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In situ multi-frequency measurements of magnetic susceptibility as an indicator of planetary regolith maturity

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Abstract

Space weathering is now generally accepted to modify the optical and magnetic properties of airless planetary regoliths such as those on the Moon and Mercury. Under micrometeorite and ion bombardment, ferrous iron in such surfaces is reduced to metallic iron spheres, found in amorphous coatings on almost all exposed regolith grains. The size and number distribution of these particles and their location in the regolith all determine the nature and extent of the optical and magnetic changes. These parameters in turn reflect the formation mechanisms, temperatures, and durations involved in the evolution of the regolith. Studying them in situ is of intrinsic value to understanding the weathering process, and useful for determining the maturity of the regolith and providing supporting data for interpreting remotely sensed mineralogy. Fine-grained metallic iron has a number of properties that make it amenable to magnetic techniques, of which magnetic susceptibility is the simplest and most robust. The magnetic properties of the lunar regolith and laboratory regolith analogues are therefore reviewed and the theoretical basis for the frequency dependence of magnetic susceptibility presented. Proposed here is then an instrument concept using multi-frequency measurements of magnetic susceptibility to confirm the presence of fine grained magnetic material and attempt to infer its quantity and size distribution. Such an instrument would be invaluable on a future mission to an asteroid, the Moon, Mercury or other airless rocky Solar System body.

Keywords: magnetic susceptibility, space weathering, planetary regolith, maturity
1. Overview of space weathering

Amongst the first things to be noted on analysis of the Apollo and Luna samples brought to Earth was that regolith samples had quite different magnetic and optical properties from rock samples, even those which were chemically and mineralogically similar (Hapke et al., 1975). It became clear that these differences were due to a surface maturation process operating in the upper few millimetres of the regolith. Various metrics were defined to quantify the amount of time a particular regolith had been exposed in this way (Langevin and Arnold, 1977). These all rely on the cumulative effects of solar wind bombardment, micrometeorite impacts and cosmic rays. Such weathering agents, and their effects on the regolith, are collectively known as space weathering. The most durable of these metrics was the ferromagnetic resonance (FMR) index, defined as $I_s/FeO$, where $I_s$ is the magnitude of an observed resonance feature and $FeO$ is the weight percentage of iron oxide in the regolith (Morris, 1976).

This strong absorption feature, measured with an electron spin resonance (ESR) spectrometer, is believed to originate from spherical metallic iron grains of between approximately 4 and 33 nm in diameter (Morris, 1976). These same grains are now understood to play a key role in the optical effects of space weathering, which result in the reddening, darkening and a reduction in spectral contrast of visible and near-infrared (VNIR) reflectance spectra. The theory that vapour-deposited coatings might be responsible for the optical and magnetic properties of the regolith was first advanced during the initial analyses of lunar samples (Hapke et al., 1975) but was not verified until modern laboratory techniques were applied (Keller and McKay, 1993). Theoretical modelling has also demonstrated that a vapour coating containing spherical metallic iron grains can indeed replicate the optical effects of space weathering (Hapke, 2001). Various terms have been used to describe this iron, in particular sub-microscopic metallic iron (SMFe) and nanophase iron (npFe). As this paper refers mainly to the magnetic properties of nanometre sized iron particles, the latter is perhaps more appropriate here.

Several missions, including the MESSENGER and BepiColombo missions to Mercury, the Dawn asteroid mission and several lunar orbiters are currently scheduled to perform remote sensing of airless bodies, or more specifically their regoliths. Determining surface mineralogy from such measurements is greatly hindered by space weathering. The spectral alteration can in fact be so severe as to mask completely weak absorption features, making even mineral identification impossible, let alone quantitative comparisons.
Ideally, all remote sensing measurements would be supported by in situ, ground truth, data. If the same weathering processes that occur on the Moon also play key roles on other airless bodies, ferromagnetic resonance should be a useful measurement on those as well. ESR spectrometers work by applying a magnetic field across a sample, causing unpaired electrons to align their magnetic moments either parallel or anti-parallel to the field. These two states have different energy levels, with a separation determined by the strength of the applied field and the gyromagnetic ratio (the “g-factor”), which is modified from the free electron value by the electronic environment of the nucleus. A transition can be induced between these two states by the absorption of electromagnetic radiation with the same photon energy as their separation. Thus an absorption spectrum can be produced by varying either the frequency of applied radiation or the strength of the magnetic field. The nature of such spectra can reveal much about the environment of the unpaired electrons, which in inorganic materials are typically associated with transition metals. In ferromagnetic materials, such as the metallic iron grains found in the lunar regolith, the resonance feature is orders of magnitude stronger than that seen in a paramagnetic material, due to the coupling of spins. The frequency and field strength at resonance are used to derive the g-factor, which varies from the free electron value of approximately 2.0 according to the electronic structure; most lunar samples measured have values of $2.10 \pm 0.03$ (Manatt et al., 1970).

Typical laboratory ESR spectrometers are necessarily massive and unwieldy pieces of equipment, using large electromagnets to generate substantial magnetic fields (typically on the order of hundreds of milli-Tesla). A fixed monochromatic source of microwave energy is usually employed and the reduction in received energy monitored as the magnetic field strength is scanned.

Miniaturised ESR/EPR spectrometers have been proposed for planetary missions (Kim et al., 2004). In such instruments, it is typically the microwave frequency that is scanned whilst the magnetic field strength is held constant. Two configurations were developed by Kim et al. (2004), one requiring sample ingestion and the other a “contact sensor” using a microstrip resonator. Such an instrument has been suggested to search for organic radicals on Mars and to identify radiation damage in minerals (Yen and Kim, 2004). This approach leads to a considerably lower mass and power than laboratory equipment; the field prototype had a mass of only 1.7 kg.

This reduction in mass is very promising and should be further developed. However, this paper proposes a much more compact instrument concept which uses multi-frequency measurements of magnetic
susceptibility to infer the presence of sub-microscopic iron. Theoretically it could have a mass an order of magnitude less than the ESR instrument. Additional data that could be provided by such a sensor include basic magnetic mineralogy and electrical conductivity of the regolith.

2. Magnetic properties of extraterrestrial regoliths

2.1. The lunar regolith

Since most of our understanding of space weathering derives from the Moon, the case of the lunar regolith will be discussed first. Metallic iron in lunar regoliths is thought to derive from several sources: direct meteoritic input (e.g. from metal-bearing meteorites), reduction of hydrogen-rich regolith as a result of micrometeorite impact heating (hydrogen having been implanted from the solar wind) and the production of surface-correlated iron from the re-condensation of vapour produced in solar wind sputtering and micrometeorite impacts. Subsequent gardening of the regolith can result in this iron being re-worked into the regolith, for example becoming bound into agglutinates. One possible way of distinguishing these sources of iron is by their grain size range and their location in the regolith (Morris, 1980), although thermal annealing processes can increase grain sizes over time (Noble and Pieters, 2003) and so this approach is not uniquely diagnostic. Determining the relative contributions of these processes on the Moon is important for understanding their differing contributions throughout the Solar System, which should scale with factors including the heliocentric distance, the size of the body, presence of a magnetic field etc.

In terrestrial geology, magnetic susceptibility is primarily dominated by iron oxides such as the titanomagnetite series (Carmichael, 1989). Magnetism on Mars is also believed to be dominated by iron oxides and sulfides (Rochette et al., 2005). In the lunar (Fuller and Cisowski, 1987), and by analogy Mercurian or asteroidal, environments such oxidised minerals are not readily formed. Extensive analysis of lunar samples has shown that the main carriers of ferromagnetism on the Moon are metallic iron and iron-nickel grains. As such, magnetic susceptibility ($\chi$) should correlate well with the amount of metallic iron in the regolith. It has in fact been shown for a limited set of samples that $\chi/FeO$ correlates extremely well with $I_s/FeO$ and so should make a good maturity index (Oder, 1992). This normalisation to the weight percentage of $FeO$ is required since the amount of metallic iron is related to both the degree of weathering and the amount of iron oxide in the original, unweathered, material.
Although no such in situ extraterrestrial measurements have been made, low field magnetic susceptibility (that is, magnetic susceptibility measured at a field too low to produce irreversible changes in the sample magnetisation) has been measured in the laboratory for many samples of lunar regolith. The typical range of mass susceptibility for lunar regoliths is around 1400 – 4400 $10^{-8}$ m$^3$ kg$^{-1}$ (Carmichael, 1989), depending on the mineralogy and maturity of the sample.

Magnetic susceptibility is, of course, not a unique measurement of iron content. The majority of lunar minerals are paramagnetic and the total susceptibility also reflects their various contributions. However, the cumulative effects of weathering are understood to increase the ferromagnetic metallic iron content in the regolith as it matures. Although the susceptibility of this iron is a complicated function of temperature and grain size, it is always considerably larger than the paramagnetic susceptibility. Thus only a few wt% of metallic iron, as found in a mature lunar soil, can dominate the magnetisation of such a sample.

Ferromagnetic susceptibility is critically dependent on the magnetic domain state of the magnetic carrier. Large iron grains will be multi-domain (MD), such that neighbouring domains are oriented with opposing magnetic polarities in order to reduce magnetostatic energy. It is relatively easy to change the magnetisation of such a material and hence the coercivity is low. Below a critical size, this energy saving is less than that required to split a single domain into two, and hence the material will remain single domain (SD). In this state, ferromagnetic materials are strongly resistant to magnetic change and hence have a higher coercivity. It is magnetite grains of this type that allow the Earth’s geomagnetic signature to be recorded and retained over geological timescales. Even so, any acquired magnetism decays over time in an exponential fashion, described by its relaxation time. As the grain size is decreased further, thermal effects become important. At a critical temperature and size, thermal agitation overcomes the magnetic ordering and the atomic moments of such particles are free to orient with an applied magnetic field. Such particles will behave like paramagnets, but with a vastly greater magnetic moment and magnetic susceptibility, and hence are called superparamagnetic (SPM). Usually, a material is considered SPM if its relaxation time is comparable to or smaller than the measurement time in a typical experiment (i.e. if its decay is observed). The boundary between SD and SPM grains in a given sample is therefore a function of the experiment being performed and the temperature of the sample. Figure 1 shows a plot of the variation of susceptibility of metallic iron grains at room temperature with size, based on Néel theory (Néel, 1949) and following Stephenson (1971a), which demonstrates how SPM particles can have a magnetic susceptibility an order of magnitude larger than SD grains; this figure will be discussed in more detail later.
Metallic iron with characteristic of all of these size ranges (SPM, SD and MD) has been detected via magnetic measurements of lunar materials, although a large proportion of the Fe\(^{0}\) in mature regolith is superparamagnetic (Dunlop and Özdemir, 1997). Theoretical studies have shown that the range of sizes and shapes possible for SD metallic iron are rather small, and almost non-existence for spherical grains (Butler and Banerjee, 1975). These authors calculate that only 9% of the metallic iron the lunar regolith need be single domain to reproduce the measured magnetic characteristics. Somewhat oblate spheroid grains, for example with an elongation of only 10%, are sufficient to fulfil this criterion. The FMR signature, however, arises from grains that are single domain and close to spherical (and hence have negligible shape anisotropy). Thus it is likely that metallic iron grains dominated by both magnetocrystalline (spherical) and shape (spheroid) anisotropy are present in the lunar regolith.

It is, however, the presence of extensive SPM material in lunar regoliths which dominates their magnetic susceptibility. The proportion of SPM grains is, in turn, a function of space weathering. It can be seen that measuring the initial magnetic susceptibility of a sample in situ, coupled with measurements of bulk composition from complementary instrumentation, should give a good first indication of the degree of regolith maturity and hence the degree of spectral alteration that should be expected in, and ideally removed from, remote reflectance spectra.

Simple but effective models have shown that a given reflectance spectrum of an un-weathered material can be numerically manipulated to simulate weathering by the linear addition of a volume and surface correlated component of metallic iron (Hapke, 2001). In practice, the spectrum is inverted to obtain the single scattering albedo using a simplified radiative transfer model. Once the complex refractive index of the measured sample has been obtained, this is combined with the optical constants of metallic iron and the process reversed. The size of the host grains, the weight percentage of fine grained iron and the distribution between surface and volume correlated iron are all critical parameters in this model.

Thus in situ measurement of the amount and size distribution of metallic iron could theoretically allow weathered spectra to be inverted to yield the un-weathered properties. Unfortunately this is a non-trivial task even in a terrestrial laboratory. Attempts have been made to measure the size distribution of metallic iron
spherules in a small subset of lunar samples by SEM and TEM (James et al., 2003), but this clearly is not
useful for in situ investigation.

2.2. Other Solar System regoliths

The discussion of regoliths here applies mainly to airless bodies, where both solar and micrometeorites
regularly impinge upon the surface. However, evidence from Martian meteorites also points to a mechanism
for impact shock metamorphism of olivine to produce similar nanoparticles, probably during larger impacts
and over a larger spatial scale (Van de Moortèle et al., 2007).

Mercury is also most likely a highly weathered surface, as its location in the inner Solar System results in a
high impact flux and greater average impact velocities than at the Moon (Cintala, 1992). However, the
intrinsic magnetic field discovered by Mariner 10 and verified recently by Messenger (Anderson et al., 2008)
is expected to stand off the solar wind, at least some of the time, limiting the role of solar wind sputtering, at
least at certain combinations of latitude, heliocentric distance and solar condition.

Asteroidal regoliths are also of great interest, and here it should be noted that the presence of a magnetic
field can also play a role, again preventing access to the surface of a body. In the asteroid belt, where solar
wind sputtering might be expected to dominate over impacts, weathering could potentially be inhibited
(Vernazza et al., 2006).

2.3. Laboratory regolith analogues

The motivation for this paper derived from laboratory experiments performed to simulate the space
weathering process, with particular reference to Mercury. In these experiments (Bentley, 2004; Bentley et al.,
in preparation), powdered olivine samples were irradiated under vacuum with a pulsed IR laser to simulate
the weathering process. As with previous experiments (e.g. Sasaki et al., 2001) this resulted in optical
changes resembling those seen to have occurred in lunar samples. A variety of magnetic techniques was
then used to characterise the changes, including ESR spectroscopy, vibrating sample magnetometry and
multi-frequency measurement of the magnetic susceptibility.

In these latter experiments (Bentley et al., in preparation), a Bartington MS2-B sensor was used to record the
magnetic susceptibility before and after irradiation. This instrument uses an AC technique with a field
strength of approximately 250 µT (peak) and measurement frequencies of 0.465 kHz and 4.65 kHz. These frequencies are sufficiently low that any conductive losses should be minimal. Samples of San Carlos olivine, sieved to < 63 µm and each with a mass of 2 g, were measured using the Bartington device before and after irradiation. The total bulk magnetic susceptibility of the samples typically increased several-fold after irradiation, as might be expected if paramagnetic ferrous iron is being reduced to metallic iron. Additional evidence from ESR spectroscopy and other magnetic methods support the hypothesis that metallic iron, some of it superparamagnetic, is produced.

The increase in bulk susceptibility can be used to make a first, coarse, estimate of the amount of metallic iron that could cause such a change. As an example, one such experiment showed an increase in mass specific magnetic susceptibility after irradiation of $8.79 \pm 0.09 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. If it is assumed that the increase derives solely from the production of multi-domain metallic iron, which has a room temperature initial susceptibility of $3.77 \times 10^{-4} \text{ m}^3 \text{ kg}^{-1}$ (Stephenson, 1971b), this corresponds to only 0.023 wt%, or substantially less if a sizeable fraction is superparamagnetic, and hence has a susceptibility up to 66 times higher (Stephenson, 1971a)! Clearly this technique is highly sensitive to the changes attributed to space weathering, which can produce several wt% metallic iron in mature lunar regolith.

The Bartington device also allowed investigation of the frequency dependent nature of the sample. The un-irradiated samples showed an identical susceptibility at both frequencies, within experimental errors. The same samples after irradiation, however, showed a coefficient of frequency dependence (CFD) of over 4%. Typically a CFD of less than two percent is measured if the material contains no SPM grains, a value in the range 10 – 14% is found for a sample containing virtually all SPM grains and a value in the middle has a mixture of SPM and coarser grains (Dearing, 1999). This frequency dependence arises as a result of the two measurement frequencies corresponding to two different observation times, each of which defines a different SD/SPM threshold; the theoretical explanation for this behaviour will be discussed later.

There is hence a clear rationale for making in situ measurements of magnetic susceptibility; it can provide an estimate of the metallic iron content and detect the presence of SPM particles. The following section describes how such a sensor might be developed for making a contact measurement on a planetary lander, rover or penetrator and discusses the major hurdles and the operational and calibration difficulties arising.
3. An in situ magnetic susceptibility instrument for planetary regolith maturity determination

3.1. Methods of measuring magnetic susceptibility

Methods of measuring magnetic susceptibility can be divided into two categories. The first measures the force experienced by a sample placed in a magnetic field gradient. In the laboratory, the Evans and Faraday balances are examples of this type. The second uses electromagnetic induction. In the simplest setup, an alternating current is applied through a coil. The sample to be measured is placed inside, or close to, the coil. Magnetic susceptibility is directly related to magnetic permeability $\mu = \mu_0(1 + \chi)$, which in turn is related to the inductance of a coil immersed in a medium. The required measurement is therefore one of inductance, which can be performed quite simply by a variety of electrical circuits. Typically, AC bridges are used to measure an unknown inductance, in which the resistive and reactive components of the inductance must be separately balanced (Collinson, 1983). In this configuration, when the bridge is unbalanced by the presence of a sample, either the off-balance current can be read, or the bridge can be balanced again to give a zero-current at the null detector. It should again be pointed out that both the real and imaginary parts of the complex magnetic susceptibility are of interest here, and thus these should both be measured. Hence some phase discrimination, or lock-in amplifier is needed to record both the signal in phase with the driving alternating field and that in quadrature ($\pi/2$ out of phase).

For a single coil configuration, the self inductance change due to the magnetic susceptibility of surrounding material is purely reactive, resulting in a change in the quadrature component of the coil impedance. In reality it is likely that the surrounding medium has a non-zero electrical conductivity. Induced currents flowing through the medium also modify the effective resistance of the coil and this must be accounted for. In such a configuration, the inductance change is usually measured by observing the change of frequency of an LCR circuit in which the inductor is coupled to the sample material.

3.2. The benefit of multi-frequency AC measurements

The measurement of initial magnetic susceptibility at a single frequency can be very useful; the Apollo sample collection has been extensively characterised in this way, and more recently it has been used to classify stony meteorites (Rochette et al., 2008) – a technique that has also been proposed for in situ use (Rochette et al., 2004). The additional benefits gained from performing the measurement at several oscillator frequencies are discussed here.
The utility of multi frequency measurements can be explained with reference to the work of Néel (1949), who showed that the relaxation time ($\tau$) for a collection of uniformly magnetised (i.e. SD), non-interacting uniaxial grains is related to the volume ($v$), temperature ($T$), saturation magnetisation ($j_s$) and microscopic coercivity ($h_c$) of these grains, by equation 1, where $k$ is the Boltzmann constant and $f_0$ is a constant, approximately $10^9$ s$^{-1}$ for iron.

$$\tau = \frac{1}{f_0} \exp\left(\frac{vh_s}{2kT}\right)$$

Equation 1

The coercivity depends on the dominant anisotropy in the material, which in metallic iron is either magnetocrystalline (spherical grains) or shape (non-spherical grains), and using an AC technique the measurement time can be taken as the inverse of the frequency. A spherical iron grain has a microscopic coercivity dominated by magnetocrystalline anisotropy, given by $h_c = 2K_1/j_s$, where $K_1$ is the uniaxial anisotropy constant. A value of $4.8 \times 10^4$ Jm$^{-3}$ will be used here (Dunlop and Özdemir, 1997), although considerably higher values have been reported for iron nanoparticles (Lacroix et al., 2008).

Knowing these parameters, it is possible to calculate the grain volume (the critical volume) at the boundary between stable single-domain (SD) and superparamagnetic (SPM) grains, and hence the critical grain diameter. For example, in a 1 kHz measurement of a collection of spherical metallic iron grains, this boundary occurs at a diameter 20.3 nm. In other words, grains smaller than this are SPM, whilst those larger are SD. This is of course only strictly applicable for a material comprising SD grains of a single size. In reality a range of grain sizes is likely to be present, resulting in a spectrum of decay times, blocking temperatures and volumes. In addition, the saturation magnetisation depends on temperature, although can be considered constant well below the Curie point (Stephenson, 1971a), and the coercivity depends on both grain size and temperature. Nevertheless these approximations are sufficient to explain the fundamental behaviour of fine particle magnetism with respect to frequency.

With re-arrangements of Equation 1, it can be seen that the critical volume is proportional to the logarithm of the measurement time, and so increasing the frequency (decreasing the measurement time) moves the boundary to smaller grain sizes. As a result, a material with a significant amount of very fine-grained ferromagnetic material will experience a decrease in total magnetic susceptibility with increasing frequency, as proportionally more grains become SD. As an example, the Bartington magnetic susceptibility instrument
referred to earlier uses measurement frequencies of 0.465 kHz and 4.65 kHz, corresponding to transition grain diameters of 20.7 nm and 19.5 nm, respectively. Thus a decrease in the measured susceptibility between these two frequencies can be explained by the presence of spherical iron grains in this grain size range. This can be readily observed in Figure 1 by imagining a grain with diameter 21 nm, for example. In an AC measurement at 1000 Hz this grain is single domain, however at 100 Hz this same grain is SPM and has a magnetic susceptibility 14.5 times larger.

Thus direct measurements of magnetic susceptibility with frequency can be used to make inferences about the size distribution of magnetic carriers, however the logarithmic nature of the frequency dependence results in a rather limited iron particle size range. Figure 2 demonstrates this on a plot of SPM/SD transition diameter for metallic iron at room temperature as a function of frequency. It still, however, provides a mechanism for performing a limited degree of magnetic granulometry and at the least is a useful indicator of the presence of superparamagnetic materials. Such a dual frequency measurement, if it had been carried out on the NEAR spacecraft, could have provided additional vital evidence about the nature of space weathering on asteroids.

Since the blocking volume also depends on temperature, knowledge of the regolith temperature would also be required. If deployed as part of an instrumented sensor package such as the proposed HP³ mole concept (Spohn et al., 2001), such high precision temperature measurements would already be included.

3.3. Complementarity to other measurements

It is worth considering what instrument package might be deployed in a future mission, and hence what synergy can be drawn from flying a magnetic susceptibility instrument alongside more traditional instruments. This section therefore discusses typical in situ instruments that make complementary measurements, and how these measurements might be related.

3.3.1. Mössbauer

The most obvious complementary measurement is that of Mössbauer spectroscopy, which is specifically tailored to the study of iron and iron bearing materials. In nano-scale materials, such as superparamagnetic iron, the magnetic ordering of larger particles is not present. As such, the magnetisation in the absence of an
applied field orients randomly, leading to a net zero hyperfine magnetic field. The signature for SPM iron is therefore a singlet situated at zero velocity, while larger iron grains appear as a distinctive sextet.

As seen previously, the determination of whether a particle is SD or SPM is made by both the sample temperature and the so-called “observation time”. In the case of a Mössbauer measurement, this time corresponds to the duration of a Larmor precession of the $^{57}$Fe nucleus and is of order $10^{-8}$ s. For spherical metallic iron room temperature this results in a blocking diameter of approximately 11 nm. As a result, much of the iron seen as SPM with typical AC susceptibility measurements will be SD in a Mössbauer measurement.

Measurements of lunar samples have shown that both SD and SPM iron can be detected with Mössbauer spectroscopy (e.g. Morris et al., 1998). The remaining question is whether an in situ instrument would have sufficient sensitivity to detect such metallic iron. For example the lunar regolith contains on average approximately 0.5 wt% metallic iron, with $0.20 \pm 0.10$ wt% in the size range 0.4 – 30 nm (Morris et al., 1998). The MIMOS II instrument operating on the Mars Exploration Rover (MER) vehicles is capable of detecting magnetite and hematite at the 1-2% level (Klingelhöfer et al., 2003). Newer generations of the instrument (e.g. MIMOS-IIa) are expected to show a significant improvement in sensitivity, however, thus making space-borne Mössbauer and multi-frequency magnetic susceptibility measurements complementary (i.e. probing different SD/SPM thresholds).

3.3.2. Near-IR

Visible and near-IR reflectance spectroscopy are powerful tools to determine mineralogy remotely, typically from orbit. However, it is becoming more common for landed elements to also carry such an instrument, integrated, for example, into a microscope for close-up analysis. Comparison of the spectral properties of rocks and regolith on a small scale with their magnetic properties would be a useful combination to confirm the local effects of space weathering. These data could then be extrapolated to gain an understanding of global weathering properties from orbital remote sensing data.

3.3.3. XRS

X-ray spectroscopy (XRS) of asteroid 433 Eros has been used to argue in favour of a space weathered surface, showing that the minor element ratios correspond well with those of ordinary chondrites (Foley et al., 2006) and suggesting that this supports space weathering as the agent of sulphur depletion, rather than
partial melting. Space weathering preferentially removes the volatile components of the regolith, whilst
leaving the abundances of rock forming minerals unchanged. Melting would, on the other hand, also change
the ratios of other elements. Such indirect evidence for space weathering can therefore be measured with
such techniques. However, the primary space weathering process (responsible for the major optical and
magnetic effects) is a change of oxidation state, and the formation of metallic iron. This is more directly
addressed by magnetic or Mössbauer measurements. Thus magnetic susceptibility and XRS are excellent
complementary measurements for studying weathering and potential elemental depletion processes.

3.4. Instrument design and development

Although no magnetic susceptibility sensor has yet been successfully deployed on a planetary surface, there
is a rich history of proposed instruments and scientific rationales. In the pre-Apollo era, magnetic
susceptibility was proposed as part of a surface and downhole instrument suite designed for characterising
the lunar surface (Texaco, Inc., 1961). This suite was developed to breadboard level, but was of a similar
size to terrestrial equipment.

Magnetic susceptibility instrumentation was then proposed as a future surface instrument after initial analysis
of the lunar samples (Housley, 1977). Recent measurements of the terrestrial meteorite collection (Rochette
et al., 2003 and 2008) have suggested the use of such a sensor on future asteroid (Rochette et al., 2004)
and Mars (Rochette et al., 2006) missions. Finally, with attention turning to a human return to the Moon,
magnetic susceptibility has been again proposed for identifying useful in situ resources; in fact the SPM
metallic iron particles that are the key to space weathering could also allow the production of lunar “bricks”
due to their absorption of microwave energy (Taylor and Meek, 2005).

A magnetic susceptibility instrument has been launched once previously, on the Phobos 2 mission. Carried
onboard the PROP-F “hopping” lander (Kemurdzhian et al., 1988), it was a contact sensor using an AC
bridge technique designed to make measurements of the magnetic susceptibility of Phobos at each hop
(Dolginov et al., 1989). Unfortunately contact was lost with the orbiter before PROP-F was due to be
deployed, so no measurements were made.

The utility of making multi-frequency magnetic susceptibility measurements should now be clear. However,
to describe a credible instrument concept, a set of top-level science and instrument requirements must be
defined. The range of expected values for bulk initial magnetic susceptibility must be chosen for the target
mineralogy; in lieu of detailed knowledge, one can baseline a range sufficient to cover typical lunar regolith samples ($1400 - 4400 \times 10^{-8} m^3 kg^{-1}$ (Carmichael, 1989)). With laboratory instruments, a decade of frequency difference is typically enough to establish the presence of SPM material, but this naturally depends on the measurement accuracy of a field device. Extending this range will help, but will also enhance the ability of such an instrument to perform magnetic granulometry. As noted, however, higher frequencies result in additional energy dissipation in conductive samples due to the generation of eddy currents, but this can in itself be useful for measuring electrical conductivity, if proper care is taken.

Of course this measurement cannot be made remotely and requires the sensor to be close to the regolith, ensuring flux linkage with the material being measured. Several deployment mechanisms can be considered for different mission profiles. As with all such sensors, mobility (horizontal or vertical) adds greatly to the utility of the data and a magnetic susceptibility sensor could be deployed on a rover or even a sub-surface penetrating mole. If deployed on a long-range rover, the opportunity is presented for recording maturity data at several locations, for comparison with orbital data. This is vital for bodies other than the Moon where we do not have the laboratory data to calibrate remote sensing techniques for separating compositional and maturity variations, as has been performed for the Moon (Lucey et al., 2000). Alternatively, a mole-borne sensor would be extremely useful for obtaining depth profiles and examining the stratigraphy of a single location. Regolith cores extracted on the Moon show that there is a complex intermixing of layers of different maturities at any given location, with a general trend towards decreasing maturity with depth (Basu and McKay, 1995). Such a sensor would be able to examine this in situ for other bodies. In addition there is some evidence for shock-produced fine-grained iron, which might be expected in a given layer with some lateral extent, following a large impact (Cisowski et al., 1973). Layers of differing maturity could also be accounted for by the creation of a palaeoregolith, in which layers of regolith with a given maturity are “sandwiched” between lava flows of low susceptibility (Crawford et al., 2007).

Low mass and power magnetic susceptibility instruments already exist commercially for terrestrial applications, and have a suitable range and resolution for the measurements described here. Of course these are not space qualified and substantial re-development would be required before flight. Some of the potential issues that would arise are discussed here.
3.4.1. Coil geometry

Of fundamental importance to any magnetic susceptibility instrument is the design of the coils. A choice of a single coil (operating by self inductance) or multiple coils (mutual inductance) must first be made. There are several advantages to a multi-coil design. Temperature variations affect both coils equally and so temperature drifts are minimised. In addition, the geometry of the magnetic field can be optimised to focus the region of investigation, resulting in finer spatial resolution, important for investigating layered structures in a regolith, for example. The volume of material probed also depends on the spacing of the coils. Finally, compensating coils can be used to minimise direct coupling between the transmitter and receiver. Once this decision has been made, the coil geometry must be optimised for the configuration and application. The aim is to ensure maximum flux linkage with the medium in question; however additional constraints such as the available volume and geometry must be taken into account.

Several coil geometries could be considered, in particular a planar configuration in which the transmitter and receiver coils are arranged for a contact measurement, for example in the foot of a lander, rover wheel (measuring once per revolution, and allowing a free-space calibration in between) or at the end of a robotic arm. Alternatively a 3-coil linear arrangement, which could be included in an instrumented mole, can be considered. The central coil can either be a transmitter or receiver, with a matched pair playing the opposite role. However, other configurations could be considered, for example incorporating the coils into tracks on a flexible substrate mounted on the inner wall of the mole and avoiding the difficulty of passing signal-carrying wires through the coil.

3.4.2. Calibration

Since measurement of susceptibility using an AC bridge is a relative technique, some method of calibration is required before each measurement. On the Earth this is performed by making a measurement away from any magnetic material, essentially giving a “zero”. In the confines of a lander, and in particular during the penetration of a subsurface mole, this may be impractical.

Aside from zeroing in free space, the only realistic option that does not involve deployment booms, arms or other mechanisms, is to measure a known material when in close proximity to the sensor. If deployed in a mole, the hammering mechanism could offer a ready solution to this problem by manufacturing the mechanism from a magnetic alloy with stable properties. During each cycle a zeroing measurement could be made when the hammer was close to the sensor. However, a suitable material must be found that has
properties that do not change over time, with temperature, and with the energising frequency etc.

Alternatively a single-point calibration can be performed by incorporating a calibration material into the housing of the instrument deployment mechanism.

A secondary issue is calibration of the volume over which the sensor integrates. Measurements of volume susceptibility rely on the sample filling the volume over which the sensor is sensitive. Even so, density changes in a material can be mistakenly recorded as a difference in magnetic susceptibility. For this reason laboratory measurements are often made using mass specific susceptibility, which is normalised by the sample mass (and hence density). Since in situ measurements cannot easily determine the sample mass, additional steps must be taken to ensure consistent values.

Gattacceca et al. (2004) have shown a method for determining the integration volume of an AC magnetic susceptibility sensor based on measurements alone. This relies on taking measurements at different distances from the sample, such that a different fraction of the integration volume is filled (and recorded) at each distance. This method is suitable for deployment on a rover or robotic arm, but not on a mole. In this case measurement of the bulk density surrounding the instrument could be used to ensure inter-comparability between measurements. Such a sensor, using gamma backscatter densitometry, has already been proposed and built to a breadboard level in a prototype of the HP$^3$ mole-borne instrument package (Ambrosi et al., 2006; Spohn et al., 2001).

A final point to note is that such a sensor would be rather sensitive to the presence of metal in the instrument housing, or indeed the host spacecraft itself. This can already be seen from laboratory measurements where care has to be taken over the location of the instrument; conductive losses reduce the measured magnetic susceptibility. There are therefore some additional restrictions placed on where and how a magnetic susceptibility sensor can be mounted.

### 3.4.3. Thermal and mechanical stability

The value of inductance of a coil is strongly affected by the mechanical stability of the coil windings. Careful choice of the (electrically insulating) former would have to be made to ensure a consistent inductance over the expected temperature range. Continuous measurement of temperature and also “blank” measurements of a calibration material before and after measurement of the actual sample can both be used to remove this drift from the measured value.
While temperature stability of the coil is vital, additional science is possible if the sample temperature can be varied, either actively within the instrument, or passively during, for example, a diurnal cycle. An ideal instrument design would allow the sample to be heated whilst insulating the coil itself from such changes, maintaining the stable oscillator frequency. This is discussed further in section 3.5.

3.4.4. Choice of frequency

One of the critical parameters in making an AC susceptibility measurement is the frequency at which the oscillator is energised. In typical magnetic susceptibility meters, a low frequency is used to prevent conductive losses in the sample medium. However, this must be traded against the desire to increase the frequency range (and hence the iron particle size range) available for magnetic granulometry of superparamagnetic grains.

3.5. Additional science

Not only can such a sensor measure the bulk magnetic susceptibility and search for the superparamagnetic iron indicative of space weathering, but it can also potentially measure electrical conductivity and magnetic mineralogy. When recording magnetic susceptibility in a two-coil (transmitter and receiver) configuration, the response of the coil is measured in phase with the driving current, but the quadrature component is also useful, providing a measure of electrical conductivity. Indeed this technique is often used in terrestrial borehole logging. The internal magnetic field generated by the movement of domain walls and the rotation of domain magnetic moments corresponds to the magnetic susceptibility of the sample and this results in the in-phase signal. The quadrature component represents losses in the sample, from both magnetic hysteresis and eddy currents. Thus the magnetic susceptibility is written as a complex quantity when frequency is considered. As well as being of intrinsic scientific interest, electrical conductivity is of particular interest at the surface of Mercury, where it has been suggested that surface conductivity may play a role in the closure of field aligned currents believed to be generated during magnetic substorms, first detected by Mariner 10 (Janhunen and Kallio, 2004).

Another common technique in terrestrial geomagnetic laboratories is thermomagnetic analysis, whereby the magnetic susceptibility is recorded as a function of temperature. Ferromagnetic materials will show a sudden drop in susceptibility at their Curie temperature. Hence measurements of a particular regolith sample over a range of temperature could aid in the identification of magnetic phases, as previously suggested by Rochette
et al. (2004). These temperature changes could either be natural, such as those due to diurnal oscillations, or as a result of active heating. Building a coil around, for example, the oven of another instrument might be a way of making magnetic measurements over a range of temperatures. In addition, Equation 1 demonstrated that temperature also controls the critical grain size, and thus heating a sample shifts the superparamagnetic boundary to larger particle sizes, allowing a small degree of granulometry as seen in Figure 3. Again, the dependence is weak, but nonetheless useful. In terrestrial laboratories samples measured in this way inevitably partially oxidise, however much care is taken, but the vacuum environment of an airless planetary body is ideal for such measurements. It has also been shown that the shape of the thermomagnetic curve far below the Curie point is also diagnostic of the size distribution of a single domain ensemble (Stephenson, 1971a).

4. Conclusions

Micrometeorite impacts and solar wind sputtering are now understood to produce nanophase metallic iron from ferrous iron in airless planetary regoliths during the regolith maturation / space weathering process. Metallic iron is ferromagnetic and hence amenable to a wide range of magnetic techniques. Magnetic susceptibility is known to correlate well with the more frequently used ferromagnetic resonance index used to describe regolith maturity and thus is a useful parameter for understanding the regolith evolution at a given location. In addition, multi-frequency measurements of susceptibility can be used to identify the very fine grained SPM iron particles resulting from space weathering. Definitive confirmation of space weathering as the agent of spectral alteration on asteroids and other planetary surfaces besides the Moon would be extremely useful.

Laboratory weathered regolith analogues have confirmed both an increase in initial susceptibility and the introduction of a frequency dependence, along with lunar-like spectral alteration, for even low degrees of alteration. Thus a multi-frequency magnetic susceptibility sensor has been proposed as a means of identifying and potentially quantifying the effects of space weathering in a planetary regolith surface. Direct granulometry with this technique has a rather limited range, but coupled with temperature dependent measurements and complementary instrumentation inferences could nonetheless be made. Such data could
eventually be used with models of the spectral alteration process to remove some of the changes caused by space weathering from remote spectra.

This measurement could be carried out most easily by an AC method in which the change in inductance of a coil placed close to a sample provides a measure of magnetic susceptibility. Terrestrial instruments with low mass and power exist, but the challenges in developing a space-borne instrument are not trivial. In particular, the thermal stability of the instrument is key to achieving a high precision measurement.

Deployment as part of a mole-borne instrument suite including temperature and density measurements would be extremely complementary, but the required high level of miniaturisation and integration and risk of potential interference suggest that a surface contact instrument may be more feasible.

Additional properties that could be measured with such an instrument include mineralogy (through Curie point identification if the sample temperature can be varied), and electrical conductivity. Measurements of the susceptibility with temperature can also help to further constrain the metallic iron grain size distribution.
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References


Figure captions

Figure 1. Theoretical calculation of the size dependence of volume magnetic susceptibility of spherical metallic iron at room temperature. Several different AC measurement frequencies are shown, and the susceptibility is scaled relative to that of SD grains for comparison. It can be seen that SPM grains can have a susceptibility an order of magnitude higher than SD grains, and that the SPM/SD boundary shifts to smaller grains as the measurement frequency increases.

Figure 2. The SD/SPM boundary for metallic iron grains at room temperature as a function of frequency, on a logarithmic scale. It is clear that the nature of the dependence allows only a small degree of granulometry to be performed. Realistically, measurements would likely only be performed at low frequencies where dissipative effects can be avoided.

Figure 3. The SPM/SD boundary changes with temperature as well as frequency, although again the dependence is relatively weak. In reality the curve is more complex since other parameters, for example the saturation magnetisation, are temperature dependent.
Figure 2

Diameter at SPM/SD boundary (nm)

log$_{10}$ (frequency Hz)

Metallic iron @ 290 K