Magnetic and Electrical Properties

Magnetic Properties of Lunar Samples

Abstract. *A breccia sample (10023) from the moon was found to have a strong and fairly stable remanent magnetization. If this sample was not magnetized by local fields in the spacecraft or in the lunar receiving laboratory, it must have been magnetized on the moon. This could have happened in a variety of ways, such as cooling through the Curie temperature, by continuous thermal cycling, or by impact, but all of these require the presence of a magnetic field. Such a field could have been of internal origin in the moon, or it could have been a residual effect from the earth's magnetic field at a time when the moon and the earth were much closer together. Thermomagnetic studies identify the presence of iron with about 1 percent nickel (igneous), iron with about 5 to 10 percent nickel (meteoritic), iron with about 33 percent or more nickel (meteoritic), and ilmenite.*

We studied the magnetic properties of a solid breccia sample (10023) and a powder sample (10084). Preliminary investigation of this solid sample and others was carried out with a fluxgate magnetometer (*1*). This breccia sample was found to have a magnetic remanence of 7.7 $\times$ 10^{-3} emu/g and an induced magnetization of 7.6 $\times$ 10^{-3} emu/g in a field of 0.92 oersted (*1*).

Magnetic studies of two major areas are reported. The first is a detailed investigation of the natural remanent magnetization (NRM). This property should reveal something about the magnetic history of the moon because any NRM present in the samples would be the result of exposure to a magnetic field. The moon does not at present have a significant field (*2*). In an orbiting vehicle 300 km above the surface it was shown that the magnetic moment of the moon was less than 4 $\times$ 10^{20} cgs (the present value for the earth is approximately 8 $\times$ 10^{25}) and that the regional surface field must be less than 16 γ (1 γ = 10^{-5} oersted). As a result the presence of a significant and stable remanent magnetization would suggest either that the moon once had an intrinsic magnetic field of its own, much larger than the present one, or that it was in the vicinity of another body, such as the earth, which had a significant field.

The second area of study is to consider the application of magnetic techniques to identify the amount and types of various iron-bearing minerals. This approach could positively identify very minute amounts of such minerals as magnetite, iron oxyhydroxides, siderite, pyrite, and many others (*3*). In the particular context of the lunar samples as discussed in the preliminary examination, it is clear that the major role to be played is the identification of iron and iron-nickel minerals. The preliminary report suggests also that small amounts of troilite (FeS) and large amounts of ilmenite are present in the igneous rock.

Measurements of the NRM of the breccia sample show that the sample has a strong magnetization of 2.8 $\times$ 10^{-3} emu/g. The direction of this magnetization is of course not known with respect to north but it is pointing up at about 60° from the horizontal as defined by the upper surfaces. The sample was subjected to alternating field demagnetization in fields up to 300 oersteds. The decay of the magnetization is quite similar to that for thermoremanent magnetization (TRM) in typical basaltic rocks with unoxidized magnetite grains a few microns in size (*4*). The direction of magnetization is essentially unchanged during the demagnetization process although some scatter is present in repeat measurements at 300 oersteds (Fig. 1a). This type of demagnetization curve is not typical of rocks with a highly stable magnetization but it is typical of many rocks generally considered adequate for paleomagnetic studies. There is no doubt that this specimen acquired its remanent magnetization in the presence of a magnetic field. It is possible that this was a field of several hundred oersteds in the spacecraft or the lunar receiving laboratory but this seems unlikely and if similar results are found on many samples this possibility will be even less likely.

The following pertinent minerals were observed in the breccia sample using a reflecting microscope. (i) Iron is present in particles a few microns in size, generally associated with troilite. This iron is probably of igneous origin and has a Curie temperature of 760°C suggesting the presence of a few percent

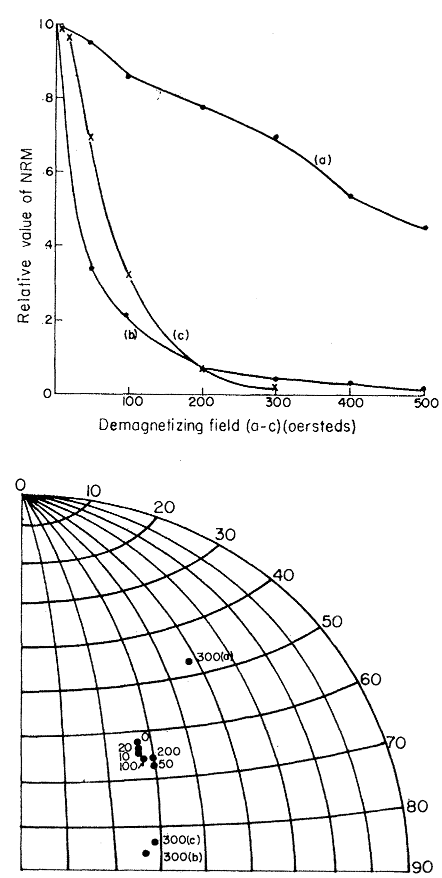

Fig. 1. (Top) Alternating current demagnetization curves of natural remanent magnetization. (a) Oxidized basalt, Flagstaff, Ariz.; (b) unoxidized basalt, Flagstaff, Ariz.; (c) lunar breccia sample (10023). (Bottom) Stereogram of directions of magnetization on demagnetization (a–c).

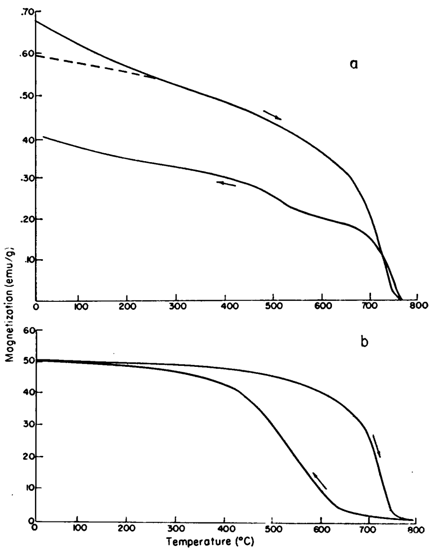

Fig. 2. Saturation magnetization versus temperature curves (at 3000 oersteds). (a) Surface powder showing presence of iron and two iron-nickel phases (10084,90). (b) Particle of iron-nickel separated from breccia sample 10023. Apparent thermal hysteresis is due to phase change in kamacite.

of impurities—perhaps 1 or 2 percent nickel or silicon. (ii) In the breccia, ragged particles of iron-nickel are observed. These have a range in grain size from 1 or 2 μm up to 50 μm or more. The particles are believed to be α-phase (body-centered), and on heating they change to the nonmagnetic γ-phase (face-centered) at 750°C and on cooling revert to the α-phase at 650°C. (iii) Troilite (FeS) is abundant but it cannot be detected magnetically. If it were nonstoichiometric it would give a ferrimagnetic Curie temperature of 320°C. The fact that none is seen magnetically means that it is antiferromagnetic and stable on heating both in air and in vacuum. (iv) Ilmenite ($FeTiO_3$) is present in great abundance as reported (*1*). It shows lamellar twinning parallel to the 0001 plane. As will be seen from the low temperature magnetic data, it is nearly stoichiometric. (v) Very small amounts of a deep gray phase are found, intergrown in the ilmenite grains. The composition of this is not known, although it is possible that it is chromite.

Very few studies of the magnetic properties of meteorites and tektites have been made in the past and the available literature is quite limited. Stacey *et al.* (*5*) examined a series of chondritic meteorites and found that many of them do have a significant remanent magnetization carried by α-phase iron-nickel which has 5 to 6 percent nickel (kamacite). They suggest that this means that there was an ancient field in the parent body of the meteorites. As they point out, this phase loses its magnetization on heating at 750°C where a phase change from the α form to the γ form occurs on heating. On cooling the reverse phase change takes place at a lower temperature giving an apparent thermal hysteresis.

This irreversibility is characteristic of iron-nickel alloys with less than 30 percent nickel. Pure iron undergoes a phase change from the α-phase to the γ-phase at 910°C. Alloying with nickel causes the transition to occur at lower temperatures and it reverts to the α-phase on cooling at still lower temperatures unless cooling is at a very slow rate. Bozorth (*6*) gives a graph of the effective temperature of this change on cooling.

In our experiments on the powdered sample (10084) of surface fines, a similar phenomenon was found. A vibrating sample magnetometer (Princeton Applied Research, FM-1) was used to measure the magnetization while heating the samples (Fig. 2a). The heatings were done in a vacuum of somewhat less than 1 μm because heating in air caused complete oxidation of the ferromagnetic phase. Even at the pressures used, it is seen that some oxidation took place since the measurements are not fully repeatable. This was the result of some oxidation of the fine particles, since subsequent tests done by measuring the magnetization before and after heating to 800°C in a furnace with a pressure of less than 3×10^{-5} mm Hg showed that no such breakdown occurred.

In the heating curve of Fig. 2a, three distinct phases can be identified. The first of these has a Curie temperature of about 760°C and is essentially repeatable. This phase is an iron phase, and on heating up to 800°C it undergoes no phase change. The Curie temperature is however distinctly less than that of pure iron (770°C), and from studies of the dependence of Curie temperature on composition this phase must contain a few percent of an impurity such as 1 or 2 percent of nickel or silicon. This phase is believed to be due to the iron found in the igneous rocks (*1*). A second phase is present in the powders which on cooling appear to have a Curie temperature of about 570°C. This type of curve is better illustrated in Fig. 2b, which is a temperature versus magnetization curve for a single iron-nickel particle taken from the breccia sample. On heating, the sample loses its magnetization at about 750°C and reacquires it at about 600° to 650°C on cooling. This curve is completely repeatable and indicates the presence of an iron-nickel alloy as considered above for meteorites. The graph from Bozorth (*6*) suggests that 5 to 7 percent nickel is present in this phase which is typical of the kamacite of iron-nickel meteorites. This phase is not present in the igneous rocks (*1*) but is present in both the powders and the breccias.

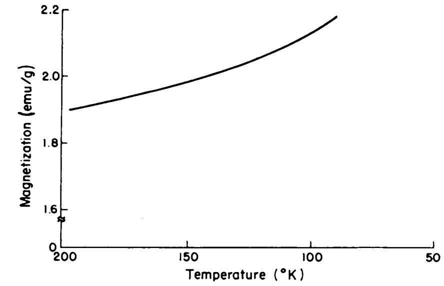

Fig. 3. Saturation magnetization versus temperature curve (at 5800 oersteds) of lunar powder sample (10084,90) at low temperatures.

A third phase is indicated in the curve of Fig. 2a (above the dashed line). On heating and cooling there is a distinct change in the magnetization at about 200°C but the temperature is not well defined. Results similar to this have been discussed by Hoselitz (*7*) who shows that a γ-phase of iron-nickel gives just this type of magnetic response. Since the temperature at the lunar surface probably decreases to about 100°K during the lunar night, this phase must be γ-phase and remain in this state down to this temperature. This requirement can be met by an iron-nickel alloy with a Curie temperature of 200°C and with 33 percent or more nickel. This is probably due to the presence of meteoritic taenite which is common in iron meteorites (*8*). The lack of a distinct Curie temperature may be due to the presence of a range of nickel concentrations.

A similar set of experiments was done at low temperature with the same vibrating magnetometer by making observations down to liquid nitrogen temperature (77°K). On cooling to this low temperature an additional magnetic phase appears (Fig. 3). The shape of the curve is that of a paramagnetic substance; however it will not fit the standard $1/T$ relation. It does however fit a relation of the form $1/(T + \theta)$ where $\theta = 64$°K. This is the relation expected above the Néel temperature for an antiferromagnetic substance such as ilmenite which is known to occur abundantly in these samples. The Néel temperature for ilmenite is reported as 68°K; thus the ilmenite present must be nearly stoichiometric, because solid solution with hematite would tend to make the ilmenite ferrimagnetic and to raise the characteristic Néel temperature.

Hysteresis loops were run on several of the powdered samples (10084) in an attempt to add to our understanding of the magnetic properties. From these observations it is possible to determine the ferromagnetic content assuming that the value of saturation magnetization quoted for iron holds for this material [217.8 emu/g (*6*)]. These results indicate that the powdered material has about 0.3 to 0.5 percent of iron and iron-nickel present in the form of ferromagnetic particles. As pointed out by Senftle *et al.* (*9*), the shape of spherical iron particles in tektites controls the susceptibility up to fields of 6000 oersteds. Our measurements were made in fields of 7500 oersteds. The saturation remanent magnetism is about one-tenth the saturation magnetization, and this suggests that there is a considerable fraction of the iron material present in the form of particles a few microns or so in size. Iron in larger grain sizes does not have such a high remanence. In fact, these data are much like those reported for basalts (*4*) in which particles of magnetite of about this size were found. The bulk coercive force is typically about 100 to 200 oersteds, which again is a value considerably higher than that of larger iron particles and which suggests the presence of some grain fractions with a fairly high coercive force.

The weak field susceptibility was measured on a bridge (Geophysical Specialities MS 3-B) in fields of about 1 oersted. This gave a value of 1.13×10^{-3} emu/g for the powder sample and a value of 1.1×10^{-3} emu/g for the breccia sample.

Several magnetic phases have been identified in this study but it is clear that only the iron or iron-nickel particles, or both, are responsible for carrying the large and fairly stable remanent magnetization found in the sample. These particles are of sufficiently small size as observed both magnetically and optically to be the carriers of the NRM but it is still not known how the magnetization was acquired. If we assume that the magnetization is not caused by exposure to large man-made fields, the following possibilities need to be considered.

1) It is a thermoremanent magnetism (TRM) acquired when the specimen cooled in the presence of a magnetic field. The precise field strength required is not known but it is likely to be within an order of magnitude of the present field of the earth. The novel possibility that it was acquired at the time of the phase change from γ to α needs to be considered as well as the possibility that it is a normal TRM.

2) It is a remanent magnetization caused by the thermal cycling found at the lunar surface in the presence of a nonrandom applied field. This possibility can be further amplified by consideration of the work of other investigators (*10*). If this is a real possibility the effect should attenuate very rapidly with depth beneath the surface.

3) It may be related to the shock process that formed the breccias. Magnetostriction could well be important in this material, and a preferred alignment could be expected if a magnetic field were present at the time of stressing. Unless the shock process itself somehow generates a local magnetic field no remanence would be expected. In general, shock processes reduce the NRM which is already present (*11*).

It is interesting to note that all of these mechanisms require the presence of a magnetic field so that such a remanent magnetism can be formed, and it is tentatively concluded that the moon did have a magnetic field at some time in its history or that these rocks became magnetized when the moon was very much closer to the earth than at present. If the effect found is limited to the breccias, it may be either because no field was present when the igneous rocks were formed or because the shock or the presence of iron-nickel particles increases the magnetic stability of the breccias relative to the igneous rocks.

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Magnetic Properties of Lunar Dust and Rock Samples

Abstract. *Determinations on 20- to 80-milligram portions of the rock samples and the −150 mesh fraction of the lunar dust show pronounced Curie points between 680° and 780°C. Remanent intensities of five rock fragments vary from 8.4×10^{-5} to 0.30×10^{-5} emu/gram. Upon demagnetization, two of the samples had only viscous magnetization and two other samples had stable magnetizations with remanent coercivities in excess of 50 oersteds. Partial thermal demagnetization suggests that these apparently stable moments may have been acquired in a magnetic field in excess of 1500 gammas.*

Current theories regarding the origin of the earth's magnetic field require the presence of a conducting fluid core (*1*, *2*). Consequently, it is of considerable interest to know whether the moon ever had an appreciable magnetic field. If it had one in the past, the implication would be that the interior was at one time a conducting fluid or that the moon was within the earth's magnetic field at the time the rock cooled. Studies of the magnetic properties of five Apollo 11 lunar rock samples, as well as the dust, show that some of the samples have a stable magnetic moment that could have been acquired as a result of cooling in the presence of a magnetic field. The samples studied are (i)