# Reports

## Chondritic Meteorites and the Lunar Surface

Abstract. *The landing dynamics of and soil penetration by Surveyor I indicated that the lunar soil has a porosity in the range 0.35 to 0.45. Experiments with Surveyor III's surface sampler for soil mechanics show that the lunar soil is approximately incompressible (as the word is used in soil mechanics) and that it has an angle of internal friction of 35 to 37 degrees; these results likewise point to a porosity of 0.35 to 0.45 for the lunar soil. Combination of these porosity measurements with the already-determined radar reflectivity fixes limits to the dielectric constant of the grains of the lunar soil. The highest possible value is about 5.9, relative to vacuum; a more plausible value is near 4.3. Either figure is inconsistent with the idea that the lunar surface is covered by chondritic meteorites or other ultrabasic rocks. The data point to acid rocks, or possibly vesicular basalts; carbonaceous chondrites are not excluded.*

It has long been realized that available measurements of radar reflectivity of the lunar surface are sufficient to establish a functional relation between the chemical constitution of the surface and its porosity. Until recently this relation has been used for estimates of the porosity from assumptions about the chemical constitution. It is of even more interest to reverse the process, if possible, and to derive limits on the possible chemical properties of surface material from measurements of the porosity.

The landings of Surveyors I and III and operation of the surface sampler (*1*) have yielded information on the physical properties of the surface material. When a soil is sheared, it may exhibit volume changes ranging from compression to expansion, depending upon its initial state of packing; the manner in which this occurs can be recognized by visualization of the behavior of an idealized granular material consisting of equal-sized spheres (*2, 3*). If the spheres are arranged in their closest packing state, a face-centered cubic array, and then subjected to increasing shearing stresses, the mass will expand in total volume as the spheres ride up over each other; the volume of individual spheres does not alter, but the pore volume is enlarged. Alternatively, when the medium consists of spheres in the loosest packing state, the simple cubic arrangement, application of a shearing stress causes the total volume to decrease as the spheres slide over one another into a more stable arrangement; the pore volume diminishes.

Usually the packing arrangement is characterized by a parameter termed the "porosity" ($n$) of the medium, where

$$n = (\text{volume of voids})/(\text{total volume}) \quad (1)$$

In the present connection, the voids referred to are those between the individual grains; voids inside grains (vesicles), that do not crush during shear, play no part in the volume-change behavior.

In terms of the ideal medium composed of equal spheres the porosity at closest packing is 0.26, whereas the loosest-possible packing arrangement gives a porosity of 0.48. In real granular soil, composed of irregular fragments of rock, porosities as low as 0.26 are not obtained, and the lower limit to porosity is about 0.35 for a soil having a wide range of grain sizes in the closest-attainable packing state. For a soil having grains all smaller than a few tenths of a millimeter in diameter and essentially lacking cohesion, the porosity of the one material may range from about 0.50 in its loosest state to about 0.35 for the tightest packing achievable; at the higher initial porosity the soil will contract on shearing; at the lower initial porosity it will expand.

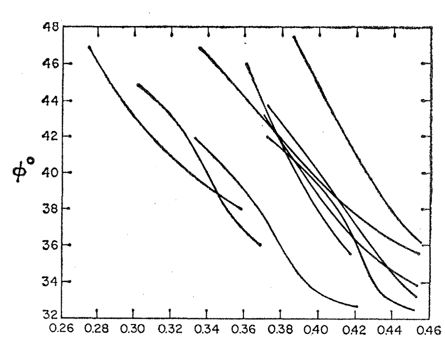


Fig. 1. Friction angles of various soils, versus porosity [redrawn from Spencer (*6*)]. Each curve represents behavior of one soil over a range of porosities; $n$, porosity.

When a particular soil is sheared, its volume changes (increases or decreases) until it reaches a condition, compatible with the applied stress system, at which no further change in volume occurs; the porosity at this constant-volume state is commonly about 0.45 for low values of stress.

After the landing of Surveyor I it was concluded by Scott (*4*) that the behavior of the soil in contact with the footpads was consistent with that of a material possessing a small amount of cohesion and an angle of friction between 30° and 40°. The resistance of the soil in contact with the footpads was most plausibly explained in that model by a material having a density comparable to ordinary terrestrial soils —about 1.5 g/cm$^3$.

On the other hand, by adopting a different model of soil behavior, Jaffe (*5*) concluded from an elementary analysis of the records of the shock-absorber strain gauge, without taking into account the dynamic behavior of the spacecraft's landing gear, that the density was lower than this figure—in the range 0.6 to 0.7 g/cm$^3$. In his analysis Jaffe also found that the mechanical behavior was best explained as that of a soil that compressed under the footpad during landing. To explain the resistance of the soil to penetration by the Surveyor I footpad, Jaffe (*5*) is compelled by his low value of density to assign a value of 55° to the angle of internal friction of the lunar soil; he points out that this value is much higher than is commonly observed on Earth (26° to 45°) even in soils composed of very angular fragments. It is questionable whether such a friction angle is possible in a compressible soil of the density obtained by Jaffe, since it is usually observed in terrestrial soils that the friction angle decreases as the porosity increases (Fig. 1) (*6*). In Fig. 1 each curve represents the behavior of one soil; soils having wide ranges of grain sizes form the curves on the left side of the diagram; more-uniform soils fall on the right.

Spencer (*7*) has made cross-sectional profiles through the rim of soil pushed up by footpad 2 of Surveyor I, and one may use these to compare the volume of soil displaced by the footpad with the volume of the depression in which the footpad is resting. If one assumes that no cavity exists below the footpad (a region that is, of course, invisible) one finds that the volume of soil ejected approximately equals the volume of the depression made by the footpad (about 2000 $cm^3$), within limits estimated to be $\pm 15$ percent. The material was, therefore, not totally compressible, but behaved in a manner similar to that of a fine-grained terrestrial soil on being sheared. This finding would indicate that the soil at the Surveyor I site possessed a porosity, in essentially a normal terrestrial range, of 0.35 to 0.45, excluding the volume of closed voids (vesicles) in individual grains.

In the test performed with the surface sampler for soil mechanics carried by Surveyor III, the lunar soil again appeared to be relatively incompressible. When the sampler was pushed into the surface in a static-bearing test, the adjacent surface rose, and cracked (because of the cohesion) out to a distance that is indicative of the angle of internal friction of the soil. If the material had been substantially compressible it would not have exhibited the observed effects upon being subjected to a bearing test. These conclusions therefore contradict Jaffe's (*5*) results indicating a compressible, low-density, granular material.

The reason for this finding appears to lie in the analysis of the Surveyor I landing. Jaffe calculated his value of soil density from the observation that no initial large forces, attributable to soil inertial resistance, appeared on the strain-gauge record. However, a more detailed computer analysis, involving the dynamics of Surveyor I's landing gear, indicates that such an initial spike would not be recorded even during a landing on soil of normal density (*8*). The velocity of landing is so low that the principal resistance to penetration by footpad arises from the strength of the soil; the initial effect of the soil's density is almost negligible. The soil's density cannot therefore be calculated from an elementary analysis of the history of the shock-absorber force.

To apply these results to the question of the chemical nature of the lunar surface, we make use of Fig. 2, giving the relation between grain dielectric constant and bulk dielectric constant in a granular material (*9*). The relation shown here is that of Böttcher (*10*) [misspelled as equivalent to "Betner" by Krotikov (*11*)]. This relation is found by Gault *et al.* (*9*) to provide a reasonable upper limit to the values of the grain dielectric constant as a function of porosity and bulk dielectric constant. The formula is

$$(\epsilon - 1)/3\epsilon = [(\epsilon_0 - 1)/(\epsilon_0 + 2\epsilon)] - (1 - n) \quad (2)$$

where $\epsilon$ is the dielectric constant of the material in bulk; $\epsilon_0$, that of the solid portion of the material; and $n$ is the porosity—the ratio of void space to total volume in a sample of the material.

For the bulk dielectric constant, the radar-reflectivity values, treated on the assumption that Moon is essentially a specularly reflecting dielectric sphere, yield values from 2.6 to 2.8 relative to vacuum, depending on the exact method of treatment of the small nonspecular component (*12, 13*). On the other hand, after a careful review of the problem, Hagfors (*14*) concludes that the radar reflections may not come from the surface but from a deeper layer. By this assumption one can explain the values as low as 1.6, or thereabouts, obtained from radiometric studies of Moon. We conclude that the limits 1.6 to 2.8 cover the range of the proposed values. (Brown *et al.* (*15*) consider that values as high as $3.5 \pm 0.7$ are possible; their *theory* is not yet available, and consideration of this point is now probably premature.)

The reflectivity *measurements* of Brown *et al.* (*15*) show that the landing sites of Surveyors I and III have about the same radar-reflection behavior as the lunar surface in general; general theories on the lunar dielectric constant are therefore applicable to the particular regions whose mechanical properties were measured by these probes.

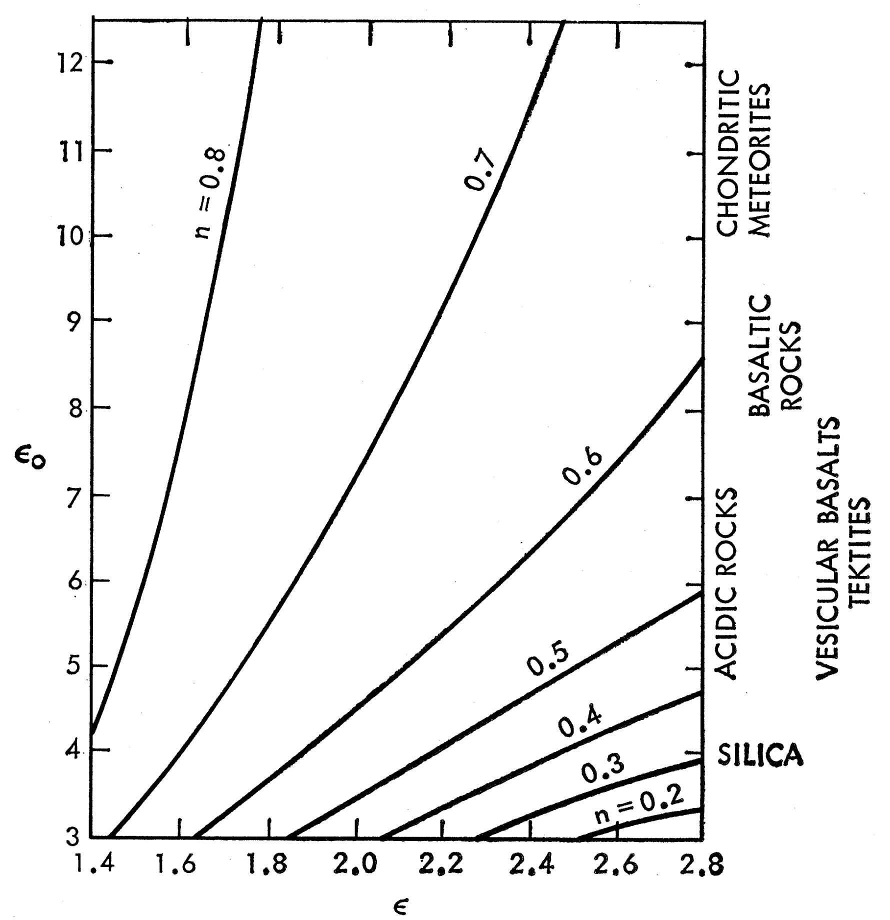


Fig. 2. Relation between the bulk dielectric constant ($\epsilon$) and the dielectric constant of the grain ($\epsilon_0$), according to the Böttcher formula (*10*); $n$, porosity.

Taking 50 percent as an upper limit to the possible values of the porosity, the highest value of the grain dielectric constant is 5.9, which is inconsistent with the values found for chondritic meteorites (*15*). Because of the difficulty of measuring the dielectric constant in conducting materials, Fensler *et al.* (*16*) give values for only two chondrites—Leedy and Plainview; they did, however, measure enough other ultrabasic rocks to give assurance that high values of the dielectric constant (7.2 or more) are associated with such rocks.

The value of 5.9 is reached by stretching the data in each respect (bulk dielectric constant, conversion formula, and porosity) in favor of the hypothesis of very basic material. Using the more-plausible values of 2.7 for the bulk dielectric constant (*12*) and 40 percent for the porosity, and the Krotikov formula (*11*),

$$(\sqrt{\epsilon}-1)/\rho=(\sqrt{\epsilon_0}-1)/\rho_0 \qquad (3)$$

where $\rho$ is the bulk specific gravity, and $\rho_0$ is that of the solid material, we find 4.3 plausible for the grain dielectric constant. This finding would indicate either an acid rock (granite, rhyolite, or tektite) or a vesicular basaltic rock.

The discrepancy between the maximum value of 5.9 for the grain dielectric constant, and the much higher values for chondrites, could be removed if we could assume that the chondritic material is highly vesicular, having 25 to 40 percent of the volume of the average grain occupied by voids (in addition, of course, to the intergranular voids amounting to 50 percent of the volume). Unfortunately it is well-established that chondritic meteorites are not vesicular in this way; some of them are porous, but the porosity is intergranular—not intragranular.

Shock might conceivably produce porosity in chondritic meteorites. If this were so, and if the lunar surface were the source of chondritic meteorites, then we would expect the porosity to be greatest in pieces that had been most strongly shocked. Pieces expelled from Moon would be more strongly shocked and therefore more porous than those that were simply knocked from one place to another on Moon. But in fact we find that chondritic meteorites reaching Earth are never porous; thus it follows that chondritic material on Moon should not be porous. Measurements now available of dielectric constant do not cover carbonaceous chondrites.

Although these results are based on soil experiments at only two lunar sites, the optical, radar, radiometric, and thermal data indicate that the lunar surface is much more homogeneous than Earth's; these experimental data are probably typical of the maria at least. We conclude that the surfaces of the lunar maria are probably not composed of material similar to ordinary chondritic meteorites.

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## Galaxies as Gravitational Lenses

Abstract. *The probability that a galaxy gathers light from another remote galaxy, and deflects and focuses it toward an observer on Earth, is calculated according to various cosmologic models. I pose the question of whether an object called a quasar is a single, intrinsically luminous entity or the result of accidental alignment, along the line of sight, of two normal galaxies, the more distant of which has its light amplified by the gravitational-lens effect of the nearer galaxy. If galaxies are distributed at random in the universe, the former alternative is true. But, if we assume that most galaxies exist in pairs, we can find about 30 galaxies occurring exactly one behind the other in such a way as to enable amplification of the order of 50. This model explains also the variations in intensity in quasars, but fails to explain others of their observed properties.*

When electromagnetic waves pass near a massive object, within distance $r$ of its center, they are deflected toward the mass by an angle ($\theta$) predicted by the general theory of relativity:

$$\theta=4\ GM/rc^2$$

where $G$ is the gravitational constant, $M$ is the mass of the object, and $c$ is the velocity of light in vacuum.

Einstein (*1*) pointed out that the mass can act as a lens, deflecting the light coming from a distant star $S$ and focusing it. This lens has peculiar focusing properties: light coming from infinity and grazing the limb of the mass is focused closer to the mass than is light passing at greater distance from the center of the mass (Fig. 1).

For certain values of $M$ and $d$, the light from star $S$ passes through an annulus of radius $r$ and is deflected and reaches the observer. The minimum distance $d_m$ at which this happens satisfies the equation

$$4\ GM/ac^2=\theta=a/d_m;\ \text{or}\ d_m=a^2c^2/4\ GM$$

where $a$ is the radius of the mass $D$. Thus the only objects in the sky that can act as gravitational lenses are those situated at distances greater than $a^2c^2/$-$4\ GM$. Using the known values for the radii and masses of stars and galaxies, one can predict which of them (Table 1) is a candidate for action as a gravitational lens.

One concludes from Table 1 that any object like Sun can demonstrate