Comparison of magnetic particles in airborne dust on Mars and in the Harmattan dust from south of Sahara

Jens Martin Knudsen, Morten Bo Madsen, Victor Kakane, Theodore Awadzi, Stubbe Faurschou Hviid & Henrik Breuning-Madsen

Abstract

The magnetic properties experiments on the Mars Pathfinder mission indicate that Martian airborne dust is slightly magnetic (average saturation magnetisation: $\sigma_S = 4\ Am^2kg^{-1}$). For purposes of comparison, similar experiments on the magnetic properties of terrestrial airborne dust on the Earth have been performed at the University of Ghana. The main result of these experiments is that the airborne Harmattan dust in Ghana is substantially less magnetic than the dust suspended in the Martian atmosphere.

Key words

Mars, Mars Pathfinder, dust, magnets, Harmattan

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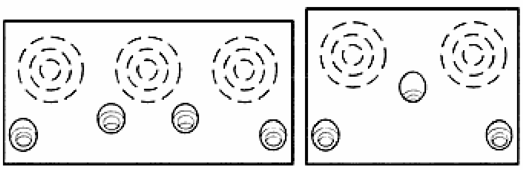
The Mars Pathfinder landed in Ares Vallis on the planet Mars in July 1997. This landing site was selected because of its location in a drainage plain resulting from a catastrophic outflow of water from the highlands. The Pathfinder lander carried a package of instruments called The Magnetic Properties Experiments (MPE). A detailed description of the MPE on the Pathfinder has been published elsewhere (Gunnlaugsson et al., 1998, Smith et al., 1997a). Among the instruments carried by the Pathfinder lander were two magnet arrays placed at a distance of 118 cm and 145 cm from the lander camera, called the Imager for Mars Pathfinde (IMP). Each magnet array consisted of five small permanent magnets embedded in two adjoining magnesium blocks. Each magnet was constructed as a ring magnet with a circular disk magnet placed symmetrically inside the ring. As the figure shows, a magnet array actually consists of two magnesium blocks in order to minimise the overlap of the magnetic fields of magnet no. 2 and 3. The outer diameter of the ring magnet is 18 mm, and the diameter of the disk magnet is 6.5 mm. Characteristic values of the magnetic field B and the magnetic field gradient ∇B are shown below each of the magnets. The strongest magnet, which is magnet no. 1 is to the right. The magnitude of the force on a magnetic particle in a magnetic field is proportional to the field B and the magnetic field gradient ∇B:



Magnet #	5	4	3	2	1
B [mT]	11	23	49	70	280
|∇B| [Tm⁻¹]	5	11	21	45	150

***Figure 1:** Front view of a magnet array on Mars Pathfinder. Positions of magnets are indicated by dashed lines. Furthermore, the seven holes used for mounting are shown. Characteristic values of the magnetic field and field gradients are shown below each of the five magnets.*

$$F = m\ \frac{k_i}{\mu_0}\ B\nabla B$$

where k_i is the specific magnetic susceptibility [dimension: $m^3\ kg^{-1}$], m is the mass of the particle and μ_0 is $4\pi\ 10^{-7}$ Vs/Am. For more details, see Madsen et al. (1999). For the attraction of a given magnetic particle, the relative strength of the magnets is determined by the product of the magnetic field and the magnetic field gradient. Based on the values given in figure 1, the relative strength of the magnets is given as approximately; 100 : 9 : 3 : 0.7 : 0.2. Note that the strength of magnet no. 4 is less than 1 % of the strength of magnet no. 1.

The Pathfinder magnet arrays were passively exposed to airborne dust on Mars. The arrays were periodically imaged by the IMP and the images transmitted to Earth. It is these images that form the basic data on which the conclusions of the magnetic properties of the Martian dust are based, as the ability to capture a given particle is dependent not only on the strength of the magnets, but also on the magnetic properties of the particle.

Results from the Pathfinder mission

Figure 2 shows an image of the upper magnet array on Pathfinder recorded on sol 68 (1 sol = 1 Martian day≈24 hours, 37 minutes). A "bull's eye" pattern could already be seen on magnet 1, on sol 5. The observed "bull's eye" patterns strengthened with time. On sol 68 a clear "bull's eye" pattern was observed on the three strongest magnets and a weak pattern was discernible on magnet no. 4. No dust was observed on magnet no. 5. The images of the magnet arrays may be seen also on the Danish Mars Project Homepag (http://ntserv.fys.ku.dk/mars, 1999).

A magnet called the tip plate magnet was placed at a distance of 7 cm from the right eye of the IMP. The tip plate magnet is a single "bull's eye" magnet mounted in a magnesium block with a wedged surface (Gunnlaugsson et al.,1998). The purpose of the wedged surface is to ensure a varying magnetic strength along the ring magnet. Furthermore, the small disc magnet is not placed symmetrically inside the ring, but is off centered by 0.9 mm. Figure 3 shows an image of the tip plate magnet recorded on sol 78.
The amount of dust attracted to the tip plate magnet clearly reflects the change of magnetic strength around the ring. The magnetic properties of the tip plate magnet vary in

Figure 2: Dust collected on the magnet array of the Pathfinder lander. Imaged on sol 68 using the 440-nm filter.

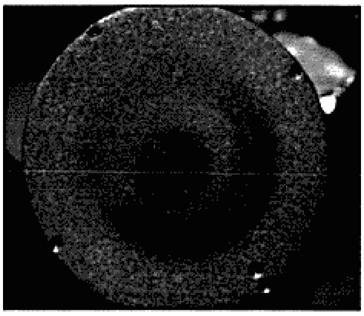


Figure 3: Dust collected on the tip plate magnet of the pathfinder lander. Imaged on sol 78.

strength from magnet 1 to magnet 4 of the magnet arrays. The results obtained from the tip plate magnet essentially confirm the results obtained from the magnet arrays. It was observed that there was no tendency to spontaneous formation of chains of magnetic particles on the tip plate magnet (Smith et al., 1997b). This result suggests that the particles attracted to the magnet are not single phase ferrimagnetic particles (Madsen et al., 1999).

Interpretation of the results from Mars

The interpretation of the results of the MPE on Mars Pathfinder have been published by Hviid et al. (1997) and Madsen et al. (1999). The linear dimensions of the particles suspended in the Martian atmosphere are 3 mm or less. The particles are composite, consisting mostly of silicates. The reddish colour of the particles is caused by a content of Fe^{3+}-compounds, some of which may be present as particles with linear dimensions of 10 nm or less, called nanophase particles. Most, if not all, of the airborne particles are magnetic to some degree. The phase responsible for the magnetism of the particles is probably maghemite, γ-Fe_2O_3. Maghemite is a ferrimagnetic mineral with a specific saturation magnetisation of σ_S = 70 Am^2kg^{-1}, somewhat dependent on crystallite size. Some of the maghemite in the Martian dust may be present as superparamagnetic particles.

The average saturation magnetisation of the Martian dust particles is estimated to be $\sigma_S = 4\pm2$ Am^2kg^{-1}, corresponding to a content of about 6 % of maghemite (by weight). The content of maghemite will vary from particle to particle. Due to the fact that some particles also stuck to magnet no. 4 (see figure 2) it is concluded that a few of the particles may have a saturation magnetisation of about 10 Am^2kg^{-1}, corresponding to a content of up to 15 % of maghemite. It should perhaps be noted that through simulation experiments in the laboratory it has been shown that hematite (α-Fe_2O_3), which is a canted antiferromagnet, sticks to the strongest magnet only (Smith et al., 1997a, Madsen et al., 1999). The saturation magnetisation of hematite is $\sigma_S = 0.4$ Am^{2}kg^{-1}.

The interpretation of the results, if true, seems to require some form of hydrolytic alteration of the bedrock. This may include precipitation from solutions, which had reacted hydrothermally with the rocks below the surface and emerged as springs (Burns, 1993), or surface weathering of crystalline or glassy volcanic rocks (Bell et al., 1993, Morris et al., 1993, Banin et al., 1997).

Magnetic Properties of the Harmattan dust in Ghana

Considering the results of the magnetic properties experiments of the dust in the Martian atmosphere, one question naturally arises: What would be the result of a similar experiment on Earth? In order to answer this question, the magnetic properties of the Harmattan dust in West Africa is compared to the results from the Mars experiment. The source of the Harmattan dust is thought to be the Northern part of the Chad Basin around Faya Largeau (Hamilton & Archbold 1945, McTainsh & Walker 1982). Fine grained sediments entrain there the Harmattan winds, which blow in a WSW-direction across the Savana region of West Africa and out over the Atlantic. Møberg et al. (1991) showed from Northern Nigeria that the dust contains about 25% clay, 60 % silt and 15% very fine sand, and the dust deposition is of an order of 700-1000 kg/ha. Furthermore, the dust seems to be more nutrient rich than the soils on which it is deposited, and it is particularly more rich in organic matter and phosphorous, but poorer in 1:1 layer silicate clay minerals and iron-oxyhydroxides. The magnetic properties of the Harmattan dust were investigated on samples collected at the University of Ghana, Legon in Accra, during the Harmattan in January-February 1998. Ghana is situated further away from the Chad Basin than Northern Nigeria, so the textural composition of the dust might therefore be somewhat finer than that found by Møberg (1991). A magnet array was placed at a height of 2 m above the ground and it was exposed to the airborne dust from the Sahara for a period of more than 2 months, about the same length of time as the array was exposed to the windblown dust on Mars. Figure 4 shows a picture of the magnet array in Ghana at the end of this period.

The magnet array used for the experiments in Ghana had a slightly different set up from the ones used on Mars. Firstly, the magnet arrays on the Pathfinder lander were coated with an electrically conductive layer of platinum and were grounded to the lander to avoid any influence of electrically charged grains. These are much more abundant on Mars because of the lower atmospheric pressure. However, this electrically conductive surface is very sensitive to humidity and ordinary handling, so all copies of the magnet array used for experiments on Earth were either painted with a transparent paint, or anodized to produce a strong, wear-resistant surface that can easily be cleaned, also mechanically. Secondly, the magnet 1 and 2 were placed in the opposite sequence than the one chosen for the flight units. Thus for a direct comparison of figure 2 and figure 4, it has been decided to show the plate carrying magnets 1 and 2 from the Ghana experiment as a mirror image.

A comparison of figure 2 and figure 4 shows that the dust in the atmosphere of Mars is substantially more magnetic than the dust carried by the Harmattan in Ghana. The dust of Ghana is attracted mainly to magnet 1, while only a small amount is held by magnet 2. No dust was magnetically attracted by the weaker magnets, i.e. magnets 3, 4 and 5. The dust sticking to the array over the metal surface outside the area just above the magnets, is due to electrostatically produced charges on the dust grains. A phenomenon interesting in itself, and of great significance from the point of view of exploring Mars. We shall here consider only the magnetic properties of the dust.

The density of the dust, i.e. the average number of particles per cm3 in a Harmattan dust over Ghana is not known with certainty. Both the density of particles in the air and the wind velocities are considered to have been larger than the corresponding values of particle density (~ 1 particle cm^{-3}) and wind velocity (~ 1 ms^{-1}) on Mars, during the active period of the Mars Pathfinder mission. Qualitatively, it can be stated from mineralogical determinations of the Harmattan dust (Møberg et al., 1991) that the strongest magnet in the Ghana experiment did not capture all the particles hitting the magnet. That means that not all particles in the dust over Ghana are sufficiently magnetic to be held by the strongest magnet. Conversely, taking into account previously pub-

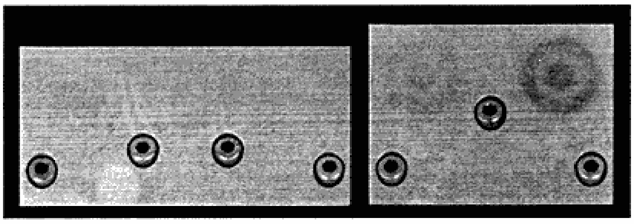


Figure 4: Dust collected on a magnet array at the University Campus in Accra, Ghana.

lished material (Madsen et al., 1999) it is believed that (nearly) all the particles suspended in the Martian atmosphere are sufficiently magnetic to be captured and held by the strongest magnet.

Mössbauer Spectroscopy of the Harmattan dust on the magnet array in Ghana

In order to determine the mineralogy of the magnetic minerals sticking to the magnets in the Ghana experiment Mössbauer spectroscopy was used. The dust adhering to magnet 1 was scraped off the array and a Mössbauer absorber was prepared. Figure 5 shows the Mössbauer spectrum recorded at room temperature (295 K) and Figure 6 shows the corresponding spectrum recorded at 17 K. The spectrum is complicated, showing the presence of several phases. The spectrum can be fitted, not well but adequately, as a superposition of three parts: a spectrum corresponding to hematite (a-Fe_2O_3), a spectrum corresponding to another magnetically ordered phase containing ferric iron, and a

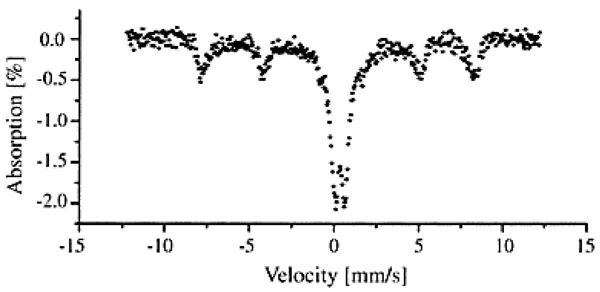


Figure 5: *Mössbauer spectrum, obtained at 295 K, of dust collected on the magnet array (magnet 1) at University Campus in Accra, Ghana.*

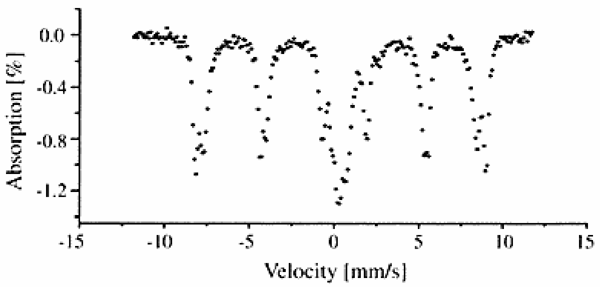


Figure 6: *Mössbauer spectrum, obtained at 17 K, of dust collected on the magnet array (magnet 1) at University Campus in Accra, Ghana.*

central doublet, probably due to a Fe-compound present as nanophase (superparamagnetic) particles.

The relative spectral area of the ferric doublet grows drastically as temperature is increased. This shows that, for (at least) one of the components, the change of temperature from 17 to 295 K involves a phase transition, either a passage of the Neél temperature for this component, or a passage of the superparamagnetic blocking temperature. The temperature dependence of the sextet component corresponding to hematite shows that hematite in this sample has no Morin transition down to 17 K. The Morin transition for macroscopic well crystalline hematite occurs at 260 K. The suppression of the Morin transition is an indication of a crystallite size below about 20 nm, or a high content of impurities in the lattice structure of the hematite. Mössbauer parameters derived from computer analysis of the Mössbauer spectra are compiled in Table 1.

The Mössbauer spectra show that the particles sticking to the magnets are composite. The distribution of the spectral area between the components of the Mössbauer spectra shows that more than two phases are responsible for this behaviour, or at least one of the components of the mixture exhibits superparamagnetic relaxation at high temperatures. It is known that macroscopic particles of pure hematite, i.e. particles of about a micrometer or larger, would stick only to the strongest magnet, while particles of goethite would not stick to any of the magnets. It is, however, also well known that antiferromagnetic particles with linear dimensions of about 20 nm or less can possess a substantial magnetic moment. Nanophase particles generally contain many lattice defects. The two sub-lattices in antiferromagnetic particles will therefore not completely balance each other in the small particles and a net magnetisation may develop. As a rule, each particle will have a magnetic moment of the order of $\sqrt{N} * \mu$, where N = the number of Fe^{3+}-ions in the particle and μ is the magnetic moment of each individual Fe^{3+}-ion (approximately 5 Bohr magnetons). As the Mössbauer spectra show, a substantial amount of the iron in the particles, which stick to the magnets, seems to be present in superparamagnetic particles. These particles, together with the macroscopic hematite particles, contain the magnetic moment, which gives rise to the fact that the particles are attracted essentially to the strongest of the magnets of a magnet array. These iron-containing particles have probably been formed by weathering of primary silicate minerals situated in the present day Sahara, at a time where this area climatically was more humid. As the chemical composition of the dust is dependent on the

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17 K / component				
hematite	53.3 (0.5)	0.49 (0.02)	-0.09 (0.04)	30 (4)
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mineralogy of a certain area, it is most likely that airborne dust from other areas might have a different mineralogical composition. Thus, in some areas the dust might be more magnetic than the dust from Ghana and have a similar composition to that of Mars. In order to prove or disprove this, it is necessary to sample in other areas characterised by airborne dust.

Conclusion

The result of the experiment in Ghana shows clearly that the magnetic properties of the Harmattan dust is different from the corresponding properties of airborne dust on Mars.
The magnetic properties of the Harmattan dust are mainly linked to macroscopic hematite and superparamagnetic particles. The experiment should be repeated in other parts of the world where the mineralogical composition of the dust is different from the Harmattan dust in Ghana, in order to investigate if airborne dust on Earth can be as magnetic as that on Mars.

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