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Planetary and Space Science 54 (2006) 28–44

Planetary and Space Science

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# Preliminary analysis of the MER magnetic properties experiment using a computational fluid dynamics model

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Received 17 December 2004; received in revised form 18 July 2005; accepted 27 July 2005
Available online 9 September 2005

## Abstract

Motivated by questions raised by the magnetic properties experiments on the NASA Mars Pathfinder and Mars Exploration Rover (MER) missions, we have studied in detail the capture of airborne magnetic dust by permanent magnets using a computational fluid dynamics (CFD) model supported by laboratory simulations. The magnets studied are identical to the capture magnet and filter magnet on MER, though results are more generally applicable.

The dust capture process is found to be dependent upon wind speed, dust magnetization, dust grain size and dust grain mass density. Here we develop an understanding of how these parameters affect dust capture rates and patterns on the magnets and set bounds for these parameters based on MER data and results from the numerical model. This results in a consistent picture of the dust as containing varying amounts of at least two separate components with different physical properties.



*Keywords:* Mars; Magnets; Dust; Wind; Computational fluid dynamics

## 1. Introduction

The airborne dust in the Martian atmosphere is distributed globally over the planet and attracts considerable interest. Since the Viking mission, permanent magnets have been used to investigate the magnetic properties of the Martian dust (Hargraves et al., 1977, 1979). Both Mars Pathfinder (Hviid et al., 1997; Madsen et al., 1999; Gunnlaugsson, 2000) and the recent Mars Exploration Rover (MER) mission (Madsen et al., 2003; Bertelsen et al., 2004; Goetz et al., 2005) employed permanent magnets to extract magnetic airborne dust directly from the atmosphere for further investigation by spacecraft cameras and, in the case of MER, mineralogical and chemical investigation by the Mössbauer spectrometer and Alpha Particle X-ray Spectrometer (APXS) on the spacecraft.

Experiments in a simulated Martian environment (Merrison et al., 2002a, b) have made it clear that the amount of dust deposited on a magnet is strongly dependent on aerodynamic factors such as wind speed and pressure. This dependence means that simulation experiments should be performed under realistic conditions in order to be used for interpretation of data from magnets on Mars.

Furthermore it is necessary to understand how dust deposition depends on parameters such as wind velocity, dust grain size, magnetic properties of dust grains and the force of gravity. One useful tool for gaining such an understanding is computational fluid dynamics (CFD) modeling, which offers the possibility of separating the different parameters and varying them in a highly controlled way, as well as monitoring the tracks of single

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doi:10.1016/j.pss.2005.07.008

dust grains. CFD modeling has drawbacks as well, the main one being that the output is never better than the assumptions put into the model. Hence comparison with laboratory simulation experiments is essential.

## 2. Theory and experiments

### 2.1. General theoretical considerations

The motion of a dust grain in a gas is governed by a balance between the drag force from the gas and other forces such as gravity and, in our case, a magnetic force. The drag force on a spherical dust grain is given by Stokes law as

$$F_\mathrm{d} = 6\pi\mu r V$$

with $r$ the grain radius, $\mu$ the dynamic viscosity of the gas and $V$ the velocity of the grain relative to the gas. Stokes law is derived on the basis of a continuous fluid with a velocity that decreases to zero at the grain surface. However any physical fluid is composed of atoms and molecules, and the assumption of continuity breaks down for grain sizes sufficiently small. We can correct for this by applying a semi-empirical correction factor called the slip factor (Davies, 1945). The slip factor $S$ is given by

$$S = 1 + \frac{\lambda}{r}\left(1.257 + 0.4\ \exp\left(-1.1\frac{\lambda}{r}\right)\right),$$

with $\lambda$ the mean free path of gas molecules. The modified version of Stokes law thus becomes

$$F_\mathrm{d} = \frac{6\pi\mu r V}{S} \tag{1}$$

with the slip factor as given above.

The equation of motion obeyed by a dust grain under the influence of drag $F_\mathrm{d}$ and gravity $F_\mathrm{g}$ is given by

$$\vec{F}_\mathrm{g} + \vec{F}_\mathrm{d} = \tfrac{4}{3}\pi r^3 \rho_\mathrm{grain}\vec{a}, \quad \vec{a} \equiv \mathrm{d}\vec{V}/\mathrm{d}t,$$

where $a$ is the acceleration and $\rho_\mathrm{grain}$ is the grain mass density. This equation has the solution:

$$\vec{V}(t) = \vec{V}_\mathrm{T} + \vec{V}_0 \mathrm{e}^{(-t/\tau)},$$

where $V_0$ is determined by the initial conditions and $\tau$ is given by

$$\tau = \frac{2S\rho_\mathrm{grain} r^2}{9\mu} \tag{2}$$

and $V_\mathrm{T,}$ the terminal velocity, is given by

$$V_\mathrm{T} = \tau g.$$

$\tau$ is a characteristic time for a grain to accelerate from rest to the terminal velocity. The characteristic time is dependent on grain size, grain density and viscosity, but not on the strength of the force being applied, which only appears in the expression for the terminal velocity. We could solve this equation similarly for other forces than gravity, as long as that force is proportional to the grain mass. By setting all forces except drag to zero we see that the characteristic time also determines how fast a grain comes to rest relative to the surrounding gas if it starts with a nonzero velocity.

This characteristic time is all-important in determining the motion of dust grains and their response to outside forces. A large characteristic time corresponds to grains not overly affected by drag and as $\tau$ increases we leave the regime where Stokes law is valid and eventually recover the equations of conventional drag-free Newtonian mechanics. In the limit of small characteristic times grains respond rapidly to changes in the outside force and reach their (small) terminal velocities rapidly. Dust grains will thus always be moving at, or close to, the terminal velocity, which is proportional to the applied force.

Dust grain diameters in the Martian atmosphere have been measured to be around 3 μm on average (Pollack et al., 1995; Tomasko et al., 1999; Lemmon et al., 2004). The mass density of dust grains in the Martian atmosphere is unknown. Both from theoretical considerations (Farrel et al., 1999) and from experimental evidence (Greeley, 1979) it seems likely that the atmospheric dust grains on Mars actually are aggregates of smaller grains held together by electrostatic forces. We also observe this in our wind tunnel experiments (Merrison et al., 2004a). Therefore the size of the grains is a dynamically varying parameter as aggregates form and break up in suspension; the density of the suspended aggregates may well be significantly lower than the bulk density of the material.

For grains of reasonable sizes (2–4 μm) and mass densities ($<4000\,\mathrm{kg/m^3}$) we calculate characteristic times of a few milliseconds or less and conclude that the behavior of such grains is close to that described above for the limit of small characteristic times. This is expected for grains that are well suspended as is the case for the Martian dust. It is worth noting that all the parameters in the expression for the characteristic time—grain radius, grain density and viscosity of the gas—enter the equations only through the characteristic time, which means that in this treatment the motion of a large low-density grain will be identical to the motion of a smaller grain of higher density. For computational purposes it is therefore not necessary to vary grain density and grain size as separate parameters. Instead we vary a single parameter, the characteristic time, which expresses the strength of the drag force relative to the inertia of the grain.

We mentioned above that motion under the influence of a magnetic force could be treated in a way similar to the treatment of gravity. The force on a magnetized dust