that the instability of the sample magnetization should be attributed to the nature of its carrier rather than to the mechanism of its formation.

To investigate the nature of the carrier(s) of remanent magnetization in the sample, small grains detached from its surface were examined with a recording magnetic balance (*4*). The investigation was carried out with a sample weighing approximately 20 mg and under an air pressure of 3×10^{-3} mm-Hg.

Figure 3 shows the dependence of the magnetization (J) on the applied field (H) at 20°C and the change in J (H = 4280 oe) during heating to 900°C and subsequent cooling. The J(H) curve shows that the original sample approached magnetic saturation at about 4000 oe and that its coercive force was approximately 70 oe. Such a low coercive force is in accord with the previously noted tendency of the sample to acquire a large component of viscous magnetization when exposed for a few minutes in a field as low as the earth's magnetic field (Fig. 1). Moreover, it suggests that there is no major component of high micro-coercivity in the sample.

The J(T) curve shows a monotonic decrease in magnetization from −180°C to the Curie temperature at 750° ± 8°C (only partly shown on Fig. 3). The high Curie temperature is diagnostic of a mineral that is uncommon in terrestrial rocks. The cooling part of the J(T) curve suggests that a substantial transformation of the original mineral took place at high temperature.

The Curie temperature of the original ferromagnetic constituent at 750° ± 8°C and the transformation of this constituent into one with a Curie point of 580°C and with lower saturation magnetization were interpreted as follows: (i) the original ferromagnetic constituent was relatively pure metallic Fe with perhaps as much as 5 percent Ni, this estimate being based on standards given by Kneller (*5*). In this context, it is noteworthy that the Fe in meteorites normally contains more than 5 percent Ni; (ii) the estimated abundance of fine-grained Fe in the sample is about 0.5 percent; (iii) it is possible that virtually all the metallic Fe was oxidized to Fe_3O_4 at higher temperatures. This is in keeping with the Curie temperature of the new mineral and with the halved saturation moment of the sample at 20°C after heating.

In the light of the above magnetic data it is not possible to state conclusively whether a substantial magnetic field witnessed the last cooling of sample 10048 on the lunar surface. It would thus be presumptuous to speculate further on the original configuration of the moon's interior along this avenue on the basis of this sample.

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Search for Magnetic Monopoles in the Lunar Sample

Abstract. *An electromagnetic search for magnetic monopoles of the minimum size predicted by Dirac, or of any larger magnitude, has been performed on 8.37 kilograms of lunar surface material. No monopole was found. This experiment sets new limits on the production cross section for monopoles and on their occurrence in cosmic radiation.*

For several years now, the hunt has been on for particles that would interact with the magnetic field just as electric charges interact with the electric field, acting as a source for the field and being accelerated by it. These particles, called monopoles, would be stable. They would have a magnetic charge measured by an integer ν, the Dirac charge 3×10^{-8} emu being used as a unit (*1*). Their existence would give credence to the only known explanation for the extraordinarily accurate phenomenon of charge quantization (*2*). According to a recent theory (*3*), they would be the most fundamental particles, the building blocks of the universe. However, no such particle or combination with a net nonzero magnetic charge has ever been found (*4–6*).

In view of the negative results of these experiments (*4–6*), the lunar surface is considered to be the most likely hiding place for monopoles, whether they belonged to the primary cosmic rays or were produced in the collision of a high-energy cosmic ray particle with a nucleon of the lunar surface. In either case, the lunar material would slow the monopole down and trap it. The reasoning that favors the lunar sample involves its great age, 3 to 4×10^9 years, and the small depth to which the surface has been churned during the long period of time. These two factors give the lunar surface the longest known exposure to cosmic rays. Furthermore, the absence of both an atmosphere and a magnetic field on the moon allows the fate of a monopole after it has been slowed down to be assessed with more certainty than it could be on the earth.

Our detection technique relies on the electromotive force induced in a coil by a moving monopole. As in previous work (*7*), the sample was transported along a continuous path threading the windings of a coil. In this experiment the coil was made of superconducting material and was short-circuited by a superconducting switch. A small current was stored in the superconducting loop before a sample was run. If a sample containing a monopole had been run, the induced electromotive force would have modified this current. After each sample had been circulated 400 times, the superconducting switch was opened and a signal proportional to the current in the loop was transferred electrically out of the cryostat, amplified, and finally recorded on an oscilloscope. A real magnetic charge would have been detected as a difference between the signal obtained when the switch was opened and the one normally observed when the opening of the switch interrupted the "standard current" that had been introduced as an overall check on the apparatus. A zero magnetic charge therefore corresponded to a nonzero standard signal. This technique assured us that the equipment was working at all times.

An overall calibration was obtained from a long solenoid in which a known change of current simulated the "missing term" in Maxwell's equations—the one describing the contribution of a "magnetic current density." A statistical study of our signals shows that the measurement of the magnetic charge was affected by a 1 standard deviation error of about ⅛ of a Dirac unit, when a ride of 400 passes was given the sample. Therefore, the smallest monopole compatible with Dirac theory was expected to produce an 8 standard deviation signal. There are reasons to believe the smallest actual charge would have twice the Dirac value (*8*), and this would correspond to twice as big a signal.

The lunar surface material analyzed in this experiment consisted of 28 individual samples. One sample was composed of three rocks (NASA 10022-1, 10023-1, and 10024-3) weighing all together 213 g. The remaining 27 samples were all fines from the bulk sample (NASA 10002). The individual samples of fines ranged in weight from 261 to 356 g, and weighed all together 8.13 kg.

The measured magnetic charge of each sample was consistent with zero, and statistically incompatible with the hypothesis that the absolute value of the magnetic charge was as large as, or larger than, a single Dirac unit of magnetic charge. We can therefore set upper limits on the number of monopoles present in the primary cosmic rays *and* on the number of monopoles produced by high energy cosmic ray particles interacting with nucleons of the lunar surface material. We quote our results at the 95 percent confidence level, including a correction of 10 percent to the monopole density to take into account the possibility that any individual sample may have contained paired monopoles of opposite charge.

The actual values of both upper limits depend upon unknown properties of the hypothetical magnetic monopole—namely, its charge, its mass, and all the parameters that determine its range inside the lunar material before it comes to rest. Therefore we express our results as a function of n, a parameter which relates the approximate range R, in grams per square centimeter, to the kinetic energy E, in Gev, by $R = 0.1\ E/n^2$. For low velocities, when the monopole loses energy by ionization only, n in this formula is the magnetic charge ν measured in Dirac units. At higher velocities, the effective value of n is expected to increase with E due to bremsstrahlung.

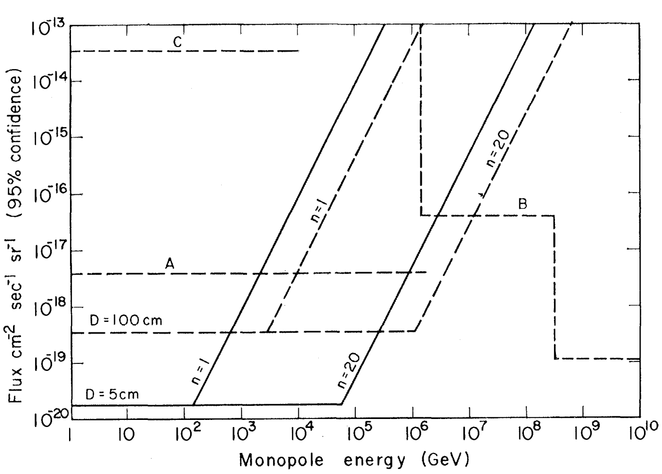
The values of both upper limits depend also upon the assumption we make regarding the depth, D, to which the lunar surface has been churned. We have represented our results in Figs. 1 and 2 for an assumed exposure time of 3×10^9 years and for two mixing depths, (i) 5 cm (solid curve), which represents effectively no mixing depth, and (ii) 100 cm (dashed curve).

In Fig. 1, we plot our upper limit for the flux of monopoles per square centimeter per second, per steradian, in the cosmic rays. The curves are displayed as a function of the kinetic energy of the monopole with n and D as parameters. Curves A and B represent upper limits known from the most extensive previous searches for monopoles in cosmic rays. Curve A results from examination of deep ocean deposits (*5*), and curve B results from an analysis of tracks in obsidian and mica (*6*). The results of the most extensive search carried out in the earth's atmosphere are given by curve C (*9*).

The production of monopoles by proton-nucleon interactions depends upon the monopole pair-production cross section, σ. In Fig. 2 we have plotted the upper limit for σ, as it results from our experiment, as a function of the monopole mass for different values of D and n. The flux of primary cosmic rays above the energy E, in Gev, was assumed to be $1.4 \times E^{-1.67}$ $cm^{-2}\ sec^{-1}\ sr^{-1}$ (*4*).

The incident proton was assumed to lose 40 percent of its energy at each proton-nucleon interaction (*9*). The monopole pair-production cross section was assumed to be constant above the threshold energy for monopole pair production. Curves A and C represent the limits for σ as known from previous work (*5* and *9*, respectively). Curve D comes from a search for monopoles in a meteorite (*10*) as interpreted in reference (*4*). Curve E corresponds to the most extensive accelerator study made to date (*11*).

The search for monopoles in the lunar sample of Apollo 11 resulted in the finding that there was neither an unpaired north or south monopole in any of the 28 samples studied. This result sets upper limits on the presence of monopoles both in the primary cosmic rays and in the proton-nucleon interactions, without any assumption concerning the migration of the monopoles through matter under the influence of the magnetic field. If the lunar mixing depth is less than 10 meters over a



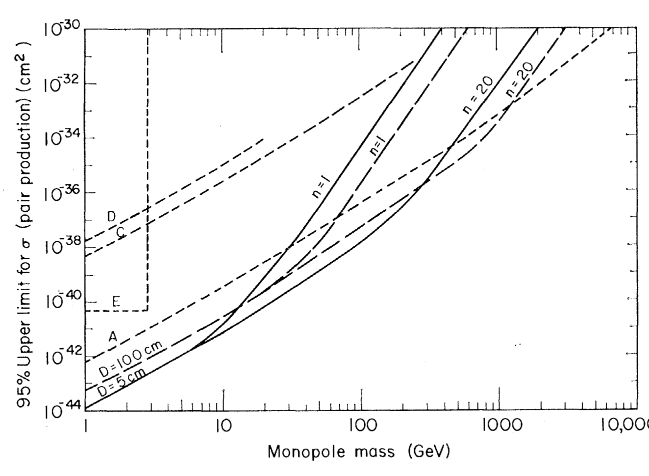


Fig. 1 (left). Ninety-five percent confidence level upper limit on the flux of monopoles as a function of monopole energy. The solid and dashed curves for D=5 and 100 cm are from this work. The parameters n and D are defined in the text. Data for curyes: A, reference (*5*); B, reference (*6*); C, reference (*9*). Fig. 2 (right). Ninety-five percent confidence level upper limit on the monopole pair-production cross section in proton-nucleon collisions. The solid and dashed curves for D=5 and 100 cm are from this work. The parameters n and D are defined in the text. Data for curves: A, reference (*5*); C, reference (*9*), D, reference (*10*); E, reference (*11*).

period of 3×10^9 years, our upper limits are lower than any previous values except in high ranges of mass and energy, as shown in Figs. 1 and 2.

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Magnetic Properties of the Lunar Crystalline Rock and Fines

Abstract. *Magnetic measurements have shown that nondiamagnetic minerals in a lunar crystalline rock of type B are (free Fe^{2+} in paramagnetic pyroxenes) : (antiferromagnetic $FeSiO_3$) : (antiferromagnetic $FeTiO_3$) : (ferromagnetic iron) = 4.3 : 7 : 20 : 0.08 in weight percentage. The abundance of ferromagnetic Fe in the lunar fines is about 7.5 times its abundance in the crystalline rock. The natural remanent magnetization of the crystalline rock of 7.5×10^{-6} emu/g in intensity may not be attributable to its thermoremanent magnetization.*

Mineralogical and chemical compositions of a lunar crystalline rock of type B (10024,22) were examined through a scanning x-ray microprobe to identify magnetic minerals responsible for magnetic properties of the rock sample. Electron microscope scannings and high-power optical microscope surveys were also made to clarify the mutual mineralogical relationships among the magnetic minerals. Main magnetic minerals in the sample have been identified as (i) pyroxenes [(Fe, Mg, Ca)SiO_3], (ii) almost stoichiometric Fe pyroxenes ($FeSiO_3$), (iii) almost stoichiometric ilmenites ($FeTiO_3$), and (iv) almost pure metallic irons. Fine grains of metallic irons are usually included in troilites (FeS).

The magnetization of the rock was measured in magnetic fields from 0 to 30 kilooersteds in a temperature range from 4.2° to 300°K and also in another range from 300° to 1090°K in a highly controlled non-oxygen atmosphere. The results, summarized in Fig. 1, clearly show that the magnetism of the sample consists of four phases: (i) a paramagnetic phase, which may be attributable mostly to free Fe^{2+} in pyroxenes, (ii) an antiferromagnetic phase of almost stoichiometric Fe pyroxene represented by a Néel point at 41°K, (iii) an antiferromagnetic phase of almost stoichiometric ilmenite represented by a Néel point at 57°K, and (iv) almost pure metallic irons represented by a Curie point at about 1040°K. The scanning x-ray microprobe analysis indicated that the metallic irons include such small portions of Ni (<0.2 percent) and Co (<1.2 percent) that the observed Curie point is very close to the established value (1043°K) of pure iron. Troilites surrounding these metallic irons contain 57.5 percent Fe by weight on the average. Since very little Mn^{2+} (~0.2 percent) and almost no Fe^{3+} have been detected in the rock sample, the paramagnetism of the rock can be attributed to Fe^{2+}. Because we know (i) the paramagnetic behavior of free Fe^{2+} in Fe-Mg-Ca oxide minerals such as pyroxene (*1*), (ii) antiferromagnetism of Fe pyroxene (*2*), (iii) antiferromagnetism of ilmenite (*3*), and (iv) ferromagnetism of pure iron (*4*), we attempted a quantitative simulation of the dependence of magnetization of the lunar rock on temperature. The individual referred dependences of phases i to iv on temperature and the simulated magnetization curve are illustrated in Fig. 1, where the assumed weight percentages of the four phases are free Fe^{2+} : $FeSiO_3$: $FeTiO_3$: Fe = 4.3 : 7 : 20 : 0.08. The simulated curve is in good agreement with the observed plots except for temperatures around 50°K. This discrepancy around 50°K may be due to a certain unclarified antiferromagnetism of (Fe, Mg, Ca)SiO_3, which is close to $FeSiO_3$ in chemical composition. The weight percentages of FeO and TiO_2 in the rock are evaluated from the simulation model to be 17.7 percent for FeO and 10.5 percent for TiO_2, which are in approximate agreement with the results of chemical analysis. Further, the simulated curves of magnetization versus the magnetic field for the range of $H = 0 \sim 30$ kilooersteds at various temperatures are in good agreement with observed data. Thus the model of magnetic composition of the lunar rock seems to be in good agreement with all results of its chemical and petrological analyses.

The intensity of natural remanent magnetization of the lunar rock (10024, 22) amounts to 7.50×10^{-6} emu/g. By an a-c demagnetization procedure of every 3-oersted step from 0 to 12 oersteds, the intensity of remanent magnetization is reduced to 88 percent of its initial value, and the scattering of its direction measured at each demagnetization step is within 13° and 9°, respectively, with respect to its declination and inclination. The observed stability may suggest that the remanent magnetization is not simply attributable to a contamination caused by the earth's magnetic field after the arrival of the sample at the earth's surface. However, the intensity and direction of the remanent magnetization are widely different in five separated pieces that were cut from the sample; that is, the remanent magnetization is not homogeneous at all. There is almost no doubt that the remanent magnetization is due to ferromagnetism of fine metallic irons. Experimentally, the thermoremanent magnetization of the sample is saturated with respect to temperature at about 800°C. The specific intensity of the saturated thermoremanent magnetization acquired in a unit magnetic field is 2.90×10^{-4} emu/g