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Ferromagnetic Resonance g -Factor Measurement on LUNA 20 Soil

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Abstract. FRM g -factor measurements were performed on LUNA 20 soil samples at microwave frequencies 9–87 GHz at room temperature. A frequency independent value $g = 2.0815 \pm 0.0035$ was obtained by the experiments at higher frequencies (50–87 GHz). g -values obtained at lower frequencies indicate an incomplete magnetic saturation of the ferromagnetic component of the soil at external magnetic field intensities lower than approx. 1.5 T.

Key words: Ferromagnetic resonance measurements – LUNA 20 soil – g -factor frequency dependence

Introduction

In recent years several ferromagnetic resonance (FMR) investigations have been performed on samples of lunar matter and fine grained, spherical particles of iron (with diameters smaller than approx. 30 nm) have been found to be predominantly responsible for the FMR absorption effect (see Morris 1978; Goldberg et al. 1979; Pillinger 1979, and references quoted therein). In most of these studies the main attention was directed to the problem of the FMR absorption intensity, this quantity being closely connected with the concentration of iron metal and with the surface exposure (maturity) of the lunar material (Morris 1976; Housley et al. 1976). Little interest has been given to the evaluation and discussion of other parameters determined by the FMR method, e.g. there exists a considerable lack of precise g -factor data (with an accuracy better than 0.5%) for various lunar materials.

The FMR spectroscopic splitting factor (g -factor) is a measure of the ratio of the orbital and spin contributions to the ferromagnetic moment of the substance and its value lies in the case of the transition (3d) ferromagnetic metals and alloys in the range 2.0–2.5 (Kittel 1949; Chicazumi 1964). The g -factor data are derived from FMR experiments (Bhagat 1973), by means of the Kittel's equation (Kittel 1948) in the form

$$v = \gamma' (H_e + \delta H). \quad (1)$$

This formula is valid for the case of a spherical, fully homogeneously magnetized specimen, where the static magnetization vector is aligned along the direction of the external

static magnetic field intensity H_e ; the diameter of the sample is assumed smaller than the penetration depth of the electromagnetic radiation into the material (in order to avoid the influence of the exchange – conductivity effects, Ament and Rado 1955, on the resonance condition (1)). v denotes the microwave frequency, γ' the relative spectroscopic splitting ratio, $\gamma' = g\mu_B/h$, μ_B the Bohr magneton, h the Planck's constant. δH is the field shift caused by relaxation damping and surface pinning effects, and by the magnetocrystalline and magnetostriction effects, and is usually evaluated theoretically (Macdonald 1951; Frait and MacFaden 1965; Frait and Gemperle 1971). SI units are used in this paper, the intensity of the magnetic field being given in Tesla (Crangle 1977).

For pure iron the g -factor has been established as $g = 2.088 \pm 0.008$ (Frait and Gemperle 1971; Frait 1977). Alloying pure iron with nickel, for example, increases the g -value (Meyer and Asch 1961; Bauer and Wigen 1972), combining with silicon decreases it (Frait and Fraitová 1977; Griscom et al. 1979). Therefore, by performing precise FMR g -factor measurements one should obtain additional information about the material, which is the main carrier of ferromagnetism in the lunar materials. The aim of this paper is to present the results of such measurements on soil samples obtained by means of the automatic station LUNA 20. Special attention is given to fulfilling the validity of the assumptions under which Equation (1) was theoretically evaluated, especially the requirement for complete and homogeneous magnetization of the ferromagnetic component in the regolith. A field/frequency extrapolation method (Frait and MacFaden 1965; Frait and Gemperle 1971) was used for the determination of the g -factor value.

Conditions for Homogeneous Magnetization

The fine-grained iron metal which is present in the soil is formed by a process of reduction of the iron containing compounds (ferrous oxides and silicates) due to the local impact of solar wind particles and micrometeorites on the lunar surface. The bombardment process further causes the remelting of soil particles and the aggregation of iron atoms into minute single crystalline spheres (Housley et al. 1976; Morris 1978; Pillinger 1979). The diameters of spherical particles, which are homogeneously magnetized (where the corresponding FMR measurements can be evaluated by

means of Eq. (1)) are given for the interval 4–30 nm at a magnetic field intensity of 0.3 T (*X*-band FMR measurements at 9 GHz, Housley et al. 1976). The lower limit of this range, established as the diameter at which the transition from a superparamagnetic to ferromagnetic state occurs, can be computed more accurately as 1.8 nm (at 0.33 T), according to Chicazumi 1964) or as nearly zero (at 0.33 T, according to Stephenson 1971 a, taking coercive force lower than 0.66 T). Magnetic and transition electron microscopy investigations of lunar soils (e.g. Stephenson 1971 b; Housley et al. 1973; Friebele et al. 1974; Pillinger et al. 1975) reveal that most of the iron particles are spherical with diameters less than 12 nm.

At this point we would like to point out that, in reality, the individual particles of ferromagnetic metal in the soil are most probably far from the state of perfect single crystals, because the reduction and remelting of the metal by bombardment is a highly nonequilibrium process and the cooling rate of metal particles and of their surrounding material after remelting is very high (a type of quenching process occurs, especially at sites situated in the solar shadow). Therefore the following factors should be considered in the process of evaluation of more accurate *g*-factor data from of the FMR measurements:

1. Due to nonequilibrium conditions during the growth of the iron particles, single crystals will have been formed containing many defects of crystallographic structure both inside and at the surface of the ferromagnetic particles, mainly because of the existence of the α - γ phase transition in iron (at 1,180 K in thermal equilibrium conditions) and local demagnetizing (stray) fields will occur at such defects (their maximum value for pure iron equals the saturation polarization value $J=2.1$ T). Further, the resulting magnetocrystalline energy of the particle will be lowered (compared to the case of an ideal single crystal) because of the misalignment of the crystallographic directions (mosaic structure) inside the particle. Moreover, Pillinger and Eglington (1977) and Pillinger et al. (1978) have shown that the presence of the iron metal in the regolith is associated with quantities of carbon (up to 0.2 wt% of Fe metal). As the solubility of carbon in iron metal is very low (from 200 ppm, Bozorth, 1951, to 20 ppm, Merta, 1981) the excess carbon will be contained in (or at the surface of) the iron particles in the form of clusters and precipitates (Merta, 1981) and will be a source of further magnetic inhomogeneities.

2. The iron particles are embedded inside individual grains of soil, mostly in glassy agglutinates (Agrell et al. 1970; Housley et al. 1973; Pillinger et al. 1975). As the thermal expansion coefficients of iron and of the surrounding material are different, stresses will arise inside (and at the surface of) the iron particles during their formation introducing effective magnetostrictive fields (Macdonald, 1951). The absolute magnitude of these fields can be estimated from FMR measurement of iron thin films, which have been evaporated in a vacuum on glass substrates (Frait 1962), as 0.1 T (maximum). Internal effective fields of the same order of magnitude have also been found at the border between iron single crystal and iron oxide by Frait et al. (1975).

The above mentioned effects will cause inhomogeneous magnetization or the presence of multidomain structure (Kronmüller 1977) inside the ferromagnetic sphere, even in the case of diameters smaller than the limit computed for the ideal crystals (i.e. smaller than approx. 30 nm at

0.3 T, Frei et al. 1957; Housley et al. 1976), or at external magnetic field intensities higher than the ideal demagnetizing field value (H_d) for an iron sphere (i.e. $H_d \doteq 0.72$ T). In such cases the application of the Kittel's formula for the evaluation of the *g*-factor at lower frequencies will be not fully substantiated and may lead to inaccurate results. The defects will also cause deviations in the shift and form of the FMR absorption line compared with the case of a set of many randomly oriented crystals with perfect crystalline structure. As the magnetization inhomogeneities are functions of the external static field intensity, a fictitious frequency dependence of the *g*-factor values should be observed in the case of FMR measurements at low field intensities. Most of the FMR studies on lunar regoliths were performed at *X*-band (approx. 9 GHz, $H_e \doteq 0.3$ T) and only a few resonance field data exist at higher frequencies (35 GHz, Tsay et al. 1971, Apollo 11; Goldberg et al. 1979, Apollo 16). By using these values we may find an indication of a *g*-factor decrease at higher frequencies by applying the analysis of FMR data in polycrystalline samples (Standley and Stevens, 1965). In simulated lunar materials the effects of an incomplete magnetic saturation (presence of the magnetic domain structure) were clearly shown by Griscom et al. (1975), Griscom (1980) and Friebele et al. (1977).

In order to establish a fully homogeneous magnetization of the ferromagnetic particles in the soil, and in order to obtain precise parameters (e.g. *g*-factor) from the FMR data, the resonance measurements should be performed with external static magnetic field intensities as high as possible. This means that the microwave frequency of the measurement should be in the range of mm wavelengths. The results of such measurements are presented in this paper.

Before going further, let us note that some authors (e.g. Goldberg et al. 1979) conclude that at high microwave frequencies the decrease of the penetration depth of electromagnetic radiation into the ferromagnetic metal (skin depth) negates some of the advantages of measurements at high magnetic field intensities. However, direct computation of the skin depth values for the case of plane semi-infinite ferromagnetic space, based on the macroscopic FMR theory (e.g. in the form presented by Ament and Rado 1955) shows that the frequency dependence of skin depth in the FMR region, δ_R , is less pronounced than for the case of normal skin depth far from the resonance δ , and that at the frequency of 80 GHz δ_R amounts to about 45 nm for pure iron. As quoted previously, most of the ferromagnetic particles have diameters much less than that value, therefore the penetration of electromagnetic waves is fully sufficient up to 100 GHz.

Experimental Method, Results of Measurements

The FMR measurements were performed using a microwave spectrometer, built by one of us (Z.F.), which works in the frequency region 8–100 GHz and at static magnetic field intensities up to 3.1 T. Several waveguide sets were used in order to cover the frequency range, low power (10–50 mW) klystrons and backward-wave oscillators were used to generate the microwave radiation. The frequency was measured by means of a heterodyne microwave counter with an accuracy of 0.2 ppm, the short time stability (1 min) of the microwave generators was better than 5 ppm. The static magnetic field was generated by an 15'' electromagnet (Varian), equipped with a digital stabilizer (Varian),

the pole pieces were tapered to a final diameter of 70 mm and a gap of 25.4 mm. The long time (1 h) stability of the field amounted to 1 ppm, the absolute calibration of its intensity was performed by a nuclear magnetic resonance magnetometer (marginal-oscillator type with probes of H₂O and D₂O solutions doped by paramagnetic ions, Frait et al. 1973) and by using precise electron paramagnetic resonance *g*-factor standards (Frait and Gemperle 1977) with an accuracy better than 10 ppm. The soil samples were placed in thin walled quartz capillaries with an inner diameter of 0.7 mm; the capillaries were mounted in a shorted waveguide section (no microwave cavities were used) at the location of maximum microwave magnetic field intensity. The static magnetic field was modulated by an auxiliary a.c. field of a low intensity (115 kHz, 0.02 mT), the microwave radiation reflected from the sample holder was decoupled by means of a directional junction. Low noise silicon diodes were used as detectors, the a.c. output voltage at the diode was amplified by a narrow-band low-noise preamplifier and by a lock-in detector; the FMR signal at the lock-in detector output was proportional to the field derivative of the microwave magnetic absorption of the measured material and its dependence on the external static field intensity was plotted on an *X*-*Y* recorder (Poole 1967).

The soil material was collected by the automatic station LUNA 20 at a typical highland region on the Moon (latitude 3°32'N, longitude 56°33'E) near the crater Appolonius C between Mare Fecunditatis and Mare Crisium. For a complete description see Vinogradov (1973), Pillinger and Gowar (1977), Stephenson et al. (1977).

The FMR measurements were performed on five samples of various masses (0.8 to 1.9 mg), at room temperature and at several microwave frequencies in the range 9–87 GHz. A fine-grained fraction (<50 μm) of the soil was studied, separated by a dry sieving method. The resonance static field intensities (H_e) and microwave frequency values (ν) measured in the individual experiments are shown in Table 1. The resonance line width values were determined as field differences between the inflection points of the line, they amounted to 75±5 mT (at 35 GHz) and to 80±5 mT (at 86 GHz), respectively.

Evaluation of Measurements; Discussion of Results

Having at our disposal the exact values of resonance fields and frequencies, the *g*-factor data can be evaluated by means of Equation (1). For this procedure the values of the resonance field correction δH have to be known. We have already quoted the mechanisms causing the resonance field shift and we have to compute (or in the worst case to estimate) their contributions to δH . For iron, the shift due to the intrinsic damping mechanism and to the intrinsic surface pinning is very small (of the order of 10 ppm) because of the small values of Landau-Lifshitz damping constant and intrinsic surface anisotropy of the Néel type (Frait and Fraitová 1980). The influence of exchange surface pinning caused by the surface coating of iron particles with iron oxide is also negligible, because at room temperature the FeO is above the Néel point (Meiklejohn 1958). As far as magnetostriction effects are concerned we shall assume that, in the case of many randomly oriented ferromagnetic particles in a nonferromagnetic matrix, the intensities and the directions of the effective magnetostrictive fields are also distributed randomly and their total contribution to the field correction is zero; they will cause only

Table 1. Sets of the results of measurements performed on five samples at various frequencies. Each set consists of three numbers, representing the frequency of measurements (in GHz), the intensity of external field at resonance (in T) and the *g*-factor value, respectively.

Sample	1	2	3	4	5
Frequency range (GHz)	Frequency/Resonance field/ <i>g</i> -factor $\nu(\text{GHz})/H_e(\text{T})/g$				
9	9.2099	9.2099	9.2101	9.2101	9.2101
	0.3167	0.3159	0.3168	0.3165	0.3164
28	2.1296	2.1351	2.1303	2.1324	2.1331
	28.7730	28.7730	28.7732	28.7731	28.7731
	0.9910	0.9895	0.9911	0.9905	0.9903
36	2.0911	2.0943	2.0909	2.9222	2.9264
	36.5080	36.5081	36.5081	36.5080	36.5080
	1.2580	1.2580	1.2570	1.2590	1.2600
46	2.0866	2.0866	2.0865	2.0862	2.0833
	46.5814	46.5814	46.5814	46.5810	
	1.6020	1.6025	1.6030	1.6036	
50	2.0878	2.0876	2.0865	2.0858	
	50.6702	50.6701	50.6700	50.6711	
	1.7460	1.7465	1.7455	1.7450	
60	2.0817	2.0820	2.0835	2.0842	
	59.5900	59.6072			
	2.0545	2.0535			
70	2.0803	2.0820			
	69.5673	69.5673	70.0409	70.0388	70.0386
	2.3980	2.3982	2.4120	2.4130	2.4123
80	2.0796	2.0795	2.0816	2.0807	2.0813
	79.8173	79.8172	79.8173	79.8174	
	2.7450	2.7480	2.7475	2.7480	
85	2.0832	2.0813	2.0817	2.0813	
		85.7369	85.7367	85.7365	
		2.9494	2.9504	2.9512	
87		2.0825	2.0818	2.0811	
	86.8170	86.8171	86.8171	86.8171	
	2.9905	2.9892	2.9890	2.9880	
	2.0797	2.0806	2.0808	2.0815	

a certain FMR line broadening. However, the influence of the magnetocrystalline anisotropy energy is large in the case of iron: the effective anisotropy field $H_a = 2 K_1/M$ amounts to 57.9 mT (Frait and Gemperle 1971), K_1 denotes the first order magnetocrystalline anisotropy constant, M the saturation magnetization. Several authors formulated theoretically the influence of the magnetocrystalline anisotropy for the set of randomly oriented single crystalline particles (e.g. Schloemann 1959; 1969; Tsay et al. 1971; Griscom 1981). In our case we shall use the formulas for the field shift caused by the magnetocrystalline anisotropy, δH_a , computed by Standley and Stevens (1965); they introduce δH_a as a function of the resonance line width, of the magnetization and of the magnetocrystalline energy, all quantities related to the individual particle. This relation can be written in the form

$$\delta H_a = -k'(2 K_1/M) = -k' H_a, \quad (2)$$

where k' is a complicated function of the line width (and therefore also of the frequency), k' values range from zero (infinite single particle line width) to 0.25 (zero line width).

In the second section of this paper we have presented several arguments supporting the hypothesis that the crystal structure of the individual iron particles in the soil is far from ideal and contains a large number of defects. This

conclusion is further substantiated by the fact that the derivative resonance line shape of the soil does not show fine structure (at any frequency) as should occur in the case of a set of nearly ideal single crystalline particles. For iron the inflection line width of an unperturbed single crystal, caused by intrinsic relaxation processes, amounts to only 0.62 mT (6 mT) at 9 GHz (86 GHz), respectively (Frait and Fraitová 1980), therefore fine structure should be resolved in the field derivative of the FMR absorption curve of a large set of such crystals. Indeed, in some cases of artificially prepared fine grained iron precipitates in glass (simulated lunar samples) Griscom et al. (1979) and Griscom (1980) observed a resolved fine structure in the FMR absorption derivative spectra, in good agreement with the theory of FMR line shapes (assuming a narrow line width of 1.7 mT for the individual particles). In contrast to the case of simulated specimens our FMR lines are in a good agreement with simple line shapes computed e.g. by Goldberg et al. (1979), where a much larger individual particle line width (33 mT) has been assumed (both at 9 and 35 GHz).

The discussion in the preceding paragraph will help us with the evaluation of the k' values needed in Equation (2). It is difficult to compute the individual particle line width theoretically, because the inhomogeneously broadened FMR line (by crystal structure and surface defects, stresses, inclusions of carbon, etc.) will be narrowed by the dipolar or exchange coupling of the individual atomic magnetic moments inside the particle (Geschwind and Clogston 1957; Seiden 1965; Schloemann 1969). Therefore, we shall estimate the lower limit of the single particle line width as about a third of the value assumed by Goldberg et al. (1979), i.e. 11 mT; even such a narrow line width will lead to complete smearing of the fine structure of the FMR line shape of the total soil sample. The upper limit of the single particle line width values will be estimated as the line width contribution caused by the defects for the case of highly oxidized iron single crystals, which amounts to 67 mT (at 70 GHz, Frait et al. 1975). We shall evaluate our measurements by choosing a mean value for the single particle line width as 22 mT (at 70 GHz), this yields $k'=0.182$ at 9 GHz and $k'=0.170$ at 86 GHz.

Finally, we need the effective anisotropy field (H_a) value of the individual ferromagnetic particle to complete the evaluation of Equation (2). In our model the anisotropy energy of magnetocrystalline origin related to the volume of the single particle with large defects will be lowered (relative to the case of a perfect crystal). The mean value of H_a can then be estimated by taking into account the fact that the ferromagnetic particles are randomly oriented and form a set of magnetically non-interacting objects (no anisotropy was ever observed in FMR lunar soil measurements and TEM observations show no effect of particle clustering, e.g. Housley et al. 1973; Pillinger et al. 1975). In such a case the inflection line width for the total set of particles amounts to $(5/3)H_a$ (e.g. Griscom 1981). By using this relation and by considering the mean line width value of 78 mT (measured on our samples at 70 GHz) we obtain H_a as 44 mT, and finally the δH_a values -8.2 mT (at 9 GHz) and -7.5 mT (at 86 GHz), respectively. These δH values represent 2.6% of the resonance field quantity at 9 GHz and 0.25% at 86 GHz.

The g -factor values for each individual FMR measurement were computed using of these corrections, and these are shown in Table 1 and plotted in Fig. 1 as dependent

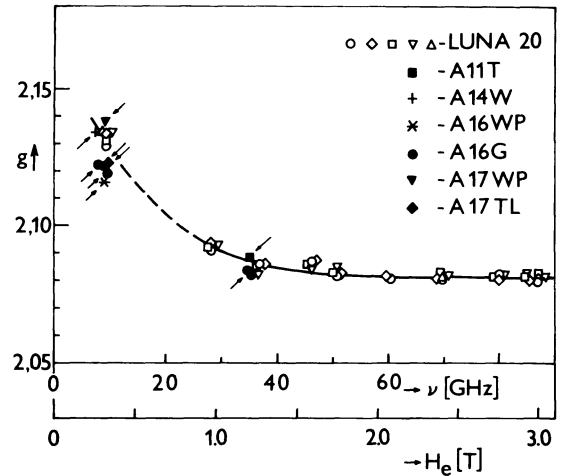


Fig. 1. The frequency/magnetic field dependence of the g -factor measured on five samples of LUNA 20 soil (see also Table 1), data from other authors' measurements are marked by arrows (see text for details)

on the microwave frequency and external resonance field intensity. The accuracy of these g -values is given mainly by the following factors. The precision of the resonance field determination amounts to about ± 1 mT (because of the relative large line width of the regolith samples of about 70 mT). However, the highest inaccuracy is given by the uncertainties in the evaluation of the mean single particle line width and effective anisotropy (needed for the δH computation). Taking into account the limits of single particle line widths discussed previously, and by assuming the accuracy of effective anisotropy field determination (computed from the regolith total line width value) as $\pm 10\%$, δH_a is given with an uncertainty of ± 4 mT. By summing up these two contributions we obtain the accuracy of resonance magnetic field as ± 5 mT, which results in a precision of the g -factor determination of $\pm 1.4\%$ (± 0.029) for our measurements at 9 GHz and $\pm 0.17\%$ (± 0.0035) at 86 GHz.

By observing Table 1 and Fig. 1 we may conclude first, that there exists a marked frequency dependence of the g -factor values at lower frequencies, however, at frequencies higher than approx. 50 GHz (resonance fields higher than 1.7 T) the g -value is constant within the uncertainty limits quoted above. The character of this dependence is in good agreement with the assumptions of the model proposed above, where at low magnetic fields the ferromagnetic component of the soil is not completely saturated. As shown by Griscom et al. (1975), Friebele et al. (1977), and Griscom (1980), in the resonance experiments on fine grained iron precipitates in a glass matrix, the presence of a domain structure in the individual particles shifts the resonance field to lower values (compared to a fully saturated material), i.e. g -values evaluated at low fields are higher than the real ones.

As far as the absolute quantities are concerned, the g -factor value measured at 9 GHz, $g=2.132 \pm 0.029$, decreases to a constant mean value $g=2.0815$ (taking into account all measurements performed above 50 GHz on all samples), the standard deviation of this average 1.194×10^{-3} ; we estimate the absolute precision as ± 0.0035 (i.e. the accuracy of individual measurements is taken as a safety margin). No other FMR data are available

for LUNA 20 soil, one can find in the literature only some FMR spectra (i.e. the magnetic field dependence of the absorption or its derivative) of Apollo (A) missions' soil samples, at 9 GHz (A11: Weeks et al. 1970; Tsay et al. 1971; A14: Weeks 1972; A16 and A17: Weeks and Prestel 1974; Tsay et al. 1973; Tsay and Live 1974) and at 35 GHz (A11: Tsay et al., 1971; A16: Goldberg et al. 1979) only, by means of which we can evaluate with reasonable accuracy (± 0.01) the g -factor values by the same procedure as for our samples. These quantities are also plotted in Figure 1, and we may observe a fair agreement with our LUNA 20 values. Only Tsay et al. (1971) quote g -values (2.08 ± 0.03 at 9 and 36 GHz) for A11 soil samples evaluated by assuming the random distribution of single crystalline particles, however, to compare them with our data is difficult because of their low accuracy. For the case of higher frequencies (above 36 GHz) we have found in the current literature no FMR measurements performed on any lunar material.

Our value, $g = 2.0815$ lies within the uncertainty limits of the g -value for pure iron ($g = 2.088 \pm 0.008$, Frait and Gemperle 1971; Frait 1977), this supports the conclusion of many other authors (obtained by observing other physical properties of lunar regoliths, see above), that the fine grained ferromagnetic component of soils is predominant iron metal. Further, the fact that our value is situated near the lower limit of the uncertainty interval for iron, points to a certain amount of alloying by some other substance. The most probable candidate for the alloying is silicon which, as SiO_2 , is far the most abundant material at the lunar surface. It has been established by several authors that the addition of silicon to iron lowers the g -factor value (Frait and Fraitová 1977; Griscom et al. 1979), the most accurate value is given in recent measurements (Püst and Frait 1981) as $g = 2.078 \pm 0.001$ for a crystal of 3.16 wt% of Si in iron. This data suggest that the fine-grained iron in the LUNA 20 regolith may contain up to 1% of Si. It is difficult to prove this by some other measurements (e.g. such an amount of silicon lowers the Curie point by only 8 K, Bozorth 1951), but a high resolution Mössbauer experiment might substantiate this hypothesis. The addition of several per cent of nickel, as mentioned by some authors (Tsay et al. 1973; Friebele et al. 1974) is less probable, in our opinion, because the addition of nickel to iron shifts the g -factor towards higher values (Meyer and Asch 1961; Bauer and Wigen 1972) and because the abundance of nickel in lunar regoliths is much smaller than that of silicon.

Conclusions

The frequency dependence of the FMR g -factor has been established for several samples of LUNA 20 soil by resonance measurements in the interval 9–86 GHz, in magnetic fields up to 3.1 T, at room temperature. A decrease from $g = 2.13$ at 9 GHz to a constant (frequency independent) quantity, $g = 2.0815 \pm 0.0035$, was observed at higher frequencies (50–87 GHz). Our data obtained at higher frequencies lie within the uncertainty limit of the g -factor for pure iron, and suggest a small amount (1%) of silicon alloying. The character of the g -factor frequency dependence at lower frequencies indicates that the fine grained iron particles observed by FMR are not completely magnetically saturated at external field intensities lower than about 1.5 T and that FMR measurements performed at high mi-

crowave frequencies are needed for reliable g -factor determination. The incomplete saturation effect is explained by means of a model, where the crystalline structure of individual ferromagnetic particles is disturbed by structural (surface and volume) defects and nonferromagnetic inclusions. The defects cause a decrease of the total anisotropy energy of the particle and give rise to additional effective demagnetizing fields and to an inhomogeneous distribution of the magnetization vector (a domain structure) inside the particle, even at external field intensities higher than theoretically needed for full saturation.

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References

- Agrell, S.O., Scoon, J.H., Muir, I.D., Long, J.V.P., Mc Connell, J.D.C., Peckett, A.. Observation of the chemistry, mineralogy and petrology of some Apollo lunar samples. Proc. Apollo 11 Lunar Sci. Conf., pp. 93–128, 1970
- Ament, W.S., Rado, G.T.: Electromagnetic effects of spin wave resonance in ferromagnetic metals. Phys. Rev. **97**, 1558–1566, 1955
- Bauer, C.A., Wigen, P.E.: Spin wave resonance studies in invar films. Phys. Rev. **B 5**, 4516–4524, 1972
- Bhagat, S.M.: FMR in metals. In: Techniques of metals research, Vol. VI, Part 2, E. Passaglia, ed.: pp. 79–164, New York: John Wiley 1973
- Bozorth, R.M.: Ferromagnetism. New York: Van Nostrand 1951
- Chiczumi, S.: Physics of magnetism. New York: John Wiley 1964
- Crangle, J.: The magnetic properties of solids. London. Edward Arnold 1977
- Frait, Z.: Ferromagnetic thin films 8. Ferromagnetic resonance. Phys. Status Solidi **2**, 1417–1459, 1962
- Frait, Z.: The g -factor in pure polycrystalline iron. Czech. J. Phys. **B 27**, 185–189, 1977
- Frait, Z., Fraitová, D.: Ferromagnetic resonance in iron-silicon alloys. Proc. 3rd Internat. Conf. on Soft Magn. Mater., Bratislava: Eur. Phys. Soc., 742–747, 1977
- Frait, Z., Fraitová, D.: FMR and surface anisotropy in iron single crystals. J. Magn. Mater. **15–18**, 1081–1082, 1980
- Frait, Z., Gemperle, R.: The g -factor and surface magnetization of pure iron. J. Phys. **32**, C 1, 541–542, 1971
- Frait, Z., Gemperle, R.: Precision g -factor measurements of electron paramagnetic resonance standards. Czech. J. Phys. **B 27**, 99–112, 1977
- Frait, Z., MacFaden, H.: FMR in metals. Frequency dependence. Phys. Rev. **134 A**, 1173–1181, 1965
- Frait, Z., Fraitová, D., Doskočilová, D.: Measurement of the proton NMR field shift in aqueous solutions containing Cu^{2+} , Cr^{3+} , Fe^{3+} and Mn^{2+} ions. Czech. J. Phys. **B 23**, 908–917, 1973
- Frait, Z., Fraitová, D., Gemperle, R.: FMR in surface oxidized iron single crystals. Czech. J. Phys. **B 25**, 906–915, 1975
- Frei, E.H., Shtrikman, S., Treves, D.: Critical size and nucleation field of ideal ferromagnetic particles. Phys. Rev. **106**, 446–455, 1957
- Friebele, E.J., Griscom, D.L., Marquardt, C.L., Weeks, R.A., Prestel, D.: Temperature dependence of the ferromagnetic resonance linewidth of lunar soils, iron and magnetite precipitates in simulated lunar glasses, and nonspherical metallic iron particles. Proc. 5th Lunar Sci. Conf. 2729–2736, 1974
- Friebele, E.J., Griscom, D.L., Patton, C.E. Characterization of ferromagnetic precipitates in glasses by ferromagnetic reso-

- nance. In: *Amorphous Magnetism II*, R.A. Levy, R. Hasegawa eds.: pp. 561–569. New York: Plenum Press 1977
- Geschwind, S., Clogston, A.M.: Narrowing effect of dipole forces on inhomogeneously broadened lines. *Phys. Rev.* **108**, 49–53, 1957
- Goldberg, I.B., Crowe, H.R., Housley, R.M., Cirlin, E.H.: Effect of sample quantity on the results of ferromagnetic resonance studies of lunar samples. *J. Geophys. Res.* **84**, 1025–1030, 1979
- Griscom, D.L.: Ferromagnetic resonance of fine grained precipitates in glass: a thumbnail review. *J. Non-Cryst. Solids* **42**, 287–296, 1980
- Griscom, D.L.: FMR condition and powder pattern analysis for dilute, spherical, single-domain particles of cubic crystal structure. *J. Magn. Resonance* **45**, 81–87, 1981
- Griscom, D.L., Friebele, E.J., Marquardt, C.L.: Ferromagnetic resonance of two-domain spherical metallic iron. *Proc. American Institute of Physics Conf.* **24**, 518–519, 1975
- Griscom, D.L., Friebele, E.J., Shinn, P.B.: Ferromagnetic resonance of spherical particles of α -iron precipitated in fused silica. *J. Appl. Phys.* **50**, 2402–2404, 1979
- Housley, R.M., Grant, R.W., Paton, N.E.: Origin and characteristics of excess Fe metal in lunar glass welded aggregates. *Proc. Lunar Sci. Conf.* 4th, pp. 2737–2749, 1973
- Housley, R.M., Cirlin, E.H., Goldberg, I.B., Crowe, H.: Ferromagnetic resonance studies of lunar core stratigraphy. *Proc. 7th. Lunar Sci. Conf.* 13–26, 1976
- Kittel, C.: Theory of the ferromagnetic resonance absorption. *Phys. Rev.* **73**, 155–163, 1948
- Kittel, C.: Magnetomechanic and spectroscopic splitting factor of ferromagnetic substance. *Phys. Rev.* **76**, 743–748, 1949
- Kronmüller, H.: The effect of the microstructure on the magnetic properties of metals. *Proc. 3rd Int. Conf. Soft. Magn. Mater.* pp. 25–30. Bratislava: Eur. Phys. Soc. 1977
- Macdonald, J.R.: Ferromagnetic resonance and internal field in ferromagnetic materials. *Proc. Phys. Soc. (London)* **A 64**, 968–978, 1951
- Meiklejohn, W.H.: Exchange anisotropy in the iron-iron oxide system. *J. Appl. Phys.* **29**, 454–455, 1958
- Merta, J.: The study of the influence of silicon and carbon content on the mobility of dislocations in iron single crystals (in Czech). Ph.D. Thesis. Prague: Institute of Physics 1981
- Meyer, A.J.P., Asch, G.: Experimental g' and g values of Fe, Co, Ni, and their alloys. *J. Appl. Phys.* **32**, 330S–333S, 1961
- Morris, R.V.: Surface exposure indices of lunar soils: A comparative FMR study. *Proc. 7th. Lunar Sci. Conf.* 315–335, 1976
- Morris, R.V.: The surface exposure (maturity) of lunar soils: Some concepts and I_s/FeO compilation. *Proc. 9th. Lunar Planet. Sci. Conf.* 2287–2297, 1978
- Pillinger, C.T.: Solar wind exposure effects in the lunar soil. *Rep. Prog. Phys.* **42**, 897–961, 1979
- Pillinger, C.T., Goward, A.P.: The separation and subdivision of two 0.5 g samples of lunar soil collected by the Luna 16 and 20 missions. *Philos. Trans. R. Soc. London* **A 284**, 137–143, 1977
- Pillinger, C.T., Eglinton, G.: The chemistry of carbon the lunar regolith. *Philos. Trans. R. Soc. London* **A 285**, 369–377, 1977
- Pillinger, C.T., Davis, P.R., Gardiner, L.R., Naziri, H., Champness, P.E.: High-voltage electron microscope observations of finely divided iron droplets in glassy agglutinates. *Proc. 6th. Lunar Sci. Conf.* 2343–2352, 1975
- Pillinger, C.T., Jull, A.J.T., Woodcock, M.R., Stephenson, A.: Maturation of the lunar regolith: Some implications from magnetic measurements and hydrolysable carbon data on bulk soils and particle separates from 12023 and 15601. *Proc. 9th. Lunar Planet. Sci. Conf.* 2167–2193, 1978
- Poole, C.P., Jr.: *Electron spin resonance*. New York: Interscience Publ. 1967
- Püst, L., Frait, Z.: Precise g-factor determination of Fe-3% Si single crystals in the temperature range 3.5–300 K. *Phys. Lett.* **A 86**, 48–50, 1981
- Schloemann, E.: Ferromagnetic resonance in polycrystals. *J. Phys. Rad.* **20**, 327–332, 1959
- Schloemann, E.: Inhomogeneous broadening of FMR lines. *Phys. Rev.* **182**, 632–645, 1969
- Seiden, P.E.: Exchange-narrowed pseudodipolar FMR linewidths in metals. *Phys. Rev. Lett.* **14**, 370–372, 1965
- Standley, K.J., Stevens, K.W.H.: The anisotropy corrections in ferromagnetic resonance. *Proc. Phys. Soc. (London)* **B 69**, 993–996, 1965
- Stephenson, A.: Single domain grain distributions. I. A method for the determination of single domain grain distributions. *Phys. Earth Planet. Inter.* **4**, 353–360, 1971 a
- Stephenson, A.: Single domain grain distributions. II. The distribution of single domain iron grains in Apollo 11 lunar dust. *Phys. Earth Planet. Inter.* **4**, 361–369, 1971 b
- Stephenson, A., Collinson, D.W., Runcorn, S.K.: Magnetic characteristics of Luna 16 and 20 samples. *Philos. Trans. R. Soc. London* **A 284**, 151–156, 1977
- Tsay, F.D., Chan, S.I., Manatt, S.L.: Ferromagnetic resonance of lunar samples. *Geochim. Cosmochim. Acta* **35**, 865–875, 1971
- Tsay, F.D., Manatt, L., Live, D.H., Chan, S.I.: Metallic Fe phases in Apollo 16 fines: Their origin and characteristics as revealed by electron spin resonance studies. *Proc. 4th. Lunar Sci. Conf.* pp. 2751–2761, 1973
- Tsay, F.D., Live, D.H.: Ferromagnetic resonance studies of thermal effects on lunar metallic Fe phases. *Proc. 5th. Lunar Sci. Conf.* pp 2737–2746, 1974
- Vinogradov, A.P.: Preliminary data on lunar soil collected by the Luna 20 unmanned spacecraft. *Geochim. Cosmochim. Acta* **37**, 721–729, 1973
- Weeks, R.A.: Magnetic phases in lunar material and their electron magnetic resonance spectra: Apollo 14. *Proc. 3rd. Lunar Sci. Conf.* pp. 2503–2517, 1972
- Weeks, R.A., Chatelain, A., Kolopus, J.L., Kline, D., Castle, J.G.: Magnetic resonance properties of some lunar material. *Science* **167**, 704–706, 1970
- Weeks, R.A., Prestel, D.: Ferromagnetic resonance properties of lunar fines and comparison with the properties of lunar analogues. *Proc. 5th. Lunar Sci. Conf.* pp. 2709–2728, 1974

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