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) a fragment of rock sample 10022, a vesicular basalt with spherical vesicules; (ii) a fragment of rock sample 10069, a fine-grained basalt with irregular vesicules; (iii) a fine-grained gabbro from dust sample 10085,16 fragment 2; (iv) a vesicular basalt fragment from dust sample 10085,16, which is similar to sample 10022 fragment 4; and (v) a fine-grained basalt fragment from dust sample 10085,16, which is similar to sample 10069; and (vi) the −150 mesh fraction of dust sample 10084.

Thermomagnetic analyses were made on the −150 mesh portion of each sample by sealing 10- to 100-mg portions in evacuated quartz glass tubes which were placed in a magnetic force balance in a high gradient field of about 2 kilo-oersteds, and heated at a rate of 1° to 2°C per second to a temperature of up to 800°C. The results of these analyses are shown in Fig. 1. The most prominent Curie point in the dust samples is between 750° and 770°C, suggesting the presence of native iron with very low nickel content. The dust sample also yields a prominent Curie point in the vicinity of 180°C after it has been heated to 800°C. This transition is also present in the initial heating curve but is only evidenced by a very slight change in slope near 200°C. When the sample is cycled below 500°C, the heating and cooling curves are very similar, and the 200°C transition remains very obscure. When cycled to 650°C, this transition becomes more prominent and when cycled to 720°C, the 200°C transition becomes quite pronounced. When the dust is heated beyond 600°C, the heating and cooling curves are quite different, suggesting that a chemical change has occurred within the sample.

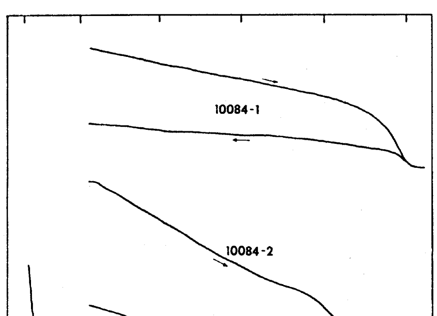

Fig. 1. Selected thermomagnetic analysis curves for lunar dust and rock samples. Vertical scale is arbitrary. Arrows indicate direction of temperature change.

Small portions (approximately 75 mg) of each of the larger rock samples (10022 and 10069) were also subjected to thermomagnetic analysis. The results of these experiments are also shown in Fig. 1 and are in general very similar to those for the dust samples. These samples were also cooled to −196°C in order to check for any ilmenite Curie points. For sample 10069 a Curie point near −170°C seems indicated, but sample 10022 shows no evidence of a Curie point above −196°C. High-temperature Curie points for sample 10069 occur at 520°C and in the range 680° to 752°C. These are not reproducible during cooling; instead they are replaced by one at 690° to 700°C and another at 115°C. In sample 10022, the high-temperature Curie points are at 485°C and at > 680°C and upon cooling at 465°C.

All of the above observations are not characteristic of normal basalts found on the earth. Instead they have many similarities to those reported by Stacey *et al.* (*3*) from chondritic meteorites. This suggests that the major magnetic constituents in these samples are iron with a low nickel content, perhaps a pyrrhotite or troilite(?), and an abundant ilmenite phase with very little, if any, Fe^{3+}.

Initial measurements of the natural remanent magnetization (NRM) of the three rock fragments from the dust sample 10085,16 and the two rocks 10022 and 10069 yielded specific intensities ranging from 8.41×10^{-5} emu/g to 0.297×10^{-5} emu/g. Two of the small samples had previously been exposed to an external field of about 60 oersteds during petrologic examination in a scanning electron microscope. Consequently, their NRM might be expected to be anomalous. The NRM moments of the three samples that had not been exposed to large external fields are 2.46×10^{-5}, 1.92×10^{-5} and 0.297×10^{-5} emu/g.

All samples were subjected to alternating field demagnetization with peak fields varying from 11 to 570 oersteds, and the results are shown in Fig. 2.

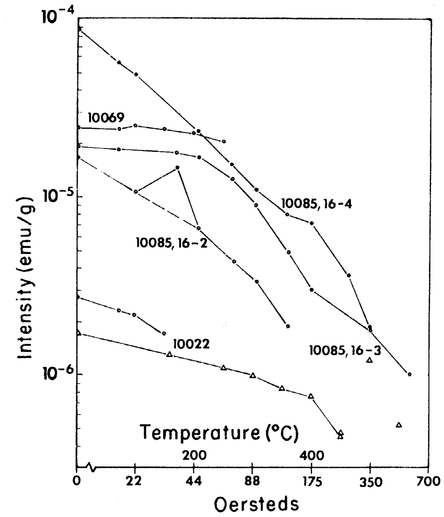

Fig. 2. Progressive alternating field (circles) and thermal demagnetization curves (triangles) for rock samples studied. Note use of log scale.

Samples 10069 and fragment 3 from dust sample 10085,16 have a stable NRM and have remanent coercivities in excess of 44 oersteds. Both these samples appear to be of the same rock type. Fragments 2 and 4 from the dust sample (the ones that had been in the scanning electron microscope) show only an IRM and no stable NRM. One is a fine-grained gabbro and the other a fragment of vesicular basalt similar to 10022. Upon alternating field demagnetization, they show an almost linear decrease on a log-log scale. Sample 10022 is more stable than fragments 2 and 4, yet it does not show the stability evidenced by fragment 3 and sample 10069.

After being demagnetized in an alternating field of 33 oersteds, sample 10022 was further demagnetized by progressive thermal demagnetization in a vacuum at intervals of 50°C. The results of this demagnetization are shown in a log-linear plot at the bottom of Fig. 2. In a second heating after the 250°C and 350°C demagnetization steps, the sample was allowed to cool in an applied field of 1000 gammas for the first 100°C and then to cool the rest of the way in the absence of any applied field (*4*). The ratio of the intensity lost in the temperature interval to that gained during cooling in the 1000-gamma field is 1.88 and 1.57 for the intervals 150° to 250°C and 250° to 350°C, respectively. Progressive thermal demagnetization showed an increasing rate of decrease in remaining moment up to 450°C, as is characteristic of samples with distributed thermal blocking temperatures. Above 450°C, no reliable demagnetization results could be obtained. The cause of this instability is not known, but it may be the result of exceeding the pronounced Curie point at 485°C (Fig. 1). The moment due to the phase with the higher Curie point may be unstable, or it may be that it is completely overridden by the moment acquired during cooling through the 465°C transition in a small residual field (10 to 20 gammas).

After alternating field demagnetization, fragment 3 of the dust sample was heated in vacuum to 450°C and allowed to cool in a field of 500 gammas. No additional detectable moment was acquired during this process. This sample was then heated in vacuum to 750°C and allowed to cool in an applied field of 1000 gammas. Again no detectable moment was acquired, indicating that it acquired its NRM in a field in excess of 20,000 gammas or that it was acquired by some means other than cooling through the Curie point. Alternatively, an irreversible chemical change may have taken place in the sample so that remanence can no longer be acquired in the same way the initial NRM was acquired.

Thus the evidence from fragment 3 of the dust sample allows no estimate of the possible range of values for the moon's field in the past. The partial thermal demagnetization of sample 10022 suggests that the sample may have acquired its initial NRM in a field of 1500 to 2000 gammas. However, the marked instability at higher temperatures leaves this conclusion somewhat in doubt; it is subject to verification by apparently more stable samples such as sample 10069.

Thermomagnetic analysis of the Apollo 11 dust and rock samples studied indicates that the major magnetic minerals are ilmenite, native iron, and possibly pyrrhotite. Of these, the native iron and the pyrrhotite (troilite?) are the dominant carriers of the natural remanence in these rocks. The natural remanences are low in all these samples in comparison with similar rocks from the earth. The stability of the NRM is low in three of the samples studied but is high in the other two. If the NRM of these samples is interpreted as being a TRM acquired by passage through the Curie point in the presence of a magnetic field, a field in excess of 1500 gammas is suggested.

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Magnetic Studies of Lunar Samples

Abstract. *The remanent magnetism of a lunar type C breccia sample includes a large viscous component with a time constant of several hours, and a high coercivity remanence, possibly acquired by impact processes on the lunar surface. Ilmenite(?) and metallic iron in breccias, and ferrous and metallic iron in glass beads separated from lunar fines (type D) were identified by high-field and low-temperature experiments. The iron appears to occur in a wide range of grain sizes including the single domain and multidomain states.*

The purpose of magnetic studies of Apollo 11 lunar materials is to ascertain whether the materials possess a stable remanent magnetization that was originally acquired on the moon, and to compare the magnetic properties of individual glass beads in the lunar fines with those of tektites. These magnetization studies could indicate past lunar magnetic environments and thus be of value in theories concerning the moon's earlier history. Intrinsic bulk and single-particle magnetic properties are also of interest with respect to the magnetic mineralogy of the lunar material.

Magnetization of type C breccia sample number 10059,24 in high applied magnetic fields was measured with a vacuum magnetic balance of the Faraday type (*1*). Results obtained for magnetization versus applied field to 8400 oe and magnetization (in 2000 oe) versus temperature between −180°C and 830°C are given in Fig. 1A. The magnetization curve rises very sharply at low fields and gradually approaches a saturation value near 2.7 emu/g. The thermal curves show a well defined Curie temperature at 775°C, and a suggestion of a second Curie or Néel point slightly below −180°C. These are interpreted as due to reported metallic iron and ilmenite (*2*), with a Curie point of 770°C and a Néel point of −205°C, respectively (*3*). About one-half the original room-temperature magnetization was lost during the heating experiment, but subsequent prolonged heating at 800°C did not further change the shape of the cooling curve, which indicated that the changes took place during the first heating cycle. There is also a small inflection in the cooling curve near 250°C; no interpretation is given for its origin.

Similar high field experiments were made on individual glass beads (0.1 to 1.5 mg) selected from lunar fines type D sample number 10084,86. A quartz-spring balance with the sample in a dry helium atmosphere (*4*) was used for these studies. The low field (< 3000 oe) magnetization at room temperature varied from 10 to 100 × 10^{-4} emu/g, and saturation magnetization varied from nil to 1.2 emu/g. Magnetization (in 3400 oe) versus temperature measurements indicated a Curie point of 770°C, but unlike the breccia, identical heating and cooling curves with a shape resembling the cooling curve of Fig. 1A (without the inflection at 250°C) were obtained. The magnetization versus applied field curve of individual glass beads are very different from those of the breccia: some were linear up to about 5000 to 7000 oe and reached saturation values of about 1 emu/g at 9000 oe. Other individual glass beads did not exhibit saturation magnetization in high fields at room temperature, indicating that essentially all the iron is in the paramagnetic state. Low temperature measurements verified this fact and also showed that in those glass beads that had an appreciable saturation magnetization, only a small part of the iron was in the metallic form with the major part in the paramagnetic state. In some respects these magnetic properties are very similar to those of tektites (*5*); moreover, electron microprobe analysis for total iron detected essentially the same concentrations of ferrous and metallic iron that are indicated magnetically; these concentrations