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THE LUNAR ENVIRONMENT AND ITS EFFECT ON OPTICAL ASTRONOMY

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Abstract

The Moon's geologic environment features 1) gravity field one-sixth that of Earth; 2) sidereal rotation period of 27.3 days; 3) surface with greater curvature than Earth's surface (a chord along a 10-km baseline would have a bulge of 7.2 m); 4) seismically and tidally stable platform on which to make astronomical observations (most moonquakes have magnitudes of 1 to 2 on the Richter scale, within the Earth's seismic noise, resulting in ground motions only 1 nm); 5) tenuous atmosphere (the total mass at night is only 10^4 kg) that has an optical depth of 10^{-6} and does not cause wind-induced stresses and vibrations on structures; 6) large diurnal temperature variation (100° to 385°K in equatorial regions), which telescopes must be designed to withstand; 7) weak magnetic field, ranging from 3 to 330×10^{-9} T, compared to 3×10^{-5} T on Earth at the equator; 8) surface exposed to radiation, the most dangerous of which are high-energy (1-100 Mev) particles resulting from solar flares; 9) high flux of micrometeorites which are not slowed down from their cosmic velocities because of the lack of air (data indicate that microcraters > 10μm across will form at the rate of $3000/m^2/yr$); 10) 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 (800 to $1000 kg/m^3$ in the upper few millimeters, rising to 1500 to 1800 kg/m^3 at depths of 10-20 cm), is porous (35-45 percent, cohesive (0.1 to 1.0 kN/m^2), and has a low thermal diffusivity (0.7 to 1.0 x 10-8 m^2/sec); about 29 percent of the regolith is <20 μm in size--this dust could pose a hazard to optical telescopes); 11) rubbly upper several hundred meters in which intact bedrock is uncommon, especially in the lunar highlands; and 12) craters with diameter-to-depth ratios of 5 if fresh and <15 km across (larger and eroded craters have diameter-to-depth ratios >5).

Introduction

The environment at the Moon's surface makes it nearly ideal for astronomical observations. It is dramatically different from Earth's environment and presents fascinating challenges to engineers designing observatories on the lunar surface. Some of the virtues of the lunar environment for observations can also damage equipment. This paper summarizes the nature of the lunar surface, its tenuous atmosphere, and its radiation environment.

Small Size and Rotation Rate

The strength of the Moon's gravitational field is about one-sixth that at Earth's surface; the surface gravity is 1.62 m/s^2 and the escape velocity is 2.37 km/s. The lower gravity allows use of materials of lower strength than on Earth for structures of equivalent size. Alternatively, much larger structures can be built on the Moon. The Moon has a slow sidereal (the time it takes to complete one revolution) rotation period of 27.3 Earth days, so days and nights each last almost 2 weeks. Consequently, observing times are long, but solar energy systems require some way to store energy during the long lunar night. Finally, 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 along it of 7.2 m; a 60-km baseline would have a bulge of 260 meters.

Stable Platform

The Moon provides a stable platform on which to build structures. Seismic properties are summarized in table 1, which is adapted from Goins et al. (1981). 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 the average, about 500 deep events were recorded each year during the 8 years that the Apollo network operated. 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 (Nakamura et al. 1979). They occur much less frequently than do deep moonquakes, only about 5/y. Shallow moonquakes do not appear to be related to tidal flexing of the Moon or to surface features. For comparison, most earthquakes occur at depth of 50 to 200 km.

Lunar seismic activity is drastically less than terrestrial seismicity (table 1). Lunar seismographs detected only 500 quakes per year. In contrast, 10,000 detectable quakes occur each year on Earth. Note that the magnitudes of detectable quakes is different on Earth and the Moon, due mostly to greater seismic noise on Earth. In fact, most moonquakes are in the magnitude 1 to 2 range on the Richter scale, which is in the Earth's seismic background. The weak lunar seismic background produces ground motions that are astonishingly small, only about 1 nm.

Seismic waves are intensely scattered near the lunar surface. This causes the energy of the waves arriving at a given point to be spread out, so 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. (1981) are greater than those reported by Lammlein et al. (1974) 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. Lunar base activities such as mining will increase the seismic background, but a preliminary assessment indicates that artificial seismic signals are damped out to below the lunar background within about 10 km of the source of the noise (Taylor 1989).

Tidal forces raise and lower the lunar surface about as much as on Earth, where body tides deflect the ground about 10-20 cm twice each day, but 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 taken into account when designing arrays of optical telescopes.

Atmosphere

The lunar atmosphere is a collisionless gas. The total nighttime concentration in only $3x10^{-13}$ mol/m^3, or 2×10^5 mol/cm^3 (Hoffman et al. 1973). Its total mass is 10^4 kg, about the mass of air in a movie theater on Earth at one bar. This trifling atmosphere allows phenomenal seeing for astronomy; its optical depth (assuming it is composed of oxygen, the most potent absorber of ultraviolet light) is a minuscule 10^{-6}. The virtual lack of air also eliminates engineering problems associated with wind (Johnson 1988), but might add others, such as difficulty in lubricating moving parts. It is also, of course, the prime reason why the lunar surface is assailed by micrometeorites. The small atmosphere is also partly to blame for the high radiation flux.

At night, the Moon's atmosphere is composed chiefly of H_2, He, and other noble gases. These are derived from the solar wind, except for ^{40}Ar, which is produced by the decay of ^{40}K inside the Moon and then diffuses out (Hoffman et al, 1973). No daytime measurements of gas concentrations were made due to instrument limitations, but enhancements in the levels of CO_2, CO, and CH_4 a short time before sunrise indicates that these gases were being desorbed at sunrise (Hoffman and Hodges 1975). Hodges (1976) calculates that CO_2, CO, and CH_4 probably dominate the daytime atmosphere, but the pressure is still extremely low. They are absent at night because they condense out of the atmosphere onto soil particles.

Surface Temperatures

Surface temperatures change drastically from high noon to dawn on the Moon, presenting a challenge to those designing lunar structures, subject to thermal expansion and contraction. At Apollo 17, for example, the temperature ranged from 384° K to 102° K during the month-long lunar day (Keihm and Langseth 1973). Furthermore, the temperature decreases rapidly at sunset, falling about 5K/hr. These data apply to equatorial regions only. In polar regions, the predawn temperature is about 80° K (Mendell and Low 1970). The temperature in permanently shadowed areas at the poles could be lower. Telescopes must be designed to withstand the large variation in temperature. On the other hand, the cold nighttime temperature will permit cooling of many systems without the use of cryogenics.

The temperature variation is damped out rapidly at depth in the lunar soil (Keihm and Langseth 1973). 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 for some purposes, but not as a heat sink because the lunar soil has a very sluggish thermal conductivity (see below).

Magnetic Field

No magnetic field is now being generated inside the Moon, although there was a source of magnetism several billion years ago. It is not known whether this was generated by a dynamo in a metallic core, as on Earth, or by local, transient events such as meteorite impacts. Whatever its source, the lunar magnetic field is much weaker than is Earth's (Dyal et al. 1974). On the surface, the lunar magnetic field strength ranges from 3×10^{-9} to 3.3×10^{-7} T. For comparison, Earth's field at the equator is 3.0×10^{-5} T. The lunar field is too weak to shield the surface from solar flares or cosmic rays. There is also a field external to the Moon, derived from the solar wind. This ranges from 5 x 10^{-9} T in the free-streaming solar wind to about 10 x 10^{-9} T in Earth's geomagnetic tail, in which the Moon resides 4 days during each lunation.

Radiation Environment

Because of the Moon's small magnetic field and nearly absent atmosphere, sunlight and solar and galactic nuclear particles hit its surface unimpeded. The Sun's spectrum peaks in the visible, at about 500 nm, but a significant amount of it, 7 percent, is in the ultraviolet, between 280 and 400 nm (Robinson 1966). Since the solar constant is 1393 W/m^2 at the Earth-Moon distance from the Sun (Coulson 1975), the total ultraviolet flux is 95 W/m^2.

There are three sources of radiation with different energies and fluxes; see Taylor (1975) for a summary: 1) high energy (1-10 Gev/nucleon) galactic cosmic rays, with fluxes of about 1/cm^2/s and penetration depths of up to a few m; 2) solar flare particles with energies of 1-100 Mev/nucleon, fluxes up to 100 cm^2/s, and penetration depths up to 1 cm; 3) solar wind particles, which have much lower energies of about 1000 ev, tiny penetration depths (10^{-8} cm), but high fluxes (10^8/cm^2/s). These penetration depths refer to the primary particles only. Reactions between them and lunar material cause a cascade of radiation that penetrates deeper (Silberberg et al. 1985), up to a few m. The combination of high flux and energy make solar flare particles the most dangerous to people working on the lunar surface and to electronic devices, such as charge-coupled devices, deployed directly on the surface. Telescope design must take this into account.

Micrometeorite Flux

The lack of a significant atmosphere on the Moon allows even the tiniest particles to impact with their full cosmic velocities, ten to several tens of km/sec. This rain of minute impactors could damage telescope mirrors and other instruments on the lunar surface. Almost all lunar rock samples contain numerous microcraters, commonly called "zap pits," on surfaces that were exposed while on the lunar surface. Studies of lunar rocks (Fechtig et al. 1974) have revealed the average flux of projectiles over the past several hundred million years. However, data from the Surveyor 3 TV camera shroud returned by the Apollo 12 mission and study of Apollo windows (Cour-Palais 1974) indicate that the present flux of particles with <10^{-7}g, which are capable of producing craters up to 10 m across, is about ten times greater than that measured on lunar rocks. Study of louver material from the Solar Max satellite (Barrett et al. 1988) confirm that fluxes are greater now than during the average of the past several hundred million years. Combining the fluxes of particles $<10^{-7}$g measured on spacecraft with those $>10^{-7}$g measured on lunar rocks, Johnson et al. (1989) arrived at the flux estimates in table 2.

It is obvious from these data that microcraters in the 1 to 10 μm size will be common on surfaces exposed at the lunar surface. Even 100 μm craters will not be uncommon, with one produced on each m^2 of surface every other year or so. It appears that sensitive surfaces, such as mirrors on optical telescopes, will have to be protected. The use of collimators will help reduce the flux reaching a telescope mirror. For example, a mirror 1 m across located at the base of a tube 3 m long would receive 5 percent of the values listed in table 2 (Johnson et al. 1989).

Regolith

The lunar regolith, also called the 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 meters, with most areas in the range 5 to 10 meters. Impacts by micrometeorites have reduced much of the regolith material to a powder. Its mean grain size ranges from 40 to 268 μm and varies chaotically with depth (Heiken 1975). About 20 percent of the regolith is composed of particles smaller than 20 μm. The chemical composition of the regolith reflects the composition of the underlying bedrock, modified by admixture of material excavated from beneath or thrown in by distant impacts

The mechanical properties of lunar regolith samples were measured during the Apollo program, both *in situ* on the lunar surface and on returned samples in laboratories back on Earth (e.g., Mithcell et al. 1972). The bulk density of the regolith is very low, 800 to 1000 kg/m^3, in the upper few mm, the lunar regolith is more cohesive, 0.1 to 1.0 kN/m^2, than 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, leading to an increase in soil density (Carier et al. 1973).

The lunar regolith is an excellent insulator. Its thermal diffusivity at depths of 30 cm is 0.7 to 1.0×10^{-8} m^2/s and it thermal conductivity is 0.9 to 1.3 x 10^{-2} W/m/K (Langseth et al. 1976). This in not surprising considering the high porosity and lack of air. At depths <30 cm, thermal diffusivity is somewhat lower.

The finest grain-size fraction of the regolith poses some problems for astronomical facilities. It can be moved around by rocket launches and landings, surface vehicles, or astronaut suits. This must be controlled by proper procedures (Johnson et al. 1989). A small amount of lunar dust might be transported by charge differences built up by photoconductivity effects. Criswell (1972) described a bright glow photographed by Surveyor 7 and explained the phenomena 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 does not appear to be a significant transport mechanism on the lunar surface, but its effect on the surfaces of telescope mirrors must be evaluated. On the other hand, the reflectivities of the laser reflectors left on the lunar surface apparently has not decreased, so perhaps electrostatic effects also remove dust from some surfaces.

Upper Few Hundred Meters

The upper few hundred m of 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 k. Consequently, it might be difficult to find extensive areas of intact bedrock.

Active seismic experiments (Cooper et al. 1974) indicate that the velocity of compressional waves is about 100 m/s at depths of less than 10 meters, which is in the regolith, and about 300m/s at depths between 10 and 300 m. These velocities are too slow to correspond to coherent rock, implying that the upper few hundred meters of the lunar surface is rubble (Cooper et al. 1974). 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 are by their nature weakly or unconsolidated materials and, therefore, not able to withstand tensional stresses.

A few localities might have intact bedrock, however. Many mare basalt flows, for example, form visible layers of crater walls or, as at the Apollo 15 landing site, in the walls of sinuous rilles (river-like depressions). 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.

Topography

Fresh lunar craters up to 15 km in diameter have a consistent diameter/depth ratio of 5 (Pike 1974). More specifically, craters <15 km across follow the relation $d=0.196D^{1.010}$; craters >15 km follow the relation $d=1.044\ D^{0.301}$ where d is the crater depth and D is the diameter as measured from rim crest to rim crest (Pike 1974). Large craters are much shallower for their diameters than are smaller ones. Crater morphology changes as a crater is eroded by meteorite bombardment, during which a crater becomes wider and shallower, thereby increasing the diameter-to-depth ratio. Thus, even the smoothest areas on the lunar surface are undulating plains, so building precisely horizontal transportations systems might require cut-and-fill operations. No place on the Moon is as flat at the plains of St. Augustin, site of the VLA.

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References

1. Barrett, R.A.; Bernhard, R.P.; McKay, D.S. 1988. Impact holes and impact flux on returned solar max louver material. Lunar and Planetary Science XIX: 39-40.

2. Carrier, W.D. III; Bromwell, L.G.; Martin, R.T. 1973. Behavior of returned lunar soil in vacuum. Joun. Soil Mech. Found. Div., ASCE 99:979-996.

3. Cooper, M.R.; Kovach, R.L.; Watkins, J.S. 1974. Lunar near-surface structure. Rev. Geophys. Space Phys. 12:291-308.

4. Coulson, K.L. 1975. Solar and terrestrial radiations. Academic Press.

5. Cour-Palais, B.G. 1974. The current micrometeoroid flux at the Moon for masses <10-7 g from the Apollo window and Surveyor 3 TV camera results. Proc. Lunar Sci. Conf. 5th, 2451-2462.

6. Criswell, D. 1972. Lunar dust motion. Proc. Lunar Sci. Conf. 3rd, 2671-2680.

7. Dyal, P.; Parkin, C.W.; Daly, W.D. (1974). Magnetism and the interior of the Moon. Rev. Geophys. Space Phys. 12:568-591.

8. Fechtig, H.; Hartung, J.B.; Nagel, K; Neukum, G. 1974. Lunar microcrater studies, derived meteoroid fluxes, and comparison with satellite-borne experiments. Proc. Lunar Sci. 5th, 2463-2474.

9. Goins, N.R.; Dainty, A.M.; Toksoz, M.N. 1981. Seismic energy release of the Moon. J. Geophys. Res. 86: 378-388.

10. Heikien, G. 1975. Petrology of lunar soils. Rev. Geophys. Space Phys. 13:567-587.

11. Hodges, R.R., Jr. 1976. The escape of solar-wind carbon from the Moon. Proc. Lunar Sci. Conf. 7th, 493-500.

12. Hoffman, J.H.; Hodges, R.R. 1973. Molecular gas species in the lunar atmosphere. The k/Moon 14:159-167.

13. Hoffman, J.H.; Hodges, R.R.; Johnson, F.S. 1973. Lunar atmospheric composition results from Apollo 17. Proc. Lunar Sci. Conf. 4th, 2865-2875.

14. Johnson, F.S. 1971. Lunar atmosphere. Rev. Geophys. Space Phys. 9:813-823.

15. Johnson, S.W. 1988. Engineering for a 21st century lunar observatory. J. Aerospace Eng. 1:35-51.

16. Johnson, S.W.; Taylor, G.J., Wetzel, J.P. 1989. Environmental effects on lunar astronomical observatories. Submitted to Second Symposium on Lunar Bases and Space Activities in the 21st Century.

17. Keihm, S.J.; Langseth, M.G. 1973. Surface brightness temperatures at the Apollo 17 heat flow site: Thermal conductivity of the upper 15 cm of regolith. Proc. Lunar Sci. Conf, 4th, 2503-2513.

18. Lammlein, D.R.; Latham, G.V.; Dorman, J; Nakamura, Y.; Ewing, M. 1974. Lunar seismicity, structure, and tectonics. Rev. Geophys. Space Phys. 12:1-21.

19. Langseth, M.G.; Keihm, S.J.; Peters, K. 1976. Revised lunar heat-flow values. Proc. Lunar Sci. Conf. 7th, 3143-3171.

20. Mendell, W.W.; Low, F.J.; 1970. Low-resolution differential drift scan of the Moon at 22 microns. J. Geophys. Res. 75:3319-3324.

21. Mitchell, J.D.; Houston, W.N.; Scott, R.F.; Costes, N.C.; Carrier III, W.D.; Bromwell, L.G. 1972. Mechanical properties of lunar soil; density, porosity, cohesion, and angle of internal friction. Proc. Lunar Sci. Conf. 3rd, 3235-3253.

22. Nakamura, Y.; Latham, G.V.; Dorman, H.J.; Ibrahim, A.-B.K.; Koyama, J.; Horvath, P. 1979. Shallow moonquakes: depth, distribution and implications as to the present state of the lunar interior. Proc. Lunar Planet. Sci. Conf. 10th, 2299-2309.

23. Pike, R.J. 1974. Depth/diameter relations of fresh lunar craters: revision from spacecraft data. Geophys. Res. Lett. 1:291-294.

24. Robinson, N. 1966. Solar radiation. Elsevier Pub. Co.,New York.

25. Silberberg, R.; Tsao, C.H.; Adams Jr., J.A. 1985. Radiation transport of cosmic ray nuclei in lunar material and radiation doses. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.) The Lunar and Planetary Institute, Houston, TX. p. 663-669.

26. Taylor, G.J. 1989. Astronomy on the Moon: geological considerations. Submitted to Second Symposium on Lunar Bases and Space Activities in the 21st Century.

27. Taylor, S.R. 1975. Lunar Science: A Post-Apollo View. Pergamon Press, New York.

28. Vondrak, R.R. 1974. Creation of an artificial lunar atmosphere. Nature 248:657-659.

Table 1. Comparison of moonquake and earthquake intensities (From Goins et al. 1981)

	Moon	Earth
Number of events/year	5 shallow (m>2.2)* 500 deep (m>1.6)*	10^4 (m>4)*
Energy release of largest event	$2x10^{10}$ joule (shallow) $1x10^6$ joule (deep)	10^{19} joule
Magnitude of largest event	4.8 (shallow) 3.0 (deep)	9
Seismic energy release/year	$2x10^{10}$ joule yr^{-1} (shallow) $8x10^6$ joule yr^{-1} (deep)	10^{18} joule yr^{-1}

*m=magnitude

Table 2. Microcrater product rates on the Moon, estimated from data given by Fechtig et al. (1974), Cour-Palais (1974), and Barrett (1988).

Crater diameter (μm)	Craters/m^2/yr
>0.1	300,000
>1	12,000
>10	3,000
>100	0.6
>1000	0.001