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

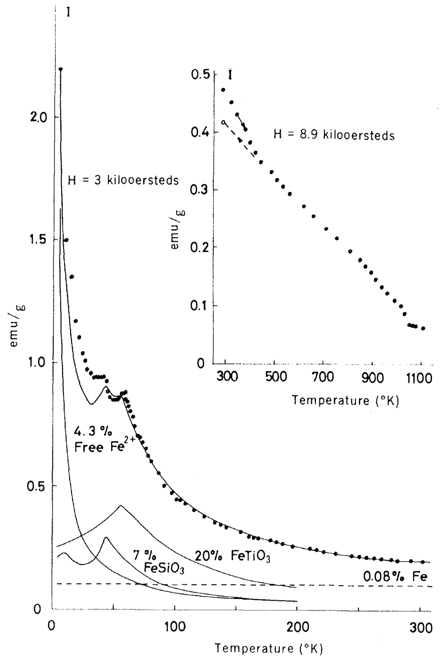
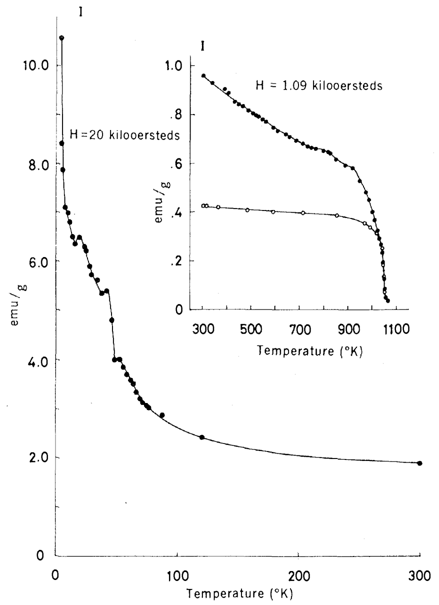


Fig. 1 (left). Magnetization (I) versus temperature (T) for lunar crystalline rock 10024, 22. Solid circles are observed values; unbroken lines are the simulated curve and the basic curves of the dependences of magnetization of Fe^{2+}, FeTiO$_3$ on temperature; the broken line is the basic dependence of the Fe particle on temperature.

Fig. 2 (right). Magnetization (I) versus temperature (T) for lunar fines 10084,89. Solid circles are observed values before heating to 800°C; open circles are observed values after heating to 800°C.



oersted^{-1}. If the observed natural remanent magnetization is assumed to be the thermoremanent magnetization, the magnetic field during the cooling period must be about 2600 γ. This value seems hardly probable. Moreover, the heterogeneity of the remanent magnetization is incompatible with the homogeneity of the thermoremanent magnetization. The saturated magnetization and the saturated isothermal remanent magnetization of the ferromagnetic component of this rock at room temperature are 1.55×10^{-1} emu/g and 1.52×10^{-3} emu/g, respectively; these values are about 2×10^4 and 2×10^2 times as large, respectively, as the natural remanent magnetization.

Although the cause of the observed natural remanent magnetization has not yet been identified, it seems likely that the remanent magnetization might be caused by (i) an instantaneous local magnetic field generated by some kind of lightning, (ii) the piezomagnetic effect caused by meteorite impacts in the presence of a weak solar wind magnetic field, or (iii) a simple heterogeneous distribution of fine single-domain particles of metallic irons.

The same sequence of analyses was used for lunar fines (10084,89). Both x-ray microprobe and magnetic analyses have shown that magnetic minerals in the lunar fines are basically the same as in the lunar crystalline rock 10024,22; that is, that magnetic minerals in the fines are paramagnetic pyroxenes, antiferromagnetic Fe pyroxenes, antiferromagnetic ilmenites, and metallic irons (see Fig. 2). However, the saturation magnetization of the ferromagnetic component (metallic iron) of the lunar fines at room temperature amounts to 1.17 emu/g, which is about 7.5 times as large as the same magnetic parameter of the crystalline rock. The curve of magnetization versus temperature in Fig. 2 also indicates that the abundance of antiferromagnetic ilmenite is less and the abundance of antiferromagnetic and paramagnetic pyroxenes is more in the lunar fines than in the crystalline rock.

Analyses of the magnetization versus magnetic field curves at various temperatures have shown that about 20 percent of metallic iron in the crystalline rock and about 50 percent of metallic iron in the fines is superparamagnetic and in the form of very fine grains, which are less than 100 Å in mean diameter and which are superparamagnetic at temperatures above room temperature. These fine grains seem to be easily oxidized to become wüstite (FeO) at high temperatures, even in a high vacuum chamber. The remaining metallic irons are considered to be of fairly large size, and their magnetization curve is subjected to the shape demagnetization effect. For instance, five pieces of 92 spherules separated from 150 mg of the lunar fines are iron spherules with diameters that range from 20 to 100 μm and with Fe contents that range from 85 to 90 percent (±5 percent).

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Magnetic Resonance Properties of Some Lunar Material

Abstract. *Paramagnetic resonance spectra of Apollo 11 fines and rocks were measured at 9 and 35 gigahertz and at 4°, 80°, and 300°K. At both frequencies the material has an intense absorption at* $g = 2$, *with a line width of ~950 gauss. Fe ions with strong exchange interactions produce this resonance. A comparison of the resonance absorption due to* Fe^{3+} *showed that the energy of the crystal field interaction was ~0.1 per centimeter.* Mn^{2+} *was identified in several samples, and an absorption at* $g = 1.89$ *was tentatively attributed to* Ti^{3+}. *The nuclear magnetic resonance spectra of* ^{27}Al *had a distribution of asymmetry parameters* η *ranging from 0.25 to 0.75 and had nuclear quadrupole coupling constants* e^2qQ/h *of approximately 3 megahertz.*

Elements present in lunar material (Apollo 11) with the highest relative abundance, which would be expected to produce electron paramagnetic resonance absorption (EPR), are Ti, Cr, Mn, and Fe (*1*). Ti^{3+}, Mn^{2+}, and Fe^{3+} have the highest probability of being detected (*2*). Exposure of rocks and