MAGNETIC HYSTERESIS CLASSIFICATION
FOR THE LUNAR SURFACE AND THE
INTERPRETATION OF PERMANENT
REMANENCE IN LUNAR SAMPLES

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Magnetic Hysteresis Classification of the Lunar Surface and the Interpretation of Permanent Remanence in Lunar Surface Samples

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Abstract:

A magnetic hysteresis classification of the lunar surface is presented. Particular emphasis is placed on the mode of origin of the samples which determine their hysteresis properties. The hysteresis ratios $R_H$ and $R_I$, where $R_H$ is the ratio of remanent coercive force ($H_R$) to coercive force ($H_c$) and $R_I$ is the ratio of saturation remanence ($I_R$) to saturation magnetization ($I_S$), are the basic data used for the classification.

There is a distinct correlation between natural remanence (NRM), saturation magnetization ($I_S$), and the hysteresis ratios for the rock samples. The hysteresis classification is able to explain some aspects of time dependent magnetization in the lunar samples and relates the initial susceptibility to NRM, viscous remanence, and to other aspects of magnetization in lunar samples.

The framework of the hysteresis classification can be utilized in evaluation of the processes active in the formation of the regolith, and specifically in the classification of microbreccia types. The stability of permanent remanence, the recognition of two modes of time dependent remanence, one associated with the superparamagnetic fraction, the other with the multidomain fraction in lunar samples, as well as other magnetization features, are compatible with the classification and indeed are predictable if the hysteresis properties are measured.
Since up to 60% of the iron in the lunar soil may be super paramagnetic at 400° K, and only 10% at 100° K, the 50% which becomes ferromagnetic over the cycle has the characteristics of thermoremanence and may provide for an enhancement in measurable field on the dark side during a subsatellite magnetometer circuit.
Introduction:

Permanent magnetism is present in all samples returned from the moon, and fields ranging up to 300 gamma have been measured by astronauts using a portable magnetometer. However, at present time there is no clear indication as to what is the magnetization mechanism or what is the source of the field which induced the permanent magnetism.

The simplest explanation is to assume a dipole field in a manner analogous with thermoremanence acquisition in the earth's crustal layer. There are difficulties involved with assuming a dipole field. A dynamo is required to generate and sustain the field, and since there is no field at present, a dipole up to about $3.4 \times 10^9$ years is necessary, active for the period of time coincident with the radiometric record. The apparent inhomogeneous distribution of magnetization in the lunar surface layer would also seem to argue for obliteration of the dipole record.

There are problems associated with remanence acquisition in iron containing samples. The remanence acquisition efficiency of iron containing samples depends on the size and shape of the iron grains. Paleointensity estimates for a normal basalt and a contemporaneous reduced sample (Wasilewski, 1972) containing the same Fe+FeTiO$_3$+Fe$_2$TiO$_4$ assemblage found in lunar rocks differed by two orders of magnitude. The paleointensity estimate
for the normal basalt was 0.33 Oersted, and for the reduced sample the estimate was 0.0031 Oersted. This disagreement was not expected even for the simple NRM-TRM comparison which was used for estimating the inducing field. The extreme case of shape was also investigated. A needle was given a TRM both parallel and perpendicular to the needle axis. For the perpendicular case no remanence could be measured, but for the parallel case a strong remanent component was measured. The only conclusion which can be reached is simply that the paleofield estimates published for lunar samples cannot be taken seriously.

Carbonaceous chondrites and other meteoritic samples contain oriented vector magnetism (Wasilewski, 1972) indicating that other sources of permanent remanence inducing fields exist aside from the geomorphic dynamo.

The body of experimental data which exists to present does not explain (a) the precise mode of remanence, (b) the type of inducing field, (c) the time of magnetization, (d) the magnitude of the inducing field. To attempt to answer the numerous questions precipitated by the measurement of permanent remanence in the lunar samples, we must first understand what kind of ferromagnetic dispersion we are dealing with and what effect thermophysical processes active in a lunar environment would have on the remanence characteristics of lunar samples.
Magnetic hysteresis characterization provides a step in the proper direction. In this paper I will demonstrate that the magnetic hysteresis characteristics are diagnostic and can be utilized as a classification tool for all lunar samples and that thermophysical processes will effect changes in the hysteresis characteristics of lunar samples which are both predictable and useful.

Some Magnetic Hysteresis Aspects of Iron Dispersions Relevant to Lunar Research:

The makeup of the ferromagnetic dispersion in terms of the size and shape of the ferromagnetic components and the range of saturation magnetization will determine the magnetic hysteresis of the dispersion.

If a superparamagnetic dispersion of iron has a magnetization value, \( M_S \), at saturation, it will after time, \( t \), have a value, \( M = M_T \), defined by

\[
M_T = M_S \exp\left(-\frac{t}{\tau}\right)
\]

where \( \frac{1}{\tau} = f_0 \exp\left(-\frac{K_1}{kT}\right) \) (Neel, 1949). A spherical iron particle of radius, 115 \( \AA \), with the crystalline anisotropy, \( K_1 \), being the only anisotropy, has a value of \( \tau = 10^{-1} \) seconds, and when the radius increases to 150 \( \AA \), the value of \( \tau = 10^9 \) seconds, and the particle is a stable ferromagnetic grain. Superparamagnetism is defined with \( H_c = 0 \), and though it does not contribute to \( H_c \), it will reduce \( H_c \), if present with single domain particles, according to the argument \( H_c \cdot q/\tau_R \) in the equation.
\[ H_c = H_c \left(1 + \left(\frac{H_c q}{lR} \right) \epsilon \right) / (1 - \epsilon)^{-1} \]

where \( q = \frac{V M_x}{3kT} \) for superparamagnetism, where \( V \) is the volume, \( M_x \), the magnetization, \( k \), Boltzman's constant, and \( T \), the absolute temperature. If large multidomain grains are present with single domain grains, the same argument holds as above, except that \( q = (NM_s)^{-1} \), where \( N \) is the demagnetization factor. The above discussion is based on the work of Kneller and Luborsky (1964), summarized by Kneller (1969).

It has been experimentally verified by Wasilewski (1972) that mixing two distributions represented by discs of basaltic rock, one with \( H_c = 50 \) Oersted, the other with \( H_c = 420 \) Oersted, produces a reduced \( H_c \) value in accordance with the calculations of Wohlfarth (1954) for two sorts of particles with \( H_{c1} < H_{c2} \). Exact agreement cannot be expected since each \( H_c \) disc value is the effective \( H_c \) value for a distribution itself, with the resultant distribution being bimodal.

In a fine dispersion, the initial susceptibility is more sensitive to the larger particles and the approach to saturation is largely governed by the smaller particles in the distribution.

Since a single domain particle cannot change its magnetization except by rotation of the spontaneous magnetization against anisotropy forces, the particle has coercivity determined by the crystalline anisotropy characteristic of the material. For iron and dilute
FeNi alloys with high saturation magnetization the coercivity is proportional to the magnetization, and it is easily demonstrated experimentally and theoretically (Kittel, 1949) that shape anisotropy is the usual anisotropy that figures in the evaluation of the coercivity of irregular grain dispersions.

For oriented iron particles (Luborsky and Paine, 1962) the $H_c$ value and the $R_I$ value depend on the measurement angle, $\theta$, with respect to orientation. The maximum $R_I$ occurs for $\theta=0^\circ$ and the minimum for $\theta=90^\circ$. The maximum $H_c$ value occurs at an angle, $\theta=50^\circ$, for dilute assemblages, but for increased packing magnetostatic interaction becomes important and the $50^\circ$ maximum is suppressed. The minimum values of $H_c$ occur at $90^\circ$. The lunar soil may contain an oriented thin film surface of metallic iron, and it is clearly shown (Carter, 1971) that the surface of the soil particles contain fine (0.03 to 0.5 $\mu$m) mounds of magnetostatically interacting iron. A definite surface anisotropy which should provide a magnetic stratigraphic boundary zone in a core should be present, particularly if the metallic coating is associated with discrete cratering events.

Rotational hysteresis ($W_R$) measurements provide a useful check on the existence of exchange anisotropy and magnetically uniaxial components. The only rotational hysteresis work to date was performed by Runcorn et al.
(1970). They wrongly ascribe the large $W_T$ values at high measuring fields to iron, explaining the $W_T$ losses to shape anisotropy. Their Figure 9 appears to be impossible as the work of Jacobs and Luborsky (1957) and Campbell et al. (1957) clearly demonstrates. High field $W_T$ is due to anisotropy of uniaxial, induced, or exchange character (see Meikeljohn, 1962). For Ni, Fe$_3$O$_4$, and Fe in bulk or dispersed systems, no significant high field $W_T$ is expected. That Runcorn et al. have observed high field $W_T$ is of course significant, but their interpretation is quite wrong. They also observed high field $W_T$ for an assemblage of polycrystalline iron spheres (5$\mu$m). There is something peculiar with their experiment since their result (a) does not agree with theoretical studies nor (b) does it agree with previously determined $W_T$-$H$ curves for single and multidomain iron. Intergrowths such as Fe-FeS, where exchange anisotropy has been observed (Greiner et al., 1961), or Fe-FeO epitaxial overgrowths will give the results they observed. This proposition can be easily verified (Meikeljohn, 1962).

In iron dispersions, if size is important, then both $H_C$ and $H_R$ are linear functions of temperature. If shape is important, there should be different effects, since the temperature coefficient of $H_C$ depends on shape.

There are two types of time dependent effects which can operate in the lunar samples. The first is ascribed
to the superparamagnetic component which was considered earlier (equation 1), and the other is due to multi-

domain iron which is described by $\Delta I = S \log t + \text{constant}$. It should be noted that $S$, the viscosity coefficient
depends on (a) the shape of iron particles (Street et al., 1952; and Yakubaylik, 1967) and on (b) the alloy compo-
sition, since the magnetization value and structure will change.

**Magnetic Hysteresis in Lunar Samples:**

A tabulation of some data presented by Nagata et al. (1970, 1971, 1972) for Apollo 11, 12, and 14 samples is
presented (Table 1). The samples are placed into two
groups based on $R_I$ and $R_H$ values. **Group A** contains crystal-
line rocks and thermally metamorphosed breccia samples,
(F 4 - Jackson and Wilshire, 1972). **Group B** contains
the lunar fines and the welded breccia samples, (F 1 -

The hysteresis loop and the various parameters, including the measurement paths, are illustrated in Figure 1.
The hysteresis ratios $R_I$ and $R_H$ are demonstrated to be characteristic for each group of natural materials
(Wasilewski, 1970, 1972, 1972, 1972). The $R_I$ and $R_H$ values plot as two distinct groups (Figure 2A). One
group with $R_I < 0.02$ and $R_H < 10.0$ contains the igneous
rocks and thermally metamorphosed breccia samples, the
other group with $R_I > 0.04$ and $R_H > 10.0$ contains the fines.
and welded breccia samples.

The $H_C$ values for all samples fall between 10 and 50 Oersted (Figure 2B), as shown by the dotted lines, and the lunar samples are subdivided into two groups on the basis of the $R_I$ vs. $H_C$ data, one group with $R_I$ between 0.004 and 0.02 contains the crystalline rocks and thermally metamorphosed breccia samples, the other with $R_I$ between 0.04 and 0.072 contains the lunar fines and welded breccias. The $R_I$ vs. $H_C$ data clearly demonstrate that $H_C$ is a meaningless parameter when applied to lunar samples, and the reasons for this are quite obvious. Wasilewski (1972, 1972) has discussed this aspect of natural materials in terms of the experimental and theoretical work of Meikeljohn (1953), Wohlfarth (1958), Stoner and Wohlfarth (1948), and Kneller and Luborsky (1964). Mixtures of single domain iron particles with either multidomain or superparamagnetic particles will result in a reduction in $H_C$. A given volume fraction of superparamagnetic material will reduce $H_C$ more than an equivalent volume of multidomain material.

The $R_I$ vs. $H_R$ plot (Figure 2B) results in two distinct and characteristic groups defined on the basis of $R_I$ and $H_R$ values. For the first group, which includes the crystalline rocks and thermally metamorphosed breccia samples, $R_I < 0.02$, and $H_R$ varies between 75 and 180 Oersted, while for the second group, which includes the fines and welded breccias, $R_I > 0.04$, and $H_R$ varies between 300 and 520 Oersted. The $R_I$ vs. $H_R$ plot appears to be most infor-
The presence of three discrete iron modes provides for a range in grain $H_c$ ranging from $H_c = 0$ for the superparamagnetic material to $H_c \sim 10^3$ for single domain material. All of the hysteresis loops thus far presented for lunar samples show constriction in the region of low measuring fields. This constriction can be found in partially oxidized terrestrial basalts (Wasilewski, 1972), chondrite meteorites (Wasilewski, 1972), and in the lunar samples (Nagata et al., 1970, 1971, 1972).

**Discussion:**

The data presented in Table 1 is quite systematic despite the limited sampling. The samples were arranged in order of increasing $R_H$ values, and all other parameters follow a systematic increase or decrease accordingly. It is also of interest to note that Nagata has defined two types of viscous (VRM) behavior for the analyzed lunar samples, and type I VRM behavior is associated with group A hysteresis characteristics, and type II VRM behavior is associated with group B hysteresis behavior.

Saturation in the positive $H$ direction will result in a finite remanence when $H$ is returned to zero. This remanence depends on the magnetization mechanisms in the single domain and multidomain size fractions, but does not depend on the superparamagnetic or paramagnetic components. The $H_c$ value is meaningless, as was indicated
earlier, and the $H_R$ field is that required to produce a zero remanence state in the sample after saturation. A direct sample to sample comparison of this value is informative since it indicates the magnitude of the field needed to reverse half of the irreversible remanence left in the sample after saturation. The $R_I$ value is also a relative indication of the amount of irreversible magnetization, and, as can be seen in the $R_I$ vs. $H_R$ plot, this value increases as $H_R$ increases.

In practice the $R_H$ value is a complex number, in that it can depend on

(a) grain size
(b) grain shape
(c) packing fraction
(d) grain alignment
(e) exchange anisotropy
(f) degree of strain anisotropy
(g) degree of strain anisotropy
(h) anisotropic structures
(i) size distribution
(j) amount of superparamagnetism.

The lower the $H_R$ value the more viscous is the size fraction larger than single domain size. There are two components which are included in time dependent changes, (a) the superparamagnetic fraction and (b) the multidomain fraction. This is reflected in the $R_H$ values, the $H_C$
values, and the initial susceptibility. For a constant $H_R$ value the $R_H$ value will depend on the amount of superparamagnetism. A more detailed study of viscous behavior based on low temperature analysis of the blocking spectrum will allow the size spectrum of superparamagnetism to be separated from the multidomain size spectrum.

This is a critical aspect of lunar magnetization since the total magnetization of the sample depends on the handling of the sample over a temperature range equivalent to the range in which the Apollo samples were handled, and unless the blocking spectrum for this range is defined I do not believe we can eliminate the noise associated with the transfer of the samples from the moon to earth.

Based on the experimental studies of Nagata et al. (1970, 1971, 1972), Thorpe and Sentfle et al. (1970, 1971), Jedwab (1971, 1972), Carter (1971), Carter and MacGregor (1970), Chao et al. (1971), and many others we can conclude that the relative significance of superparamagnetism (SP) can be specified:

$$SP(\text{Fines}) > SP(\text{Welded Breccia}) > SP(\text{Igneous Rocks}) > SP(\text{Thermally Metamorphosed Breccia}).$$

Therefore, the $H_C$ value will be reduced relatively more significantly in the reverse order of the list above, and the $R_H$ value will depend on the $H_R$ value almost exclusively, particularly since the $H_C$ values (Table 1
and Figure 2B) are limited to a narrow range.

The $H_R$ value will depend on the shape and range of the size distribution. For igneous rocks and thermally metamorphosed breccia samples the $H_R$ value is expected to be lowest since the majority of iron grains will be multidomain with single domain or small multidomain grains carrying any stable component. As the shape of the size distribution becomes wider, shifting to a smaller size range, or bimodal, as in the case of the fines and welded breccia, the $H_R$ value should increase since a large fraction of the iron will be single domain or nearly so. The fines contain the broadest size distribution of ferromagnetic components, and welding the fines should not produce any significant alterations to the distribution. Thermal metamorphism will destroy some or all of the superparamagnetism, and an effective shift of the size distribution will result in a decrease in $H_R$, $R_H$, and $R_T$, as observed.

The data thus far accumulated provides distinct evidence that the lunar samples are quite different from terrestrial samples, mainly because there is iron in the lunar samples.

The consistent $R_H$ and $H_R$ values for the lunar fines suggest a common origin and common size and shape modes for the ferromagnetic fraction. Though data is sparse at present, there is a definite suggestion that the per-
manent remanence of each lunar sample can be understood in terms of the hysteresis properties of each sample. The path the hysteresis parameters will take depends on the mode of origin and acting thermomechanical processes. A soil can be welded, thermally metamorphosed, or shock lithified. Each of the three processes will produce different effects depending on

(a) the behavior of the SP component  
(b) the change in the ferromagnetic component size distribution  
(c) the magnetostatic interaction  
(d) the influence of the shape of the ferromagnetic components  
(e) the composition of the alloy, i.e. Ni+Co content.

Conclusions:

I. There are well defined groups of lunar materials based on their magnetic hysteresis properties.  
II. Natural remanence correlates directly with saturation magnetization, the $R_I$ value, and the initial susceptibility for crystalline rocks.  
III. In lunar samples the low $H_C$ values are due in part to the presence of superparamagnetic iron and in part to multidomain iron.  
IV. The $H_C$ value is a meaningless parameter for lunar samples.  
V. The $H_R$ value is important and diagnostic since it
is due to near single domain and multidomain grains. It is independent of the superparamagnetic fraction.

VI. Microbreccia samples can be analyzed non-destructively and classified as to their mode of origin based on magnetic hysteresis. This approach will be more effective with a more systematic array of data.

VII. It is possible that the measured surface fields can be due to a magnetized regolith. This requires further verification, but it is a distinct possibility which must be considered.

VIII. A soil can be subjected to welding, thermal metamorphism, or shock lithification. Each of the three processes will produce different hysteresis characteristics and remanent states depending on

(a) the behavior of the SP component

(b) the change in the effective grain size distribution

(c) the development of eutectic intergrowths

(d) the phase composition, i.e. Ni+Co content

(e) the thermomagnetic anomalies of the ferromagnetic components.

IX. Two distinct viscous or time dependent features are characteristic of iron in the lunar samples. The first concerns the superparamagnetic fraction, and the second concerns the soft multidomain iron fraction. Both features are temperature dependent.
X. From the hysteresis data and other published results it appears that relative superparamagnetism (SP) can be specified:

\[ \text{SP(Fines)} > \text{SP(Welded Breccia)} > \text{SP(Igneous Rocks)} > \text{SP(Thermally Metamorphosed Breccia)}. \]

The \( H_c \) value will be relatively reduced in the opposite order.
**TABLE 1**

(Tabulation of data from Nagata et al.)

**Group A - Crystalline rocks and thermally metamorphosed breccia**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$X_o(10^3)$</th>
<th>$I_n(10^5)$</th>
<th>$I_s$</th>
<th>$R_H$</th>
<th>$R_I$</th>
<th>$I_R(10^2)$</th>
<th>$H_C$</th>
<th>$H_R$</th>
</tr>
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<tr>
<td>14053</td>
<td>2.24</td>
<td>203.0</td>
<td>2.2</td>
<td>4.0</td>
<td>0.019</td>
<td>4.0</td>
<td>20</td>
<td>80</td>
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<tr>
<td>14303</td>
<td>0.69</td>
<td>13.0</td>
<td>1.27</td>
<td>6.6</td>
<td>0.016</td>
<td>2.1</td>
<td>27</td>
<td>180</td>
</tr>
<tr>
<td>14311</td>
<td>0.46</td>
<td>0.81</td>
<td>0.74</td>
<td>8.2</td>
<td>0.006</td>
<td>0.43</td>
<td>17</td>
<td>140</td>
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**Group B - Welded breccia**

<table>
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<th>Sample</th>
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<th>$I_n(10^5)$</th>
<th>$I_s$</th>
<th>$R_H$</th>
<th>$R_I$</th>
<th>$I_R(10^2)$</th>
<th>$H_C$</th>
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<td>520</td>
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<td>0.044</td>
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</table>

- Lunar fines

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<th>$I_s$</th>
<th>$R_H$</th>
<th>$R_I$</th>
<th>$I_R(10^2)$</th>
<th>$H_C$</th>
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<td></td>
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<tr>
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<td>450</td>
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</table>
FIGURE CAPTIONS

**Figure 1** - Schematic diagram of magnetic hysteresis loop illustrating the measurement paths and defining the loop parameters

- $I_R$ - Remanent magnetization
- $I_S$ - Saturation magnetization
- $H_C$ - Coercive force
- $H_R$ - Remanent coercive force
- $R_I = I_R/I_S$
- $R_H = H_R/H_C$

(1-2-1, measurement path for full loop; 1-3-0, measurement path which reduces $I_R$ to zero and defines $H_R$)

**Figure 2A** - Relationship between $R_I$ and $R_H$ for lunar samples (Data from Nagata et al., 1970, 1971, 1972)

**Figure 2B** - Relationship between $R_I$ and $H_R$ for lunar samples (Data from Nagata et al., 1970, 1971, 1972)

The $R_I$ vs. $H_C$ values for the lunar samples are included in the dotted areas labelled I and II.
FIGURE 1

MAGNETIC HYSTERESIS LOOP
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