ELECTRICAL CONDUCTIVITY OF
LUNAR SURFACE ROCKS AND CHONDRITIC METEORITES

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Abstract. The electrical conductivities of several samples from returned Apollo 11 and 12 lunar rocks and from chondritic meteorites were measured from 300 to 1100K. Collectively the lunar samples represent all three of the major NASA classifications of lunar surface rocks. Of general interest is the observation that the conductivities of the lunar samples are much larger than the values which have previously been used in theoretical discussions of lunar phenomena. It is also found that the conductivity at 300K, $\sigma(300)$, is extremely sensitive to the thermal history of the sample for both lunar and meteoritic material. Magnetic measurements are presented to help characterize the changes which occur upon heating.

1. Introduction

Solution of some of the most interesting and significant problems in lunar physics require direct knowledge of the electrical conductivity of the Moon's interior. For example, the effects of lunar conductivity on the magnetic field of the solar wind have been studied theoretically by several investigators (Gold, 1966; Sonett and Colburn, 1967; Hollweg, 1968; Blank and Sill, 1969, 1970; Schwartz and Schubert, 1969) with the general conclusion that if the lunar conductivity is sufficiently large, strong disturbances in the form of shock waves in the solar wind will be produced on the sunlit side of the Moon. Since no such shock waves were observed in the neighborhood of the Moon by a series of Lunar Explorer-35 experiments (Ness *et al.*, 1967), it was concluded that the bulk lunar conductivity is less than 10^{-7} $(\Omega\ \text{cm})^{-1}$. Similarly, Ness (1969) is currently observing fluctuations in magnetic fields in the vicinity of the Moon with the Explorer-35 magnetometer, and Dyal *et al.* (1970) have recently initiated magnetic measurements with a three-component magnetograph on the lunar surface. These studies are directed towards detailed examinations of the electromagnetic interaction of the solar wind and the Moon, and again analysis of the data will require a detailed knowledge of the electrical conductivity of the Moon. Finally, Tozer and Wilson (1967) and England *et al.* (1968) have previously used the conductivity of materials from the Earth's mantle, in particular terrestrial olivines, to estimate the variation of the lunar conductivity based on several models of the Moon's thermal history. However, studies of petrographical, mineralogical, chemical and physical properties of Apollo 11 and 12 lunar samples (which can be found at Levinson, 1970) indicate that their composition and general physical properties are

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significantly different from those of terrestrial olivines and emphasize the need for direct determinations of the electrical conductivity of lunar samples.

Nagata *et al.* (1970a) have recently reported preliminary conductivity measurements of a sample of Apollo 11 crystalline igneous rock (10024.22). In this paper we report more detailed studies of several lunar rock samples from an Apollo 12 ingeous rock (12053.47) and a sample from an Apollo 11 microbreccia (10048.55). Collectively, these samples represent all three of the principal NASA classifications of lunar surface rocks. These studies show that the observed lunar conductivities are larger by several orders of magnitude than previously assumed model values. In addition, we find large increases in the conductivity measured at 300 K, $\sigma(300)$, after heating samples to temperatures above approximately 500 °C. Supplementary magnetization measurements indicate that these increases in $\sigma(300)$ are accompanied by decreases in the amount of iron in fine-particle, superparamagnetic phases and increases in the amount of iron present in paramagnetic pyroxene phases. The electrical conductivities of several samples of a chondritic meteorite were found to exhibit similar behavior. Of the several explanations for this behavior discussed below, we believe it most likely that the conductivity of these samples is dominated by the pyroxene phases and that the large changes in $\sigma(300)$ reflect a redistribution of iron within the pyroxene.

2. Sample Description

The lunar conductivity sample originally studied by Nagata *et al.* (1970a) was a slab $4.7 \times 5.7 \times 1.1$ mm cut from a coarse-grained (NASA type B, 0.2 to 3.0 mm grain size), crystalline gabbro (10024.22). The principal minerals were plagioclase 13%, clinopyroxenes 46%, and ilmenite 11%.

The Apollo 12 conductivity samples (approximately $6 \times 6 \times 2$ mm) were cut from a fine-grained (NASA type A, 0.2 to 0.3 mm grain size), igneous basalt. The principal minerals were plagioclase 60%, clinopyroxenes 20%, ilmenite 15%, and olivine 5%.

A lunar conductivity sample (approximately $6 \times 6 \times 1$ mm) was cut from a fine-grained microbreccia (10048.55). The dominant mineralogy of the lunar breccias is mainly pyroxene and plagioclase.

In addition, Apollo lunar samples are generally found to contain small amounts of native iron in fine-particle form which makes a significant contribution to the magnetic properties of these samples. The plagioclases are generally calcic while the pyroxenes tend to be subcalcic, often with rather large $(Fe^{2+}/Fe^{2+}+Mg)$ ratios. More detailed descriptions of these lunar rocks can be found in *Lunar Sample Information Catalog, Apollo 11* and in Levinson (1970), particularly pp. 1–54.

Two meteoritic samples (approximately $6 \times 6 \times 2$ mm) were cut from an olivine hypersthene chondrite (L6) from the New Concord (Ohio) fall. These samples are predominantly olivine and orthopyroxenes with about one-third of the iron in metallic phases. The pyroxenes have Fe/Fe + Mg ratios near 0.2 and low-calcium contents. A third meteoritic sample was cut from a carbonaceous (type III) chondritic meteorite (Allende). For this meteorite the matrix is composed of iron-rich olivines

and various metallic Fe, Ni phases whereas the chondrules are Mg-rich pyroxenes with iron principally near the chondrule surfaces.

3. Experimental Procedure

Conductivity samples were placed between two nickel electrodes encased in a boron nitride holder. In some cases silver paste was used to improve electrical contact between electrodes and sample. Samples were heated in a vacuum furnace through which high-purity He or He-2% H_2 gas flowed at a pressure of one atmosphere. No effects were observed which could be ascribed to either the choice of atmosphere or the presence of silver paste. Temperature was monitored with a Pt versus Pt-10% Rh thermocouple anchored to the boron nitride holder. The resistivity parallel to the short sample dimension was measured quasi-statically at 5°C intervals with the temperature increasing at an approximate rate of 100°C/h by two-probe techniques. For resistivities greater than 5×10^5 Ω, the current flowing through the sample as a result of a constant applied voltage was measured. Resistances less than 10^7 Ω were measured with a wheatstone bridge. The two methods gave identical results for inter-mediate resistances. Considering sample geometries, conductivities could be deter-mined with uncertainties of order 2% from approximately 10^{-10} to 10^{-1} $(\Omega \text{ cm})^{-1}$. The lower limit results from leakage currents and instrumental noise, and the upper limit is due to contact and lead resistances.

During the conductivity studies, it became apparent that the conductivity depended on the thermal history of the sample. To affect a more complete description of the conductivity, the magnetization of samples both in the as-received condition and after heating to 810°C was measured as a function of magnetic field (0 to 16 kOe) at 5 and 300 K and as a function of temperature (5 to 100 K) at 3 and 10 kOe. A modified commercial vibrating sample magnetometer and throttling dewar were used for the magnetic measurements. The magnetic samples ($\sim$ 50 mg) were about one-fourth the size of the conductivity samples, however, several different magnetic samples from each category were measured with identical results indicating that the changes in magnetic properties reported below are significant.

4. Experimental Results

A. CONDUCTIVITY MEASUREMENTS

The variation of electrical conductivity with temperature $\sigma(T)$ during heating is shown for a sample from 12053.47 in Figure 1 by the curve labelled (1). This behavior is typical of all samples of lunar surface rocks studied. Initially, the conductivity increases relatively slowly with increasing temperature to about 450 to 500°C. Above these temperatures the increase in conductivity is much more rapid. Above 800°C the conductivity appears to be leveling off, however, this possibly is an adventitious effect due to contact resistance. After the sample was cooled to 300 K (cooling time approximately 12 h), the conductivity is approximately six orders of magnitude larger

than the original value. The result of a second measurement of $\sigma(T)$ for this same sample is shown in Figure 1. During these measurements silver paste was used to improve electrical contact and the furnace atmosphere was flowing He gas. The conductivity of a second sample from 12053.47 was measured without silver paste and in a slightly reducing atmosphere of flowing He-2% H_2 gas, Figure 1, curve (2).
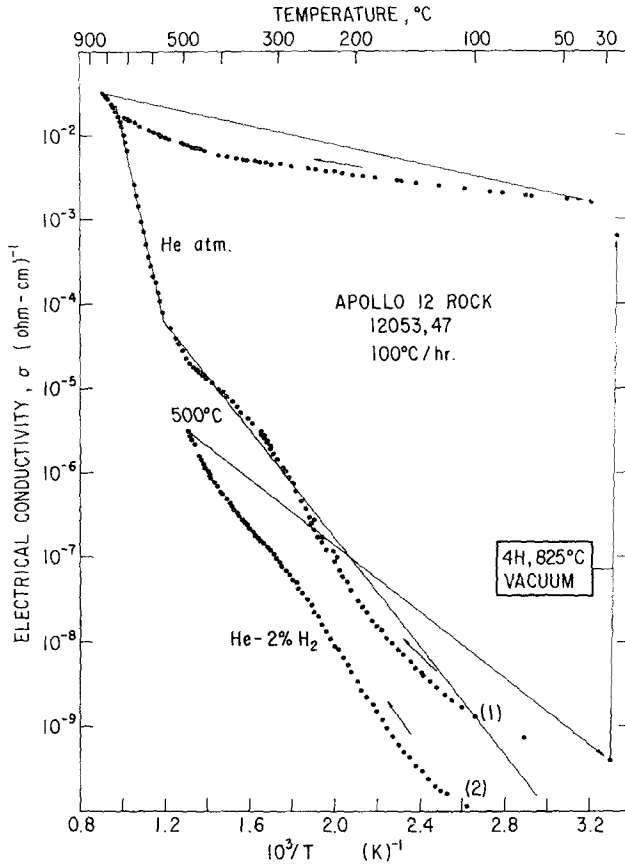

Fig. 1.   Electrical conductivity of two samples from Apollo 12 basaltic rock (12053.47) measured with increasing temperatures.

The conductivity increased with temperature in a manner similar to that of the first sample and at 500°C had just shown the start of the region of rapid increase in conductivity. This sample was cooled to 300 K and the conductivity was observed to have increased slightly. This sample was then sealed in a quartz tube in He atmosphere at a pressure of 2×10^{-6} torr and heated to 800°C for 4.5 h and quenched into a brine bath. The conductivity at 300 K was measured to be much larger than the original value and essentially identical to that of the first sample. (These features are

illustrated in Figure 1.) There was no change in sample weight during this last heat treatment to within one part in 2200. It was tentatively concluded, therefore, that the large increases in $\sigma(300)$ reflect marked changes within the lunar material and are not due to extraneous effects arising from the experimental techniques. This second sample from 12053.47 was given successive one-week anneals at the following temperatures: 450, 525 and 600 °C. During these heat treatments the sample was sealed in a quartz tube in an He atmosphere at a pressure of 10^{-6} torr. The conductivity decreased slightly after heating at 525 °C and at 600 °C, however, the value of $\sigma(300)$ was still highly inflated relative to its original value.
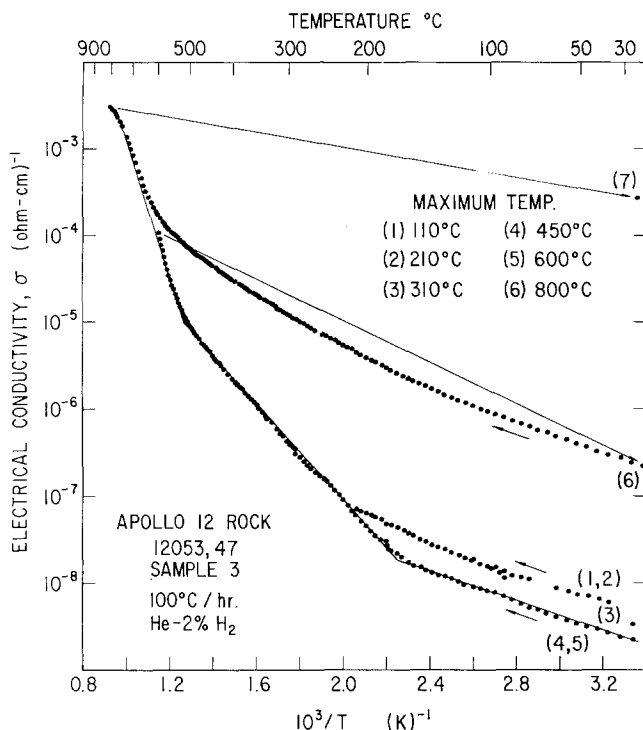

Fig. 2.   Electrical conductivity of sample 3 from Apollo 12 basaltic rock (12053.47) during successive heating runs (1 through 6) to progressively higher maximum temperatures. Only the initial value is shown for run 3.

To study in somewhat more detail the changes in $\sigma(300)$, a third sample from 12053.47 was heated in several stages to successively higher temperatures. The results of these measurements are illustrated in Figure 2 and indicate two temperature regions in which changes in $\sigma(300)$ occur. For maximum heating temperatures, T_m, from about 100 to 350 °C, $\sigma(300)$ decreases slightly – perhaps by an order of magnitude. For temperatures, T_m, above 450 °C, $\sigma(300)$ increases dramatically with in-

creasing T_m. In Figure 3, the conductivity of a sample from 10048.55 is shown which exhibits the same features. In this case the low-temperature recovery is particularly evident in the initial heating curve labelled (1) as a time dependence for $\sigma(T)$. In Figure 4 the original data of Nagata *et al.* (1970a) for a sample from 10024.22 is shown. The manner in which this data was taken was such that it is impossible to
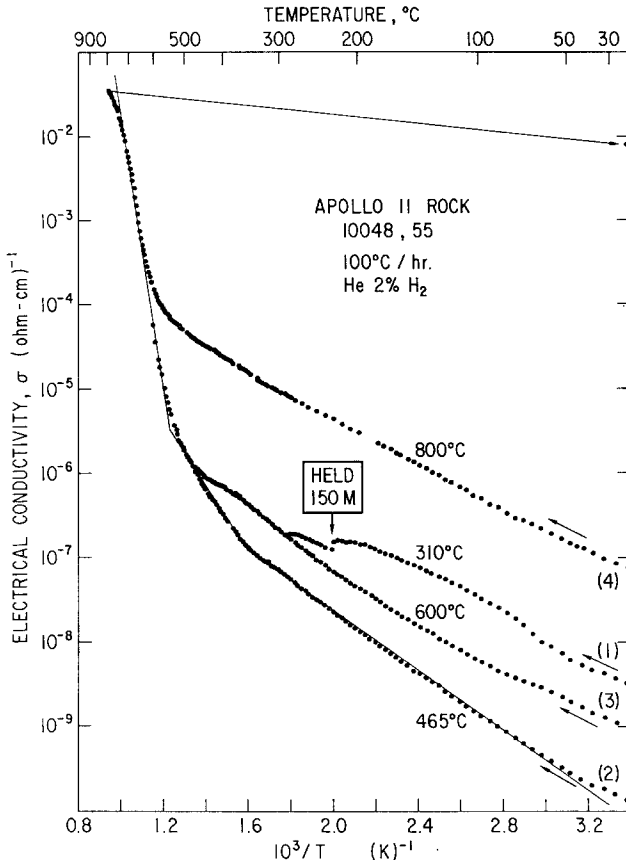

Fig. 3.   Electrical conductivity of sample from Apollo 11 microbreccia (10048.55) during successive heating runs (1 through 4) to progressively higher temperatures (labels on each curve indicate maximum temperature for that run).

determine whether irreversible changes occurred in $\sigma(T)$ upon heating, however, the general form of the data is entirely compatible with the other data reported here.

In Figure 5, curves of $\sigma(T)$ are shown for two samples from the hypersthene meteorite (New Concord). These samples show very unusual variations of σ during initial heating, i.e. sudden drops in $\sigma(T)$ in sample B and rapid increase in $\sigma(T)$ at low temperatures for sample A. This behavior possibly is due to changes in the bulk H_2O content. On subsequent temperature cycles the changes in $\sigma(T)$ are similar

to those in the lunar samples. In Figure 6, the electrical conductivity for the carbonaceous meteorite (Allende) is shown for several heating cycles. All meteoritic samples show increases in $\sigma(300)$ after heating to temperatures above $\sim 550°C$, however, the value of $\sigma(300)$ after heating to $\sim 810°C$ is not as large as for lunar samples. More-
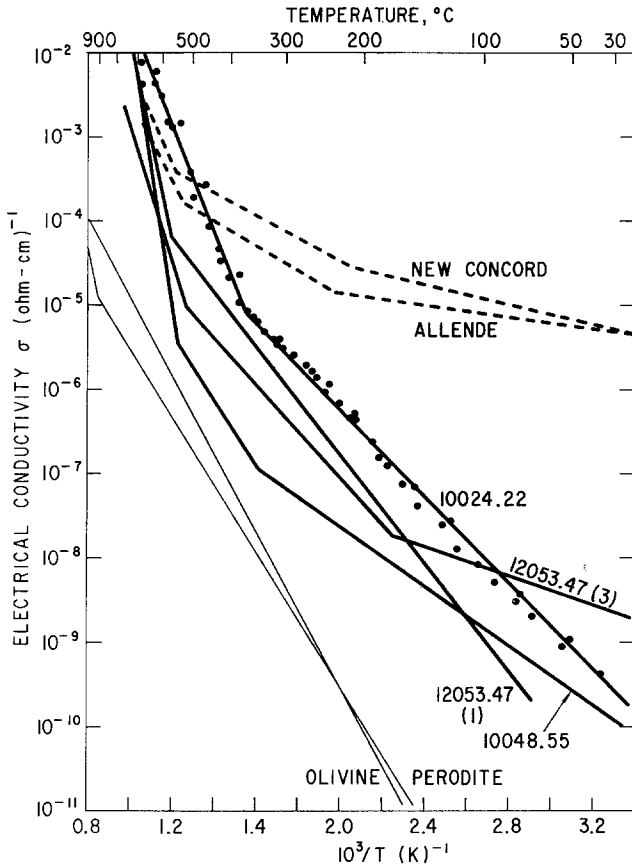

Fig. 4. Electrical conductivity of lunar crystalline rock 10024.22, data (see Nagata *et al.*, 1970a). The lines represent mathematical descriptions of initial heating curves of lunar (solid lines), meteoritic (dashed lines) and terrestrial (light solid lines) samples. The relevant parameters are listed in Table I.

over, meteoritic conductivities exhibit relative maxima near 700°C. Heating in the range 700 to 800°C has little effect on $\sigma(300)$; however, heating above 800°C results in continued increases in $\sigma(300)$.

B. MAGNETIC MEASUREMENTS

In Figure 7 magnetization curves are shown for samples from 10048.55 in both the 'as-received' condition and after heating to 800°C. The outstanding feature is a

decrease in the constriction of the low field portion of the loops after heating the sample to 800°C. This constriction is best described by the ratio of the remnant coercive field H_c^{rem} and the coercive field H_c. For single phase material (H_c^{rem}/H_c) is of order one or two; however, the presence of a strong paramagnetic phase can cause
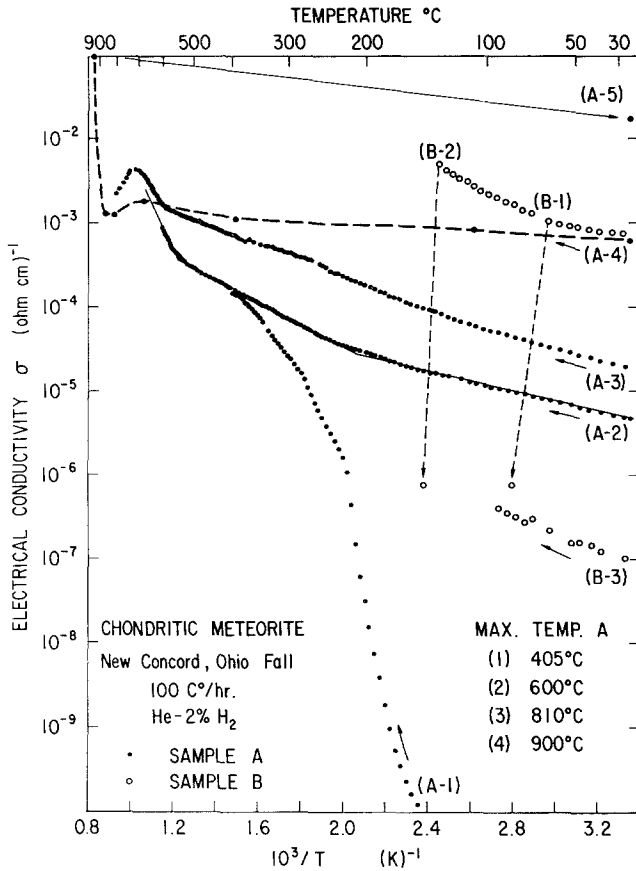

Fig. 5.   Electrical conductivity of two samples from New Concord, Ohio, meteorites. The conductivity of sample B showed large sudden decreases represented by the dashed arrows. Sample A was heated to successively higher maximum temperatures in runs A-1 through A-5.

substantial decreases in H_c and consequently larger values for (H_c^{rem}/H_c). Nagata *et al.* (1970) have discussed these features in connection with other lunar samples, and they have identified the source of contrictions as fine (~ 100 Å), superparamagnetic iron particles. The magnetization curves shown in Figure 7 indicate that one effect of heating the samples to 800°C is to reduce the amount of superparamagnetic iron. The high field portions of the magnetization curves support this interpretation.

    Nagata *et al.* (1970b) have described the manner in which magnetization versus
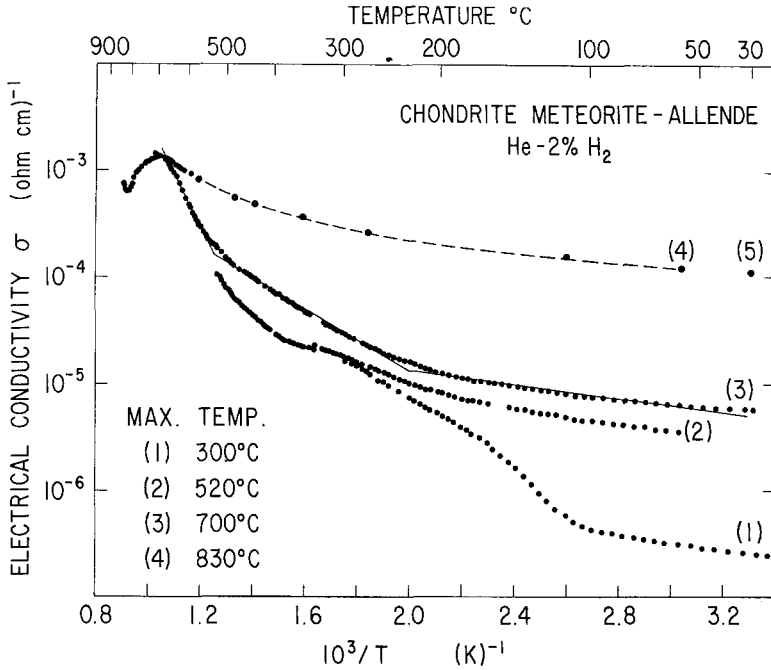
Fig. 6. Electrical conductivity of sample from Allende meteorite for several heating runs to successively higher maximum temperatures.
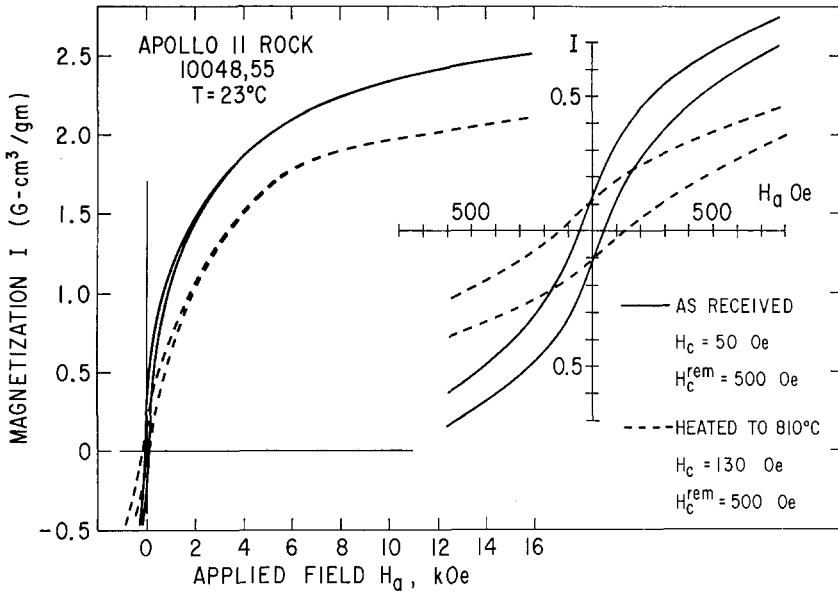

Fig. 7. Hysteresis curves for samples from Apollo 11 microbreccia (10048.55) in the 'as-received' condition (solid lines) and after heating to 800°C (dashed lines).

temperature curves at low temperatures reflect the presence of various magnetic phases in the lunar material. In Figure 8, the dots represent the magnetization at an applied field of 12 kOe for a sample in the 'as-received' condition. The large increase at low temperatures is associated with a paramagnetic pyroxene phase, whereas the shoulder near 56 K indicates the presence of antiferromagnetic ilmenite. The long
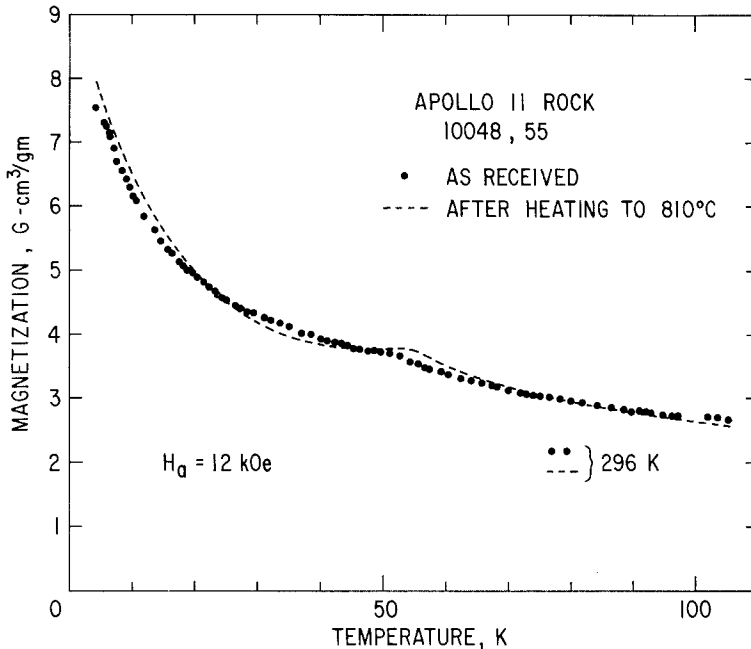

Fig. 8.   Magnetization versus temperature traces in an applied field of 12 kOe for samples from Apollo 11 microbreccia in the 'as-received' condition and after heating to 800°C (dashed lines).

gradual slope from 20 to 40 K indicates the presence of iron-rich pyroxenes including antiferromagnetic ferrosilite.* The dashed line represents the magnetization of a sample after heating to 800°C. The principal change is an increase in the paramagnetic pyroxene phase relative to the iron-rich pyroxenes. Magnetization versus field curves at 5 K also indicate substantial increases in the paramagnetic phase and decreases in the ferromagnetic component of samples which have been heated to 800°C.

* Shenoy *et al.* (1969) have presented evidence of magnetic ordering at temperatures ranging between 10 and 40 K for iron-rich orthopyroxenes. Complimentary to this are recent electron probe investigations of lunar samples which find definite variations in Fe, Mg, and Ca concentrations within single pyroxene grains. In particular, the grain rims tend to be deficient in Fe and Mg and rich in Ca.
    Electron probe analysis (see Bomback) of lunar pyroxenes which exhibit extensive zoning demonstrate that this effect is associated with changes in cation concentration as high as 100% over distances of several hundred microns.

5. Discussion

The interpretation of the conductivity measurements is complicated by several factors particularly the absence of comparative data as even for terrestrial rocks, investigations of electrical conductivity are not extensive and only a few minerals have been studied in well-characterized conditions (Parkhomenko, 1967). Furthermore, rock samples are inherently heterogeneous. For the crystalline lunar samples, phase sizes ($\sim$0.3 mm) are of the order of the sample dimension ($\sim$2 mm along the current direction) and sampling errors can produce large variations in the bulk conductance. (In fact, the largest difference in the conductivities of lunar samples reported here are between two samples from the same rock 12053.47.) Thus, it is easy to imagine that paths exist, such that conduction occurs entirely within one of the major phases (i.e. plagioclase or pyroxene for the lunar samples) so that the bulk conductance is determined by the most highly conductive phase. On the other hand, the existence of small regions of highly conducting material, such as metallic phases, will short-circuit the less conductive portions of the sample and will in effect reduce the length of the conduction path through the major phases. However, empirical evidence (Noritomi and Asada, 1955) indicates that plagioclases are relatively poor conductors compared to the samples studied here. Consequently, the electrical conductivities of both the lunar and meteoritic samples are expected to be dominated by the pyroxene phases, however, in the latter samples the conductivity will be larger due to the relatively large volume of metallic material. There appears to be no empirical information on the conductivity of pyroxenes, however, from an extremely general point of view, (Adler, 1970), the 3-d holes associated with the transition element iron could produce large conductivities. If this is the case then the conductivity will be extremely sensitive to the concentration, distribution and valency of the iron atoms and hence to the thermal history of the specimen accounting for the large changes observed on heating and cooling.

Our magnetic studies have confirmed that there is a redistribution of Fe within the pyroxene during heating of the conductivity samples into the temperature range in which large changes occur in σ(300). Hafner and Virgo (1969, 1970) have presented evidence for an order-disorder transformation in orthopyroxenes which occurs at temperatures from about 480°C to well above 800°C. This transformation primarily involves an intracrystalline redistribution of Fe and Mg among cation sites. It is known that this transformation does not alter the exsolution lamellae,* and it is difficult to believe that diffusion is such as to remove the variations in concentration on the scale observed by Bomback.

Magnetic measurements also showed that the amount of iron in fine superparamagnetic clusters decreased after heating to 800°C. Previous magnetic studies (Nagata et al., 1970) have shown similar effects after heating even in quite hard vacua. These effects were attributed to the formation of iron oxides, probably FeO. Several iron

* J. S. Lally, U.S. Steel Research Center, has informed us that heating to above 600°C does not affect the exsolution structure in lunar pyroxenes.

oxides, including FeO, are highly conductive (Adler, 1970). The small amount of FeO which could be present would not be detectable by either our magnetic measurements or our weight-gain determinations and would lead to the highly conductive condition observed here only if it were distributed as filaments spanning the sample. This seems rather improbable.

Ishikawa and Sawada (1956) have observed large increases in the electrical conductivity of ilmenite after heating in vacuum (10^{-5} torr) due to oxidation. However, the changes in $\sigma(300)$ for fully oxidized ilmenite are considerably smaller than the changes observed here. In addition, oxidation of ilmenite to this extent would have been detected in our weight-gain measurements.

After an initial heating to relatively low temperatures, $\lesssim 400\,°C$, lunar and meteoritic samples exhibited definite changes in $\sigma(300)$. For lunar samples these changes were small decreases in $\sigma(300)$; whereas, for the meteoritic samples the changes were large and both increases and decreases were observed. Since this is the temperature range in which defect recovery may be expected, it is tempting to suggest an interpretation along these lines. Although electrical conductivity is expected to be quite sensitive to defect concentration, lunar samples show extremely little radiation damage, especially in bulk samples of this sort, and structure indicative of relatively well-recovered impact damage. After examining several experimental variables, such as pre-heat treatments and electrode contacts, it is equally difficult to find a suitable explanation for the low-temperature behavior in the experimental techniques. For convenience the electrical conductivity data for the lunar and meteoritic samples were fit to expressions of the form

$$\sigma(T) = \sum_i \sigma_i^0 \exp\left(-E_i/kT\right). \tag{1}$$

Reasonable representations of the data could be obtained using only two or three terms. In Figures 1 to 6, the solid lines represent these mathematical expressions and the relevant parameters, σ_i^0 in $(\Omega\ \text{cm})^{-1}$ and E_i in eV, are collected in Table I. The table is arranged to emphasize the temperature region in which the various terms are dominant. In general, these expressions are representative of the initial heating curves. To facilitate comparison the curves are collected in Figure 4 and compared to two terrestrial materials, olivine and periodite, which have been used as analogues of lunar material. The lunar conductivities are larger than those of the model materials by several orders of magnitude. Many materials have conductivities characterized by two or more activation energies. In similar materials the high-temperature, high-energy contributions are frequently associated with ionic diffusion. Hafner and Virgo (1969, 1970) have found activation energies slightly less than 1 eV for Fe^{2+}, Mg disordering in orthopyroxenes, whereas energies of order 3 eV are more characteristic of disordering in feldspars. These energies are comparable with the high-temperatures activation energies of lunar and meteoritic samples in the temperature range in which large increases in $\sigma(300)$ occur. Activation energies for lunar and meteoritic conductivities at lower temperature (0.3 to 0.5 eV) are similar to those for ilmenite and

TABLE I

Activation energies, E_i, in eV and prefactors σ_i^0 (listed in parentheses) in $(\Omega\,\text{cm})^{-1}$ for the electrical conductivities of lunar, meteoritic, and terrestrial materials. The arrangement of the table suggests the temperature range in which each term is dominant

Material	0 —————————	————— 400 —————	————— 800 °C
Lunar			
10024.22[a]	0.51 (7.9×10^{-2})	1.25 (1.96×10^{-3})	3.2 (3.1×10^{4})
10048.55	0.35 (0.82×10^{-4})	0.46 (0.85×10^{-1})	2.3 (2.6×10^{14})
12053.47 (1)	0.59		1.6 (5.3×10^{9})
12053.47 (3)	0.17 (1.53×10^{-6})	0.55 (3.13×10^{-2})	(1.4×10^{5})
Meteoritic			
New Concord	0.11 (3.7×10^{-4})	0.26 (1.13×10^{-2})	1.13 (2.33×10^{3})
Allende	0.07 (0.71×10^{-4})	0.29 (0.91×10^{-2})	0.95 (1.44×10^{2})
Terrestrial			
Periodite[b]	0.81 (3.8×10^{-2})		
Olivine[b]	0.92 (0.55)		
Ilmenite[c]	0.33 (0.143)	0.467 (4.75×10)	→ (900 C) → (1140 C)
Basaltic Andesite[d]	0.1 (3.16×10^{-5})	0.3 (10^{-4})	1.5 $(3 \cdot 10^{5})$

[a] Nagata *et al.* (1970a)
[b] England *et al.* (1968)
[c] Ishikawa and Sawada (1956)
[d] Noritomi and Asada (1955)

may be associated with the activation of electrons or holes at the Fe^{2+} sites in the pyroxenes.

6. Summary

The electrical conductivities of samples of lunar surface rocks and chondritic meteorites were measured from 300 to 1100 K. The lunar samples, which represent all the major NASA classifications of lunar surface rocks, have similar conductivities and dependences on heat treatment. The conductivity of lunar surface rocks can be represented by equations of the form

$$\sigma(T) = \sum_i \sigma_i^0 \exp(-E_i/kT),$$

with the parameters listed in Table I. The lunar conductivities are larger by several orders of magnitude than those previously used in theoretical calculations (see Figure 4 for a comparison of electrical conductivities of lunar, meteoritic and terrestrial rocks). The chondritic meteorites initially were much more conductive than the lunar rocks presumably due to the large volume of metallic and pyroxene phases in the meteorites.

The electrical conductivities of both the lunar and meteoritic samples were quite sensitive to their thermal history. This dependence can be characterized as changes in the conductivity, $\sigma(300)$, measured at 300 K. A general feature of all samples was that $\sigma(300)$ increased markedly after heating to temperatures above $\sim 500°C$. For meteorites these changes probably started at slightly higher temperatures, $\sim 550°C$, and the increase was not so dramatic as for the lunar samples.

Although the conductivities are not understood on any fundamental basis, the discussion presented above suggests that the conductivity of these samples is due primarily to the pyroxene phases and that the increases in $\sigma(300)$ after heating above 500°C reflect a redistribution and possibly a change in valence of the iron within the pyroxenes. Although the temperatures at which these changes begin, the environments used in the measurements, and the weight·gain determinations all contraindicate oxidation, it is possible that oxidation of the pyroxene is important to understanding the changes in $\sigma(300)$. Certainly, empirical studies are needed on single-phase samples of pyroxene as functions of temperature, composition, and degree of order. There is also the real possibility that studies of the electrical conductivity may provide an unusually sensitive method for monitoring radiation and impact damage in pyroxene-bearing rocks.

Acknowledgements

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