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MAGNETIC CHARACTERISTICS OF LUNA 16 AND 20 SAMPLES

By A. STEPHENSON, D. W. COLLINSON and S. K. RUNCORN, F.R.S.
Department of Geophysics and Planetary Physics, School of Physics, University of Newcastle upon Tyne

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CONTENTS

The natural remanent magnetization of rock fragments L2015,3,1 and L2015,3,11 was found to be $< 3.5 \times 10^{-7}$ and $< 40 \times 10^{-6}$ G cm^3 g^{-1} respectively. The former sample, from isothermal remanent magnetization (i.r.m.) measurements, contained very little iron, while the latter sample had a much higher iron content and exhibited i.r.m. characteristics similar to breccia samples from Apollo missions. Susceptibility and i.r.m. measurements have shown that Luna 16 fines contain about four times as much iron as Luna 20 samples and that the light fractions from the density separations contain about twice as much iron as the heavy fraction. Like the Apollo fines, the magnetic behaviour of Luna 16 and 20 fines is dominated by small iron particles, most of which are superparamagnetic and of grain size less than about 13 nm.

Introduction

Magnetic studies on lunar samples fall into two main categories. The first is the study of the magnetic properties of the constituent minerals and the behaviour of these when present in a rock in the form of particles of different size and shape. The second is the investigation of any natural remanence which the rock may possess and the determination from its magnetic characteristics of the mechanism by which it became magnetized and the strength of field which was then present.

The results on Apollo lunar samples have shown that the lunar spinels which are present, unlike spinels in terrestrial basalts, are incapable of holding a remanence at room temperature because this exceeds their Curie points. These are low because of the presence of ions such as Fe^{2+} and Cr^{3+} which interact much less strongly than the Fe^{3+} ions which are present in terrestrial spinels. The only major carrier of remanence in lunar rocks is metallic iron which has been found to be present in the form of particles ranging in size from several nanometres to hundreds of micrometers and these dominate the magnetic properties.

Because of the very small amounts of the Luna material available, palaeointensity determinations such as have been carried out on Apollo samples (Stephenson, Collinson & Runcorn 1974) have not proved possible on the two rock chips investigated, but some of the magnetic measurements done on Apollo fines samples have been carried out on the various fractions of Luna fines obtained by density separation.

Magnetic characteristics

(a) *Rock fragments*

The natural remanent magnetism (n.r.m.) of two rock fragments was investigated by means of a small scale magnetometer (Collinson & de Sa 1971). L2015,3,1 (11.3 mg) was a whitish, angular chip with some black crystalline inclusions. The n.r.m. of the fragment was $< 3.5 \times 10^{-7}$ G cm³ g⁻¹† and there was no detectable growth of viscous remanent magnetism in a weak field. The black inclusions are magnetic to the extent that they show susceptibility effects, with susceptibility in the range 10^{-2} to 10^{-3} G cm³ g⁻¹ Oe⁻¹‡; this value, together with the fact that no detectable isothermal remanence was acquired in a high field (3500 Oe), suggests that there is a negligible amount of iron in this fragment, and that the black material does not contribute any n.r.m. to the parent rock.

L2015,3,11 (6.6 mg) was a breccia fragment, with sparsely distributed black opaque material visible in the surface. The minimum remanence detectable with the magnetometer in this fragment is about 40×10^{-6} G cm³ g⁻¹, and the observed value was less than this. The shape of the isothermal remanence against field curve was very similar to that obtained from similar Apollo rock samples, as was also the saturation intensity, 0.97×10^{-3} G cm³ g⁻¹. Magnetically, this fragment appears to be very like the various breccia rocks returned by the Apollo missions.

(b) *Fines separates*

Several fines samples were investigated. Those which had been subjected to density separation were L1627,10,1; L1627,11,1 and Luna 20 samples L2015,10,1 and L2015,11,1. They were of size 48–250 μm and the samples coded 10 were the lighter fractions removed after density separation in a liquid of density 2.96 for the Luna 16 samples and 2.78 for the Luna 20 samples. The masses of each sample were 12 mg (Luna 20) and 18 mg (Luna 16).

Measurement of the room temperature low field susceptibility yielded results which were similar to values found for Apollo fines. The susceptibilities of these four samples are shown at the top of table 1, the Luna 16 samples being stronger than the Luna 20 samples by a factor of about 4. It is to be noted that the density separation is remarkably effective in separating out a strong magnetic extract which is present in the lighter fraction. This light fraction for both Luna 16 and 20 samples was a factor of about 2.6 times as strong in susceptibility as the heavy fraction.

A Curie point determination on L2015,10,1 (figure 1) sealed in an evacuated quartz tube and using a field of 7 kOe indicated the presence of metallic iron ($T_c \simeq 770$ °C) as in the case

† 1 G cm³ g⁻¹ = 1 A m² kg⁻¹.
‡ 1 G cm³ g⁻¹ Oe⁻¹ = 4π10⁻³ m³ kg⁻¹.

of Apollo fines samples, and after the heating a similar decrease of the induced moment to 54 % of its initial value occurred, presumably due to partial oxidation. This is also similar to the behaviour of Apollo fines samples.

The acquisition of isothermal remanent magnetization (i.r.m.) was measured for the four samples. At 4000 Oe the samples were within 7 % of saturation (i.r.m.$_s$), the extrapolated saturation values being shown in table 1. The Luna 16 samples were thus stronger in i.r.m. than the Luna 20 samples by a factor of about 4.5 and the light fractions were about 2.1 times as strong in i.r.m. as the heavy fractions. Five further fines samples (see table 1) were also measured. These had i.r.m. curves identical in shape to the density separated samples, suggesting that the various fractions contained essentially the same iron particle sizes. The shape of the curves was also identical to that obtained for Apollo 11 fines which have been studied in detail (Stephenson 1971). Figure 2 shows the average curve obtained for the Luna samples together with the result for Apollo 11 fines.

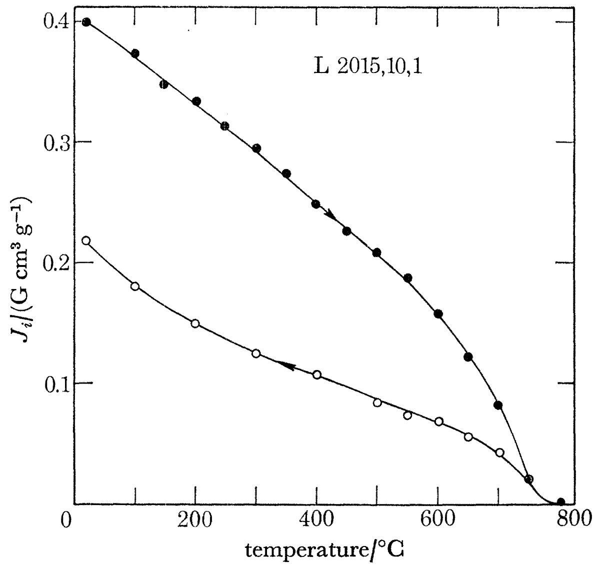

FIGURE 1. Variation of induced magnetization in 8 kOe with temperature for sample L2015,10,1.

TABLE 1. ROOM TEMPERATURE VALUES OF INITIAL SUSCEPTIBILITY (χ_i), EXTRAPOLATED SATURATION i.r.m. (i.r.m.$_s$) AND INDUCED MAGNETIZATION IN 10 kOe (J_i)

sample	description	$10^3\ \chi_i$ / G cm³ g⁻¹ Oe⁻¹	10^3 i.r.m.$_s$ / G cm³ g⁻¹	J_i (10 kOe) / G cm³ g⁻¹
L1627,10,1	light fraction, $48 < d < 250$ µm	3.9	156	1.98
L2015,10,1	light fraction, $48 < d < 250$ µm	1.0	36	0.42
L1627,11,1	heavy fraction, $48 < d < 250$ µm	1.4	77	1.44
L2015,11,1	heavy fraction, $48 < d < 250$ µm	0.4	17	1.24
L1627,3	handpicked fraction, $d > 250$ µm	1.7	88	1.12
L1627,7	$d < 48$ µm	2.7	97	1.02
L2015,7	$d < 48$ µm	0.9	31	0.57
L1627,9	finest fines	4.0	149	1.89
L2015,9	finest fines	0.9	31	1.26

Measurement of the induced magnetization with field yielded similar results for seven of the nine samples, saturation failing to be reached in 12 kOe. Figures 3 and 4 shows the results obtained on Luna 16 and 20 samples respectively. This behaviour is similar to Apollo 11 fines (Runcorn *et al.* 1970) and indicates the presence of parmagnetism or very small superparamagnetic particles. Samples L1627,7 and L2015,10,1, however, both saturated in about 4 kOe indicating the absence of this component. Larger superparamagnetic particles are, however, undoubtedly present in L2015,10,1 since all of the four density separated samples (the others were not measured) exhibited logarithmic time decay of their saturated i.r.m. of about 4.5% per decade. This is due to relaxation of that part of the spectrum of the single domain grain distribution which is on the super-paramagnetic-stable boundary (i.e. at a diameter of about 13 nm). This also suggests that similar iron particle sizes are present in the various density separated fractions.

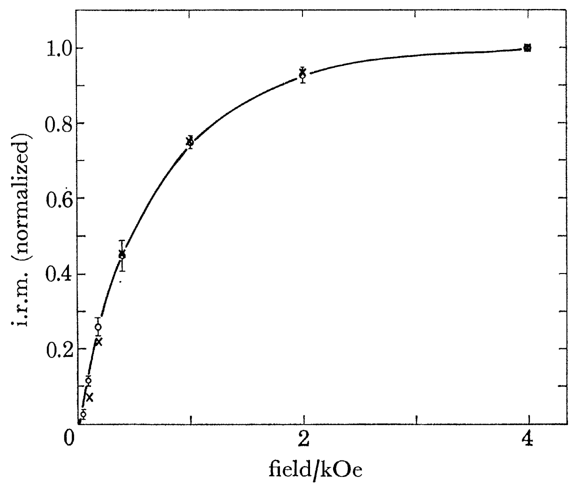

FIGURE 2. Average acquisition of i.r.m. curve for the 9 Luna fractions showing standard deviation of intensities which are normalized to the value in 4 kOe. Apollo 11 fines result is also shown ×.

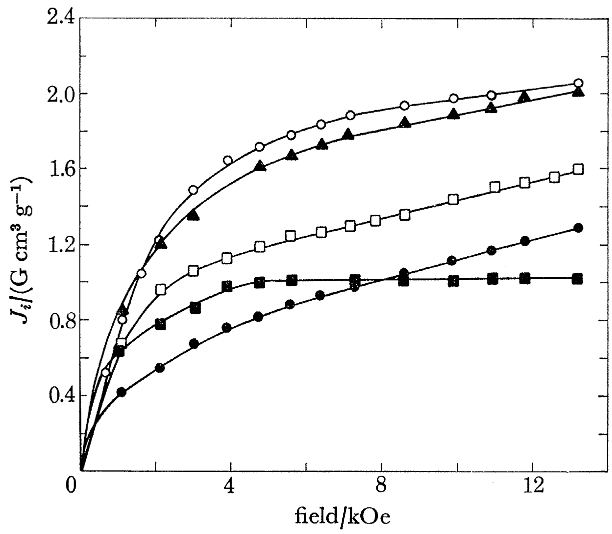

FIGURE 3. Variation of induced magnetization with field for Luna 16 fractions. ○, L1627,10,1. □, L1627,11,1. ●, L1627,3. ■, L1627,7. ▲, L1627,9.

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CONCLUSION

Observations that the i.r.m. curves, the induced magnetization curves, and the logarithmic decay of saturated i.r.m. were very similar to Apollo 11 fines sample suggests that a similar iron particle size distribution is present in the density separated Luna fractions, i.e. $N(v) \propto 1/v^2$ (Stephenson 1971), where N is the number of grains of volume v and the relation is valid over particle diameters covering at least the range 3–13 nm. A similar distribution was also found

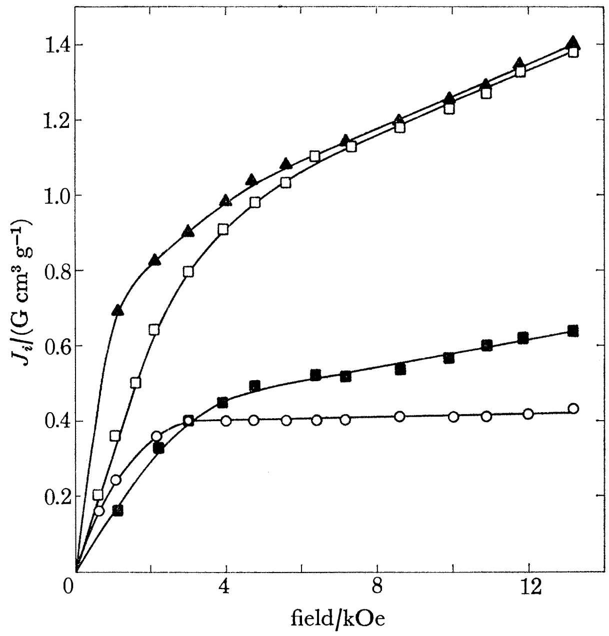

FIGURE 4. Variation of induced magnetization with field for Luna 20 fractions. ○, L2015,10,1. □, L2015,11,1. ■, L2015,7, ▲, L2015,9.

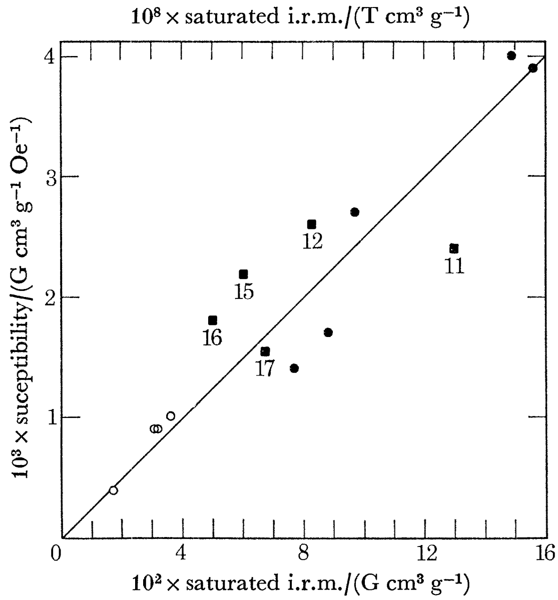

FIGURE 5. In itial susceptibility plotted against saturated i.r.m. for Luna 16 fractions (●) and Luna 20 fractions (○). Results for several Apollo fines samples are also shown for comparison (■).

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for Apollo 15 fines sample 15101,75 (Collinson, Stephenson & Runcorn 1973) and has also been found for an Apollo 14 breccia 14313 (Dunlop, Gose, Pearce & Strangway 1973). This interpretation is also supported by the observation that while the different fractions varied in susceptibility and saturated i.r.m. by an order of magnitude, the ratio of the two parameters remained essentially constant (figure 5). This suggests that different quantities of a similar spectrum of iron grain sizes is present in most of the fractions. Various Apollo fines samples are also shown for comparison.

The iron content of the Luna fractions can be estimated from the susceptibility results of table 1 if it is assumed that the single domain iron content, most of which is in the superparamagnetic state with grain size less than about 13 nm, is proportional to the susceptibility. Taking as a reference Apollo 11 fines, which had a susceptibility of 2.4×10^{-3} G cm^3 g^{-1} Oe^{-1} and an estimated iron content from magnetic measurements of 0.9 % ($\pm$ 0.3 %) (Stephenson 1971), the iron content of the Luna fractions varies from about 0.15 % for L2015,11,1 to 1.5 % for L1627,9.

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