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Electrical conductivity and the thermocline of the Moon

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Knowledge of electrical conductivity of lunar materials is required in order to understand various lunar surface and interior phenomena including deduction of lunar temperature profiles. Studies by several investigations of electrical conductivity in controlled environments and at elevated temperatures of Apollo lunar rocks, terrestrial pyroxenes and olivines, and synthetic glasses have shown that conductivity values are dependent primarily on concentration, distribution and oxidation state of iron and only secondarily on silicate crystal structure (e.g. olivine, pyroxene or glass). This general observation provides a reasonable basis for using laboratory conductivity data to deduce lunar interior temperatures from conductivity profiles determined by studies of the interaction of solar wind and Moon. Furthermore, correlation of conductivity with iron content provides a basis for the existence of lunar surface conductivity inhomogeneities. In this presentation, salient laboratory measurements of electrical properties by several investigators are discussed in the context of lunar observations from space missions and compared with appropriate lunar evolutionary models.

Introduction

One of the fundamental issues concerning the 'constitution, evolution and origin of the Moon' which has been debated at least since well before the Apollo missions is the exact nature of the lunar temperature profile, i.e. the so-called hot-Moon, cold-Moon controversy. Direct methods of probing the lunar interior are rather limited but fortunately the interaction of the solar wind with the whole Moon as manifested in certain low frequency electromagnetic phenomena provides a rather sensitive indicator of interior electrical properties. The measurement and interpretation of these phenomena by surface and orbiting magnetometer are discussed in detail in other papers (see, for example, Dyal *et al.* 1974; Sonett *et al.* 1974), and it will suffice to say that observed distortions in the ambient magnetic field due to whole-Moon induced current flows can be used to derive conductivity profiles. Knowledge of the temperature-dependence of the conductivity of lunar material can then be used to deduce a temperature profile. Other measurements or observations provide useful constraints resulting in satisfactory consistent results. Information about factors controlling the electrical conductivity of lunar materials is also of value to efforts to verify and explain the existence of inhomogeneities in the surface conductivity of the Moon (Schubert *et al.* 1974). Thus, a major objective of the work summarized here has been to obtain good data for the electrical conductivity of an extensive suite of lunar samples and on the basis of all relevant information determine the material most representative of the lunar interior (Schwerer *et al.* 1974). An alternate approach favoured by others has been to use single-crystals of terrestrial silicates, particularly pyroxenes and olivines, which were reduced in the laboratory under conditions appropriate to the presumed oxygen activity of the lunar interior (Duba & Ringwood 1973; Dyal *et al.* 1974). The use of single crystals has the advantage that difficulty of interpretation inherent with multiphase and cracked lunar samples is eliminated. However, the electrical properties of poorly conducting materials, such as lunar silicates, are extremely sensitive to the type and concentration of chemical and lattice defects and laboratory reduction is likely to result in nonequilibrium or nonstiochiometric defects. Clearly identification of the electrical properties appropriate to the lunar interior must be based on judicious inferences for data from both sources. In addition to electrical conductivity, intrinsic and remanent magnetic measurements, Mossbauer spectroscopy and electron petrography have all been used to characterize the form and distribution of iron in the various mineral and metallic phases present which largely determine electrical conductivity.

In the course of these individual phases of the work, a considerable amount of detailed magnetic (Nagata *et al.* 1975) and mineralogical (Huffman *et al.* 1974) data on lunar igneous rocks and breccias have been catalogued as well as important new concepts on brecciation, the crystal chemistry of olivines and the nature of ordering in silicates (Huffman & Dunmyre 1975; Nord *et al.* 1975). Except when directly relevant to the main theme of the paper, the work is cited only by key reference.

Experimental techniques

Experimental techniques utilized in the programme are well established and are described here briefly for the convenience of the general reader. Specific details can be found in the relevant references.

Electrical conductivity

Low frequency ac. and dc. electrical conductivity measurements were made for wafers about 2 mm thick which had been cut from Apollo lunar samples with a metal–matrix diamond wheel. Electrical contacts were attached by using silver or platinum conductive paint and platinum electrodes. Conductivity specimens were mounted in a three-electrode assembly and heated in a controlled atmosphere furnace to about 1000 °C. For the samples and conditions used in these experiments, various checks confirmed that reproducible data representative of pristine lunar material were obtained for samples heated in potentially reducing environments (Schwerer *et al.* 1974). These practices were followed in developing the data discussed in this paper.

Magnetic measurements

Measurements of remanent and intrinsic magnetic properties for an extensive suite of lunar samples have been reported (see, for example, Nagata *et al.* 1975). Complete interpretation of remanent properties in terms of ancient lunar fields and evolutionary processes have been deferred pending fuller development of an understanding of remanent mechanisms appropriate to fine iron particles, which are the principal remanence carriers in lunar materials. Development of the required mechanistic theories depends in part on characterization of lunar samples with regard to the distribution and oxidation state of iron, origins of metallic iron and intrinsic magnetic properties. These aspects of magnetic studies have been emphasized in recent reports (Nagata *et al.* 1975; Pearce *et al.* 1974), and obviously relate closely to the electrical studies and to Mossbauer effect studies described below.

Mossbauer spectroscopy

^{57}Fe absorption spectra of a large number of pristine and heat-treated samples were analysed to develop quantitative information on the relative percentages of Fe contained in the various phases present. Of particular interest with regard to the present paper are the (relatively small) changes which occur in the Fe phase distributions of lunar and terrestrial samples during high temperature conductivity measurements in reducing atmospheres; these results have been summarized elsewhere (Schwerer *et al.* 1974, and references therein). At low temperatures (4–20 K), a distinctive set of magnetic hyperfine peaks are observed in many high olivine lunar samples which are interpreted as arising from superparamagnetic clusters of Fe^{2+} spins in olivine (Huffman *et al.* 1974). It has recently been shown that these clusters can be dissolved by annealing at high temperatures ($\gtrsim$ 970 °C) at oxygen activities within the olivine stability field (Huffman & Dunmyre 1975). Further work aimed at relating the degree of such superparamagnetic clustering in lunar olivines to thermal history is in progress.

Electron petrography

Light optical thin sections were prepared for high voltage electron microscopy by argon ion thinning. The substructure, especially the grain size, lattice defects, exsolution features and long-range order domains as well as shock-induced glass formation contributed in various ways to the interpretation of the conductivity data.

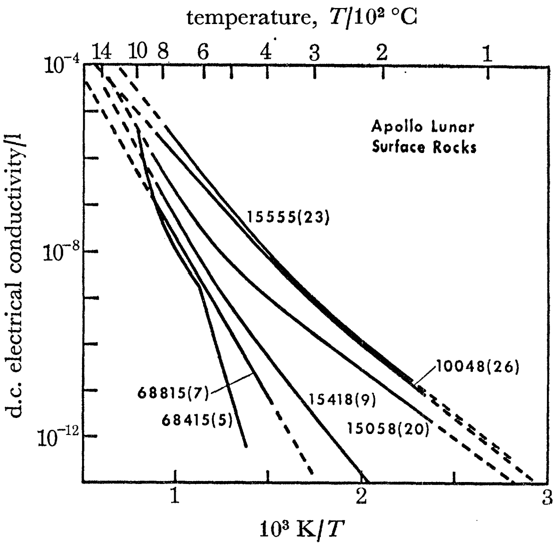

FIGURE 1

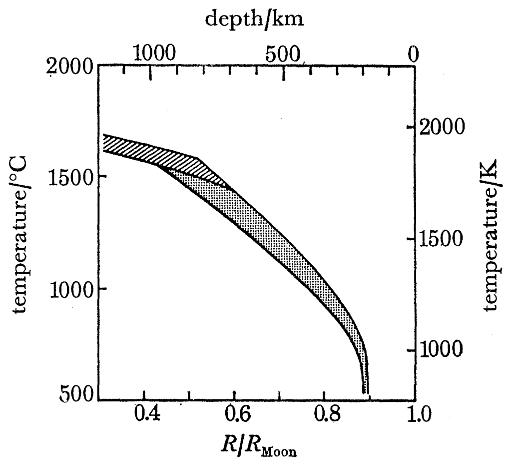

FIGURE 2

FIGURE 1. Temperature-dependence of d.c. electrical conductivity of lunar surface rocks. Parenthetical numbers indicate iron contents in mass percent; other labels are N.A.S.A. rock identification numbers for Apollo II (10xxx), 15 (15xxx) and 16 (6xxxx) missions.

FIGURE 2. Temperature profile for lunar interior based on conductivity profile from geomagnetic tail results (Dyal *et al.* 1974) and laboratory conductivity data for samples with iron contents of 5–15 mass percent (see figure 1). Cross hatch region denotes solidus range for basalt or pyroxenite interiors.

LABORATORY ANALYSES OF ELECTRICAL CONDUCTIVITY

Measurements of the electrical conductivity of a suite representative of returned samples of lunar rocks, supported the expectation that the conductivity of the multiphase specimen is determined by the silicate phases present in large volume fractions and forming continuous networks as evidenced by petrographic analyses (Schwerer *et al.* 1974). The major lunar silicates – pyroxene, olivine and plagioclase – contain varying amounts of iron in solution which is known from extensive studies on terrestrial minerals to influence conductivity very markedly (see, for example, Duba *et al.* 1973). This is clearly seen in the conductivity data for six representative lunar samples shown in figure 1. The parenthetical numbers indicate iron content. These results are in general agreement with measurements by Olhoeft *et al.* (1974) for other lunar rocks. Most conducting samples are comparable to the most poorly conducting terrestrial silicates attesting to the pronounced effects of even small amounts of ferric iron, i.e. Fe^{3+}, present in such terrestrial samples.

Very large hysteresis effects (10^4–10^6 increase between heating and cooling) were noted during the early phase of the work and were traced to an extremely strong sensitivity to the oxygen activity of the furnace atmosphere. This is consistent with the known dominant role of Fe^{3+} when present in determining conductivity. Subsolidus formation or dissolution of metal iron clusters resulting in changes in low activation energy mechanisms of extrinsic conduction as well as intrinsic conduction were also monitored by extensive magnetic and Mossbauer analyses and verified in part by electron petrography. The details of this work, especially concerning a new type of Fe^{2+}-clustering in olivine (Huffman & Dunmyre 1975) are not germaine to this paper, but it is important to emphasize that a sound basis for selecting lunar conductivity data appropriate to the lunar interior has been established.

Lunar temperature profile

Orbiting and surface magnetometer measurements of distortions in the geomagnetic tail caused by deep interior circulating currents induced by the solar wind have been used by Dyal *et al.* (1974) to deduce electrical conductivity profiles for the Moon. The results indicate a conductivity of $\sim 10^{-4}$ at 30 % of the Moon's radius and $\sim 10^{-6}$ at the 90 % point. The former value is consistent with analysis of other lunar electromagnetic phenomena by Sonett *et al.* (1974). The whole-Moon susceptibility (Parkin *et al.* 1974) and other characteristics (Ringwood & Essene 1970) suggest an average iron content for the lunar interior of between 7 and 16 %. This is about the centre of the group of conductivity curves shown in figure 1.

The temperature profile based on these laboratory data and the conductivity profile reported by Dyal *et al.* (1974) is shown in figure 2. This is compatible with seismic and other types of temperature-sensitive operations which impose additional constraints in the profile (see, for example, Dainty *et al.* (1974)). As is apparent from the figure, the results strongly support advocates of a hot-Moon hypothesis.

Discussion of experimental difficulties and assumptions inherent in the theoretical interpretation of magnetometer data have been glossed over outrageously in this summary, but even in the extreme these factors could not change the form of the apparent lunar profile in any important respect.

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