarized various geomagnetic effects which are assumed to be associated with discrete solar streams from an active sun. He goes on to suggest possible mechanisms for supra-thermal particle generation as a possible source of auroral effects and considers cosmic ray modulation by solar plasmas as well as magnetic storm effects. From these considerations, densities for quietest conditions appear to be at least  $10^2$  ions/ $\text{cm}^3$  with a minimum velocity of 500 Km/sec. Under active conditions, densities of  $10^5$  ions/ $\text{cm}^3$  and velocities of 1500 Km/sec or more are obtained.

Russian workers<sup>10</sup> studying the dissipation of a high temperature non-

stationary solar corona in the presence of a directed stream of matter also conclude that the density of particles in solar streams near the earth is between  $10^3$  and  $10^5$  particles/cm<sup>3</sup>. Summaries of observations together with some views on the nature of the solar plasma prior to the launching of the Russian space probe of January 2, 1959 have also been given.<sup>11</sup> Velocities of between 1000 and 3000 Km/sec are suggested with stream concentrations ranging from 10 to  $10^3$  particles/cm<sup>3</sup>. With the low density stream, a background gas at about  $10^4$  degrees Kelvin is also considered to be present.

It should be emphasized that the properties of the solar plasma under discussion pertain to conditions away from the perturbing influence of planetary magnetic fields. Such fields will shield out or markedly change the influence of the solar plasma in nearby regions of space. In the case of the earth, we may compute the approximate distance beyond which solar effects to be discussed will be active. Roughly, the requirement is that the plasma kinetic energy density exceed the magnetic energy density and we may write this condition as

$$\frac{1}{2} n m v^2 = \frac{B^2}{8\pi}$$

In the equatorial plane of the earth, assuming a pure dipole field, we have

$$B = B_0 \left( \frac{r_0}{r} \right)^3$$

from which the minimum distance for onset of the effects is

$$r = r_0 \left( \frac{B_0^2}{4\pi n m v^2} \right)^{1/6}$$

Assuming the earth's surface field (horizontal component) as  $B_0 = 0.4$  gauss, setting  $r_0 = 6.4 \times 10^8$  cm as the terrestrial radius and taking the stream density  $n$  to be  $10^3$  particles/cm<sup>3</sup> with  $v = 10^3$  Km/sec and  $m$  appropriate for protons, we find  $R = 2.9 r_0$ . For this illustrative case, we would expect effects beyond 8,000 miles from the earth's surface. This is to be taken only as an order of magnitude figure for a variety of reasons, particularly because of the perturbation of the earth's dipole field by the plasma itself and possibly by a radial solar magnetic field. It does appear that "stationary" satellites orbiting at 22,000 miles might be affected. Note that  $r$  varies slowly with  $n$  and  $v$ .

In the case of the moon, as discussed in another chapter of this report, it is not known what magnetic field to expect and so it is not possible to calculate the region around the moon which would be protected from solar streams. We do, in general, expect the lunar magnetic field to be low, and it might be mentioned here that the recent Russian observations on gaseous emission from the moon have been interpreted as being due to excitation from the solar plasma during interaction with gases released from the lunar surface. That these gas releases are not volcanic and therefore do not imply a liquid core has been suggested by J. H. Fremlin of University of Birmingham among others. If these interpretations are correct, it would re-enforce the argument that the lunar magnetic field is indeed very small.

Before leaving the matter of the density and velocities of the solar

streams, it should be mentioned that two groups have raised objections to the general magnitudes chosen here. Lars Block, in a series of papers in *Arkiv för Fysik*,<sup>12</sup> has suggested that the gas densities required for explanation of certain of the effects observed are much lower than those suggested by Parker, for example, although no specific reference is made to Parker's work. On the other hand, Block does not consider the observational data on the behavior of cometary tails. Furthermore, it has been suggested that the Alfvén field which Block employs for his calculation does not fit the data currently being obtained by Babcock and Babcock but requires larger fields than have actually been observed. The Block model has not been pursued to the point of fully evaluating it, but it does appear at first glance rather difficult to reconcile the cometary information with this model which is based primarily on zodiacal light observations.

A second study which should be mentioned is that of E. J. Opik<sup>13</sup> made in 1956. Opik concerns himself with detailed calculations on the interplanetary dust and the terrestrial accretion of meteoric matter. In the process, he has made calculations of the rate of sputtering of meteorites by the solar plasma. Such calculations as a basis for objection to relatively high interplanetary stream densities was revived recently by Bergstrahl.<sup>14</sup> Opik's data both on the drag and sputtering from fast corpuscular radiation of low temperatures may be summarized in Table I, taken from his paper.

Table I

DRAG AND SPUTTERING FROM FAST CORPUSCULAR RADIATION OF LOW TEMPERATURE

$v = 10^8$  cm/sec;  $N_e = 600 \text{ cm}^{-3}$ ;  $T = 10^4 \text{ }^\circ\text{K}$   
 Electrostatic charge of the particles = 200 volts  
 Proton energy = 5220 volts

$r$ , cm (particle diameter)	$10^{-4}$	$10^{-3}$	$10^{-2}$	$10^{-1}$	1
$\delta$ , gr/cm <sup>3</sup> (particle density)	3.5	3.5	3.5	0.6	0.6
Effective cross-section, $S$ , cm <sup>2</sup>	$4.98 \times 10^{-7}$	$1.54 \times 10^{-8}$	$3.14 \times 10^{-4}$	$3.14 \times 10^{-2}$	
Radial drag per physical cross-section dyne/cm <sup>2</sup>	$1.59 \times 10^{-4}$	$4.9 \times 10^{-3}$	$1.00 \times 10^{-3}$	$1.00 \times 10^{-5}$	$1.00 \times 10^{-3}$
Ratio of radial drag to radiation pressure	3.53	1.09	0.222	0.222	0.222
Ratio of tang drag to Poynting-Robertson effect	1060	318	66.6	66.6	66.6
$\theta$ , (transit time)	10	300	14000	24000	240000
Time of destruction by sputtering, years	1.0	10	100	170	1700

His drag data are included for completeness only and are not particularly germane to our discussions. Two points are to be noted from this table: the average transit time,  $\theta$ , refers to the time required for particles moving in nearly circular orbits to travel inward from two to zero astronomical units distance. The time for destruction by sputtering is calculated on the basis of a yield of five atoms or molecules for each impinging proton. Subsequent to the Opik calculations, it has become clear that the sputtering of oxides by ions rather than neutral atoms of this energy is probably two decades lower than the yield<sup>15</sup> assumed by Opik. The calculations that we will make in subsequent sections are concerned with metallic surfaces or, at worst, surfaces with very thin oxide coatings so that we will take a yield of one in such cases even though the yield for a sputtering of meteors might be 0.05 to 0.01. Clearly, this is a highly speculative matter and points up the need for good sputtering measurements on both meteoritic materials and materials of construction such as those treated in later sections. In any case, with a reduction of the order of one or two orders of magnitude which could come at least in part from a lower sputtering yield, the time of destruction by sputtering as calculated by Opik becomes of the order of the transit lifetime.

The exposure time to sputtering which is appropriate for calculations of lifetime is, of course, in part determined by the origin of the meteorites. If one assumes that the meteorites are a result of a grinding process in the asteroid belt, then the times of exposure appropriate for such calculations are of the order of the transit lifetimes rather than the cosmic age of the

material in the meteorite. In general one must be very cautious in assigning an effective time for the sputtering process to occur. Urey<sup>16</sup> has recently suggested from a considerable body of data on meteorites that an effective age of the order of millions of years rather than billions of years for the stone meteorites is correct, whereas the irons range around  $10^9$  years. He discusses the possibility that the stone meteorites originate from the moon rather than from other possible sources in which case transit times could be quite short. A few last comments might be made concerning the instability of the solar stream somewhat beyond the orbit of earth as will be alluded to again in the next section. Both this instability and some sort of self-shielding might be possible explanations for the survival of iron meteorites. It is, at present, not possible to decide what the sputtering ratio should be after the solar streams become unstable and perhaps change their velocity distribution appreciably. It is interesting to note that this instability could occur before interaction with the asteroid belt, e.g. a little beyond 1 A.U. Opik's calculations also ignore both the existence of a very low threshold for some sputtering processes and the possible existence of elements heavier than hydrogen in the solar streams. It is possible that both of these effects could be used to force the effective velocities on his model to such low values as to endanger the entire structure of his theory. These points will be treated further elsewhere.<sup>17</sup>

## Section Two

### The Interplanetary Magnetic Field

Measurements on the actual magnetic field existing in the space will become available in the very near future. In the meanwhile, however, the magnitude and the nature of these fields must be inferred from other observations. For purposes of this discussion, we shall assume a picture of the interplanetary field due essentially to Parker and described in references already noted. These ideas suggest a radial solar field falling off as  $R^{-2}$  as a result of protons streaming from the solar surface. In this picture, one imagines a dipolar field which has been stretched into a perfectly radial one because of the outward high velocity stream of plasma. Somewhat beyond the orbit of earth, instabilities in the radial streaming can occur and a disordered entangled field of rather low magnitude results. It is not completely definite in this model where such disordering would occur and the general location of these instabilities is inferred from observations on cosmic ray data and solar flares. In any case, if the moon is embedded in the well-behaved radial solar field, it becomes possible to discuss single particle dynamics in a definite manner. It is clear that such an assumption is speculative.

At one astronomical unit from the sun we desire now to calculate the magnetic field strength on the assumption of a completely radial field. For this purpose we, of course, need information on the general solar field at the surface of the sun. Data reported in the literature indicate that the

average surface field could be anywhere from 0.1 gauss to 10 gauss. Recently, however, Babcock and Babcock have continued their measurements on the nature of the average solar field and it appears that a figure of approximately one gauss is realistic.<sup>18</sup> The picture of the sun emerging is one of equatorial disorder overlaid by a well-behaved dipolar field near the poles. The average field in the disordered region is consistent with the figure we have taken, but there are clearly local details in the structure near the equator. Because of the general configuration of the solar system, if one assumes a perfectly dipolar field coupled with perfect radial streaming, one would arrive at essentially zero field in the plane of the earth with, however, very high gradients. We shall assume that the mixing is sufficient to allow us to ignore this consequence of perfect symmetry and shall take a field strength appropriate to points somewhat away from the plane of symmetry of the dipole. Under these circumstances, a simple calculation shows that a field of approximately  $2.2 \times 10^{-5}$  gauss is appropriate. This field is sufficiently small so that one must be concerned with fields of other origins. For example, it might be mentioned that Hoyle has suggested a field of  $10^{-3}$  gauss for regions beyond 10 earth radii.<sup>19</sup>

These large uncertainties in both the nature of the solar plasma and the magnetic field make us clearly dependent on future measurements before quantitative results can be obtained.

### Section Three

#### Single Particle Dynamics

In other chapters we have discussed the formation of a plasma cloud due to x-irradiation of the lunar surface by the detonation of a nuclear device. Calculations were made on the energy deposition in various layers of the lunar surface for typical weapon temperatures. The resulting rock vapor will, of course, rarefy out into space from the lunar surface. Since it will have appreciable conductivity it will distort and perturb markedly any magnetic field and plasma which might be pre-existent. The interaction of a single typical particle from this rarefying cloud calculated on the basis of no perturbation of the environment will, however, be of interest because it can provide feeling for some of the effects which might be encountered and might relate to the real motion of particles in the high velocity tail of the rarefying cloud which could precede the main body of the bomb-produced plasma. For these fast particles, hydromagnetic disturbances would not yet have upset the environment. We shall assume the material of the rarefying lunar gas to be olivine with an atomic weight of 21, an average atomic number of 10.5 and we shall assume, quite arbitrarily, an effective charge for a typical particle of unity. For such a material, the rms velocity as a function of temperature is given by

$$V = 3.5 \times 10^3 T^{1/2} \text{ cm/sec.}$$

We may take the appropriate velocities for various temperatures and calculate the Larmor radius,  $r_L$ , corresponding to these velocities in the

unperturbed solar magnetic field. These data are shown in Table II.

Table II

Temperature, °K	RMS Velocity for Olivine v (km/sec)	Larmor Radius for Olivine r <sub>l</sub> (cm)
10 <sup>4</sup>	3.45	3.4 x 10 <sup>6</sup>
10 <sup>5</sup>	11.5	11.5 x 10 <sup>6</sup>
10 <sup>6</sup>	34.0	3.4 x 10 <sup>7</sup>
10 <sup>7</sup>	115.0	11.5 x 10 <sup>7</sup>
10 <sup>8</sup>	340.0	3.4 x 10 <sup>8</sup>

Since we have assumed a radial solar magnetic field to be the only one present in this exploratory calculation, we may compute the transit time for a typical particle moving in the direction of the sun to the position in this radial field where mirroring will occur. In general, the field at the mirror point B<sub>m</sub> is given by

$$\frac{B_m}{B_i} = \frac{1}{\sin^2 \theta_i}$$

B<sub>i</sub> is the field at the point of injection and θ<sub>i</sub> is the angle of injection. Since our magnetic field goes as 1/r<sup>2</sup> this expression is exact rather than dependent upon adiabatic invariance as shown as early as 1896 by Poincaré who calculated trajectories in a monopole field. We may immediately write the mirror radius in terms of the injection radius as

$$r_M = r_i \sin \theta_i$$

Taking the injection radius to be one astronomical unit and considering the

particle injected at 60 degrees, one finds that the mean length of the trajectory to the mirror point is approximately  $2 \times 10^{12}$  cm. We use a particle injected at 60 degrees as a typical case since contained within a cone of this angle will be one-half of all the particles, assuming that the injection is isotropic.

We may obtain a lower bound to the time required for travel to the mirror point by using the initial velocity along the solar radius. A more detailed calculation would consider the transfer of energy from transverse to radial components but, as will be seen, this lower bound calculation is completely adequate to establish the point we wish to make. In general, a lower bound to the mean time to the mirror point is given by

$$t > \frac{r_i (1 - \sin \theta)}{\frac{\sqrt{3kT}}{m} \cos \theta}$$

and if we set  $\theta$  equal to 60 degrees and take a temperature of the order of  $10^5$ °K, we find this time is of the order of 40 days at a minimum. Now this is to be compared with times required for other aspects of the interplanetary environment to have their effect on this single particle. In particular, the outward streaming solar plasma electrons will be de-celerated in the rarefying lunar cloud and set up electric fields which will drag on the clouds travelling toward the sun in precisely the same way that drag is produced on cometary tails. The ratio of solar gravity to this drag has been computed for the cometary case by various investigators. In particular, Kiepenheuer<sup>20</sup> gives for this drag ratio,  $\mu$ , the expression

$$\mu = 1.6 \times 10^{17} \frac{r_i}{v^2}$$

where  $n$  is the particle density for the solar stream and  $v$  is the relative velocity. Although our materials are somewhat dissimilar, we may use this expression to compute to order of magnitude the time required for the relative velocity of the two systems to change from  $v_0$  to  $v_f$ . This time is simple

$$t = \int_{v_0}^{v_f} \frac{v^2 dv}{1.6 \times 10^{21} n g_s}$$

where  $g_s$  is the solar acceleration.

If the change in relative velocity,  $\Delta V$ , is small this may be written as

$$t \approx \frac{\Delta V^2}{2 g_s \mu}$$

while if the change in velocity,  $\Delta V \sim v_0$ , this expression becomes

$$t = \frac{v_0^2}{2 g_s \mu}$$

Now if we wish to stop a lunar particle moving with an initial velocity corresponding, let us say,  $v$  to rms velocity at a temperature  $10^5$ °K, then  $\Delta V$ , the change for relative velocity is small and for solar stream conditions corresponding to  $\mu = 100$ , we find that the stopping time is of the order of  $10^4$  to  $10^5$  seconds. If one is dealing with an intense solar stream so that  $\mu = 1000$ , this is reduced to  $10^3$  to  $10^4$  seconds. If, on the other hand, we wish to actually turn the particle which initially started toward the sun and have it attain the velocity of the solar plasma stream, the times required are of the order of  $10^5$  to  $10^6$  seconds for  $\mu = 100$  and proportionately less for conditions when  $\mu = 1000$ . We might note here that at one astronomical unit  $g_s$ , the acceleration due to solar gravity, is equal to

$$g_s = 27,440 \left( \frac{1.4 \times 10^{11}}{2 \times 1.5 \times 10^{13}} \right)^2 = 0.67 \text{ cm/sec.}^2$$

Therefore, for  $\mu = 100$ , the plasma acceleration is of the order of 67 cm/sec and for  $\mu = 1000$  the plasma acceleration is of the order of 670 cm/sec. These figures are to be compared to accelerations due to lunar gravity of the order of 167 cm/sec at the surface of the moon. Thus, if  $\mu = 1000$ , lunar gravity will be small from the beginning, while if  $\mu = 100$ , the effect of lunar gravitation will be small after three or four lunar radii have been traversed by the escaping particles. This would take only a few minutes at the velocities under consideration. In any case, it appears that the perturbing influence of collisions for the outward streaming solar gas will completely override any effects directly due to the solar magnetic field so that attempts to calculate single particle orbits and mirroring points in the absence of collisions with the solar streams are pointless.

In passing we might note that the effects we have been treating have also been suggested as active in reducing the normal steady-state lunar atmosphere. This possibility is mentioned among others by Kozyrev.<sup>21</sup> The Russians have also suggested that a lunar cloud, produced by artificial means, could aid in soft landings on the moon. They suggest tests to determine settling times using special rockets to produce the clouds.<sup>22</sup> Such ideas might be worth further thought in the present context.

It is of some interest to consider the time required for ionization of a neutral particle originating in the detonation by electromagnetic radiation from the quiet sun. If we take a cross section for photo ionization of the order of  $5 \times 10^{-18} \text{ cm}^2$  and consider photons of 10 electron volts as effective with this

cross section, we find that the time required for ionization is of the order of  $10^5$  to  $10^6$  seconds by this process. In this calculation, a flux of 6 erg/cm/sec is assumed as indicated by the measurements of Byram et al.<sup>23</sup> This ionization process is, of course, only one of a number of mechanisms which will be operating. The mean time to ionization by solar protons, however, assuming a cross section of  $10^{-18}$  cm<sup>2</sup> with a velocity of 1000 Km/sec and a density of  $10^3$  particles/cm<sup>3</sup> is one order of magnitude longer than that required for UV ionization. From such calculations as these, it appears that single particles which are neutral at the beginning of the process might remain neutral long enough to travel of the order of the earth-moon distance without acquiring a charge. Before such a conclusion can be definitely established, it would be necessary, however, to consider other mechanisms than those discussed above including stripping reactions, charge exchange and other possibilities.

If single particle calculations were to be taken seriously, we could, in principle, calculate the shape of the cloud of lunar material released by the detonation and from such calculations decide how visible such a cloud would be and for how long. In fact, taking a particle injected at an angle  $\theta$  as representative of the behavior of the entire system, one may readily show that the volume enclosed by the orbit of such a particle in a time  $t$  is given by the expression

$$V = \frac{\pi t \cos \theta m^{1/2}}{B^2 E_H} (3KT)^{3/2}$$

If one assumes that this volume is then filled with lunar debris, one may make calculations on the question of visibility. Taking a temperature of  $10^5$ °K, taking  $\theta$  as  $60^\circ$  and using a time of  $10^5$  seconds after the burst, one finds the volume,  $V$ , to be of the order of  $10^{25}$   $\text{cm}^3$ . If we assume  $10^6$  kilograms of matter have been injected as a result of the bomb x-ray pulse and uniformly distributed in this volume, we find a particle density of the order of  $10^6$  particles/ $\text{cm}^3$  which is perhaps two to three orders of magnitude larger than the density normally present in interplanetary space. If a cloud is singly ionized we may compute a lower bound to the brightness by considering only Thompson scattering. The number of electrons along the diameter of the cloud is about  $10^{14}$  so that the system is optically thin and one finds a scattered solar flux of the order of  $10^7$  photons/ $\text{cm}^2/\text{sec}$ , which is a significantly high number and is equivalent to  $5 \times 10^{-13}$  lumens/ $\text{cm}^{-2}/\text{sec}$ . This would be visible with a 16x telescope with one inch aperture. To this scattered solar flux must be added other scattered radiation and especially resonance fluorescence light.

It should be mentioned that many observational techniques on the bomb cloud may be suggested by drawing an analogy with work on the solar corona. Possibilities which come immediately to mind are:

- (1) Observations on the scattered Fraunhofer lines of the sun. The spread in such lines  ~~$\Delta\lambda$~~  is proportional to  $\sqrt{T}$  of the bomb cloud electrons so interesting temperature histories could be obtained. Severe broadening occurs at  $10^5$ °K.
- (2) Doppler shifts in lines. Such data might permit detection of ordered motions in the cloud.
- (3) Polarization measurements.

Parenthetically, we may calculate the solar radiation pressure on the assumption of pure Thompson scattering. At one astronomical unit, per electron, the radiation pressure from radiation  $h\nu$  is given by

$$P = \frac{1}{3} F \frac{h\nu}{c} \quad \text{where } F \text{ is the solar flux}$$

$$\text{and } \frac{1}{3} = \frac{8\pi}{3} \left( \frac{e^2}{m_0 c^2} \right)^2 = 6.65 \times 10^{-25} \text{ cm}^2$$

P at 1 A. U. is equal to  $3 \times 10^{-29}$  dynes. The force of solar gravity for mass 21 particles is  $2 \times 10^{-23}$  dynes and since polarization forces keep the plasma acting as one body, it is clear that gravitational effects overwhelm light pressure effects and one is left with solar stream and magnetic interactions as the dominant factors. It becomes clearly necessary then to reconsider all of these qualitative estimates in a more realistic way, taking into account the magnetohydrodynamics of the situation. The degree to which such a treatment will differ from the single particle trajectory picture may be readily indicated by a trivial calculation of the spherical volume of the rarefying lunar vapor when the magnetic pressure from the solar field equals the material pressure. Although a sphere is assumed, it is evident that expansion will be anisotropic and probably a "sausage" would be a more realistic model. In our illustrative case of a  $10^5$ °K gas and a mass  $10^6$  kilograms, the radius computed on this basis is of the order of  $10^{10}$  cm. On the other hand, such an estimate as this ignores the presence of the already existing interplanetary plasma.<sup>24</sup> For a system volume corresponding to a radius  $10^{10}$  cm, the mass of lunar material results in a particle density of only 10 lunar particles/cm<sup>3</sup> whereas the background gas might be two orders of

magnitude higher than this. It is apparent that engulfing of the normally present interplanetary medium will reduce the overall radius of the cloud and change its composition as well. In this process various sorts of hydro-magnetic instabilities could also result. It may be, therefore, that the picture developed on a single particle model is not quite as far off dimensionally as one might first assume. Clearly, however, the phenomenology should be treated in more detail before any firm conclusions can be drawn.

An individual aspect of the behavior of the lunar plasma which deserves attention and which can be treated in a somewhat realistic way is discussed in an appendix to this chapter. It is concerned with production of relativistic electrons as a result of plasma interaction with inhomogeneous magnetic fields by mechanisms other than the usual Fermi acceleration. If such a mechanism is operating, it may lead to interesting observable effects not only for detonations near the moon but also elsewhere in space.

#### Section Four

##### Influence of Solar Plasmas on Experimental Apparatus

During the course of the present considerations as well as in many other investigations of this general topic, the need has arisen for optical tracking aids and for other experimental structures to be erected in space or on the lunar surface possessing large surface area and low total mass. The desire for such structures is discussed in the chapter on optical problems in this report as well as elsewhere. With these types of structures in mind, it is of interest to compare the force per unit area exerted on a

material body by solar plasma streams with that produced by light pressure. The latter, in general, is given by the sum of momenta carried by incident solar radiation minus the parallel component of reflected or absorbed and subsequently re-radiated flux plus the anti-parallel component of momentum from re-radiated flux. If we assume a perfect reflector, no re-radiation can occur, and the force per unit area at 1 A.U. reaches a maximum value of about  $9 \times 10^{-5}$  dynes/cm<sup>2</sup>.

If we assume a solar plasma containing let us say 600 particles/cm<sup>3</sup> and travelling at an average velocity of 1000 Km/sec we obtain a force of  $10^{-5}$  dynes/cm<sup>2</sup> if the beam is simply stopped in the material. For an active sun during a severe storm, with stream densities of  $10^5$  particles/cm<sup>3</sup> and velocities of, say, 2000 Km/sec, we obtain  $6.7 \times 10^{-3}$  dynes/cm<sup>2</sup>. Thus, for quiet conditions the plasma produces 0.11 times the maximum light pressure, but during a storm, it may exert perhaps 75 times the solar radiation pressure on a perfect reflector at 1 A.U. from the sun.

The very difficult problem of locating and tracking a small instrument package in the vicinity of the moon, for example, has led to the very interesting suggestion that highly reflective balloons be periodically discharged from the package.<sup>25</sup> According to this suggestion, dispersion of these balloons by light pressure would then produce an advancing line of objects of high visibility. If such a system were indeed employed, it would be of interest to attempt to observe additional accelerations above the light pressure value which could be ascribed to the solar plasma. Conceivably,

some information on the fluctuations in momentum transfer due to changes in solar plasma velocities and densities could also be obtained from such observations. No telemetry of data would be required. Consideration should, however, be given to possible destruction of the balloons or their reflective coatings by the plasma. This will be discussed more fully in the next pages since these effects are also germane to questions of long-lived passive communications reflector satellites and durability of balloon markers<sup>26</sup> for the lunar surface assuming the absence of a lunar magnetic field<sup>27</sup> and to power generation equipment using thin films.

Before leaving the subject of the forces exerted by solar plasmas mention may be made of an apparent revival of interest in the idea of using light pressure for propulsion. Originally suggested in the literature of science-fiction,<sup>28</sup> it has received attention in the serious lay press<sup>29</sup> and in the American Rocket Society Journal.<sup>30</sup> The practicality of these ideas has already been questioned on other grounds by Greenwood<sup>31</sup> and there is no need to repeat his criticisms here. To the list of problems may be added the thought that in the presence of a strong solar plasma stream, the forces on the shrouds of a "solar sail" will be orders of magnitude greater than the results given by Garwin, for example. The latter author, in arriving at his conclusion that light pressure propulsion is practical, proposes the use of commercially available metallized plastic film of 0.1 mil thickness and suggests, as an improved design, that film of thickness  $2 \times 10^{-5}$  cm be used. Assuming such a structure could be built, if it were struck by a solar plasma

stream, considerations to follow show that its function might be seriously impaired in a short time.

When high velocity ions or atoms impinge on a solid surface, momentum transfer processes or, in some cases, chemical processes lead to the ejection or sputtering of atoms from the surface. For the case of physical sputtering of metals, the threshold energy  $V_0$  for particles of atomic weight  $M$  impinging normal to a surface of atomic weight  $M_s$ , is given by

$$V_0 = \left( \frac{1.6 \times 10^5 (M + M_s) \phi}{M^2 M_s W} \right)^2$$

where  $\phi$  is the heat of sublimation of the surface material in kcal/mol and  $W$  is the bulk sound velocity for the material in cm/sec.

This semi-empirical expression was obtained by Wehner<sup>32</sup> and fits experimental observations obtained with thick samples at room temperature or above. Applying these results to the sputtering of very thin structures or coatings by the hydrogen-rich solar plasma stream can only give very approximate results because of: (1) the possibility of chemical sputtering through metal hydride formation which would require much lower threshold energies, (2) the difference between thin film properties and bulk mechanical properties which can change the kinematics of momentum transfer - empirically, this might be accounted for by changes in  $\phi$  and  $W$ , and (3) differences between ionized and neutral atom sputtering mechanisms.<sup>33, 34</sup> For protons on aluminum, the calculated threshold for perpendicular incidence, using  $\phi = 75$  kcal/mol and  $W = 5.1 \times 10^5$  cm/sec, is  $V_0 = 560$  electron

volts. The energy of solar protons may be readily computed and, for 1000 Km/sec streams, is  $\sim 5100$  electron volts. Thus, even for considerably slower streams than suggested by some of the observations, sputtering thresholds at normal incidence are likely to be exceeded by large margins.

The yield of sputtered atoms per incident particle is a more difficult subject and observations as well as theoretical predictions vary widely. Depending on the circumstances, yields ranging from 0.05 to well over 1.0 might be appropriate for our situation on the basis of the measurements reported by Weiss and by Wehner and the calculations of Whipple.<sup>35</sup> Still higher yields would presumably be observed at other than normal incidence; Goldman and Simon<sup>36</sup> suggest a secant  $\theta$  dependence in the theoretically simple case of high energy sputtering with the yield going with energy as  $\ln V/V$ . In view of the uncertainties involved, we shall assume a sputtering yield of unity and note that the destructive effects to be computed can be readily scaled to other values.

Consider now a reflective structure consisting of metallized plastic. In order to achieve high visible opacity, a metal thickness of the order of  $300 \text{ \AA}$  will be required which, in the case of aluminum, would weigh about  $10^{-5}$  grams/cm<sup>2</sup> and contain about  $2 \times 10^{17}$  atoms/cm<sup>2</sup>. Supporting the metal coating would be a plastic film which, in the case of marker balloons or focusing collectors, might be 0.1 mil to 0.25 mil thick and which would weigh between  $25 \times 10^{-5}$  grams/cm<sup>2</sup> and  $60 \times 10^{-5}$  grams/cm<sup>2</sup>. Thus, metal thicknesses in excess of 10 times the assumed value (e.g.  $3000 \text{ \AA}$

of aluminum) begin to cost heavily in payload for fixed structural area. For light pressure propulsion, where plastic film thicknesses of  $2 \times 10^{-5}$  cm have been proposed<sup>30</sup> even the 300 Å coating adds one-third to the mass per unit area.

Complete stripping of a coating by sputtering would occur in a time  $t$  given by

$$t = \frac{N L d}{M \sigma \langle n v \rangle}$$

where  $N$  is Avogadro's number

$L$  is coating thickness

$\sigma$  is sputtering yield assumed independent of  $L$  but averaged over angle and weighted according to the incident velocity distribution

$M$  is coating atomic weight and  $d$  is density

$\langle n v \rangle$  is the solar flux averaged over the exposure time

Optical properties will, of course, begin to change well before complete removal is effected. This expression does, however, ignore atoms removed from one part of the structure and deposited on another region either because of the physical design of the structure or by virtue of image charge forces. Most sputtered particles are neutral. We also ignore atoms ejected in the forward direction through the structure. Mass losses or atomic displacements from this latter mechanism could be quite important especially for very thin films.

The time required for solar protons to destroy a 300 Å coating, on the basis of an average yield of unity, a density of 600 particles/cm<sup>3</sup> and a

velocity of 1000 Km/sec would be less than one month of exposure. For densities and velocities corresponding to an intense storm ( $v = 1500$  Km/sec and  $n = 10^5/cm^3$ ) the coating would be completely removed in about  $10^4$  seconds. This time is within an order of magnitude of that required for an average beam from a single solar event to pass the earth at a velocity of 1000 Km/sec. A beam length in space of about  $10^{11}$  cm is suggested by Kiepenheuer<sup>37</sup> to account for the time dependence of geomagnetic effects while Unsöld and Chapman give a beam length of  $1.2 \times 10^{12}$  cm. Thus, depending on how literally one takes the assumptions, a single encounter with a beam ejected from an active sun could conceivably destroy the reflective coating. Scaling to other assumptions about proton densities, velocities, and yields is direct and obvious.

We turn now to an aspect of the solar plasma usually ignored - the presence of elements heavier than hydrogen. Except for Unsöld and Chapman's attention to possible Ca II content of a stream, a plasma consisting purely of protons and electrons is generally assumed. However, since the corpuscular beams appear to be merely segments of the solar corona blown out bodily, one should expect both helium and higher Z elements to be present. If one assumes no fractionation occurs during acceleration, an assumption which might be more applicable to individual streams from an active sun than to quiet conditions, it would be reasonable to expect a plasma composition similar to that of the corona itself, by weight roughly 75 per cent hydrogen, 23 per cent helium and 2 per cent heavy elements.<sup>38</sup> For the last we may

take an average atomic weight of around 32.<sup>39</sup> In the plasma a population ratio, H:He:Heavy, of about 75:6:0.06 might then be expected. Charged heavy species would travel at the same velocity as the general proton stream because of polarization fields and would therefore possess correspondingly higher energies and momenta. From the viewpoint of any impulse delivered to a structure, the influence of all but the helium is negligible (and, in fact, is partially taken into account by the methods used to calculate stream properties from observations in the first place). From the viewpoint of sputtering, however, the presence of these components could lead to appreciable effects. In comparison to protons, momentum transfer from such particles to atoms of a surface is more efficient, differences between charged and neutral components not so marked, and a variety of chemical sputtering mechanisms possible. For example, the work of Weiss et. al. for silver shows a sputtering yield for  $\text{He}^+$  higher than for  $\text{H}^+$  by a factor of about nine in the 10 kev region. This alone would make the sputtering by solar  $\text{He}^+$  about equal to that by solar protons.

The heavy component in a 5 kev proton stream would have an average energy in the vicinity of 160 kev while the sputtering threshold for such particles incident normally on an Al surface would drop to the order of 94 electron volts because of higher momentum transfer efficiency. It might be noted that if such particles were present even in the form of a cold stationary gas, perhaps the remnants of previous solar streams, and the structure under consideration was moving along with the earth (but outside

the magnetic shielding limit), the equivalent energy of the gas impinging on the surface would be about 180 ev - well above the sputtering threshold.

Similar considerations to the above may be made concerning the longevity of thin coatings of prescribed emissivity applied for purposes of temperature regulation of extra-terrestrial structures.

If the surface of the plastic film itself, rather than an overlying metal coating, were exposed to the solar plasma, radiation damage effects over and above those caused by solar ultra-violet and x-ray emission are to be expected. Hydrogen evolution leading to charring and carbonization at exposures of more than  $10^{10}$  Rad (1 Rad = 100 ergs/gram) should occur. If the reflecting film were behind the plastic, a marked drop in albedo would presumably precede final destruction by some sort of sputtering away of the carbon skeleton of the polymer.

Radiation damage produced by relatively slow, heavy particles of the kind present in solar plasmas has not been extensively studied. As a first approximation, we shall assume the dose to be delivered uniformly over the range of the incident particles. This is justified because multiple scattering and similar effects will smear any strong dependence on details of the primary energy loss mechanisms. Since hydrogen evolution results from molecular excitation and ionization, direct conversion from energy loss to chemically effective dosage should be permissible down to a limit below which elastic collisions predominate as a result of the incident particle velocity dropping below the pertinent orbital electron velocities. Seitz<sup>40</sup>

suggests, for this limit, the point at which the incident particle velocity is that of an electron with about one-eighth to one-quarter of the required excitation energy  $E_t$ . If  $E_t \sim 4$  ev, the proton energy required for excitation would be 1 to 2 kev. For the heavy element component, the lower limit would be around 30 to 60 kev. In both cases, the velocities associated with the solar plasma are well above the required limits. For a rough estimate we shall compute the range of the particles and then convert the energy loss sustained up to these limits to Rads.

For solar protons, the range measurements of Cook *et. al.*<sup>41</sup> may be used along with a range-energy relation of the form  $R = kE^{2/3}$  to obtain a range of  $\sim 10^{-5}$  grams/cm<sup>2</sup> for a velocity of 1000 Km/sec. For a density of 600 particles/cm<sup>3</sup> the dose would be about  $5 \times 10^5$  Rads/sec. Carbonization requires of the order of  $10^{10}$  Rads and hence would occur in about  $2 \times 10^4$  seconds. For a beam from an active sun, the time required would be about 100 seconds or less than the exposure time provided by a single major event.

For the heavy elements discussed earlier, the range may be computed from the expression<sup>42</sup>

$$R = 6 \times 10^{-7} \frac{(Z_1^{2/3} + Z_2^{2/3})}{Z_1 Z_2} \left( \frac{A_1 A_2}{A_2} \right) A_1 E \text{ grams/cm}^2$$

where  $Z_1$ ,  $A_1$  and  $Z_2$ ,  $A_2$  are the atomic number and weight of the absorber and stream particles respectively.  $E$  is stream energy in kev.

The range of this component in plastics is thus calculated to be 5 to  $10 \times 10^{-5}$  grams/cm<sup>2</sup> for velocities presumed appropriate to a quiet sun. For storm conditions, with velocities of 1500 Km/sec or more, the range of the particles would exceed  $25 \times 10^{-5}$  grams/cm<sup>2</sup> allowing them to completely penetrate a 0.1 mil structure. The dose delivered to these thicknesses of material is of the order of 3500 Rads/sec for the quiet sun, assuming  $8 \times 10^{-4}$  heavy particles per proton, and might rise to perhaps  $5 \times 10^5$  Rads/sec due to an intense beam. The corresponding time to deliver  $10^{10}$  Rads from the heavy component alone is about 40 days in the former case. The dosage from the heavy component is naturally small compared to the proton component but is effective over larger thicknesses. It does not require any sputtering away for total penetration of sufficiently thin sections.

The detrimental effect of solar plasmas on the performance of various thin, lightweight structures which might be erected in space has been shown to be potentially serious. The precise magnitude of the problem cannot be established with certainty, but assumptions which appear reasonable in the light of present knowledge lead either to very low durability or to high payload penalties. For certain effects, even a reduction of plasma density by one or more orders of magnitude, as a result of more complete data collected in the future, would still imply a considerable problem.

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Appendix I

ACCELERATION OF ELECTRONS IN MIRRORING PLASMAS

## Appendix I

### ACCELERATION OF ELECTRONS IN MIRRORING PLASMAS

In this appendix, we wish to describe briefly a possible mechanism for the production of fast electrons, in the mev range of energy, from a nuclear burst and specifically not involving nuclear beta decay. The existence of a very simple and general mechanism for generating fast electrons, which has remained unnoted in much of the weapons effects literature, but which has been described qualitatively for the case of cosmic rays by the Russian scientist Veksler,<sup>1</sup> is the basis for this discussion. Veksler has suggested that relativistic electrons in cosmic space can be generated by the motion of a small neutral cloud of ionized plasma in an inhomogeneous magnetic field. We shall repeat here the essentials of his argument and then apply the ideas to the behavior of a nuclear bomb case plasma.

Consider a small cloud of neutral plasma moving as an entity with a velocity  $v_0$ . For simplicity, let us assume that the inhomogeneous field has a symmetry axis and the neutral cloud is moving along this axis which we will denote by  $z$ . When the cloud enters the field, the radial component of the magnetic vector subjects the electrons and ions to an equal, but oppositely directed, Lorentz force. Under this force the particles are accelerated in the plane perpendicular to the motion of the cloud. The resulting currents cause the cloud to become polarized since the resulting de-celerating force acting on electrons is greater than that acting on ions

by the ratio of the masses. The polarization field binds the electrons to the ions and the plasma as a whole is de-celerated and, during the process, energy is extracted from the ions by the electrons. This process continues until the forward motion of the ions is stopped or reverses and the entire plasma rebounds from the magnetic mirror.

Following Veksler, since the forces of polarization which arise will not allow the ions to break away from the electrons, we have, for anytime, the equations

$$\frac{d(m v_{\theta e})}{dt} = - \frac{e}{c} v_z H_r, \quad \frac{d(M v_{\theta i})}{dt} = \frac{e}{c} v_z H_r$$

From which it follows that:

$$v_{\theta i} = - \frac{m}{M} v_{\theta e}$$

where  $v_{\theta i}$  and  $v_{\theta e}$  are the mean ion and electron velocities in the plane perpendicular to the velocity vector of the cloud as a whole, and  $H_r$  is the radial magnetic field component. From this, it follows that when the forward motion of the plasma has stopped, the kinetic energy of the ions is much smaller than the kinetic energy of the electrons. The kinetic energy of the ions is given by

$$W_i = \frac{M_0 v_{\theta i}^2}{2} = \frac{m^2}{2M_0} v_{\theta e}^2$$

which implies that the electron energy will be

$$W_e = \frac{M v_{\theta e}^2}{2} = \frac{m_0^2 \gamma^2}{2M_0} v_{\theta e}^2$$

since the radial kinetic energy of the ions is negligible and the cloud is essentially stopped. If we define  $\gamma$  by the equation

$$\gamma = \frac{1}{(1 - V_0^2/c^2)^{1/2}}$$

and we have the energy of the electrons as

$$W_e = m_0 c^2 (\gamma - 1)$$

in which case the energy of the electron may be written

$$W_e \approx \frac{M_0 c^2}{2} \left( \sqrt{1 - \frac{2V_0^2}{c^2}} - 1 \right) \approx \frac{M V_0^2}{2}$$

neglecting small terms. Thus, an average energy of each electron will be

$$W_e = m_0 c^2 (\gamma - 1), \quad \gamma = \frac{M_0 V_0^2}{2m_0 c^2} + 1$$

Now let us assume that the bomb case in a nuclear detonation has an average atomic weight of approximately 60. It is known from various calculations that the case disassembles with a velocity of the order of 2 to 3 x 10<sup>8</sup> cm/sec. Parenthetically, it might be mentioned that Argo et al. have calculated that the outer portion of the case may attain velocities of the order of 4 x 10<sup>8</sup> cm/sec due to radiation pressure and secondarily to hydrodynamics. Under these circumstances,  $\gamma$ , in the expressions above, is approximately seven and the average energy of the electron in the plasma as it is stopped by the mirror field reaches approximately 3 mev. It is interesting to note that the fraction of the bomb yield going into case motion may thus, in principle, be converted into a good source of high speed electrons comparable to those released by high energy fission product

decay but appearing over a much shorter time. Furthermore, the influence of the magnetic field before mirroring occurs might well keep the source of fast electrons fairly localized even though the burst is some distance away.

Whether measurable effects from a space or lunar burst due to this mechanism can be observed remains to be explored. However, it would appear that some of the high altitude, and especially the ARGUS series of nuclear detonations, might show phenomena which could be interpreted on the basis of this mechanism. The appropriate data relating to this question are not available to us at present. Parenthetically it might be mentioned that if this mechanism does indeed operate successfully, it becomes of possible interest in connection with certain auroral phenomena<sup>3</sup> and also possibly in the matter of detecting nuclear bursts in space.

It is interesting to note that in the ARGMA Anti-Missile Research Meeting for April 21-22, 1959, K. M. Watson suggested the salting of weapons with Boron-11 to obtain a faster beta ray emission rate that is produced by ordinary fission product decay. By this means, he suggests that beta jets could be produced reaching powers of the order of a few hundred watts. If the mechanism suggested in the present discussion were operable, such salting might not be necessary to get the effects. Watson also has suggested that Fermi acceleration mechanisms, occurring in turbulent regions around a burst in space, might produce electrons of the energies of the order of 100 mev. It seems possible that the efficiency of the present mechanism might be comparable to the process suggested by Watson.

The arguments put forth for the existence of the mirror accelerating mechanism are certainly not rigorous ones and it may well be that other factors enter which reduce, in a fundamental way, the effectiveness of the energy transfer. Then too, even if the arguments are valid, due consideration must be given to energy loss processes, scattering and other complications. In view of the relative complexity of the phenomenon from an analytical viewpoint, it might be worthwhile to appeal to laboratory experiment to establish the existence of the process.

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Chapter VIII  
ORGANIC MATTER AND THE MOON

## Chapter VIII

### ORGANIC MATTER AND THE MOON

Since the deposition of an instrumented package on the lunar surface is implicit in many of the experiments discussed in this report as well as being imminent as a result of other U. S. or Russian activities, there has been considerable recent concern that terrestrial organisms and organic matter, deposited with the package, may obscure detection of possible organisms or organic matter indigenous to the moon.<sup>1, 2</sup> If such a biological contamination of the moon occurred, it would represent an unparalleled scientific disaster, eliminating several possibly very fruitful approaches to such problems as the early history of the solar system, the chemical composition of matter in the remote past, the origin of life on earth, and the possibility of extraterrestrial life. Because of the moon's unique situation as a large unweathered body in the middle of the solar system, scientific opportunities lost on the moon may not be recouped elsewhere. Accordingly, it is of interest to determine (a) the survival probability of a terrestrial life-form on the moon, and (b) the possibility that organic matter was produced during the previous history of the moon, has survived to the present epoch, and could be confused with the remains of contemporary terrestrial life-forms.

#### Section One

##### Survival of Terrestrial Organisms on the Moon

There seem to be three major hazards to survival of terrestrial life on the moon - - the temperature variation, corpuscular radiation, and solar electromagnetic radiation - - which we consider in turn. The probable absence of oxygen, water and other substances from the moon's surface is not,

of course, evidence against survival, particularly of dormant anaerobic microorganisms; but it does preclude the possibility of their reproduction.

Temperatures range from about + 100° C. to about - 150° C. during a lunar day and night, but since many microorganisms, and especially bacterial spores, can survive temperatures in this range, we neglect the debilitating effects of the temperature variation.

Cosmic rays, charged particles emitted by the sun, and continuous and discrete solar electromagnetic radiation are all incident on the moon. Whether they arrive at the lunar surface, however, depends on the existence of a lunar magnetic field and a lunar atmosphere. At the present writing, the strength of the lunar magnetic field is not known (except perhaps in the U. S. S. R.). However the mean density of the moon is comparable with terrestrial surface material; this has always been understood as indicating the absence of an extensive liquid iron core, and presumably the absence of an appreciable lunar magnetic field as well. On the other hand it is not definitely ruled out that the field strength is comparable with the terrestrial value. By terrestrial experience, and from the Stormer theory,<sup>3</sup> energetic charged particles arriving from great distances would be constrained to strike the surface at high magnetic latitudes; cosmic rays and the solar proton stream would then be primarily excluded from a wide band around the lunar magnetic equator.

The work of Biermann on the acceleration of comet tails indicates a flux of solar protons in the vicinity of the moon of about  $5 \times 10^{10}$  protons  $\text{cm}^{-2} \text{sec}^{-1}$ , and a mean particle energy of a few kev (v., e. g., 5). Charged particles will be excluded from regions where the magnetic energy density is greater than the particle kinetic energy density. For the surface of the moon, then, the lunar magnetic field strength must exceed about  $10^{-2}$  gauss for these solar

proton streams "or wind" to be deflected.

From lunar occultations of cosmic radio sources, it can be estimated that the lunar atmosphere contains less than  $10^{14}$  molecules above each square centimeter of surface.<sup>4</sup> Ultraviolet absorption cross-sections for all molecules likely to be in the lunar atmosphere are generally less than  $10^{-16}$  cm<sup>2</sup> at all wavelengths. Hence the optical depth in the ultraviolet is less than  $10^{-2}$ , and there is no attenuation of incident solar ultraviolet radiation by the lunar atmosphere. For the solar proton wind, a 1 to 5 kev proton has a range of about  $10^{-2}$  cm atmosphere,<sup>6</sup> or, roughly  $3 \times 10^{18} / \mu$  molecules cm<sup>-2</sup> for a lunar atmosphere of mean molecular weight  $\mu$ . Consequently, if the lunar magnetic field strength is less than about  $10^{-2}$  gauss, the solar proton stream strikes the moon's surface with negligible loss of energy due to its passage through the tenuous lunar atmosphere. The same conclusion applies to the more energetic cosmic rays.

Now what is the effect of these radiations on terrestrial microorganisms deposited on the lunar surface? We consider microorganisms because they are known to be much less radiosensitive than other life-forms,<sup>8</sup> at least in part because there is less which can go wrong in a simple organism than in a complex one. In addition, the accidental deposition of many microorganisms on the lunar surface is a much more likely contingency than the accidental deposition of large numbers of other life-forms.

In Appendix I, expressions are derived (eqs. 7 and 8) for the time in which a population of  $N_0$  organisms, having a mean lethal dose,  $D$ , for a given radiation, and characteristic dimensions,  $a$ , is reduced to  $N$  organisms by radiation of intensity  $I$ . In Table I, these lifetimes are tabulated for a number of values of  $N/N_0$  and  $a$ . The intensities are those appropriate to

the lunar surface for negligible atmosphere and magnetic field strength, and so are equally appropriate to interplanetary space in the vicinity of the earth-moon system. Consequently the derived lifetimes are also those of an unprotected microorganism in free space, and so have a bearing on the panspermia or cosmozoa hypothesis (v., e. g., 1, 22). The X-ray emission in Table I is taken from a theoretical study of the solar corona<sup>7</sup> and is consistent with rocket observations at quiet sun; the continuous uv intensities are computed from an integration of the Planck equation for appropriate ultraviolet black-body temperatures; and the cosmic ray flux is adopted from the flux inferred to exist at the top of the earth's atmosphere.

For a given organism, the mean lethal dose in roentgens is approximately invariant, under the same environmental conditions, for all ionizing radiation, corpuscular and electromagnetic. Data are not available however for the mean lethal dose for the relatively slow particles in the kilovolt solar streams. For the larger organisms these streams will destroy surface structures rather than irradiate the bulk of the organism. Such a situation might lead to marked changes in the mean lethal dose. It is difficult to know the direction of change. Viruses characteristically lie in the range  $D = 10^5$  to  $10^6$  r; protozoa generally have the same range.<sup>8, 11</sup> Bacteria usually have somewhat lower mean lethal doses,  $10^3$  to  $10^4$  r for E. coli, for example, and  $10^4$  to  $10^5$  r for the spores of B. mesentericus and A. niger.<sup>12</sup> However, there has been no systematic search for radioresistant microorganisms, and it is possible that microorganisms having mean lethal doses as high as  $10^7$  r exist. In addition, D in general has some functional dependence upon such factors as the temperature, the oxygen tension, the time interval in which the killing dose is applied, and the presence of an external aqueous medium.

The dependence is in different directions in different organisms, and the interaction of the various effects is quite complex; but the resulting variation in D is rarely as great as a factor of ten. Considering all these points, then, it appears that a conservative estimate for an average mean lethal dose due to ionizing radiation is  $10^7$  r.

For the non-ionizing ultraviolet radiation, D has a strong functional dependence on wavelength, corresponding to the wavelength variation of molecular absorption cross-sections. There is an absorption maximum at roughly  $\lambda$  2600 due to the biochemically ubiquitous purines and pyrimidines, and another, more pronounced, maximum shortward of  $\lambda$  2300, due to simple diatomic functional groups, such as N-H. Ultraviolet mean lethal doses are given in ergs  $\text{cm}^{-2}$ , and are generally measured at  $\lambda$  2537. To obtain a mean value of D appropriate for a wide range of wavelengths we must know the wavelength variation of D. For common strains of E. coli, for example,  $D(\lambda 3000) = 10^5$  ergs  $\text{cm}^{-2}$ ,  $D(\lambda 2537) = 10^4$  ergs  $\text{cm}^{-2}$ , and  $D(\lambda 2300) = 10^3$  ergs  $\text{cm}^{-2}$ .<sup>12</sup> Considering the decrease of D shortward of  $\lambda$  2300, a conservative (i. e., upper limit) mean value of D for the wavelength region  $\lambda$  3000 to  $\lambda$  2000 appears to be the value at  $\lambda$  2537; this should be roughly applicable for an ultraviolet black-body spectrum with a Wien peak longward of  $\lambda$  3000. The mean lethal dose at  $\lambda$  2537 for the more radioresistant bacteria, such as B. subtilis spores, Sarcina lutea, and the B/r strain of E. coli, are approximately  $10^5$  ergs  $\text{cm}^{-2}$ .<sup>12</sup> An unusual case is the protozoan Paramecium multimicronucleatum, for which  $D(\lambda 2537) = 10^6$  ergs  $\text{cm}^{-2}$ .<sup>11</sup> Considering, finally, the environmental dependences of D mentioned in the preceding paragraph, and the possibility of undiscovered microorganisms of extreme radioresistance, we adopt as a mean value of D for ultraviolet

radiation in the region  $\lambda 3000$  to  $\lambda 2000$ ,  $D = 10^7$  ergs  $\text{cm}^{-2}$ . For the region shortward of  $\lambda 2000$ ,  $D$  is certainly less than  $10^6$  ergs  $\text{cm}^{-2}$ .

Where the computed lifetimes are greater than a month, they have been divided by two - except for the cosmic ray lifetimes - to allow for the lunar night. For times shorter than a month, continuous solar illumination has been assumed, but of course, all such times may be as long as a month if the organism is deposited in a region soon after the terminator has left the region.

A 1 kg. instrumented lunar package may easily contain  $10^{10}$  microorganisms;<sup>1</sup> it is very unlikely that any packages for the immediate future will contain as many as  $10^{20}$  microorganisms. Accordingly, we see from Table I that all microorganisms deposited and exposed to the sun will be killed by uv in a few hours. Similarly, fully illuminated microorganisms in cislunar space will also survive only a few hours. Hence the panspermia hypothesis is untenable for unprotected microorganisms of comparable radiosensitivity to terrestrial microorganisms. On the other hand, suppose some microorganisms somehow survived in space and are deposited in a lunar crevasse or other depression, always shielded from solar radiation. Then, killing will be effected only by cosmic radiation. Because of secondary cascade, cosmic radiation reaches an intensity maximum slightly greater than the surface value at a depth of about 10 cm on the moon, according to recent work.<sup>13</sup> It is reduced to  $10^{-1}$  the surface flux at a depth of about one meter, and to terrestrial surface values at a depth of a few meters. Hence, microorganisms shielded from the sun, but just beneath the lunar surface will not be killed by cosmic radiation for several hundred million years; microorganisms at greater depths will have even longer lifetimes. Similarly, cosmozoa imbedded in, fo

Table I

## LIFETIMES OF DEPOSITED MICROORGANISMS ON THE MOON

Irradiation	Intensity in ergs cm <sup>-2</sup> sec <sup>-1</sup>	Adopted MLD	$\rho/\mu$ in gm cm <sup>-2</sup>	a in cm	Lethality Times in Seconds				
					$10^{-1}$	$10^{-5}$	$10^{-15}$		
Ultraviolet continuum, $\lambda$ 3000 to $\lambda$ 2000	$10^4$	$10^7$ erg cm <sup>-2</sup>	opaque	opaque	$2 \times 10^3$	$1 \times 10^4$	$2 \times 10^4$	$3 \times 10^4$	$5 \times 10^4$
Ultraviolet continuum, $\lambda$ 2000 to $\lambda$ 1000	$10^2$	$10^6$ erg cm <sup>-2</sup>	opaque	opaque	$2 \times 10^4$	$1 \times 10^5$	$2 \times 10^5$	$3 \times 10^5$	$5 \times 10^5$
Solar proton wind, quiet sun	$10^2$	$10^7$ r <sup>a</sup>	$10^{-3}$	$10^{-3}$	$2 \times 10^4$	$1 \times 10^5$	$2 \times 10^5$	$3 \times 10^5$	$5 \times 10^5$
Soft X-rays $\lambda \sim 50 \text{ \AA}$ quiet sun	$10^{-1}$	$10^7$ r	$10^{-3}$	$10^{-4}$	$2 \times 10^7$	$9 \times 10^8$	$2 \times 10^9$	$3 \times 10^9$	$3 \times 10^9$
Cosmic rays, quiet sun	$10^{-3}$	$10^7$ r	400	Almost trans- parent	$4 \times 10^{14}$	$2 \times 10^{15}$	$4 \times 10^{15}$	$6 \times 10^{15}$	$8 \times 10^{15}$

<sup>a</sup>For the larger organisms these streams will destroy surface structures rather than irradiate the bulk of the organism. Such a situation might lead to marked changes in the mean lethal dose.

example, a meteorite would have lifetimes comparable to the age of the solar system, and the panspermia hypothesis cannot be ruled out under these circumstances.

Now what is the possibility that microorganisms deposited on the moon will actually be shielded? The nature of the lunar surface is a complex and much debated problem,<sup>14</sup> which need not be reviewed here. But it is of interest to call attention to a few points. From eclipse temperature measurements and radio observations it is known that there is a dust covering on the moon, but estimates of its depth range from millimeters to miles. However, Whipple<sup>15</sup> has called attention to the experimental fact that dust, in a vacuum, and irradiated with a corpuscular and electromagnetic flux of approximately solar composition, will congeal, forming a low-density, semi-porous matrix. If the lunar surface material has a similar structure, it would appear very possible for microorganisms to be lodged in the interstices of the matrix, in such positions as to be shielded from the sun's rays at all angles of insolation. Under these conditions, the survival for very great periods of time of dormant anaerobic microorganisms deposited near the surface would seem to be a possibility which cannot be neglected. A determination of the microstructure of the moon's surface material is therefore of great importance.

The killing of an organism, of course, does not necessarily involve its chemical dissociation, and long after death occurs, in an anhydrous aseptic environment, many aspects of the organism's characteristic biochemical structure will be maintained. After long periods of continued irradiation, enough bonds would be broken to destroy most of the long-chain biological polymers such as proteins and nucleic acids. The problem is complicated by the existence of radiation protection devices (catalase,

cytochromes, sulfhydryl compounds, photoreactivation mechanisms) in most contemporary organisms. Because of the Franck-Rabinowitch cage effect, the collection of dissociated molecules arising from the original organism would tend to remain in close physical contact. Ionizing radiation is very much more efficient than non-ionizing radiation in depolymerizing and dissociating organic molecules. Breaking of all hydrogen molecular bonds and charring occurs at about  $10^{10}$  r (v., e. g., 5). Charring by the solar proton wind occurs in from months to years, depending on the size of the dissociated organism. If, however, the lunar surface magnetic field exceeds  $10^{-2}$  gauss and the proton wind does not penetrate to the surface, it may take as long as several thousand years for charring to be induced by soft solar X-rays. Thus the value of the lunar magnetic field strength has great relevance for the question of possible biochemical contamination of the moon.

As dissociation advances, lunar temperature effects would become more important, small molecules being readily dissociated at  $100^{\circ}$  C. For example, the most thermostable amino acid, alanine, has a thermostability half-life at  $100^{\circ}$  C. of approximately  $10^3$  years,<sup>16</sup> with most other amino acids having half-lives not less than ten years. Molecules shielded from dissociation by radiation would be relatively unaffected by lunar temperatures, and if lodged beneath a few centimeters of insulating lunar surface material, could have very long lifetimes.

## Section Two

### Production of Organic Matter in the Early History of the Moon

There is reason to believe that the moon, along with other bodies in the solar system, was formed some  $5$  to  $6 \times 10^9$  years ago from the solar nebula, a vast gas and dust cloud of essentially cosmic distribution of the elements.<sup>17</sup>

The contraction timescale for the solar nebula was the Helmholtz-Kelvin period, approximately  $10^8$  years. At the end of this period, the sun approached the main sequence in the Hertzsprung-Russell diagram, thermonuclear reactions were initiated, and solar electromagnetic and especially corpuscular radiation dissipated the nebula from around the protoplanets and their atmospheres. The dissipation timescale for the solar nebula is estimated by Kuiper as between  $10^8$  and  $10^9$  years.<sup>18</sup> After the clearing out of interplanetary space, hot exospheres established in the protoplanetary atmospheres led to efficient evaporation of the planetary envelopes, a process aided by the long mean free paths in interplanetary space and the low escape velocities (due to smaller mass/radius ratios for the protoplanets than for the present planets). The time for the evaporation of the prototerrestrial atmosphere appears to be roughly  $10^8$  years.<sup>19</sup>

During the events just outlined, chemical compounds and condensates were raining down on the protoplanetary surfaces, forming the outermost layers. After the evaporation of the atmospheres of the terrestrial protoplanets, internal heating must have vaporized much of the condensates, thereby forming secondary atmospheres of similar chemical composition to the initial protoatmospheres. The present Martian, Venusian and terrestrial atmospheres are believed to be ultimately of such secondary origin. Similarly, the moon must have possessed a secondary atmosphere at one time, which, however, since has been lost to space because of the low lunar escape velocity. If not replenished from the interior, a lunar atmosphere will escape to space in roughly  $10^3$  years, as can be computed from the work of Spitzer.<sup>20</sup> Hence the lifetime of the secondary lunar atmosphere depended entirely on the supply rate of gases from the lunar interior. This is difficult to estimate,

but it is not impossible that extensive lunar vulcanism lasted for  $10^7$  or  $10^8$  years. Although it is unlikely that the lunar craters are volcanic in origin, other lunar surface features exist which are of undoubted volcanic origin. <sup>32</sup>

We now consider the penetration of solar ultraviolet radiation into the various gaseous envelopes which surrounded the moon in its early history. The absorption cross-section of ammonia, the most prominent nitrogen-containing molecule in cold cosmic gases, shortward of  $\lambda 2600$  is greater than  $10^{-19}$  cm<sup>2</sup>. Hence, as long as the mean density of ammonia exceeded  $10^6$  molecules cm<sup>-3</sup> between the moon and the sun in the solar nebula, solar uv shortward of  $\lambda 2600$  did not reach the lunar vicinity. This ammonia density corresponds to a hydrogen number density of about  $10^9$  molecules cm<sup>-3</sup> for cosmic abundances; i. e., about  $10^{-15}$  gm cm<sup>-3</sup>. Interplanetary densities of this order were reduced rapidly, <sup>18</sup> and we conclude that during most of the  $10^8$  to  $10^9$  years in which the solar nebula was being dissipated, solar uv shortward of  $\lambda 2600$  was reaching the protoatmosphere of the moon. Because the lunar protoatmosphere had not yet begun to escape, due to the short mean free paths within the solar nebula, the lunar protoatmosphere remained opaque to solar uv during this period. After the dissipation of the solar nebula, the lunar protoatmosphere was opaque in the uv for most of its lifetime. In this same period, the moon must have been situated within the protoatmosphere of the earth, and so the moon's surface must have been protected from solar uv by lunar and terrestrial protoatmospheres for almost  $10^8$  years. After the evaporation of these protoatmospheres, and the origin of the secondary lunar atmosphere, it is not clear how long the secondary atmosphere was maintained at sufficient density to absorb all incident solar radiation shortward of  $\lambda 2600$ . The true time may be anywhere between  $10^3$

and  $10^8$  years, depending on the rate of gaseous exhalation from the primitive lunar interior. But from terrestrial experience, one might expect the larger value to be nearer to the truth.

The later solar nebula in the vicinity of the moon, and the primary and the secondary lunar atmospheres, all having cosmic composition, were composed largely of  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ , with smaller amounts of  $\text{H}_2$ , He,  $\text{N}_2$ , CO,  $\text{CO}_2$ , Ar, Ne, and the interaction products of these molecules. The effect of solar ultraviolet light (and electric discharges) on such an atmosphere is well known; organic molecules of fair complexity (up to molecular weight  $\sim 100$ ) are produced efficiently, almost independently of the relative proportions of precursors. Amino and other organic acids, pyrroles, pyridines, and simple hydrocarbons and their polymers are among the synthesized molecules.<sup>21, 22</sup> The syntheses are in general non-equilibrium processes; radiation both produces and destroys the organic molecules, but the net production rate is proportional to the photon flux. In addition, because the molecular weight of these molecules was greater than the mean molecular weight of the nebula or atmosphere, they diffused to the surface under the influence of the lunar gravitational field. The time for such molecules to diffuse to atmospheric depths where photo-dissociating uv does not penetrate can be shown to be of the same order as the time between absorptions of photo-dissociating photons.<sup>23</sup> Consequently, with reaction products being removed from the system, the quantum yield in the primitive lunar envelopes must have been greater than that in contemporary laboratory experiments in which reaction products are not being removed from the system.

Recently a series of experiments on uv synthesis of organic molecules which permits quantitative conclusions has been performed by W. Groth in

Bonn.<sup>24</sup> The overall quantum yield,  $\phi$ , for the production of amino acids alone from a gas mixture of ethane, ammonia and water is between  $10^{-4}$  and  $10^{-5}$ . The value appears to be approximately independent of wavelength between  $\lambda$  2537 and  $\lambda$  1470. Because of the rapidly decreasing  $\text{NH}_3$  absorption cross-section longward of  $\lambda$  2600, radiation of much longer wavelengths should be synthetically ineffective.

In the primitive lunar envelopes, methane, not ethane, was the principal carbon molecule. The quantum yield for the photoproduction of ethane from methane is about  $10^{-1}$  at  $\lambda$  1470.<sup>25</sup> Assuming the synthesis of amino acids from methane, ammonia and water is a wavelength-independent as the synthesis from ethane, ammonia and water, we conclude that the  $\phi$  appropriate to primitive conditions is about a factor of ten less than Groth's laboratory value. This point should be checked experimentally. Since the time between collisions is much shorter than the time between absorptions of uv photons in the primitive lunar atmosphere,<sup>23</sup> the differing pressures, temperatures, and densities should not significantly alter the overall quantum yields. It is difficult to estimate by what factor the overall quantum yield should be increased to allow for the gravitational diffusion of the synthesized molecules out of the radiation field. Simultaneous irradiation over the whole range of wavelengths shortward of  $\lambda$  2600 should also increase  $\phi$ . Provisionally, let us take an overall quantum yield for the photoproduction of amino acids in the primitive lunar atmosphere or neighboring solar nebula of  $\phi = 10^{-6}$  between  $\lambda$  2600 and  $\lambda$  1470, remembering that there is an uncertainty of at least a factor of ten. If we knew the flux of solar radiation between these wavelengths in primitive times, we would be able to compute the arrival rate of amino acids on the ancient lunar surface.

The present solar flux at  $\lambda 2600$  is that of a black-body of temperature about  $5000^\circ\text{K}$ .<sup>26</sup> We are interested in the radiation flux after the sun's evolutionary track in the Hertzsprung-Russell diagram has joined the main sequence, and the dissipation of the solar nebula has begun. At the juncture with the main sequence some  $5 \times 10^9$  years ago, the luminosity was about half a bolometric magnitude less than at present, and the radius about  $0.87 R_\odot$ .<sup>27, 28, 29</sup>  $10^9$  years later, about  $4 \times 10^9$  years ago, the solar radius was about  $0.90 R_\odot$ , while the solar luminosity had increased from about  $0.69 L_\odot$  to about  $0.73 L_\odot$ .<sup>29</sup> We write  $L_\odot$  and  $R_\odot$  for the present solar luminosity and radius. Knowing the luminosities and radii at these two representative times, the ultraviolet black-body temperature and geometrical dilution factors can be computed, and the radiation flux shortward of a given wavelength at the two times obtained by integrating the Planck equation. The ultraviolet temperatures were about the same at the two times ( $0.975$  the present temperature) as are the dilution factors (about  $0.8$  the present value). The quiet solar ultraviolet photon fluxes of wavelength shortward of  $\lambda 2600$  in the vicinity of the moon at these times is then computed to be  $Q = 7 \times 10^{14}$  photons  $\text{cm}^{-2} \text{sec}^{-1}$ , roughly the present value.

Assume now that uv radiation of intensity  $Q$  falls for  $t$  seconds on an opaque, gaseous envelope surrounding the moon, and produces molecules of molecular weight  $\mu$  with quantum efficiency  $\phi$ . Let  $r$  be the distance from the center of the moon such that all molecules of molecular weight  $\mu$  produced at distances less than  $r$  are gravitationally captured by the moon, while those produced at distances greater than  $r$  will escape. The synthesized molecules will be distributed over a moon of radius  $R$ . The mean surface density of

deposited material will then be

$$\sigma = \left( Q \phi r^2 \mu t / 4 N_A R^2 \right) \text{ gm cm}^{-2}$$

where  $N_A$  is Avogadro's number.

Because of the moon's proximity to the more massive earth, much material produced in the lunar vicinity must nevertheless have been captured by the earth. We adopt as a minimum value of  $r$ ,  $r = R$ ; i. e., we neglect lunar gravitational capture of molecules produced outside a cylinder of lunar radius extending from the moon to the sun. This approximation is, of course, very nearly exact for the secondary lunar atmosphere; but it gives only minimum values of  $r$  for the times of the solar nebula and the original lunar protoatmosphere.

In Table II we have listed values of  $\sigma$  computed from the above equation for  $Q = 7 \times 10^{14}$  photons  $\text{cm}^{-2} \text{sec}^{-1}$ , and  $\mu = 100$ , for various values of  $t$  and  $\phi$ .

Table II

LUNAR AMINO ACID SURFACE DENSITIES IN  $\text{gm cm}^{-2}$

t in years	$\phi$			Envelope
	$10^{-5}$	$10^{-6}$	$10^{-7}$	
$10^3$	$10^{-2}$	$10^{-3}$	$10^{-4}$	secondary lunar atmosphere
$10^4$	$10^{-1}$	$10^{-2}$	$10^{-3}$	
$10^5$	1	$10^{-1}$	$10^{-2}$	
$10^6$	10	1	$10^{-1}$	
$10^7$	$10^2$	10	1	
$10^8$	$10^3$	$10^2$	10	
$10^9$	$10^4$	$10^3$	$10^2$	lunar protoatmosphere solar nebula

We see that very considerable amino acid surface densities were produced from the solar nebula and lunar protoatmosphere ( $t = 10^7$  to  $10^9$  years). However, most of this material rained down while the moon was still being formed, and therefore must either be buried at great depths below the present lunar surface, or have been thermally dissociated in the volcanic processes which evolved the secondary lunar atmosphere. Organic matter produced in the secondary lunar atmosphere appears to have a much better chance of residing near the present lunar surface and having avoided dissociative processes (see below). Miller<sup>21</sup> and Groth<sup>24</sup> find efficient production of other substances besides amino acids, some with greater quantum yields (especially formic and acetic acids) and many with lesser quantum yields. The overall deposition of organic matter after the moon's formation may well have exceeded  $10 \text{ gm cm}^{-2}$ . This figure is greatly in excess of any possible accretion of cometary or interstellar organic matter.<sup>23</sup> During the time of deposition, the lunar atmosphere would have inhibited thermo- and photo-dissociation of the deposited molecule.

As the secondary lunar atmosphere gradually escaped to space, and replenishment from the interior eventually fell off, the rate of atmospheric organic synthesis decreased and the penetration of short wavelength radiation to the surface increased. In addition, the surface temperature gradually rose, due both to the loss of the insulating atmosphere, and to the concentration of radioactive elements towards the surface as a consequence of the formation of the lunar mantle. The effect of heat and uv on the molecules described above is most remarkable. Although the second law of thermodynamics is obeyed, a large fraction of the molecules, with activation energies supplied, partake in organic syntheses of a higher order of complexity. Polypeptides

arise from amino acids, hydrocarbon dimers and trimers form long-chain polymers, and in general very complex organic molecules are constructed (almost all of which, incidentally, are utilized by and are part of contemporary terrestrial organisms).<sup>22, 30</sup> Finally, because complicated molecules are more resistant to heat and radiation than are simpler molecules (at least in part due to the Franck-Rabinowitch cage effect), the syntheses are biased towards the net production of the most complicated organic molecules (v., e. g., 31).

Although continued radiation and high temperatures would lead to the eventual destruction of all these molecules, we must remember that meteoritic matter was falling into the lunar atmosphere throughout the period of organic synthesis. Whipple<sup>15</sup> estimates that about 50 gm/cm<sup>2</sup> of meteoritic matter falls on the moon each 10<sup>8</sup> years at present rates of infall. In addition, it is almost certain that the rate of meteoritic infall on the moon in primitive times was much greater than today. For example, Kuiper<sup>32</sup> believes the moon, receding from the earth because of tidal friction, passed through a sediment ring of silicates and ices which encircled the earth. As one consequence of this meteoritic infall in primitive times, the moon's surface must have received a dust cover, probably composed primarily of silicates and ices, which can be identified, at least in part, with the present lunar surface material. The organic molecules would then be covered by a protective layer insulating them from the extremes of lunar temperature and absorbing the incident solar radiation and subsequent meteoritic infall. The laying down of the initial protective covering could have itself caused some destruction of the molecules because of heat generation during impacting of the initial meteoritic infall. For a sufficiently dense atmosphere during

this initial phase such an effect would not be serious. Provided that no large scale destructive events have subsequently occurred, it is therefore not unreasonable to expect the presence of both simple and complex organic molecules on the moon, beneath the dust layer, and with an average surface density of as much as  $10 \text{ gm cm}^{-2}$ . These remarks apply properly only to regions on the moon where it is certain there have been no extensive lava flows; the southern highland appears to be such a region. <sup>32</sup>

A sample of appropriate lunar sub-surface material should then have an organic fraction easily detectable by simple chemical analyses. When compared with suitable laboratory results, a quantitative and qualitative analysis would give important clues on the early history of the solar system.

Because of its great potential importance, the admittedly very speculative possibility must be raised that life arose on the moon before the secondary lunar atmosphere was lost. There is considerable likelihood that conditions on the moon  $5 \times 10^9$  years ago were not very different from conditions on the earth  $5 \times 10^9$  years ago. Recent thinking on the origin of life on this planet is increasingly inclined towards a very rapid origin for the first self-reproducing system. <sup>22, 31</sup> If a similar event also occurred on the moon, natural selection may be expected to have kept pace with the increasingly more severe lunar environment, at least for some period of time. Although the chances of extant life on the moon seem exceedingly remote, there is a finite possibility that relics of past lunar organisms, if any, could be preserved indefinitely if sequestered well beneath the protective cover of the upper lunar surface material.

### Section Three

#### Conclusion

Due to the possible similarity in primitive organic syntheses on the earth and the moon, assurance cannot be given that organic matter indigenous to the moon will be distinguishable from accidentally deposited terrestrial organic matter. However, indigenous organic matter will be primarily localized beneath the congealed lunar dust layer; while deposited terrestrial organic matter should be primarily localized at the surface. Even microorganisms in dust matrix interstices shielded from solar illumination would probably be far above any indigenous lunar organic matter. If the lunar maria are frozen lava fields, a landing on them would be greatly preferable to a landing on non-lava areas such as the southern highlands. Before any moonfall is attempted, the microstructure of the lunar surface material and the lunar magnetic field should be studied as effectively as possible. In spite of the unlikelihood of biological contamination difficulties, it is still probably good scientific caution to make the instrument package as aseptic as practical considerations arrived at after serious evaluation will permit.

Appendix I

SURVIVAL TIME OF AN IRRADIATED POPULATION

## Appendix I

### SURVIVAL TIME OF AN IRRADIATED POPULATION

We consider a population of  $N_0$  organisms, each having mean density  $\rho$  gm cm<sup>-3</sup>, characteristic size  $a$  cm, and mean lethal dose of a given kind of electromagnetic or corpuscular ionizing radiation,  $D$  roentgens. The population is irradiated with an intensity of  $I$  erg cm<sup>-2</sup> sec<sup>-1</sup> of the given kind of radiation, which has a mass absorption coefficient in organic matter of  $\mu/\rho$  cm<sup>2</sup> gm<sup>-1</sup>. We are interested in the time,  $t$ , in seconds, for the population to be depleted from  $N_0$  to  $N$  organisms.

Let  $J$  be the energy absorbed by unit cross-section or organism due to a dose of  $d$  roentgens. Then, since one r corresponds to the absorption of 93 ergs/gm,

$$J = 93 \rho a d \quad (1)$$

On the other hand, if the energy incident on unit cross-section of the organism is  $E_0$ , then, by Beer's Law, the energy transmitted through the organism is

$$E_t = E_0 e^{-(\mu/\rho)\rho a} \quad (2)$$

Consequently, the energy absorbed by the organism is

$$E_a = E_0 - E_t = E_0 [1 - e^{-(\mu/\rho)\rho a}] \quad (3)$$

Now if  $E_a$  ergs absorbed by 1 cm<sup>2</sup> corresponds to a dose of  $d$  roentgens,  $E_a = J$ , and from eqs. (1) and (3),

$$E_0/d = 93 \rho a [1 - e^{-(\mu/\rho)\rho a}] \text{ erg cm}^{-2} \text{ r}^{-1} \quad (4)$$

Consequently, the time,  $\tau$ , for one organism to accumulate D roentgens due to an incident flux of I erg cm<sup>-2</sup> sec<sup>-1</sup> is

$$\tau = (D/I) (E_0/d) \quad (5)$$

Assuming an exponential survival curve for the population of organisms, the number surviving after time t will be

$$N = N_0 e^{-t/\tau} \quad (6)$$

Solving eq. (6) for t, substituting from eqs. (4) and (5), and converting from natural to common logarithms, we obtain for the time in which the population will have been depleted to N organisms,

$$t = 2.14 a \rho (D/I) \left[ 1 - e^{-(\mu/\rho) \rho a} \right]^{-1} \log_{10} (N_0/N) \quad (7)$$

In the case that the mean lethal dose, D, is given directly in units of erg cm<sup>-2</sup> instead of roentgens, as is the case for ultraviolet irradiation, eq. (7) is replaced by

$$t = 2.3 (D/I) \left[ 1 - e^{-(\mu/\rho) \rho a} \right]^{-1} \log_{10} (N_0/N) \quad (8)$$

Table I was constructed from eqs. (7) and (8) with the following simplifications.  $\rho$  was taken as unity throughout.

For an organism opaque in the given radiation, and eqs. (7) and (8) reduce respectively to

$$t = 2.14 a \rho (D/I) \log_{10} (N) \quad (9)$$

and

$$t = 2.3 (D/I) \log_{10} (N_0/N) \quad (10)$$

For an organism which is almost transparent in the given radiation,  
and a Taylor series expansion of the exponential reduces  
eqs. (7) and (8) respectively to

$$t = 2.14 (\rho/\mu) (D/I) \log_{10} (N_0/N) \quad (11)$$

and

$$t = (2.3/\mu a) (D/I) \log_{10} (N_0/N) \quad (12)$$

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Appendix II

CURRENT ATTITUDES AND ACTIVITIES REGARDING  
BIOLOGICAL CONTAMINATION OF EXTRATERRESTRIAL BODIES

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A. Organizations Active in the Field

- (1) Ad Hoc Committee on Contamination by Extraterrestrial Exploration, International Council of Scientific Unions (CETEX)

For membership and recommendations, see *Science*, 128, 887 (1958), and *Nature*, 183, 925 (1959). The organization is now defunct.

- (2) Eastern and Western Ad Hoc Advisory Groups to Committee on Long Term Projects, Space Science Board, National Academy of Sciences (EASTEX and WESTEX)

EASTEX has had one meeting, WESTEX three. Present membership of WESTEX is R. N. Bracewell, Stanford, Astronomy; M. Calvin, U. of Calif., Berkeley, Chemistry; R. Davies, Jet Propulsion Laboratory, Space Vehicles; N. Horowitz, Caltech, Microbiological Genetics; R. M. Badger, Caltech, Chemistry; J. Lederberg, Stanford, Microbiological Genetics; D. Mazia, U. of Calif., Berkeley, Zoology; A. G. Marr, U. of Calif., Davis, Bacteriology; A. Novick, U. of Oregon, Biophysics; C. Sagan, U. of Chicago, Astronomy; G. Stent, U. of Calif., Berkeley, Virology; C. B. van Niel, Stanford, Microbiological Biochemistry; H. F. Weaver, U. of Calif., Berkeley, Astronomy. Views of these organizations are discussed below.

- (3) Panel on Extraterrestrial Life, Armed Forces - National Research Council Committee on Bio-Astronautics, National Academy of Sciences

This group has just been formed. The first meeting is scheduled for July. Present composition is M. Calvin, U. of Calif., Berkeley, Chemistry, Chairman; J. R. Platt, U. of Chicago, Physics; Cmdr. M. Ross, ONR, USN; C. Sagan, ARF - Yerkes, Astronomy; G. Stent, U. of Calif., Berkeley, Virology; R. Vishniac, Harvard, Microbiology; H. F. Weaver, U. of Calif., Berkeley, Astronomy.

#### B. Present Climate of Opinion

From informal meeting notes and personal communications we have formed some idea of the prevailing climate of opinion. Naturally any summary statement cannot be uniformly supported by all individuals, but a definite view does exist both for groups a and b.

CETEX feels that the likelihood of any biological contamination of the moon is very small, since the possibility of reproduction of a deposited terrestrial microorganism is taken to be negligible. The possible confusion of deposited terrestrial organisms with indigenous lunar organic matter is considered to exist; but if the number of moonfalls is kept within bounds, CETEX feels that the contamination will be quantitatively small, and restricted to a limited fraction of the moon's area,

On the other hand, contamination is considered to be a much greater hazard for Mars and Venus, and CETEX urges the development of decontamination procedures to be used on all lunar probes in order to test later decontamination techniques for Mars and Venus.

EASTEX and WESTEX agree that a deposited terrestrial microorganism would probably be unable to reproduce on the moon, since there appears to be an absence of biochemical precursors. On the other hand we do not know the lunar sub-surface conditions; Fremlin has recently

pointed out that temperatures a few meters below the lunar surface may be many hundreds of degrees centigrade, and it is not impossible that sub-surface organic matter exists. Under these conditions reproduction of terrestrial microorganisms might occur. In view of the geometrical reproduction rate of terrestrial microorganisms under suitable conditions, and the absence of greater knowledge of sub-surface conditions, EASTEX and WESTEX urge that no moonfall be attempted until more information is available and that all lunar probes be rigorously decontaminated.

EASTEX and WESTEX consider the possible confusion of deposited terrestrial organic matter with indigenous lunar organic matter to be a greater danger than does CETEX. They point out that a hard lunar landing will probably deposit contaminants over a large fraction of the lunar surface, not a very restricted region as CETEX seems to assume. In addition there is the possibility that life arose in ancient lunar history. If a viable organism were recovered on the moon - - it would probably be detected by clone formation in a suitable medium - - the problem would arise as to whether it was lunar or terrestrial in origin. Similarities in biochemistry and/or morphology with contemporary terrestrial organisms would not necessarily indicate contaminatory origin, because primitive life-forms on other planets might very well resemble primitive life-forms on the earth. EASTEX and WESTEX also emphasize that deposited microorganisms could easily be shielded from solar radiation by lunar surface material, and so rapid radiative killing cannot be relied upon. They stress the importance of biological and astronomical information which might be destroyed by contamination.

It is interesting to note that CETEX contains no micro-biologists, and that membership was not made on the basis of applicability of the members' research to the problem at hand, but on the basis of representation from each of the constituent organizations of the ICSU. In addition there exists the statement by a CETEX member that CETEX was afraid to state the contamination case too strongly for fear its advice would not be heeded at all.

It might be argued that since the first moonfall is very likely to be by a Soviet vehicle, the concern of EASTEX and WESTEX is somewhat academic. There have been no Soviet scientists calling attention to the contamination problem, and U. S. S. R. representation on CETEX could not be secured. However, concerted effort by the American scientific community might bear fruit. For example, much of the pioneer work on the origin of life problem is by the Russian biochemist, A. I. Oparin, who might be expected to have an interest in pre-biological lunar organic molecules. Attempts are being made to contact Oparin. The U. S. propaganda possibilities following a U. S. S. R. lunar contamination - - or vice versa - - should not be overlooked.

#### C. Future Work

Work already initiated and expected to continue into the near future includes (1) development of automatic devices for detection of micro-biological reproduction on a suitable prepared medium, and (2) testing of decontaminants, especially ethylene oxide and radiation, to determine whether adequate decontamination is possible without destroying instrumentation. For radiation, at least, the situation appears marginal. Later work might include the standardization of organic components - - e. g., plastics - - of missile systems into a few characteristic, biochemically

unlikely compounds.

Research on the infrared reflection spectra of a variety of solid organic molecules is underway at the U. of Calif. , for future comparison with satellite telescope and lunar and planetary probe spectrograms. ARF work on visible and near IR absorption spectra of gaseous organic molecules for comparison with spectra of the Jovian planets will also be continued on a larger scale at Berkeley.

Publications may be expected within the next year or two from both EASTEX-WESTEX and from the Armed Forces - NRC panel on the question of biological contamination of extraterrestrial bodies. WESTEX is contemplating the writing of a handbook on the whole question of extraterrestrial organic matter, extraterrestrial life, and contamination; while the Armed Forces - NRC panel is considering monographs on individual subjects. The Bio-Astronautics Committee feels that such monographs might clear the air on controversial issues, saving much needless and repetitious argument in other committees and agencies.

CHAPTER IX  
(See Vol. II of Report)

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