FERROMAGNETIC RESONANCE PROPERTIES OF LUNAR FINES: APOLLO 16

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Electron magnetic resonance (EMR) spectra of lunar fines on which measurements have been made from the Apollo sites (11 through 16) are dominated by an intense absorption whose intensity, I, and width, ΔH, have a temperature dependence characteristic of ferro- and/or ferrimagnetic phases. The intensity of this absorption in some Apollo 14 breccias was found to decrease with increasing degree of consolidation and recrystallization.[1] On the basis of temperature and frequency-dependent characteristics of the absorption in Apollo 11 samples, it was suggested[2] that submicron Fe particles were the source of the absorption. However, the characteristics of the dominant absorption in Apollo 14-15[1,3] and 16 (see below) samples deviate considerably from those expected for such particles. On the basis of these deviations, it has been suggested[1,4] that ferric oxide phases might be present in the soil samples. Agrell[5] identified goethite in an Apollo 14 sample, abundant ferric oxide (goethite) has been observed in an Apollo 16 sample,[6] and Cernan and Schmitt reported[7] the occurrence of orange soil at the Apollo 17 site whose color may be due to ferric oxide. A sample of Apollo 16 soil (61221-11) has been observed to emit H_2O upon heating.[8] It was suggested by Weeks et al.[1] that comet impacts could furnish oxidizing conditions required for the formation of ferric oxide phase, a suggestion now advanced[8] to explain the emission of H_2O from an Apollo 16 sample.

The line width, ΔH, and specific intensity, I, of the dominant EMR absorption of 12 Apollo 16 samples and one Apollo 14 sample of fines, < 0.1 mm, are given in Table I. The range of ΔH is 540 to 640 gauss with $\Delta H_{av.} = 583$ gauss while the intensity ranges from 43 to 248 arbitrary units. Neither ΔH nor I is correlated with the grey tone of the samples although 67701-29, which has the least grey tone, does have the least intensity. With the exception of this sample, the concentration of the magnetic phase or phases responsible for this absorption has the same range as has been observed in other Apollo samples[3] (the values given in Ref. 3 are in the same arbitrary units), while the average value of ΔH is smaller than this value for other Apollo samples. The Apollo fines samples have average values of ΔH which are ranked ΔH(A-11) = 950 > ΔH(A-12) = 770 > ΔH(A-15) = 700 > ΔH(A-14) = 613 > ΔH(A-16) = 583 gauss and for which the range of values about each average overlap in only the Apollo 14 and 16 samples. (The number of Apollo 15 samples measured was only two.) A second significant difference between the Apollo 11 and Apollo 12 samples and the Apollo 14 and 16 samples is the frequency dependence of ΔH which is evident from the ratios ΔH(35 GHz)/ΔH(9 GHz) $\approx$ 1.2 for the Apollo 11 samples and $\sim$ 1.5 for the Apollo 16 samples.

The difference in the temperature dependence of ΔH is also evident from the data given in Fig. 1. In the range of temperatures from $\approx$ 175 to 300°K d $\Delta H/dT \approx$ 1.1 for the Apollo 11 sample, $\approx$ 1.6 for the Apollo 15 sample, $\approx$ 1.8 for the Apollo 14 sample and $\approx$ 2.0 for the two Apollo 16 samples: a plateau is observed in the increase in ΔH with decreasing temperature between 150 and 175°K. The plateau and subsequent rapid increase in ΔH at a slightly lower temperature are most clearly evident in data points for the Apollo 11 sample for which there is very rapid change in ΔH between 140 and 152°K. In the data

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on the Apollo 15 sample the plateau occurs at 175°K, at 150° in the two Apollo 16 samples, and is not resolved in the data for the Apollo 14 sample.

The line width, ΔH, of the EMR absorption of an ensemble of non-interacting ferro- or ferrimagnetic particles randomly oriented with respect to an applied field, H, is determined by K_1/M_s, where K_1 and M_s are the crystalline anisotropy energy and saturation magnetization, respectively, and by the demagnetizing fields due to shape anisotropies. For particles of iron and of alloys of iron, K_1M_s is only weakly dependent upon spectrometer frequency, has a temperature dependence in the 100 to 300°K temperature range which gives $d\Delta H/dT \approx 1$ with no discontinuities,[2,9] and gives at 300°K $\Delta H \approx 800$ gauss if the particles are perfect spheres, and $800 < \Delta H < 26{,}000$ gauss for other shapes.[1] The data given above are not consistent with an iron particle hypothesis. Due to the relative and absolute magnitudes of K_1 and M_s for some ferrites, demagnetizing factors due to variations of particle shapes will be less important for these compounds. Ferrites have K_1's that are a function of composition and can vary from positive to negative values, e.g., X Fe_2TiO_4 • (1 - X) Fe_3O_4.[10] Since one component of this compound, Fe_2TiO_4, is a relatively abundant mineral in lunar soils, such a ferrite is a distinct possibility. Petrographic identification of such compound would be difficult if particles of it had dimensions < μm. There is now evidence for ferric oxide compounds in an Apollo 14 sample,[5] in Apollo 16 samples[6] and in Apollo 17 samples,[7] hence the proposal that at least a portion of the intense EMR absorption observed in all Apollo soils thus far measured is due to ferric oxide phases is not only consistent with all of the EMR parameters but also with these observations.

TABLE I

SAMPLE (< 0.1 mm)	WEIGHT, ω (mg)	LINE WIDTH, [1] ΔH (at 9 GHz, gauss)	LINE WIDTH, [1] ΔH (at 35 GHz, gauss)	INTENSITY, [2] I (mg^{-1}, arbitrary units)
60051-14-1	9	588	833	9
60007-225-1 [3]	5	575	700	7
60603-2-1 [3]	7	575		8
61181-9-1	4.6	560	859	9
62242-2-1	8.5	640		25
64421-30-1	6.4	560		15
65701-17-1	6.4	592		14
66043-3-1	4.6	565		10
66081-22-1	4.0	600		19
66081-22-2	5.0	600		19
66031-7-1	9.0	613	984	22
67701-29-1	18.9	540		4
14003-60-4	5.0	633		16

(1) The line width, ΔH, is measured between the inflection points (maximum and minimum amplitude of dI/dH curve) of the absorption. (2) Intensity is calculated from the relation $I = \Delta H^2 A/\omega$ where ΔH, A and ω are line width, amplitude, measured in chart units, of dI/dH curve between inflection points of

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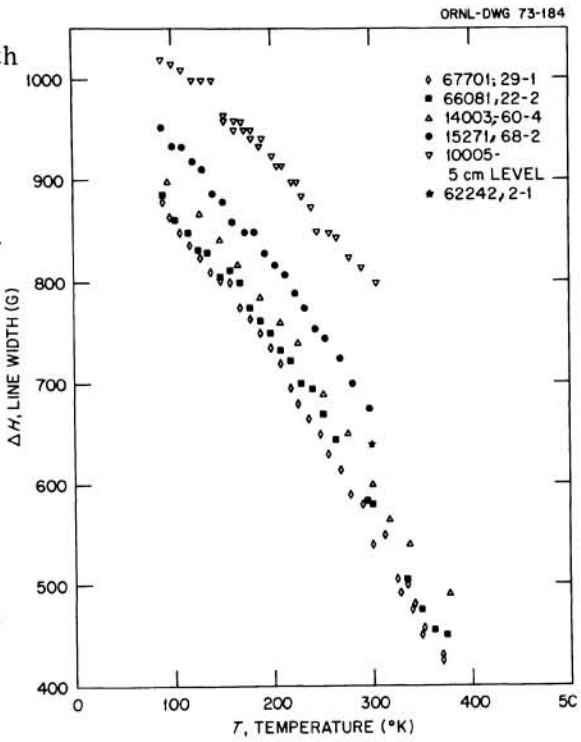
absorption, and sample weight respectively. All measurements were made with a constant modulation amplitude of the magnetic field, microwave power, and microwave cavity loss factor. I has been normalized to constant signal amplifier gain. The error in a given I is ±20%. This method of estimating intensity eliminates contributions from ferromagnetic absorptions distributed over a range of field greater than ΔH. (3) Particles, < 0.1 mm, present in the 2-4 mm particles supplied, were collected for these measurements.



Temperature Dependence of Line Width, ΔH, of "Characteristic" EMR of Soil Samples.

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