

ASTRONOMY ON THE MOON: GEOLOGICAL CONSIDERATIONS

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The Moon is an excellent site for astronomical observations. This paper describes two geological aspects related to astronomy from the Moon. First it evaluates the sources of gases near a lunar base as input to calculations reported in a separate paper on the growth of an artificial lunar atmosphere. The results suggest that mining for ^3He could produce the most gas (1 kg/sec), but rocket exhaust (0.1 kg/sec) and habitat venting (0.5 kg/sec) are also important. Second, the paper discusses criteria that need to be considered when determining the site of a lunar astronomical facility. These are longitude and latitude (equatorial sites are favored), topography (important to be relatively flat for ease of installation), distance from a lunar base (to be free of seismic noise, dust, and gases), the site's value to lunar geoscience (other factors being equal, a geologically diverse site is better), and its value as a materials resource (mining and observatories are incompatible).

INTRODUCTION

The Moon may be the best place in the inner solar system from which to make astronomical observations (Burns, 1988). As part of our University of New Mexico and BDM Corporation study of concepts for astronomical observatories on the Moon, we have investigated several geological aspects of the problem. This paper describes our initial results, in two broad categories. First, it evaluates quantitatively the sources of gases near a lunar base, which provides essential information for our calculations concerning the evolution of an artificial lunar atmosphere (Burns *et al.*, 1991; Ferrini *et al.*, 1990). Second, the paper develops criteria for the selection of sites for lunar astronomical facilities.

SOURCES OF ATMOSPHERIC GASES

There will be both natural and artificial sources of gases on the Moon. Although the present tenuous nature of the lunar atmosphere indicates that natural sources are too low to allow a significant atmosphere to develop, I list them here both for completeness and for comparison with artificial sources. As a rule of thumb, if an artificial source is of the same order as a natural one, it will not lead to a significantly enhanced lunar atmosphere. Results of the evaluations appear in Table 1 and are discussed below.

Solar Wind

The solar wind is a major source of gas to the lunar atmosphere. Most of the gases trapped in the regolith are derived from solar wind implantation. Using fluxes given by Vondrak (1974), the total amount of solar wind input to the lunar atmosphere is 5×10^{-2} kg/sec, almost all of which is H (40 g/sec) and He (8 g/sec). These gases are delivered uniformly to the sunlit part of the Moon.

TABLE 1. Sources of gas near a lunar base.

Source	Rate (kg/sec)
Solar wind	5×10^{-2}
Meteoritic volatilization	2×10^{-3}
Internal degassing	$< 3 \times 10^{-4}$
Rocket exhaust	10^{-1}
Habitat venting	0.5
Mining and Manufacturing	1
^3He mining	1
Oxygen production	10^{-3}
Glass production	10^{-5}

Meteorite and Comet Volatilization

Many of the micrometeoroids that hit the Moon are rich in volatile substances. Because meteoroids are vaporized when they impact the lunar surface, their volatiles are released to the atmosphere. Gault *et al.* (1972) estimate a flux of 2×10^{-3} g/cm²/10⁶ yr for masses smaller than 1 g. If these contain on average 10% H₂O (appropriate for CI carbonaceous chondrites, though possibly low for comets), then meteoroids contribute 2×10^{-3} kg/sec to the atmosphere. Using a flux estimated by Hartmann (1980) reduces this estimate by a factor of 2. Like the solar wind, this is distributed globally. Of course, a single, large impact of a comet or hydrated meteorite could inject a considerable amount of volatiles near the point of impact. For example, impact of a body 20 m across containing 10% H₂O would release 10⁶ kg of water vapor instantaneously. Fortunately, such events are rare, happening once every 10⁴ yr.

Internal Degassing

The Moon continuously outgasses, as shown by the release of radon (e.g., Gorenstein *et al.*, 1973). Reports of lunar transient phenomena (e.g., Middlehurst, 1967) suggest occasional large releases. However, Vondrak (1977) argues that such releases

would need to be $>10^4$ kg to be detected by the SIDE (Super-thermal Ion Detector Experiment) carried by Apollo 12, 14, and 15. Since no such release was observed during its eight years of operation, we can place an upper limit of 10^4 kg/yr, or $<3 \times 10^{-4}$ kg/sec.

Rocket Exhaust

Vondrak (1974) sounded the first alarm about the possibility that the Moon's fragile atmosphere could be modified significantly by rocket exhaust, habitat venting, and mining, pointing out that each Apollo mission temporarily doubled the lunar atmosphere. The amount of gas released by rocket exhaust is difficult to estimate, as one must assume spacecraft capabilities and frequency of flights. If we assume each landing or ascent uses 20 times the Apollo lunar module capacity (3000 kg; Johnson, 1971) and that there are 18 trips per year, then on average only 0.1 kg/sec will be released into the lunar environment.

Habitat Venting

This is also difficult to guess, principally because we must assume some critical size for the lunar base. Structural leakage accounts for $0.2 \text{ mg/m}^2\text{-sec}$ (Vondrak, 1991), about the same as expected for habitats on Mars (Duke and Keaton, 1986). Assuming each habitat has an area of 239 m^2 (cylinders 14.3 m long \times 4.6 m diameter; i.e., the nominal size of space station modules), then each would release $4.8 \times 10^{-2} \text{ kg/sec}$. If there are 10 such habitats, then they would release $4.8 \times 10^{-1} \text{ kg/sec}$. Air lock venting would also allow gases to escape. Assuming 0.6 kg/use (Duke and Keaton, 1986) and 10 uses per day, on average $7 \times 10^{-5} \text{ kg/sec}$ would escape to the lunar atmosphere, insignificant compared to leakage.

Mining

Several lunar resources have been identified as promising. I consider three of them here: ^3He for use in nuclear fusion reactors (Wittenberg et al., 1986), oxygen production from ilmenite (FeTiO_3) for use a propellant (e.g., Gibson and Knudsen, 1985), and glass production from lunar regolith (Blacic, 1985). Extraction of each of these releases gases bound in the regolith and thus poses a threat to the lunar atmosphere.

Maximum concentrations of gases in the regolith are given in Table 2. Concentrations of CH_4 , CO , and CO_2 were calculated from gas-release curves measured by Gibson and Johnson (1971) and from data reported by DesMarais et al. (1973). Although sulfur is an important constituent of the lunar regolith (about 0.2 wt%; Gibson and Moore, 1974), I have not included it

TABLE 2. Maximum concentrations (ppm) of gases in lunar regolith.

Molecule	Concentration	Reference
H_2	100	1,2
He	70	3
Ne	5.4	6
C	280	4,5,6
CH_4	8	
CO	232	
CO_2	39	
N_2	80	6,7

References: (1) DesMarais et al. (1974); (2) Gibson et al. (1987); (3) Walton et al. (1973); (4) Moore (1974); (5) Pillinger (1979); (6) Gibson (1974); (7) Mueller (1979).

because it is not released as readily as are the other gases, though the precise kinetics of sulfur release ought to be worked out.

Helium mining. Mining for ^3He is by far the worst case because the low abundance of ^3He necessitates mining and processing huge quantities of regolith. In calculating the amount of gases that will be released, I assume that regolith containing the maximum amount of gas will be mined and that we will need to produce 20 metric tons (20,000 kg) of ^3He per year, which would supply U.S. energy needs for one year (Wittenberg et al., 1986). This requires mining 8.3×10^8 metric tons of regolith per year. I assume mining takes place continuously and that 10% of the gas is lost to the atmosphere; losses might be less than 10%, but Carrier et al. (1973) report that several percent of trapped gases are lost merely by moving regolith, so to calculate the maximum gas released, I use 10%. Consider two cases: (1) heating the regolith to 700°C , which will release $>90\%$ of the He (Pepin et al., 1970) and (2) heating to 1200°C , which might enhance extraction of other species. The second case also allows us to place a better defined upper limit of gas release. Results are shown in Table 3.

TABLE 3. Gas loss (kg/sec) during ^3He mining.

	700°C	1200°C
H_2	0.13	0.13
H_2O	0.06	0.06
He	0.18	0.18
Ne	0.01	0.01
CO_2	0.05	0.1
CO	0.03	0.6
N_2	0.01	0.21
Total	0.47	1.29

For case 1, all the H is released, 10% of it as H_2O , all the He, 60% of the Ne, 50% of the total CO_2 , and about 5% of the total CO and N_2 . This results in a total of about 0.5 kg/sec of gases released. For case 2, all the H (10% of it as H_2O), He, and Ne, 90% of the CO_2 , and 80% of the CO and N_2 are released. This causes the emission of 1.3 kg/sec . It appears that He mining would release about 1 kg/sec into the lunar atmosphere, much greater than the other sources listed in Table 1.

Oxygen production. To produce 1000 metric tons per year from regolith containing 5% ilmenite at 5% efficiency, 2×10^6 metric tons of regolith must be mined. Although oxygen extraction will take place at 1000°C (e.g., Gibson and Knudsen, 1985), I use the gas release values for 1200°C to place a firmer upper limit on the amount of gas released. The amount of gas will be proportional to the amount of regolith mined, and since oxygen requires mining about 10^{-3} as much regolith, only about 10^{-3} kg/sec will be released, much less than for ^3He mining. If an enormous commercial market develops for lunar oxygen and requires 10^3 times more, then the amount of gas released would equal that from ^3He .

Glass production. If a lunar base could use 1000 metric tons per year of glass of feldspar composition, and the mined soil is in the highlands (average 70% plagioclase feldspar), then only 1.4×10^3 metric tons of regolith need be processed. In this case the regolith would be melted, releasing all the gas in it. As above, I assume 10% of that gas will escape. Using the gas contents in Table 2, this results in release of 10^{-5} kg/sec , clearly not a threat to the integrity of the lunar atmosphere. Even if a million tons of glass were needed, only about 10^{-2} kg/sec would be released.

In summary, it appears that rocket exhaust, habitat venting, and ^3He mining have the most potential for disturbing the tenuous lunar atmosphere (Table 1). These calculations will need to be improved as plans for lunar base development become clearer and as mining and processing equipment is designed.

SITE SELECTION CRITERIA

We have identified several criteria that must be considered when determining where to locate an astronomical observatory on the Moon: longitude and latitude, topography, distance from a lunar base, value of the site to lunar geoscience, and value as a materials resource.

Longitude and Latitude

The high background of very low frequency (VLF; <30 MHz) radio waves emanating from Earth requires that a VLF array be located on the lunar farside. Because of librations of the Moon, only sites with longitudes $>98^\circ$ (east and west) are permanently shielded from Earth. However, because of growing radio-frequency interference on Earth, it is in general desirable to place all radio telescopes on the farside. An exception is the Moon-Earth radio interferometer (MERI), which employs one or more radio antennas on Earth, hence must tolerate radio interference. On the other hand, even this would benefit by location on the farside because it might afford a way to distinguish interference from the signals of interest.

To view the entire sky, telescopes must be deployed over a wide range of latitudes. However, a complex VLF (or optical) array is almost certain to be a unique facility, so an optimum latitude must be chosen. Because objects of interest occur in both northern and southern skies, it seems sensible to locate a VLF array within 20° of the lunar equator. Also, polar sites are weak for viewing the planets in our solar system as all the objects of interest would be at the horizon.

Topography

The Moon's surface is divided into two distinct terrains, the highlands and the maria. The highlands compose the oldest lunar crust and are densely cratered. Relief differences are large over relatively short distances. For example, central peaks and walls of large craters can rise 3-4 km above their floors. Some large basins (craters >100 km across) have floors that are relatively smooth and light colored; the floor materials represent either volcanic flows different in composition from darker mare flows or are impact-generated, fluidized materials (which is the case of the smooth plain on which Apollo 16 landed). Because of the highlands' great age, they are covered with a thick regolith of impact-generated debris, hence tend to contain fewer large blocks of rocks. The maria are younger than the highlands and formed when lavas erupted onto the lunar surface and filled low-lying regions. Mare surfaces tend to be much smoother than highland surfaces and are much less cratered. However, they also have thinner regoliths, so crater ejecta blankets tend to contain numerous blocks of rocks.

Topography enters into the selection of a site for an observatory more for ease of deployment and operation of the facility than for scientific reasons. The rugged terrain in the highlands makes it difficult for elements of an array to communicate by line-of-sight with a single central processing station. Also, deployment vehicles would need to maneuver around many hills and valleys

created by old, degraded craters. On the other hand, blocks of rocks would be less of a hazard than in the maria. Overall, the optimum site would be a relatively old (>3.5 b.y.) mare surface. The old age would permit a relatively thick, unblocky regolith and the presence of mare basalt flows would create relatively low relief across a large region.

Distance from a Lunar Base

An observatory needs to be isolated from an active lunar base, especially if the base is the site of extensive mining operations. Several factors must be taken into account when estimating how far an observatory needs to be located from a lunar base. These are the distance from a lunar base located on a limb (90° longitude), seismic noise, atmospheric contamination, and dust.

Distance from a limb site. It might be desirable to locate a lunar base close to a nearside limb. For example, the Mare Smythii region holds great promise for lunar geoscience investigations and for lunar resource extraction (*Spudis and Hood, 1991*). To keep Earth in view continuously (for both psychological and operational reasons), the base could be no farther than about 90°E . However, lunar librations cause sites up to 98° to sometimes have Earth in view. Consequently, a radio array would need to be at least 240 km east of a lunar base located at 90°E longitude (1° equals 30 km at the lunar equator). Furthermore, radio waves from Earth would be diffracted. Assuming a perfectly spherical Moon, the diffraction region for very low frequency radio waves (300-m wavelength) is 75 km (see, e.g., *Jackson, 1975, p. 447*). Thus, this distance must be added to that caused by librations: a radio telescope must be located at least 315 km from 90° longitude.

Seismic noise. Lunar base activities will increase the general seismic background on the Moon. This might affect radio telescope antennas, especially dishes, and would almost certainly affect an array of optical telescopes. Using data from the signal strengths generated by charges placed on the lunar surface by astronauts and from impacts of the Apollo 17 lunar module, *Cooper and Kovach (1975)* developed an empirical relation between ground motion and seismic energy, $A = kE^{0.5}/r$, where A is the amplitude (nm), E is the energy (ergs), and r is the distance (km). K is an empirical constant, 2×10^{-5} . To estimate the effect of lunar base activity, let us assume that surface mining takes place continuously, and calculate the ground motion (amplitude) generated by dropping 1 m^3 of soil from a height of 2 m. This generates about 6×10^{10} ergs, assuming soil density of $2 \times 10^3 \text{ kg/m}^3$. This produces the following ground motions:

Distance (km)	Ground Motion (nm)
1	5
10	0.5
100	0.05

The lunar seismic background produces ground motions on the order of 1 nm, so it is clear from the above that even an optical-telescope array will not be affected if it is located more than 10 km from a mining operation. This analysis does include the additive effects of each mining scoop. This would seem to be important because seismic waves are not attenuated rapidly on the Moon; for example, a signal damped out in minutes on Earth lasts hours on the Moon (*Lammlein et al., 1974*). The above

analysis also does not consider more potent sources of energy such as blasting operations. A detailed analysis of artificial lunar seismicity needs to be done. Nevertheless, it seems safe to conclude that artificial seismic disturbances will not affect radio observations on the Moon.

Artificial atmosphere. The Moon's tenuous atmosphere makes it ideal for astronomical observation. However, lunar base operations could lead to a significant increase in atmospheric density, as was first pointed out by Vondrak (1974). This problem has been addressed recently by Burns *et al.* (1991). Even considering the worst case, mining for ^3He (which might contribute as much as 1 kg/sec into the lunar atmosphere; Table 1), Burns *et al.* (1991) concluded that no significant growth of the atmosphere occurs beyond 10-100 km from a lunar base, roughly the range at which seismic pollution becomes negligible. However, if lunar base activities contributed ≥ 10 kg/sec, significant damage to the environment might occur.

Dust contamination. In principle, this could be a serious problem within 1-10 km of a lunar base because of dust accelerated by rocket landings and lift-offs. However, this could be mitigated by construction of landing pads, so we do not consider it to be a serious problem, but a quantitative analysis needs to be made. It is almost certainly of little concern for radio telescopes.

Value to Lunar Geoscience

The site for any astronomical observatory on the Moon ought to be chosen for its suitability for that purpose. Nevertheless, other factors, including operational considerations such as communications, being equal, it seems reasonable to propose choosing the site that has the greatest interest to lunar geoscientists. If this

is done, any visit by a crew to repair or expand the facility could include geologic sampling as well. Even during deployment by automated vehicles, geophysical instruments could be deployed as well, although this might add to the cost and complexity of the deployment.

Value as a Materials Resource

Mining and astronomy are probably incompatible, so sites that hold obvious resource potential ought to be avoided. An alternative would be to designate areas for astronomy (and other sciences) within regions possessing resources, keeping in mind the criteria for distance from a lunar base.

Candidate Site for a VLF Array: Tsiolkovsky

The large crater Tsiolkovsky (Fig. 1) is an excellent candidate for the site of a VLF radio array. The crater is 180 km across, rim to rim, and its floor is 113 km across, providing ample space for even an advanced array. It is located on the lunar farside at 20°S latitude and 130°E longitude. Thus, Tsiolkovsky is in the equatorial zone and far from any base established on the nearside. Even a base on the eastern limb at 90°E would be 1200 km away.

The crater's floor is covered by high-Ti mare basalt (Wilbur, 1978) with an age similar to that of the Apollo 11 landing site, ~ 3.6 b.y. The floor is smooth, except where punctuated by craters. Based on its age, a thick regolith ought to be present, thereby lessening hazards from boulder fields near small craters. The central peak rises 3 km above the smooth plains. A central station located on the highest point could receive signals from

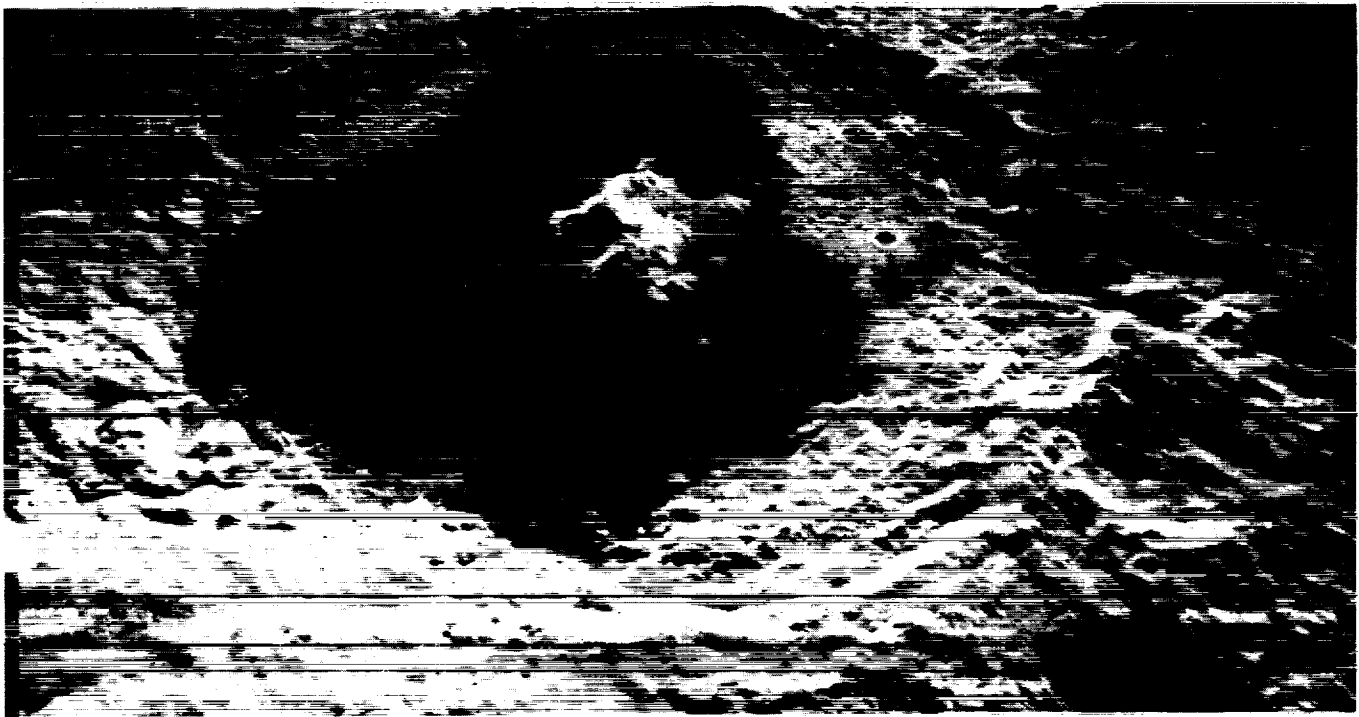


Fig. 1. The crater Tsiolkovsky, located at 20°S 130°E on the lunar farside, would be an excellent site for a very low frequency array. The crater is 180 km across and is floored by dark, smooth mare basalt flows.

anywhere on the floor; on a sphere with the Moon's radius, the horizon would be 102 km away when viewed from a mountain-top 3 km high.

Tsiolkovsky is also interesting geologically (Guest and Murry, 1969; Guest, 1971; Wilbur, 1978). It represents an opportunity to study a relatively well-preserved large crater. The central peak probably represents uplifted, deep-seated materials, an ideal place to study the field relations of highland crustal rocks. It also provides an opportunity to study eruption mechanisms and post-volcanic tectonic processes.

There are two drawbacks to Tsiolkovsky as the site for the VLF array, although neither is a fatal flaw. One is that the walls rise 4 km above the floor, thus limiting the view of the horizon to $>6^\circ$ above the horizontal (if the array is centered 40 km from the crater wall). The second problem is that the mare basalts that help make the floor smooth are of the high-Ti variety. This makes the regolith in the crater a potential source of ^3He , which is found in greater abundance in high-Ti materials. However, development of ^3He -based fusion reactors for commercial power production is far in the future and Tsiolkovsky represents only a few percent of the total amount of high-Ti basalt on the Moon, so it would not need to be exploited. Furthermore, although high-Ti basalts are the richest source of He, all lunar soils, mare and highland, contain He in extractable quantities. If Tsiolkovsky turns out to be the best site for the VLF array, it ought to be declared a scientific preserve, closed to resource exploitation.

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