Electrical Properties of Planetary Surfaces

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Electrical properties of planetary surfaces

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The electrical properties of the lunar surface are those of very good dielectric insulators. The results of the Apollo programme and laboratory studies on lunar samples have confirmed the predictions of Earth-based and spacecraft measurements of the dielectric properties of the lunar surface, and helped to increase the reliability of such studies of the surfaces of other planetary bodies. It appears that the electrical properties of the surfaces of Mercury, Venus and Mars are all very similar to those found for the Moon. Mercury has no atmosphere and in this sense is very similar to the Moon; Mars has a mean atmospheric pressure and temperature at the surface that is far below the triple point of water; while Venus has surface temperatures and pressures that are far above the critical point of water. This means that water is unlikely to contribute to the dielectric properties of either planet.

The dielectric constant of the surface of the Moon is determined largely by the bulk density and is related to the density by the formula $k = (1.93 \pm 0.17)^{\rho}$ for dielectric constant, k, at density ρ g/cm³. Thus, most soils have k about 3, while solid rocks have k about 7.5. Loss tangents appear to be dependent upon density, frequency, temperature, and possibly ilmenite content, and thus are more difficult to predict than the dielectric constant. Typical loss tangents are likely about 0.005 for the Moon, Mars and Mercury, and about 0.01 to 0.2 for Venus.

Introduction

Recent laboratory studies of the electrical properties of lunar samples (Olhoeft & Strangway 1975) and the analysis of Apollo lunar surface experiments (Keihm & Langseth 1975; Strangway *et al.* 1975) have shown the remarkable accuracy of remote Earth-based radar and radio astronomy techniques in predicting the surface properties that were found on the Moon. This adds a considerable degree of confidence to the interpretation of the results of these techniques when applied to other planetary objects. In terms of dielectric properties, as revealed by radar and radio astronomy techniques, the surfaces of Mars, Mercury, and Venus seem to be similar to the Moon (Evans 1969). The observed differences between these bodies can be explained by the nature and amount of scattering involved (in order of increasing apparent roughness: Mars, Venus, Mercury/Moon (Evans 1969). In this paper, we will present a review and comparison of the various measurements of dielectric properties of the surface of the Moon for radar studies, microwave emission, the Apollo 17 surface electrical properties (s.e.p.) experiment (Strangway *et al.* 1975), and predictions from Apollo soil mechanics findings and laboratory investigations.

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The Moon

Evans (1969), Hagfors (1970), and Muhleman (1972) have recently reviewed the results of radar and microwave emission studies of the Moon. Measurements have been performed from sub-millimetre to decametre wavelengths and show a fairly uniform dielectric constant of about 3. As illustrated in figure 1 (after Hagfors 1970). The values are around 2 at wavelengths of about 1 cm and are about 5 or 6 at wavelengths greater than 10 m. Figure 2 illustrates the increase in dielectric constant with density (after Olhoeft & Strangway 1975) as measured at a frequency of 10^6 Hz or higher in laboratory investigations of lunar samples. The data of figure 1 imply an increase in dielectric constant with wavelength, which implies a density increase with depth below the lunar surface. The uppermost surface has a dielectric constant of about 2, implying a surface density of about 1.1 g/cm³.

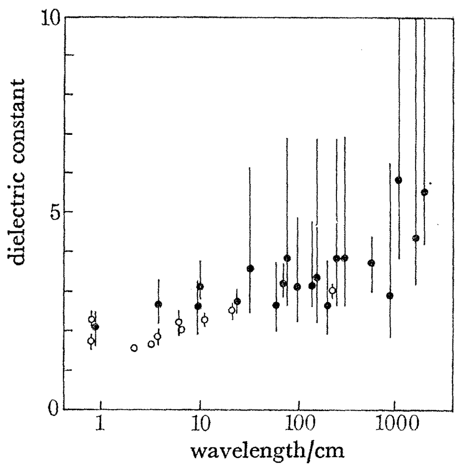

Figure 1

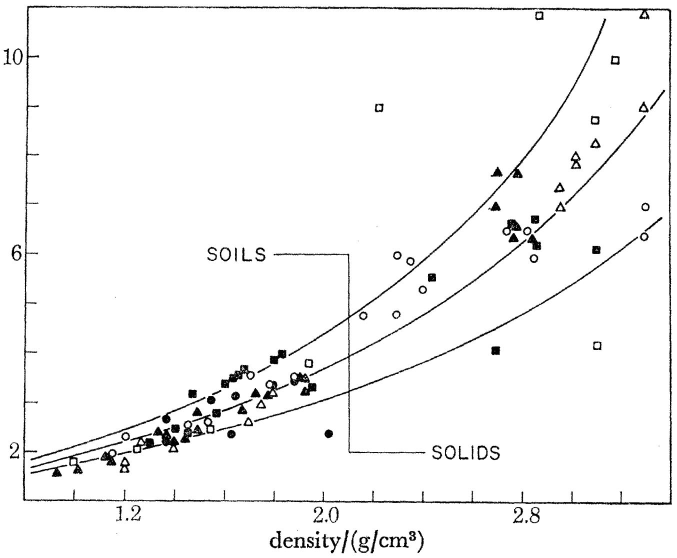

Figure 2

Figure 1. Dielectric constant of the Moon as a function of wavelength (after Hagfors 1970). (●, reflection coefficient; ○, Brewster angle, etc.)

Figure 2. Dielectric constant as a function density for returned lunar samples (data taken from Olhoeft & Strangway 1975). Centre line fits equation $K = 1.93^{\rho}$ where ρ is the density. Other lines represent the uncertainty in the least squares fit.

It has been difficult to convert the remote observations into a model of dielectric properties versus depth because the question of surface and/or volume scattering is important and scattering is in itself strongly frequency dependent. The surface electrical properties experiment conducted at the Apollo 17 landing site showed on a local basis that the lunar surface was fairly free of scatterers in a range of wavelengths from 300 to 10 m just at the wavelength limit of Earth-based experiments. It was therefore possible to derive a preliminary model of the dielectric properties versus depth at this landing site. This model is shown in figure 3 (Strangway *et al.* 1975) and implies that at a depth of about 7–10 m the dielectric constant is quite high, suggesting solid bedrock. The regolith at this site is thus about 7–10 m thick. Examining the dielectric constant against wavelength plot of figure 1 we see that only at the very longest wavelength is there a hint of a sharp increase in the dielectric constant. Since the soil layer thickness is likely to be highly variable over the front face of the Moon, we draw the inference that at wavelengths of about 10 m or longer, Earth-based radar observations penetrate to bedrock. Eventually it will be possible to convert this information to give an average value for the regolith thickness. If the Apollo 17 result is typical, this would be in the range of 7–10 m.

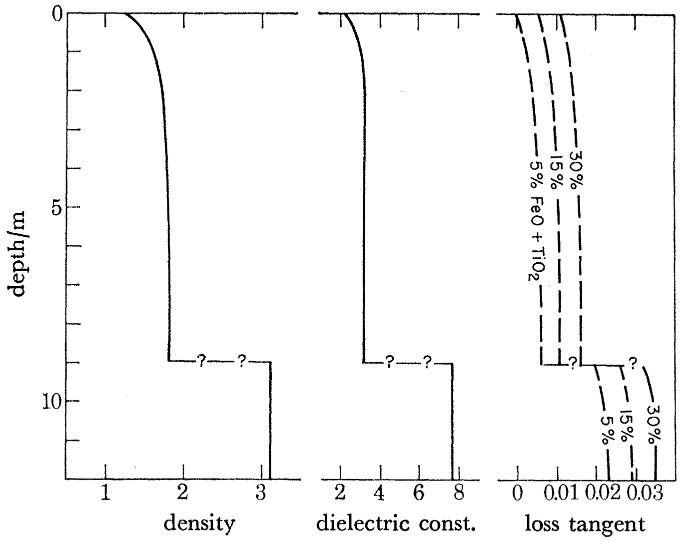

FIGURE 3. Model of dielectric constant, loss tangent and density inferred from the surface electrical properties experiment at the Apollo 17 landing site.

We notice that there is no hint of a surface layer with dielectric constant less than 3 in the s.e.p. data (figure 3). This means that there can only be a very thin surface layer of material with a low dielectric constant. This thickness is less than about 1 m at the Apollo 17 landing site. Again looking at the data of figure 1 we see that a low dielectric constant is indicated only at wavelengths less than a few centimetres.

This implies that the radar data together with the s.e.p. data can be used to infer the presence of a three-layer surface. One layer is less than 1 m thick and has a dielectric constant of about 2. The second layer is 7–10 m thick and has a dielectric constant of about 3, while the third layer has a dielectric constant of 6–7 or more. Of course the top two layers may in fact be associated with a continuous increase with depth.

It has not been possible to derive a simple 3-layer model to fit the implied slope in the dielectric constant curve at wavelengths between 3 cm and about 500 cm. We can only infer that this is due to one or more of the following:

(*a*) There is a uniform increase of density with depth. (This is contrary to the findings of the soil mechanics which infer a fairly high and uniform density.)

(*b*) There is a frequency-dependent loss tangent in which the losses increase with frequency.

(*c*) There is a frequency-dependent scattering cross-section so that there is in effect a frequency-dependent loss tangent.

Further models are needed to resolve this problem, but we note considerable progress in predicting this type of behaviour in recent papers by England (1975) and by Watts & England (1976).

Figure 4 shows dielectric property data for lunar solid sample 14310 and figure 5 shows the dielectric constant for lunar soil sample 14163. In figure 4, the circles are from Chung *et al.* (1972), the plus and cross labelled G are from Gold *et al.* (1972) (corrected loss tangent, pers. comm., Gold) and those labelled B are from Bassett & Shackelford (1972). In the region of interest to radar, the dielectric constant is frequency independent, and the loss tangent is close to 0.01. In figure 5, the fines exhibit a similar behaviour (data normalized to 1 g/cm^3 constant density). The circles are from Strangway *et al.* (1972), with G and B, as above. The triangle labelled M illustrates the mean 1 g/cm^3 dielectric constant of all lunar soils and solids from Olhoeft & Strangway (1975) (see figure 2 above), with the standard deviation indicated by the error bar. As in the case of rock 14310, the fines exhibit a dielectric constant that is roughly independent of frequency in the radar range, and with a loss tangent that is 0.01 or less in most of the frequency range. Thus, for the types of samples illustrated in figures 4 and 5, the radar assumptions of frequency independent dielectric constant and very low loss appear to be justified.

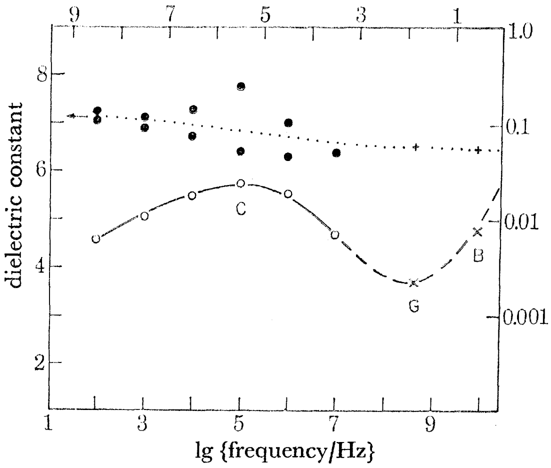

FIGURE 4

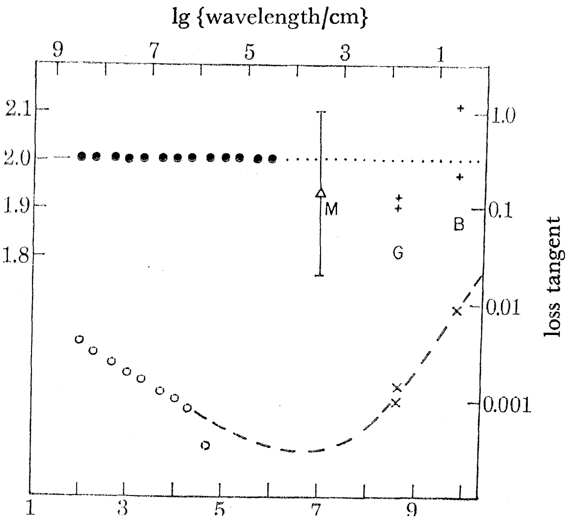

FIGURE 5

FIGURE 4. Dielectric constant (●, +) and loss tangent (○, ×) for rock sample 14310 as a function of frequency. (G, Gold *et al.* 1972; B, Bassett & Shackleford, 1972; rest of data, Chung *et al.* 1972).

FIGURE 5. Dielectric constant (●, +) and loss tangent (○, ×) for a typical lunar soil sample 14163 (data normalized to 1 g/cm^3). G, B, as figure 4; remaining data, Strangway *et al.* 1972). The value marked M is an overall mean value determined at 10^6 Hz for all measured lunar samples.

Another assumption in the derivation of dielectric constant from radar data is in the nature of scattering. Hagfors (1967), England (1975), and the above general references have treated this subject in detail. Figure 6 illustrates the wavelength dependence of lunar scattering in terms of radar limb darkening after Hagfors (1970). Zero delay represents the centre of the lunar disk, with increasing delay progressing towards the limb. The angle of incidence is given by $\phi = \arccos(1-ct/2r)$ where c is the speed of light, t is the time delay, and r is the radius of the Moon. Note that with increasing wavelength, the centre of the disk becomes brighter and the limbs darker, suggesting a decrease in lunar surface roughness with increasing wavelength and an approach to a perfect dielectric sphere. By using the scattering theory and model of Hagfors (1967, 1970), these data have been interpreted to give the r.m.s. slope against wavelength shown in figure 7. For the Moon, open triangles are from Kroupenio (1972), filled triangles from Evans (1969), the cross from Surveyor radar data (Muhleman 1968), and the plus from Davis & Rohlfs (1964). For comparison, data are also shown for Mercury (error bar, from Evans (1969)), Mars (square, from Evans (1969)), and Venus (open circles from Kroupenio (1972); filled circles from Evans (1969)).

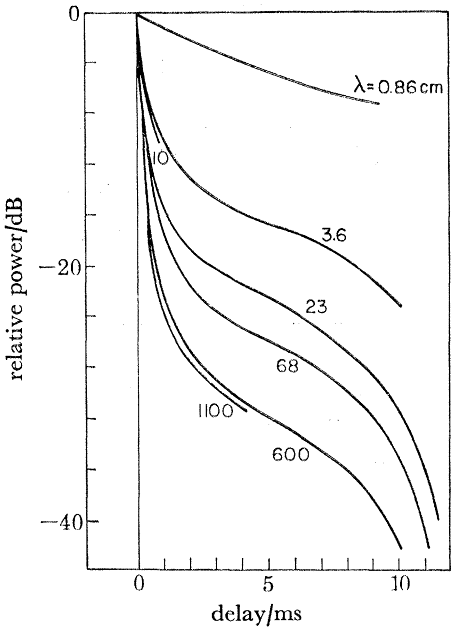

FIGURE 6

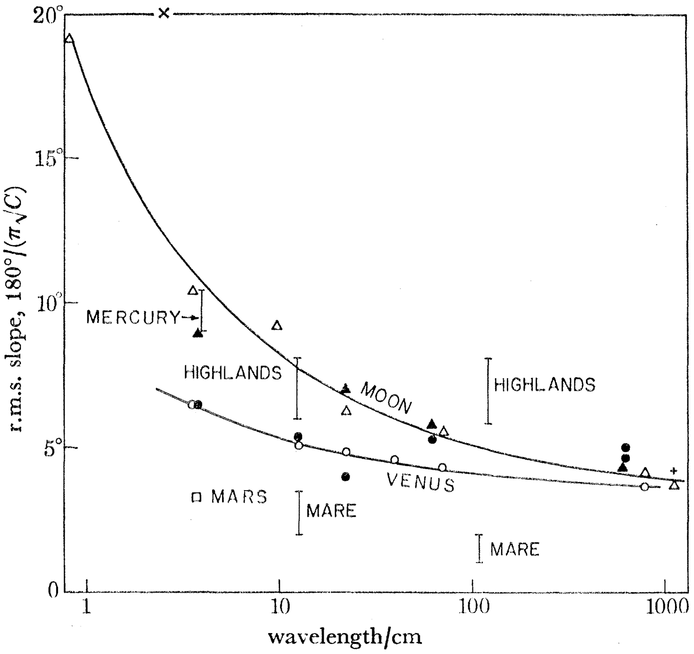

FIGURE 7

FIGURE 6. Scattering from the Moon as a function of delay time at various wavelengths (from Hagfors 1970).

FIGURE 7. Equivalent scattering in terms of r.m.s. slope for various wavelengths. △, Moon (Kroupenio 1972); ▲, Moon (Evans 1969); ×, Moon (Muhleman 1968, Surveyor data); +, Moon (Davis & Rohlfs 1964); I, Moon (Tyler & Howard 1973 – highlands and mare). I, Mercury (Evans, 1969); □, Mars (Evans 1969); ○, Venus (Kroupenio 1972); ●, Venus (Evans 1972).

In addition, Tyler & Howard (1973) had the opportunity to use Apollo communication signals backscattered from the Moon. They used spacecraft signals at 13 cm and at 116 cm and were able to derive mean slopes for mare and highland regions near the spacecraft track. For the Highlands they get r.m.s. slopes of 6–8° at both frequencies. Over mare regions the r.m.s. slope is 1–2° at 116 cm and 2–4° at 13 cm. These suggest that the mare region is considerably less scattering than the highland region and that overall Moon averages as determined in earlier studies represent a weighted average of these two major units of the front side of the Moon.

Figure 8 illustrates the microwave brightness temperature of the Moon versus wavelength (after Muhleman, 1972) with the arrow labelled A indicating the temperature measured at 1 metre depth *in situ* by the Apollo 15 heat flow experiment (Langseth *et al.* 1972). The increase in temperature with wavelength implies an increase in temperature with depth in the lunar surface. As this has been discussed in detail elsewhere, we will not elaborate here (see Muhleman, 1972; Keihm & Langseth, 1975).

MERCURY

Mercury appears to have electrical properties virtually identical with those for the lunar surface. Figure 7 illustrates the similarity in scattering at a wavelength of 3.8 cm. As discussed by Pettengill (1968) and by Evans (1969), Mercury has a mean dielectric constant of 2.4–2.8 at 3.8 and at 70 cm wavelength, with no clearly observable wavelength dependence. As Olhoeft *et al.* (1974) have shown dielectric constants for lunar soil to be roughly temperature independent to over 900 K above 10^6 Hz, it is not surprising that Mercury, even with higher temperatures, looks very similar to the Moon. There is essentially no atmosphere on either the Moon or Mercury so water will not contribute to the properties. The loss tangent may be higher due to the higher temperatures (see Olhoeft *et al.* 1974), but Chase *et al.* (1974) infer a mean loss tangent of about 0.005, again comparable to the Moon. (See Morrison 1970, for a discussion of microwave brightness temperatures.)

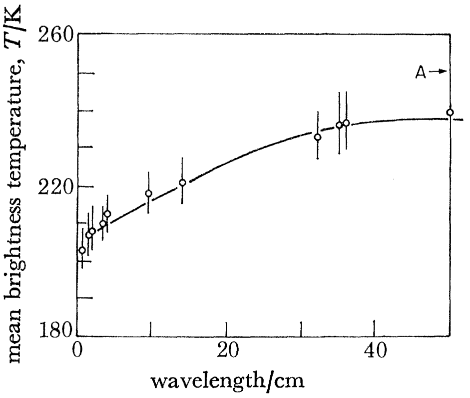

FIGURE 8

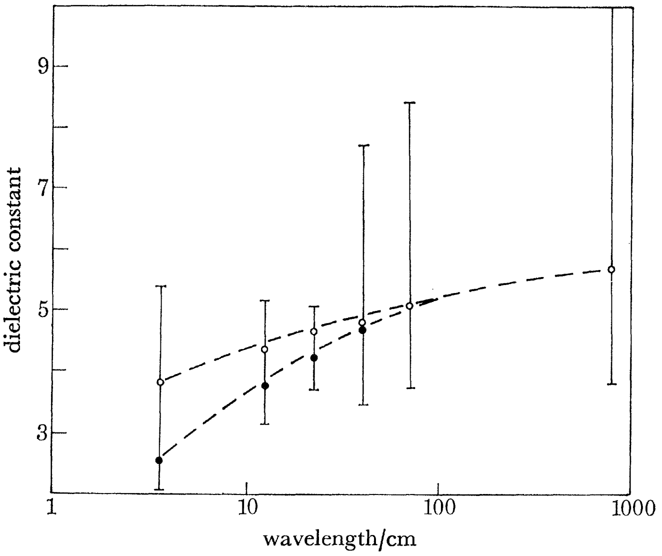

FIGURE 9

FIGURE 8. Mean brightness temperature against wavelength for the Moon (after Muhleman 1972). A, 1 m depth mean temperature at Apollo 15.

FIGURE 9. Dielectric constant against wavelength for Venus from Kroupenio (1972). The two dashed lines are models calculated from different atmospheric models.

VENUS

The electrical properties of Venus might be expected to be quite different from the Moon due to the presence of a considerable atmosphere, but as illustrated in figure 9, the dielectric constant was found to be comparable to that for the Moon (after Kroupenio 1972). At short wavelengths, the atmosphere seriously affects the radar spectra (the filled and open circles in figure 9 are interpreted from radar reflectivities assuming two different atmospheric compositions (see Kroupenio 1972)), but it is still clear that the dielectric constants are comparable to those for the lunar surface. Venera 8 has reported (Marov & Petrov 1973) temperatures and pressures for the surface of Venus as 741 ± 7 K and 9.3 ± 0.15 MPa (93 ± 1.5 bar). In such an environment, the dielectric constant of water is about 2 due to the dissociation of the water molecule. Thus, water will not play a significant role in the electrical properties of the planetary surface. Similarly, the high temperature will not significantly alter the dielectric constant as discussed above for Mercury, though the loss tangent may rise above 0.1 (Olhoeft *et al.* 1974) and thus the frequency dependence of the loss tangent may become significant (figures 5 and 6 above).

Warnock & Dickel (1972) have shown that a two-layer model of 1 m of dielectric constant 1.5 over a half-space of dielectric constant 8.3 gives a rough fit to the microwave emission spectra illustrated in figure 10 (after Warnock & Dickel 1972; dashed line is model). As they have discussed, this model has serious problems in fitting the radar reflectivity. They suggest a possible scattering mechanism as the cause of the discrepancy, but the scattering in figure 7 is not greatly different from the Moon. It is clear, however, that the surface of Venus is very similar in dielectric constant (and thus density) to the surface of the Moon. Further, the dielectric constant versus wavelength and the scattering behaviour versus wavelength are strongly suggestive of a regolith on the surface of Venus that is similar to that for the lunar surface, but somewhat smoother and/or lossier and perhaps thinner.

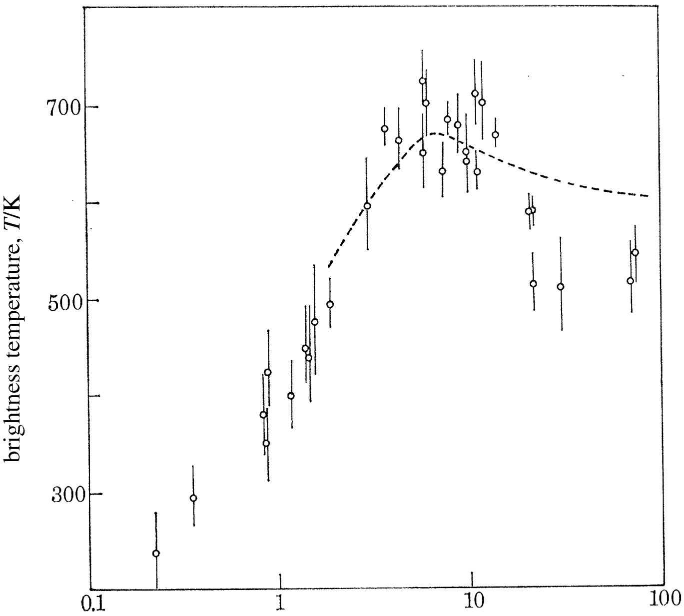

FIGURE 10

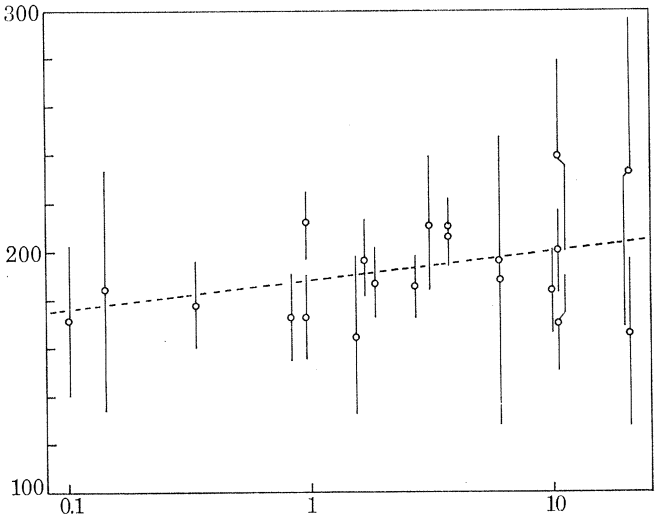

FIGURE 11

FIGURE 10. Brightness temperature against wavelength for Venus (Warnock & Dickel 1972). Dashed line is for a two-layer model (1 m, $K = 1.5$ overlying a half-space K–8.3).

FIGURE 11. Brightness temperature against wavelength for Mars (from Epstein 1971). Dashed line is the mode for a uniform dielectric sphere with $K = 2.5$.

MARS

The electrical properties of the surface of Mars appear to be somewhat more variable than for the Moon, with dielectric constants ranging from 1.5 to 5 (Pettengill *et al.* 1969; Rogers *et al.* 1970; Pettengill *et al.* 1973). Olhoeft & Strangway (1974) have discussed the electrical properties of the surface of Mars in terms of water and show that the mean Martian surface

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temperature of 213 K is low enough to completely deactivate any amount of water (including adsorbed water) as far as electrical properties are concerned. They did note, however, that the range of Martian surface pressures and temperatures found by Mariner 9 occasionally became high enough to allow liquid water, in which case the electrical properties of the surface of Mars could be drastically altered. This would tend to be a highly local phenomenon though. The presence of exposed solid rock is however a more likely cause for the high dielectric constants reported, since they seem to occur at the highest elevations. In general, the dielectric constant seems to be very similar to those for the surface of the Moon as discussed above.

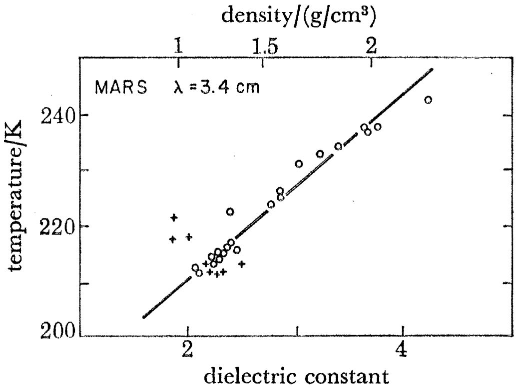

FIGURE 12. Observed correlation between the apparent temperature and the dielectric constant of Mars (from Basharinov *et al.* 1972). ○, from Promethei Sinus, Ausonia and Aeolis; +, from Cerberus. Density scale based on equation shown in figure 2.

Sagan & Veverka (1971) and Cuzzi & Muhleman (1972) have discussed the microwave temperature spectrum (illustrated in figure 11 after Epstein (1971)), showing a reasonably good fit to the data by a dielectric sphere of dielectric constant of 2.5 and very low loss. Sagan & Veverka (1971) note, however, that within the data set, a model could also be fitted (and possibly required to fit the data) which has a layer of 30 μm of precipitated water on the surface of Mars. The data to date are too inconclusive to rule out such a model, or to support it.

The Soviet Mars 2 and 3 orbiters found a very intriguing correlation which may limit models of the surface of Mars as discussed above. Figure 12 illustrates a plot of derived surface temperature versus dielectric constant from 3.4 cm wavelength radiometry after Basharinov *et al.* (1972) (see also Marov & Petrov 1973). The circles are measurements of dielectric constant (from emission polarization) and derived subsurface temperature for regions of Promethei Sinus, Ausonia, and Aeolis; pluses are from Cerberus (density across the top scale is derived from dielectric constant via figure 2). With the exception of the Cerberus region, the increase in dielectric constant directly correlates with increase in subsurface temperature. The simplest explanation of this result is that there are considerable regions of bare or nearly bare rock exposed on the surface of Mars by constant wind action. Places on the planet which are both warm and have high dielectric constant agree in principle with the properties of solid rock. We therefore can conclude with the Russian authors that parts of the Martian surface have an apparently dry soil regolith of very low density (perhaps less than 1 g/cm³) while other areas are bare or nearly bare solid rock surfaces.

CONCLUSION

Remote observations of planctary surfaces have proven to be important planetary probes. By studying the properties of returned lunar samples and examining the results of surface and orbital sounding experiments we can gain new insights into the nature of the lunar surface. A simple three-layer model accounts quite well for the lunar radar observations. This model infers a soil layer only a few metres thick, which is penetrated only at wavelengths of 10 m or more. The material seems to be quite transparent, but to account for the details of the radar curve it will be necessary eventually to include either or both a graded surface layer and a frequency dependent loss property which might be due to the effect of scattering. In any case, it is now evident that Earth-based studies only contribute to our knowledge of the outer few metres.

We review the observations made on the other planets which have shown that Mercury and the Moon have remarkably similar electrical properties. The planet Mars has moisture present and possibly even large amounts of permafrost. Nevertheless it has an appearance much like that of the Moon, since it is cold enough to deactivate all water electrically and/or any free water is minute enough in quantity to act as a monolayer. Significant variations in dielectric constant from place to place infer a range from very loose surface material to solid rock. Radar results on Venus are sketchy but they seem to infer a dielectric constant at or slightly greater than that of the Moon. Any water present is dissociated so these results can be interpreted as a function of temperature and density. There may be a somewhat higher density on the Venus surface due either to greater compaction or due to the presence of more solid rock near the surface.

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