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GEOLOGICAL CONSIDERATIONS FOR LUNAR TELESCOPES

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Abstract

The Moon's geologic environment has the following features:

1. A gravity field one-sixth that of Earth

2. A synodic rotation period (lunar day) of 29.53 Earth days and a sidereal period of 27.3 Earth days

3. A surface with greater curvature than Earth's surface — A chord along a 60-km baseline would have a bulge of 260 m.

4. A seismically and tidally stable platform on which to build observatories — Total seismic energy released is 2×10^{17} ergs/yr compared to 10^{26} ergs/yr on Earth, and most moonquakes have magnitudes of 1 to 2, within the Earth's background noise.

5. A tenuous atmosphere (i.e., the total mass at night is only 10^4 kg) that allows excellent seeing conditions and does not cause wind-induced stresses and vibrations on structures

6. A large diurnal temperature variation (100 to 385 K in equatorial regions), which telescope facilities must be designed to withstand

7. A weak magnetic field, ranging from 3 to 330×10^{-5} Oe compared to 0.3 Oe on Earth at the Equator

8. A high flux of micrometeorites which, because of the lack of air, are not retarded from cosmic velocity — Data indicate that microcraters 10 μm across will form at the rate of 300/m^2-yr.

9. A regolith 2 to 30 m thick which blankets the entire lunar surface — This layer is fine grained (average grain sizes range from 40 to 268 μm), has a low density (0.8 to 1.0 in the upper few millimeters, rising to 1.5 to 1.8 at depths of 10 to 20 cm), is porous (35% to 45%) and cohesive (0.1 to 1.0 kN/m^2), and has a low thermal diffusivity (0.7 to 1.0×10^{-4} cm^2/sec).

10. A rubbly upper several hundred meters in which intact bedrock is uncommon, especially in the lunar highlands

11. Craters with diameter/depth ratios of 5 if fresh and <15 km across — Larger and eroded craters have diameter/depth ratios >5.

The Moon's geologic environment offers wondrous opportunities for astronomy and presents fascinating challenges for engineers designing telescope facilities on the lunar surface. In this paper, the geologic nature of the stark lunar surface and the Moon's tenuous atmosphere are summarized.

General Characteristics

The strength of the Moon's gravitational field is one-sixth that of Earth's surface. This property allows use of materials of lower strength than on Earth for structures of equivalent size. Alternatively, much larger structures, such as Arecibo-type radio telescopes tens of kilometers across, can be built on the Moon. As Burke (ref. 1) shows, structural deflection of a 1-m telescope on the Moon would be less than the deflection of a 4-m telescope on Earth by a factor of 100.

The Moon has two physical characteristics that are advantageous for astronomy. One is the slow sidereal rotation period (27 days), which allows long observing times. The other property is the distance between the Moon and the Earth, 384 000 km. This distance provides an extremely long baseline for interferometer systems, using both the Moon and the Earth as locations for elements of the system (e.g., ref. 2).

Because of the Moon's smaller radius, its surface has a larger curvature than does the Earth's surface. For example, a chord along a 10-km baseline would have a bulge of 7.2 m; a 60-km baseline would produce a bulge of 260 m. Designs of large baseline arrays, therefore, need to be based on degree of curvature.

Stable Platform

The Moon provides a stable platform on which to build observatories or other structures. Seismic properties are summarized in table I, which is adapted from reference 3. There are two main categories of lunar seismic signals, based on the depth at which they originate. Almost all occur deep within the Moon at depths of 700 to 1100 km; on average, about 500 deep events were recorded annually during the 8 years of Apollo seismic network operation. These deep moonquakes are related to tidal forces inside the Moon.

Moonquakes also occur at much shallower depths (<200 km), but apparently below the crust (ref. 4). Shallow moonquakes occur much less frequently than do deep moonquakes, only about 5/yr. Shallow moonquakes do not appear to be related to tidal flexing of the Moon or to surface features. For comparison, most earthquakes occur at depths of 50 to 200 km.

Lunar seismic activity is drastically less than terrestrial seismicity (table I). Lunar seismographs detected only 500 moonquakes per year. In contrast, 10 000 detectable earthquakes occur each year. Note that the magnitude of detectable earthquakes is different from that of moonquakes; this difference is attributable mostly to greater seismic noise on Earth. In fact, most moonquakes are the magnitude 1 to 2 range, which is background level on Earth.

The total seismic energy released in the Moon is about 10^8 times less than that released in Earth. The magnitudes of the largest events on the Moon are also much less than those of the largest events on Earth (table I). The most energetic lunar events are the shallow ones, the largest recorded one being only 4.8 magnitude, corresponding to an energy of 2×10^{17} ergs. The largest recorded earthquake measured 9.5 magnitude on the Richter scale, corresponding to an energy of 10^{26} ergs.

Seismic waves are intensely scattered near the lunar surface. This scattering causes the energy of the waves arriving at a given point to be spread out; thus, the damaging effects of a moonquake would be less than those of an earthquake of the same magnitude. (In fact, values of seismic energy and magnitudes reported for the Moon by Goins et al. (ref. 3) are greater than those reported by Lammlein et al. (ref. 5) because the latter authors had not accounted for scattering of seismic waves near the lunar surface or for some instrument effects.) Consequently, it appears that the lunar surface is far more stable than any place on Earth.

The scattering of seismic waves in the Moon is significant down to a depth of 25 km but is most intense in the upper few hundred meters. This intensity implies a lack of coherent layering in this region.

Tidal forces raise and lower the lunar surface about as much as on Earth, where body tides deflect the ground about 10 to 20 cm twice each day. Because the Moon is locked into a synchronous orbit, the main tidal bulge on the Moon is a permanent feature. Nevertheless, small tidal deflections stemming from librations do occur but have much longer periods than on Earth. The tidal flexing of the lunar surface in both horizontal and vertical directions is about 2 mm along the length of a 10-km baseline (Dr. James Williams, personal communication, 1986). The precise amount of motion depends on position on the Moon. Tidal motions must be considered when designing telescope arrays.

Atmosphere

The lunar atmosphere is a collisionless gas. The total nighttime concentration is only 2×10^5 molecules/cm^3 (ref. 6). Its total mass is only 10^4 kg, about the mass of air in a movie theater on Earth at a pressure of 1 bar. This flimsy atmosphere will provide significantly better observing conditions because atmospheric twinkling will be absent. Engineering problems associated with wind also will be absent (ref. 7).

The composition of nighttime lunar atmosphere appears in table II. The gases derive from the solar wind, except for argon-40 (^{40}Ar), which is produced by the decay of potassium-40 (^{40}K) inside the Moon and then diffuses out. Because of instrument limitations, no daytime measurements of gas concentrations were made, but Hodges (ref. 8) calculates that gases of carbon compounds, specifically carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4), probably dominate. They are absent at night because of condensation from the atmosphere onto soil particles.

The tenuous lunar atmosphere can be altered significantly by large-scale operations on the Moon. Vondrak (ref. 9) has calculated that if the density of the lunar atmosphere is increased, a point is reached at which rate of gas loss is slowed drastically. This intensification could compromise a number of scientific experiments requiring a hard vacuum, including observations of the solar wind. Considering that each Apollo mission contributed 10^4 kg of gas (ref. 10), temporarily doubling the atmosphere's nighttime mass, it would appear easy to contaminate the Moon's fragile atmosphere when regular flights to and from the lunar surface begin. The atmosphere must be monitored carefully when a lunar base is established. Studying the evolution of the Moon's atmosphere will, in fact, be an interesting research project in itself.

Surface Temperatures

Surface temperatures change drastically from high noon to dawn on the Moon, presenting a challenge to those designing lunar observatories. At the Apollo 17 landing site, for example, the temperature ranged from 384 K to 102 K during the month-long lunar day (ref. 11). Furthermore, the temperature decreases rapidly as sunset approaches, falling about 5 K/hr (fig. 2 of ref. 11). These data apply to equatorial regions only. In polar regions, the predawn temperature is about 80 K (ref. 12). The temperature in permanently shadowed areas at the poles could be lower. The cold nighttime temperature will permit cooling of many types of detectors without use of cryogenics.

The temperature variation is damped out rapidly at depth in the lunar soil (ref. 11). At a depth of 30 cm, the temperature is about 250 K and varies only 2 to 4 K from noon to dawn. This steady temperature might be useful to designers of telescope facilities on the Moon, but not as a heat sink, because the lunar soil has a very sluggish thermal diffusivity, which will be discussed later.

Magnetic Field

No magnetic field is now being generated inside the Moon, although there was a source of magnetism several billion years ago. Whether this field was generated by a dynamo in a metallic core, as on Earth, or by local, transient events such as meteorite impacts is not known. Whatever its source, the lunar magnetic field is much weaker than is Earth's (ref. 13). On the surface, the lunar magnetic field strength ranges from 3 to 330 gammas (i.e., 1 gamma $= 10^{-5}$ Oe $= 10^{-5}$ gauss). For comparison, the strength of Earth's magnetic field at the Equator is 30 000 gammas. Also, the lunar magnetic field varies locally on the Moon. For example, at the Apollo 16 landing site, the magnetic field strength varied from 113 ± 4 to 327 ± 7 gammas.

There is also a magnetic field external to the Moon, derived from the solar wind. This field ranges in strength from 5 gammas in the free-streaming solar wind to about 10 gammas in Earth's geomagnetic tail, in which the Moon resides 4 days during each lunation.

Micrometeorite Flux

The lack of a significant atmosphere on the Moon allows even the tiniest particles to impact with their full cosmic velocities, ranging from 10 km/sec to several times that value. This rain of minute impactors could damage some structures and instruments on the lunar surface. Almost all lunar rock samples contain numerous microcraters, commonly called zap pits, on surfaces that were exposed to space while on the lunar surface. Studies of lunar rocks (ref. 14) have revealed the average flux of projectiles over the past several hundred million years. The number of craters of a given size (or larger) expected per square meter per year is shown in table III. It is obvious from these data that microcraters in the 1- to 10-µm size range will be common on surfaces exposed at the lunar surface. Even 100-µm craters will not be uncommon, with one produced every other year or so. It appears that sensitive surfaces, such as mirrors on optical telescopes, will have to be protected. The values in table III, however, do not reflect realistic damage potential; the micrometeorites come from the entire sky (2π sr), but many instruments will observe only a small fraction of the sky at any one time. On the other hand, evidence from the Surveyor 3 television camera shroud and from Apollo spacecraft windows (ref. 15) suggests that the current flux of particles capable of producing craters as large as 10 µm across is 10 times greater than indicated from studies of rocks.

Regolith

The lunar regolith, also called lunar soil, is a global veneer of debris generated from underlying bedrock by meteorite impacts. It contains rock and mineral fragments and glasses formed by melting of soil, rock, and minerals. It also contains highly porous particles called agglutinates, which are glass-bonded aggregates of rock and mineral fragments. Agglutinates are produced by micrometeorite impacts into the lunar regolith.

Regolith depth ranges from 2 to 30 m, with most areas in the range of 5 to 10 m. Impacts by micrometeorites have reduced much of the regolith material to a powder. Its grain size ranges from

40 to 268 µm and varies in a highly complex fashion with depth (ref. 16). The chemical composition of the regolith reflects the composition of the underlying bedrock, modified by admixture of material excavated from beneath the uppermost rock or thrown in by distant impacts.

The mechanical properties of lunar regolith samples were measured by Mitchell et al. (ref. 17). The bulk density of the regolith is very low, 0.8 to 1.0 g/cm^3, in the upper few millimeters but increases to 1.5 to 1.8 g/cm^3 at depths of 10 to 20 cm. Its porosity is 35% to 45% in the upper 15 cm and accounts in part for the low density. Except for the uppermost few millimeters, the lunar regolith is more cohesive, 0.1 to 1.0 kN/m^2, than are most terrestrial soils and has an angle of internal friction of 30° to 50°. Agglutinates and shock-damaged rock fragments are weak and break under loads and thus lead to an increase in soil density (ref. 18).

The lunar regolith is an excellent insulator. Its thermal diffusivity at depths >30 cm is 0.7 to 1.0×10^{-4} cm^2/sec, and its thermal conductivity is 0.9 to 1.3×10^{-4} W/cm-K (ref. 19). These values are not surprising considering the high porosity and the lack of air. At depths <30 cm, the thermal diffusivity is somewhat lower.

A small amount of lunar dust might be transported by charge differences built up by photoconductivity effects. Criswell (ref. 20) described a bright glow photographed by Surveyor 7 and explained the phenomenon as levitation of dust grains about 6 µm in radius. The grains were lifted only 3 to 30 cm above the local horizon and had a column density of 5 grains/cm^2. This transport mechanism does not appear to be significant on the lunar surface.

Upper Few Hundred Meters

The upper few hundred meters on the Moon have been intensely fragmented by meteorite impacts. In the heavily cratered highlands and regions underlying mare basalt flows, the fragmental region extends for at least a few kilometers. Consequently, it might be difficult to find extensive areas of intact bedrock.

Data from active seismic experiments (ref. 21) indicate that the velocity of compressional waves is about 100 m/sec at depths of less than 10 m, which is in the regolith, and about 300 m/sec at depths between 10 and 300 m. These low velocities cannot correspond to coherent rock and thus imply that the upper few hundred meters of the lunar surface is rubble (ref. 21). Rocks returned from the highlands confirm the fragmental nature of the upper lunar crust. Most are complicated mixtures of other rocks, and many are weakly consolidated. Furthermore, the rims of all craters typically are composed of weakly consolidated or unconsolidated materials and, therefore, not capable of withstanding tensional stresses.

A few localities might have intact bedrock, however. Many mare basalt flows, for example, form visible layers in crater walls or, as at the Apollo 15 landing site, in the walls of sinuous rills. Also, extensive sheets of impact-generated melt rocks occur on the floors of many large craters, such as Copernicus, which is 95 km in diameter.

Crater Morphologies

Fresh lunar craters as large as 15 km in diameter have a consistent diameter/depth ratio of 5 (ref. 22). More specifically, craters <15 km across follow the relation $R_i = 0.196 D_r{}^{1.010}$ and craters >15 km diameter follow the relation $R_i = 1.044 D_r{}^{0.301}$, where R_i is the crater depth and D_r is the diameter as measured from rim crest to rim crest (ref. 22). Large craters are much shallower in proportion to their diameters than are smaller ones. Also, the crater morphology changes as a crater is eroded by meteorite bombardment, during which a crater becomes wider and shallower, and thereby the diameter/depth ratio is increased. Finally, as noted previously, rim materials consist of weak, unconsolidated rock. This composition could cause problems in the construction of some facilities, though not of Arecibo-type antennas as these are constructed with almost no tensional forces, as Frank Drake noted during the Workshop on Astronomical Observations from a Lunar Base.

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TABLE I.- COMPARISON OF MOONQUAKE AND EARTHQUAKE INTENSITIES

[From ref. 3]

Parameter	Moon	Earth
Frequency of events, no/yr	5 shallow ($m > 2.2$)[a] 500 deep ($m > 1.6$)	10^4 ($m > 4$)
Energy release of largest event, ergs	2×10^{17} (shallow) 1×10^{13} (deep)	10^{26}
Magnitude of largest event	4.8 (shallow) 3.0 (deep)	9.5
Seismic energy release, ergs/yr	2×10^{17} (shallow) 8×10^{13} (deep)	10^{25}

[a] m = magnitude.

TABLE II.- COMPOSITION OF THE LUNAR ATMOSPHERE AT NIGHT

[From ref. 6]

Gas	Concentration, molecules/cm^3
H_2	6.5×10^4
^4He	4×10^4
^{20}Ne	8×10^4
^{36}Ar	3×10^3
^{40}Ar	7×10^3
O_2	$<2 \times 10^2$
CO_2[a]	$<3 \times 10^3$

[a] Carbon gases (CO_2, CO, CH_4) probably dominate the daytime lunar atmosphere (ref. 8).

TABLE III.- MICROMETEORITE FLUXES ON THE MOON

[Calculated from data in ref. 14]

Crater diameter, μm	Flux, craters/m^2-yr
≥0.1	30 000
≥1.0	1 200
≥10	300
≥100	.6
≥1000	.001