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The Lunar Environment: A Reevaluation With Respect to Lunar-Base Operations

The following aspects of the lunar environment which bear on the feasibility of long manned lunar-surface missions and lunar bases are reviewed: gravity and magnetic fields, radiation, surface temperature, atmosphere, meteoroid and secondary ejecta flux, nature of the terrain and surface materials, and concepts of lunar geology. Virtually all new information on these subjects is either favorable or, if unfavorable, predictable. It is concluded that, with respect to the lunar environment, lunar staytimes of 3 months could be scheduled at this time; 1-year missions appear feasible; and there are no obvious factors definitely preventing establishment of a permanent lunar base. More information is needed, however, on meteoroid flux, trafficability of the highlands, nature of lunar water deposits, geological hazards, hazards connected with lunar transient phenomena, and long-term biological effects of the lunar environment.

INTRODUCTION

Although the lunar-surface environment is continually being reevaluated to determine its impact on the Apollo program, there is no comparable reevaluation of the environment to determine its impact on establishment of a lunar base (considered here to be any manned lunar-surface mission significantly longer than 2 weeks). The purpose of this paper is to present a concise summary of current knowledge and opinion on all aspects of the lunar environment that could affect the success of a lunar base.

Some of the information presented here is from unpublished or personal sources. For this reason, and in the interest of clarity, formal bibliographic reference conventions are not followed; however, main sources of published information are listed as a bibliography at the end of the paper. Opinions expressed are those of the author and do not necessarily represent the views of NASA or of Goddard Space Flight Center.

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GRAVITY AND MAGNETIC FIELDS

The configuration of the lunar-gravity field has been partly determined by tracking Lunar Orbiter spacecraft for periods of several months. It has been found that the gravity field is more homogeneous than it was formerly believed to be, and that perturbations are not enough to cause rapid decay of low-altitude (e.g., 50 nautical miles) circumlunar satellites. At altitudes of around 200 nautical miles, satellite lifetimes of several years could be expected. These findings are important for lunar-base operations and in confirming the feasibility of lunar-orbital rendezvous mission modes, long-term orbital observation and mapping of the lunar surface, and circumlunar communications satellites for point-to-point or Earth-Moon relays.

The surface value of the Moon's magnetic field is estimated, from Lunar Orbiter and Explorer 35 data, to be under 16 gammas, which is close to that of the Quiet Sun interplanetary field. The result, which has been expected, is in accord with the lack of evidence for lunar radiation belts. One consequence of the absence of a magnetic field, together with the absence of a detectable atmosphere, is that solar and cosmic radiation probably reach the surface directly with little attenuation or scattering.

The possible biological effects of the low lunar magnetic field are not known, but recent studies summarized by Busby indicate that they may be significant. In an experiment in which mice were raised in magnetically shielded cylinders, abnormal behavior, loss of hair, and early death were exhibited after the first generation, and reproduction stopped after the fourth generation. Other experiments on human and animal subjects (including micro-organisms) have also produced indications of significant biological effects from low-magnetic-field strength. On the other hand, men working in low-strength magnetic fields for several days at a time show no ill effects. Busby points out that much additional work in this field is needed before the possible effects of very long exposure to weak magnetic fields can be known.

RADIATION

Estimates of the Moon's surface radiation environment have not changed materially since 1965. The only direct surface measurements available at this time are those from Luna 9, which reported a total dose of 30 mrads/day, chiefly from cosmic rays. The chief potential radiation hazard continues to be solar flares. Although no event violent enough to harm a command-module crew has been observed, the current-model lunar module might not provide enough protection. An exposed man in a space suit on the surface would probably receive skin doses of a few thousand rads from a violent event. Flares cannot yet be reliably predicted, but since solar protons take several hours to reach the Moon (compared with 8 minutes for the H_α light by which the flare is seen), a lunar-surface mission crew could be given warning of dangerous radiation. Shielding equivalent to 5 g/cm^2 would protect persons against all but one event in 1000; shielding equivalent to 40 to 50 g/cm^2 (as could easily be provided by the use of lunar soil) would protect against even a one-in-a-century event.

Studies by the Leander McCormick Observatory of the intensity of earthlight on the Moon's surface indicate that many operations could be carried out during the lunar night, since the expected full-Earth illumination will be equivalent to good city street lights. This would be bright enough to read by, for example. However, tasks requiring "quick and certain" seeing would be difficult; spacecraft landing at night might be precluded unless lights were provided.

SURFACE TEMPERATURES

The lunar-surface temperature range is of course important for the design of shelters and vehicles. The Surveyor telemetry provided the first direct temperature readings, with thermal compartments reaching temperatures of up to 400° K. These values were in general agreement with Earth-based data, although some non-Lambertian emission was apparent. An important indirect result of the Surveyor temperature readings was the implication that no significant amount of dust was sticking to the compartments. The lunar thermal environment, in summary, is severe but generally predictable.

ATMOSPHERE

No new direct information has been obtained about the lunar atmosphere, which is an extremely important environmental factor affecting the usefulness of the Moon as an astronomical base. However, the Surveyor spacecraft provided an empirical test of the atmosphere by obtaining many excellent pictures of the solar corona up to a distance of 20 solar radii above the lunar horizon; this and the homogeneity of the coronal image suggest that the lunar atmosphere, if any, is not likely to cause serious degradation of observations, at least for exposure times of around 10 minutes. The bright line along the horizon seen from Surveyor VI after sunset is generally thought to be the result of surface irregularities, although a particle atmosphere (a few tens of centimeters thick) had been suggested. To date, then, there is no evidence of a lunar atmosphere.

METEOROID AND EJECTA FLUX

The expected absence of a lunar atmosphere makes knowledge of the meteoroid environment of prime importance for long lunar missions. Probably the best recent information about the flux rate near the Moon is that from the five Lunar Orbiter spacecraft, which provided overlapping coverage for 14 months. Each spacecraft carried 20 pressurized can detectors with a total area of 2 sq ft; of this total of 100 detectors, 18 (made of 0.001-inch-thick copper) were punctured. This puncture rate is less than half that of similar detectors on the Earth satellites Explorers XVI and XXIII and is within a factor of 2 of the flux measured by the Pegasus satellites, which were also in Earth orbit. No directionality was noticed in the Lunar Orbiter results. It would appear that the meteoroid flux near the Moon is substantially less than that around the Earth. Since little if any degradation of Earth satellite performance by meteoroid damage has been detected even for satellites such as the Tiros series, some of which have operated for periods of 1 to 3 years, this finding is very encouraging for long-term lunar operations. It appears that any operation planned for close Earth orbit would be feasible for the lunar surface insofar as the meteoroid flux is concerned.

Closely related to the meteoroid flux problem is that of the flux of secondary fragments from meteoroid impacts. None of these have yet been detected by Surveyor spacecraft, which indicates that the former concept of a secondary-particle atmosphere is overly pessimistic. In addition, the velocities expected for secondaries are much lower than those of primary particles and are in the range of 150 to 200 m/sec. Consequently, the secondary problem does not appear to be a major one until staytimes of several years and very large exposed areas are achieved.

SURFACE CONDITIONS

Surface conditions that might affect lunar-base operations are now fairly well known for at least the mare areas as a result of the various American and Soviet soft-landing spacecraft.

Electrical properties of the Surveyor landing sites can, in principle, be inferred from the landing radar telemetry. Preliminary results from Surveyor I indicated that the radar cross-section values are close to those expected from Earth-based measurements and that the radar return was from the visible surface or from no deeper than 60 centimeters.

The Moon's gross topography has become fairly well known down to a scale of a few meters for much of its total area, in both highland and mare areas. A detailed discussion of this topic is beyond the scope of this paper. However, most of the preliminary Lunar Orbiter evaluations and Surveyor results point to the conclusion that the lunar surface offers few insuperable obstacles to lunar-base operations or long-distance surface traverses from a lunar base. Of particular interest were the pictures of the Surveyor VII landing site on the northern part of the Tycho ejecta blanket. The well-known thermal and radar anomaly presented by Tycho indicated that large rough areas of nearly bare rock might be found here; the Surveyor pictures indicated that the ejecta blanket, at least, is relatively smooth and trafficable, although the inside of the crater is probably not accessible to nor trafficable by surface vehicles.

Soil conditions have been thoroughly investigated by Surveyor spacecraft, and they are encouraging for lunar-surface operations in two respects. First, the bearing strength is quite high enough for spacecraft landing and surface travel, at least in the five landing sites. Second, the dominantly fine-grained fragmental nature of the lunar soil should lend itself to earthmoving operations such as shelter excavation, instrument emplacement, and use of soil for shielding. A further encouraging aspect is the relatively nonexotic behavior of the soil itself, and in particular its relatively low adhesion. This had been considered a major potential problem by some, but the normal performance of the Surveyor surface-sampler device indicates that little difficulty can be expected in handling the lunar soil. A possible hazard whose existence appears confirmed by Lunar Orbiter and Surveyor spacecraft is that of collapse depressions in mare areas; a fairly high proportion of craters in Alphonsus and elsewhere seem to have been formed by drainage of material into subsurface voids; the location and nature of these voids should be investigated.

GEOLOGIC CONCEPTS

A number of evolving geologic concepts have bearing on lunar-base operations. The most important of these is the now generally accepted belief that the Moon has had an extensive volcanic history (although most large craters are generally believed to have been formed initially by meteoritic or cometary impact). It has been recognized for several years that a volcanic terrain would offer many advantages to a lunar base, such as probable water deposits in the form of hydrothermal minerals, fumaroles, or subsurface hot springs, useful minerals such as sulfur, and perhaps usable natural caves. A corresponding disadvantage of a volcanic Moon is the possibility of damage by volcanic eruptions; in view of the growing belief that the lunar transient phenomena are internally caused, it would appear possible that there is currently active volcanism (and perhaps seismic activity) on the Moon. Possible sites of such activity, for example, Aristarchus, should be carefully certified before base operations are planned for them.

Another geologic concept with implications for lunar bases is that of mass wasting. The prevalence of bright slopes on old crater walls has for several years been interpreted as evidence that mass wasting is continually exposing fresh material. Many features seen on the Lunar Orbiter photographs reinforced this belief; a possible cause of such movement of material may be ground waves produced by internal seismic activity or major impacts. Since terrestrial experience shows that seismic damage is especially likely on unconsolidated terrain, it is clear that seismic activity or mass movements triggered by such activity is potentially a significant hazard on the Moon.

GEMINI PROGRAM

Medical experience of great potential interest for lunar-base operations has been derived from the Gemini program. As reported in the Gemini Summary Conference, the space environment has proven in almost all respects considerably less harmful than many had believed it to be before long-duration manned orbital missions. Weightlessness in particular has been found to produce few unforeseen effects for missions of up to 2 weeks. It seems reasonable to assume that, if crews in the confined Gemini spacecraft could withstand complete weightlessness for 2 weeks, staytimes of a few months under 1/6 g in what we hope to be the less confining quarters of a lunar base would have no harmful effects.

CONCLUDING REMARKS

It is clear that more knowledge about the lunar-surface environment is needed before a commitment to a permanent lunar base can be made. The main areas about which more needs to be known appear to be:

(1) Probability of serious meteoroid damage to structures with very large area-exposure-time products

(2) Noncatastrophic degradation of optical or other surfaces by low-density meteoroids, sputtering, and other causes

(3) Possible hazards connected with lunar transient phenomena, which have been observed to release large quantities of energy in some unknown way

(4) Trafficability of the lunar highlands

(5) Possible collapse hazards in mare terrain

(6) Location, structure, mineralogy, and water content of lunar water deposits

(7) Biological effects for very long staytimes with exposure to 1/6 g, primary cosmic rays, and low magnetic field strength

(8) Geological hazards; in particular, seismic activity, active volcanism, and landslides or debris flows

(9) Possible danger from lunar pathogens

Despite this list, it is true that the vast majority of new information about the lunar-surface environment obtained in the last few years has been favorable. It appears that as much is known now with respect to lunar-base operations as was known about the feasibility of simply landing on the Moon in 1961. Specifically, it is concluded that, from an environmental and medical viewpoint, lunar missions of 3-month duration could be confidently scheduled at this time. Furthermore, 1-year missions appear feasible enough to warrant detailed preliminary study. Finally, there are no known factors that would definitely prevent the establishment of a semipermanent lunar base (i.e., one of several years' duration with crew rotation).

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