Numerical Modeling of Magnetic Capture of Martian Airborne Dust

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Preface

The research work presented in this thesis was done by myself and others in the period September 2001 – November 2004. The main focus of the work is the Danish-built Magnetic Properties Experiment, which is a part of the Athena payload on NASA's Mars Exploration Rovers Mission. For myself personally the chance to take part in this Mars mission as a science team collaborator has been a great motivation and inspiration. I am grateful to Jens Martin Knudsen and Morten Bo Madsen from the Danish Mars group for inspiring me to seek out this opportunity, which I would not have missed.

Most of my time, however, has been spent at the Mars simulation laboratory, Aarhus University, where I have worked on numerical modeling and experimental simulation of dynamics of Martian airborne dust. Other members of the Mars group have contributed to this work in various ways and all have been pleasant company during this time.

Jon Merrison has been my constant collaborator in the laboratory. The work on electrical properties of suspended dust presented in chapter 6 of the thesis is mainly his with contributions by me, while the experimental simulations of magnetic capture presented in chapter 8 were a collaboration between Jon and me. During this time we have also had a continually running, fruitful discussion about the nature and dynamics of dust grains in my numerical model, in our simulation chamber, and on Mars. I am very grateful for his constant support and encouragement.

Haraldur Pall Gunnlaugsson has helped me with several tricky points related to the user coding for the numerical model and has helped me with analysis of data from the rovers on Mars. The data analysis presented in section 9.1 is largely his work. Jacob Jensen provided the experimental measurements of the wind profile above a flat plate presented in section 7.1.2 and Per Nørnberg has assisted me with various practical and administrative matters.

Several people assisted me with technical matters related to the Star-CD program. Notably Mersudin Bajric from CD-Adapco's Hamburg office and Dan Nørtoft Sørensen, who at that time was at the Danish Technical University (DTU).

Finally, my supervisor Jens Ulrik Andersen has given valuable criticism and advice despite being in an unenviable position as a kind of pro-forma supervisor responsible for supervising me in a field other than his own.

My participation in the Mars Exploration Rovers mission gave me the chance to travel to the NASA Jet Propulsion Laboratory in Pasadena, Los Angeles a number of times. In September 2002 I spent a month working on calibration of cameras for the mission. In the autumn of 2003 I went to three separate Operational Readiness Tests, training sessions for the science and engineering teams for the mission. Each of these tests lasted 1-2 weeks. Finally, after the landing of the rovers, I spent the first four months of 2004 working on the mission. I served operationally as a member of the Pancam and MI teams writing camera commands and doing data tracking as well as functioning as a member of the magnetic properties team analyzing magnet data.
Taking part in this mission has been a great experience and a real privilege. I have no room here to mention all the interesting people I met and worked with during this time, a few people deserve special mention, though. Much of my work during the mission happened in close collaboration with the members of the magnetic properties team Morten Bo Madsen, Walter Goetz, Preben Bertelsen and Stubbe Hviid. The magnetic properties results presented in section 3.5.5 belong to them and to other members of the group at least as much as to me. Claus Tilsted Mogensen, a former member of the group, now employed at JPL, and his wife Tina provided hospitality and a few hours away from the pressure-cooker of the mission, which was sorely needed at times.

Jim Bell, the leader of the Pancam team and Kenneth Herkenhoff, the leader of the MI team, were both inspirational and a pleasure to have as ‘bosses’. Also my coworkers from the MI and Pancam teams were helpful, friendly and great fun to spend time with whether working or relaxing.

A number of people have read greater or smaller parts of the thesis text and provided helpful comments and I am grateful to all of them. These are: Jon Merrison, my father Peder Kinch, René Thomsen, Preben Bertelsen, Jens Ulrik Andersen, Per Nørnberg, Keld Rømer Rasmussen, Walter Goetz, Haraldur Pall Gunnaugsson and Finn Folkmann.

During the writing process I rather over-exploited the hospitality of my parents Helle Münster and Peder Kinch. Going to ground in their house with regular meals and no distractions proved to have a beneficial influence on my work ethic. So did many morning coffee breaks with my sister Nanna Kinch who was working on her master-thesis elsewhere on the university campus.

Finally I would thank all the people with whom I have spent many days pondering physics, mathematics, life or whist hands during the last 9 years at Aarhus University. Especially Peter Arnborg, Peter Staanum, Brian Julsgaard, Thomas Laustsen, Michael Hvidtfeldt and René Thomsen.

The work was financed in part by the Danish Science Research Foundation grant 2006–01–0026 (‘ESA-følgeforskning’) and in part by the Faculty of Science at Aarhus University. Central material of the thesis, essentially chapters 8 and 9, will be submitted for publication in the journal ‘Planetary and Space Science[1]’ in december 2004.


Preface for Revised Edition

A number of minor corrections to the text were made prior to printing the revised edition at the time of the thesis defense. Reference lists were also updated so that references published between the printing of the two editions now appear not as submitted, but with the relevant publication information.

March 2, 2005, Kjartan Münster Kinch
Chapter 1

Introduction

1.1. The Mars Exploration Rover mission

In the early morning hours\(^1\) of January 4\(^{th}\) 2004 the NASA spacecraft Spirit touched down in Gusev Crater on Mars after a journey of a little less than seven months. Coming safely to rest after a series of airbag-assisted bounces across the Martian surface Spirit was the first spacecraft to execute a successful landing on Mars since the landing of Mars Pathfinder in the summer of 1997 and only the fourth spacecraft to do so ever. Spirit was the first of two identical landers, together constituting the Mars Exploration Rover (MER) mission. Its identical sister ship, Opportunity, landed equally successfully on the morning\(^2\) of January 25\(^{th}\) on the opposite side of the planet in Meridiani Planum.

Both Spirit and Opportunity are six-wheeled mobile rovers, designed as ‘robotic field geologists’ primarily for the study of rocks and soils\(^3\) at the two landing sites, specifically with the aim of finding clues to the past history of water on the Martian surface\(^2\). Both rovers are still active today, more than half a year after landing, and signs of extensive past water activity have been found in bedrock at both sites, first and most spectacularly by Opportunity at Meridiani, but also by Spirit in Gusev.

Despite the primary focus on rocks and soils several other subjects were studied by the MER mission, among these the properties of the airborne dust\(^4\) in the Martian atmosphere, which was studied by the rover panorama cameras and by the infrared spectrometer on the rover\(^3\), as well

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\(^1\) European time; in America it was the evening of January 3\(^{rd}\).
\(^2\) Again, European time; in America it was the evening of January 24\(^{th}\).
\(^3\) In the interest of readability the term ‘soil’ will be employed throughout this thesis to mean loose, fine-grained material on the planetary surface. Purists may mentally substitute the term ‘regolith’.
\(^4\) The term ‘dust’ is employed for the subset of the soil which is fine-grained enough to be suspended in the atmosphere, roughly grains with diameters below 50 microns.
as by a number of permanent magnets designed specifically for the purpose of identifying magnetic minerals in the airborne dust[4, 5] and determining the processes by which the dust was formed.

1.2. Dust in the Martian Atmosphere

A prominent feature of the Martian environment is the fine reddish-brown dust in the atmosphere and on the ground. The dust is most spectacularly seen during the great global dust storms, when the atmosphere fills with dust to the extent that almost no direct sunlight reaches the planetary surface. The latest global Martian dust storm was observed during the summer of 2001. Two images of Mars taken by the Hubble Space Telescope illustrate the dramatic effects (see figure 1-1), one image taken before the advent of the storm on the 26th of June and one image taken during the storm on the 4th of September: During the storm surface features on the planet are almost entirely obscured by the dust suspended in the atmosphere, and there is a clear difference in the overall visual appearance of the planet.

![Figure 1-1: Hubble Space Telescope image of Mars before and during the global dust storm of 2001[6].](image)

Although usually not as dramatic as seen during the great global storms dust is always present in the Martian atmosphere. Lifted by storms or whirlwinds (dust devils) and drifting to the ground under the influence of gravity the dust is present as a thin surface layer as well, and based on optical spectra the dust appears to be of similar composition all over the planet, as would be expected from the observation of the global storms.

Through interaction with solar and thermal radiation the atmospheric dust has a major influence on climate as well as on atmospheric structure and dynamics. Also it represents a hazard to any
mission to the Martian surface, whether robotic or manned. Dust settles on solar panels, reducing their output; it may cause degradation of moving spacecraft parts and a future manned mission will have to contend with dust entering habitats, possibly harming astronauts through inhalation or chemical reactions. Finally the dust is known to contain a strongly magnetic material. Several theories for the formation of this magnetic phase have been brought forward. Improved knowledge of the chemistry and mineralogy of the dust will help discern between different models, thus providing information about past conditions on the Martian surface[4, 5].

For all of these reasons the dust suspended in the Martian atmosphere attracts considerable scientific interest, and all missions to the Martian surface have devoted resources to studying the dust.

1.3. Magnetic Properties Experiments

The magnetic nature of Martian dust was first discovered by the magnetic properties experiment on the Viking landers[7, 8]. Two permanent magnets mounted on the backhoe of the soil sampler were covered in material after having been pressed into the soil, bearing witness to the magnetic nature of the fine material in the soil. Also a strong magnet mounted on a reference test chart captured dust directly from the atmosphere, indicating that the magnetic material is present in the airborne dust as well. Since then, both the Mars Pathfinder mission[9, 10] and the present MER mission[4] have employed permanent magnets to attract magnetic dust directly from the atmosphere.

The main element of the magnetic properties experiment on the Mars Pathfinder mission was two identical arrays of five permanent ‘bulls eye’ magnets of various strengths. These two magnet arrays were located at different positions on the lander deck, attracted magnetic dust from the atmosphere and were imaged regularly during the mission by the Imager for Mars Pathfinder (IMP) camera. After the first few sols a faint pattern was visible on the strongest magnet and as time went by the pattern grew stronger and patterns appeared on at least four of the five magnets. Figure 1-2 shows a series of such images of the upper magnet array taken on various sols[9]. The development of the patterns is clearly visible. From comparison of these patterns with laboratory simulation experiments as well as theoretical considerations it was concluded that the dust grains are composite particles, mostly silicates, with a substantial proportion of some highly magnetic mineral. Maghemite, $\gamma$-Fe$_2$O$_3$, was suggested as a candidate for this magnetic mineral. A value for the mean saturation magnetization $\sigma_s$ of the airborne dust grains was given as $\sigma_s = 4 \pm 2$ A-m$^2$/kg[10]. The content of magnetic material, and thus the saturation magnetization, was expected to vary (possibly widely) from grain to grain about this mean value.

Subsequent simulation experiments performed under realistic Martian conditions in a re-circulating depressurized wind tunnel have made it apparent that aerodynamic parameters such as pressure and wind speed have a significant influence on the process of capture of airborne dust by permanent magnets[11] and thus on the patterns generated on such magnets. Based on that work as well as on further analysis of optical spectra of Martian dust[12] the estimate of the mean saturation magnetization of the Martian dust grains was adjusted downwards to $\sigma_s = 2.5 \pm 1.5$ A-m$^2$/kg[4].

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5 A Martian solar day has a mean period of 24 hours 39 min 35 s and is referred to as a sol to distinguish this from the slightly shorter solar day on Earth.
Figure 1-2: Images of the upper magnet array on Mars Pathfinder taken on various sols through the 440 nm filter of the IMP[9].

The MER mission also carries a magnetic properties experiment[4] designed specifically to answer some of the questions left unanswered by the Viking and Pathfinder experiments. A more detailed description will be given in section 3.5, for now I just briefly mention the various elements of this experiment:

- The **sweep magnet** is designed to investigate the question of whether all Martian atmospheric dust is magnetic in nature or whether the magnetic grains represent only a fraction of the airborne dust.
- The **RAT magnets** are designed to attract magnetic dust generated by drilling in Martian rocks with the Rock Abrasion Tool (RAT) on the rover’s robotic arm.
- Finally the **capture magnet** and the **filter magnet** are designed primarily as targets that attract airborne dust for further investigation by the Mössbauer spectrometer, as well as the $\alpha$-particle x-ray spectrometer (APXS) on the robotic arm. These instruments will give chemical and mineralogical information about the airborne magnetic dust and hopefully identify the mineral(s) responsible for the magnetic properties of the dust as well as further constrain the value for the saturation magnetization of the dust. The capture and filter magnets may also be imaged by the panoramic camera (Pancam) and the microscopic imager (MI) for information on color and morphology of the dust. The patterns of dust on the capture and filter magnets are a central subject of the present thesis.
1.4. The Present Work

1.4.1. Motivation and Method

The realization that aerodynamic parameters influence the process of capture of airborne dust on permanent magnets in significant and non-trivial ways led naturally to an interest in gaining a more detailed understanding of this capture process, the goal being knowledge of which parameters are of importance and how these parameters influence dust capture. The present thesis contributes to such a general understanding.

The main tool used is computational fluid dynamics (CFD) modeling, but extensive comparisons with laboratory simulation experiments are performed. CFD modeling offers the possibility of separating the different parameters and varying them in a highly controlled way, as well as monitoring the tracks of single dust grains. It has drawbacks as well, however, 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. The specific case studied is magnetic dust capture on the MER capture and filter magnets, but the methods developed could easily be adapted to other cases and many conclusions are of a more general nature. Results from numerical modeling and laboratory simulations are compared with data from the magnets on Mars.

The thesis also contains an overview of the MER mission and its results in a more general sense. This is partly in order to put the discussion of magnetic airborne dust in a wider perspective, but also justified on a more personal level by the author's participation in MER mission operations as a member of the Pancam and MI teams.

1.4.2. Structure of the Thesis

Chapter 2 describes the planet Mars focusing on issues related to water and airborne dust.

Chapter 3 describes the MER mission, its design and general results with special emphasis on the magnetic properties experiment, and on a description of the design and operation of the Pancam and the MI.

Chapter 4 gives an introduction to basic aerodynamic concepts and develops the theory of the motion of small particles in a fluid in detail.

Chapter 5 deals with the experimental wind tunnel set-up and the methods of data analysis.

Chapter 6 discusses electrostatic forces between dust grains and the formation of aggregates in suspension. I present some experimental results from our wind tunnel that have a bearing on this subject.

Chapter 7 describes the CFD model in detail as well as considerations behind various assumptions, simplifications and parameter values.

Chapter 8 is the core of the work. This chapter presents results from the CFD calculations in comparison with results from laboratory simulations.

Chapter 9 Discusses data from the MER magnetic properties experiment in light of results from our CFD model and laboratory simulations.

Finally, Chapter 10 presents in condensed form the conclusions of the work and discusses future perspectives.
Chapter 2

The Planet Mars

2.1. Fundamental Characteristics

Mars is the fourth planet from the sun, Earth’s neighbor on the outer side. At 24 hours, 40 minutes the solar day on Mars (the sol) is remarkably close to the day on Earth, while the year is 687 earth days. The orbit of Mars is slightly elongated with an eccentricity of 0.093 and a semi-major axis of 1.52 AU; the equatorial radius is 3396 km against 6378 km for Earth, and the planetary mass is 10% of Earth’s; this makes for a surface acceleration of gravity of 3.69 m/s². The surface area of the planet is 144 million km², about the area of all the continents on Earth combined.

The obliquity of Mars’ rotation axis is similar to the value for Earth, which makes for a similar pattern of seasons. However the elongated orbit interferes with this pattern. Winter on the southern hemisphere coincides more or less with the time when Mars is furthest away from the sun, which makes the winter on the southern hemisphere harsher and longer than on the northern hemisphere. Conversely the summer is shorter but hotter on the southern hemisphere than on the northern. The Martian seasons are commonly measured by the areocentric longitude of the sun, \( L_s \). \( L_s \) is zero at the northern spring equinox, 90 at summer solstice, 180 at autumnal equinox and 270 at northern winter solstice. Due to the eccentricity of the orbit \( L_s \) does not advance with a constant velocity throughout the year. In the Earth–Moon system the orientation of Earth’s rotation axis is stabilized by the presence of the Moon. The lack of a similar stabilizing influence on Mars makes it possible that the planet has undergone large variations in the orientation of its rotation axis through geological time with accompanying variations in climate.

The geological history of Mars is commonly divided into three eras: According to present models the Noachian Age spans the first billion years of the planets history from its formation 4.6 billion years ago. This is thought to have been a period of volcanic eruptions, frequent meteoritic impacts and a warmer, wetter Mars with a denser atmosphere. During the Hesperian Age,
spanning the next billion years or so from 3.5 to 2.5 billion years ago, the planet slowly froze and
dried out, although episodic sudden catastrophic floods continued to occur after most surface
water had frozen. The *Amazonian Age* is the current era, beginning about 2.5 billion years ago,
during which Mars has been largely as it is now: dry, cold and with only a modest atmosphere
compared to Earth.

Standing on the surface of Mars an earthling would probably feel more at home than any other
place in the solar system apart from Earth, but it is still an inhospitable place. A typical value for
the atmospheric pressure is 700 Pa with variations depending on season and elevation. This thin
atmosphere, which consists mainly of carbon dioxide, offers only limited protection against solar
and cosmic radiation. Despite the longer distance to the sun the ultraviolet radiation flux on the
Martian surface is thus significantly higher than on Earth for all wavelengths below 320 nm,
which has major implications for surface chemistry as well as for any supposed surface
biology[13]. Also Mars lacks the global magnetic field, which on Earth plays an important role in
protecting the planetary surface from charged solar or cosmic particles.

The thin atmosphere also means that the temperature is low and varies strongly between night
and day. Mars Pathfinder measured temperatures[14] varying between -10 centigrade in mid-
afternoon and -80 centigrade at the coldest time right before sunrise. This is comparable to what
has been measured by other landers and may be taken as a typical variation for mid-altitude areas
close to the equator. In polar areas the temperature falls even further to the extent that some
carbon dioxide condenses out of the atmosphere in winter, causing a planet-wide seasonal
pressure variation.

### 2.2. Geology

#### 2.2.1. Morphology

Disregarding Mars, the rocky bodies of the inner solar system may be divided into two distinct
groups: Earth and Venus are large, geologically active, and have fairly young, recently reworked
surfaces. The Moon and Mercury on the other hand are no longer geologically active and have
not changed much since the formation of the solar system. Their surfaces are old and dominated
by meteoritic impact craters. Mars is somewhere in between these two groups. Most of the
surface is quite old and impact craters are common, but there has been relatively recent volcanic
activity and water and wind have also contributed to the shaping of the surface, although
erosional processes are at present slower than on Earth.
Figure 2-1: Olympus Mons imaged by the Viking 1 orbiter[15]. The volcano is ~600 km across and its peak rises 24 km above its surroundings. The central caldera is 90 km across.

An enigmatic feature of the large-scale geology of Mars is the so-called global dichotomy[16]; the fact that the northern and southern hemispheres of the planet are very dissimilar. Most of the southern hemisphere and parts of the northern are rough, heavily cratered highlands, probably formed around 3.8 billion years ago, shortly before the end of the period of heavy meteoritic bombardment. These highlands lie 1-4 kilometers above the local geoid. In contrast much of the northern hemisphere is very smooth, low lying plains that are only sparsely cratered and therefore generally supposed to be of younger origin. These plains mostly lie well below the local geoid. There are also general mineralogical differences between the two hemispheres[17]. The cause of the dissimilarity is not known; conceivably it could have been caused by a giant impact early in the planet's history.

Being smaller than the Earth, Mars cooled faster after its formation and has been less geologically active. There is no evidence on Mars for plate tectonics, which constantly reworks the surface of the Earth, but there are a number of very large volcanoes, the largest of which, Olympus Mons (see figure 2-1), is the largest volcano in the solar system. Indeed the very lack of plate tectonics is a contributing factor to the size of the Martian volcanoes. Terrestrial hotspot volcanism characteristically generates ‘strings’ of volcanoes as the continental plate moves relative to the hotspot beneath (the Hawaiian island chain is a well known example); on Mars on the other hand the volcanoes have been stationary on top of their hotspots and have kept growing.

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6. We have evidence from the Moon and other places that the rate of meteoritic impacts fell off sharply after about 3.8 billion years ago. This period of ‘late heavy bombardment’ may be viewed as the final phase of the formation of the solar system.

7. The local geoid is a Martian ‘equivalent sea level’, a fixed zero height that is at the same gravitational potential all over the planet.
throughout the planet’s history. No active volcanism is observed on Mars today, but some meteorites known to have come from Mars are so recently formed (150 million years) that they are in geological terms practically contemporary, and it seems likely that the planet still experiences sporadic volcanic activity.

### 2.2.2. Composition

The composition of the Martian surface is predominantly basaltic, although sedimentary rocks are observed (see section 2.3). Similar soil compositions have been measured by Viking[18], Pathfinder[19], and by Spirit in Gusev Crater[20] as is illustrated by figure 2-2. Soil compositions measured by Opportunity in Meridiani Planum are also similar to these.

Gusev rocks investigated by the Alpha-particle x-ray spectrometer (APXS) as well as by the Mössbauer spectrometer on Spirit are primitive volcanic basalts[21], composed of the minerals[22] olivine, pyroxene, plagioclase and - interestingly in the context of magnetic dust - also show significant amounts of magnetite. Rocks at the Pathfinder site, while also volcanic in origin, are less primitive, have anomalous silicon content for basalts and are more analogous to andesites, less primitive, more quartz–rich rocks. Measurements from the Thermal Emission Spectrometer (TES) on Mars Global Surveyor generally show Martian surface rocks to be basaltic andesites, closer to the Pathfinder rocks than the Gusev rocks. Outcrop material in the so-called Colombia hills investigated by Spirit is basaltic in composition but shows evidence for extensive alteration by water. At the Meridiani landing site Opportunity discovered extensive evaporite sediments that are believed to have been formed over a long period of time in a body of standing water( see section 3.4.3).

![Figure 2-2: Soil(left) and rock (right) compositions at different landing sites from APXS measurements[20]. Shergottites are a class of Martian meteorites while Humphrey is a rock from Gusev.](image)

The general chemical composition of the Martian surface may be summarized as follows: The main element is silicon followed by iron, which is present in greater quantities than is common on the Terrestrial surface. Aluminum, magnesium and calcium, all elements common in surface materials on Earth, are also present in significant amounts, with magnesium more prominent on Mars than on Earth while aluminum is less prominent. Sulfur is also more common than on Earth; especially the Martian soil and the Meridiani evaporite materials are very rich in sulfur. Oxygen, as on Earth, is the main anion in rocks and soil and is very common.
We also have evidence about the Martian surface composition from a group of 32 meteorites, known as the SNC\textsuperscript{8} meteorites, that originally come from Mars but were blasted off of the Martian surface by large meteor impacts and subsequently fell on Earth. The SNC’s are volcanic basalts like the Gusev rocks, although they are not identical in composition. The evidence that the SNC meteorites come from Mars is firstly that they have similar isotope ratios, different from Terrestrial rocks, proving that they all come from the same body, which is not the Earth. Secondly, all except one of these meteorites are young, less than 1.3 billion years old, which means they must come from a body that was recently geologically active; this really leaves only Mars and Venus as candidates for their place of origin. The greater mass of Venus and its position closer to the sun makes it more likely that they come from Mars. Thirdly, gases trapped in some of the SNC’s show chemical and isotopic compositions practically identical to the Martian atmosphere as measured by Viking. Finally Opportunity analysed a rock named ‘Bounce rock’, which had chemistry and mineralogy very similar to one of the SNC’s, EETA79001. The oldest of the SNC’s, the 4.5-billion-year-old meteorite ALH84001 was recently the centre of a heated controversy when it was proposed that organic molecules and rod-shaped magnetite crystals in the rock were traces of ancient biology\cite{23, 24}. Whether or not the meteorite carries traces of biology it does carry traces of a wetter, more earthlike environment early in the history of Mars.

\subsection*{2.3. Water on Mars}

Since the Earth and Mars were formed in the same region of the solar system and are of comparable size, their compositions should have been similar just after their formation. We know that the solar system holds large reservoirs of water, mainly in the form of ice, and of course there is a lot of water on the surface of the Earth; it follows that there should also have been a significant amount of water on the early Mars. At present liquid water is not stable on the Martian surface but water ice is observed both directly and indirectly in significant amounts. A polar cap of water ice on the North Pole is observed during summer, when the overlying cap of dry (CO\textsubscript{2}) ice evaporates. The dry ice cap on the South Pole never evaporates entirely, but the presence of a similar water ice cap beneath the dry ice is expected. Large hydrogen abundances have been detected by the neutron spectrometer on the Mars Global Surveyor spaceprobe\cite{25} in all latitudes poleward of \(\pm 60^\circ\). The simplest and most likely explanation for these observed hydrogen abundances is that there is large amounts of water ice mixed with the soil at polar and subpolar latitudes. There is also morphological evidence for the presence of water ice in the ground at high latitudes in that the terrain at these latitudes has a softened appearance compared to terrain close to the equator, as though the surface materials had fluidized slightly and so caused a rounding of all landforms\cite{16}.

Although water does not at present exist in liquid form on the Martian surface there is extensive evidence that liquid water was present in the past. Two distinct types of large eroded channels are observed; known as catastrophic outflow channels and valley networks respectively. Catastrophic outflow channels (see figure 2-3) are mostly found in reasonably young terrain close to the volcanic uplands of Elysium and especially Tharsis. They are very large channels, tens of kilometers wide, that typically begin at a single source of tumbled, chaotic terrain before traveling mostly straight forwards with few bends and ending in a delta-like terrain. The favored interpretation is that these channels are formed in brief melting events provoked most likely by

\footnotesize{8 From Shergotty, Nakhla and Chassigny. three of the meteorites.}
volcanic activity. Great underground water reservoirs are thus suddenly released under high pressure after the breakdown of an ice barrier and flow across the surface in a violent rush lasting a few weeks before the water evaporates or refreezes. The tumbled terrain at the source is the hole, where the ground collapsed on top of the empty water reservoir. These events could have been relatively recent, and could even sporadically be happening in the present epoch.

**Figure 2-3:** The source of a catastrophic outflow channel. The channel is 20 kilometers wide. Picture taken by one of the Viking orbiters[26].

The other type of channels is the valley networks (see **figure 2-4**). These are only found in the ancient highlands of the southern hemisphere. They are much narrower than the catastrophic outflow channels and have winding and branching shapes resembling Terrestrial river valleys. The channels are so relatively narrow that they couldn’t possibly have formed under the present atmospheric conditions since the water would evaporate too fast. The favored interpretation for these channels is that they are indeed river valleys from a time far in the past when water was stable on the surface. Whether there was actual rainfall and surface run-off or the river systems were mostly fed from groundwater is not known and the amount of time these conditions persisted is also disputed.

**Figure 2-4:** Nirgal Vallis, an ancient Martian riverbed. The main channel has a length of 800 kilometers. The picture is taken by one of the Viking orbiters[26].
The landing site of the Spirit rover in Gusev Crater lies at the end of Ma’adim Vallis, one of these ancient riverbeds. **Figure 2-5** shows a composite map of Gusev Crater. The background image is from one of the Viking orbiters, the color coding is an altitude map generated by the Mars Orbital Laser Altimeter (MOLA) on Mars Global Surveyor and the small grey strips are high resolution images by Mars Global Surveyor or Mars Odyssey. The yellow ellipse shows the projected landing area; the actual landing site is in the middle of the right half of the ellipse. The map clearly shows the last part of Ma’adim Vallis and its outflow into Gusev Crater (bottom right). The map also shows quite a number of impact craters, of which Gusev is the largest, thus illustrating the importance of meteor impacts for the shaping of the Martian surface.

**Figure 2-5:** Map of Gusev Crater. The crater itself is about 150 kilometers across. The map illustrates the importance both of water and of meteoritic impacts for shaping the planetary surface (T.J.Parker, A.Watson, F.S.Anderson, JPL,[27]).

Other evidence for past liquid water on the Martian surface is provided by extensive areas of layered terrain observed from orbit in many locations (see **figure 2-6**). The layered terrains are mostly found at low elevations in craters or valleys and are interpreted as sedimentary layers created in standing bodies of water. The discovery and exhaustive characterization by Opportunity of layered evaporite rocks in Meridiani Planum strongly supports this interpretation as will be described in detail in **section 3.4.3** below. **Figure 2-7** shows a picture by the navigation camera (Navcam) on Opportunity of a sequence of layered rocks in the ~130 m wide Endurance Crater\(^9\), which has been thoroughly investigated by the rover.

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\(^9\) The naming of local features investigated by the MER mission such as small craters, hills, rocks, dunes etc. is a practical arrangement. Such names have an informal nature, as they are not (yet) officially recognized by the International Astronomical Union.
Finally it has been suggested based on high resolution imaging and laser altimeter measurements that a large part of the northern hemisphere may once have been covered by an ocean[28]. This rests on the observation of several contact lines with geologic features suggestive of coastlines that continue for hundreds of kilometers at roughly the same altitude and the fact that valley networks tend to end abruptly at one of these contacts. The presence of an ocean covering most of the northern hemisphere for a significant amount of time would explain the remarkable smoothness and relative lack of impact craters on the low-lying northern plains. Also Meridiani Planum, now thought to have contained a lake or shallow sea, is located close to the edge of the supposed ocean and does not have any obvious limiting ‘wall’ to the north. However the proposed ocean is still controversial, one problem with the theory being the widespread presence of the mineral olivine in Martian soils and rocks as identified by infrared spectroscopy from orbit[17] and by infrared spectroscopy[29] as well as Mössbauer spectroscopy[22] in Gusev. Olivine weathers easily under wet conditions so the widespread presence of olivine poses problems for a theory of an extensive warm and wet period in the Martian past. More generally it is not clear how to reconcile the view of a warm and wet early Mars derived from morphological evidence of rivers, lakes and possibly seas with evidence from spectral data that indicate a surface dominated by volcanic materials, some of which are unstable in the presence of water[2].

**Figure 2-6:** Layered terrain photographed by Mars Global surveyor[30]. Each image is about a kilometer across(NASA/JPL/Malin Space Science Systems).
2.4. Atmosphere

2.4.1. Aeolian Features

Apart from plate tectonics and biology we see on Mars evidence for most of the processes that shape the surface of the Earth. Volcanism, water and meteoritic impacts have already been mentioned leaving only one major contributor to the shaping of the Martian surface, namely interactions with the atmosphere, i.e., the wind.

Aeolian, or wind-related, features are observed all over Mars[32] ranging from large features such as dunes, yardangs\(^{10}\), wind streaks, and the tracks of dust devils observed from orbit to smaller duneforms, ripples\(^{11}\) and wind-eroded rocks (ventifacts) observed by landers. Both Mars Exploration Rovers observed numerous such wind-related features[33], as exemplified for instance by figure 2-8, an image taken by the Pancam on Opportunity of ripples on the floor of Endurance Crater.

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\(^{10}\) A yardang is an elongated, aerodynamically shaped hill formed by wind erosion.

\(^{11}\) Ripples are low dune-like primary structures formed by creeping or saltating sand grains as opposed to dunes, which are formed by wind-borne sand.
An unresolved question has been whether the sand-related wind features observed from orbit and on various landing sites such as dunes, ripples, yardangs or ventifacts are still active. It is doubtful whether sand sized grains are capable of being transported by the present thin Martian atmosphere and none of these features have ever been observed to change. Observations of a thin crust on top of ripples at the Spirit site as well as poor sorting of grains, led to the conclusion that sand-sized grains are not currently actively transported at this site[33]. Therefore it seems probable that all the Martian sand-related features are relics of an earlier period, when the atmosphere was thicker.

Dust related features, on the other hand, *are* observed to change and clearly dust is actively being transported on present-day Mars as is evident, for example, in the great global dust storms. The occasional global storms lift large amounts of dust into the atmosphere but dust entrainment also occurs continuously on a smaller scale; caused either by small, local storms or by dust filled vortices called ‘dust devils’.

Mars Pathfinder observed the passage of dust devils by sudden drops in pressure[14] and also photographed dust devils on the horizon[34]; episodes of dust removal from the Pathfinder magnets[35] may also be interpreted as due to the passage of dust devils; dust devils have been observed from orbit (see Figure 2-9) and the tracks of dust devils are observed in many places. The Spirit rover landed in a region with many dust devil tracks visible from orbit. These tracks were observed to change over a period of half a year (Figure 2-10) but no dust devils have as yet been directly observed by either of the MER rovers, although systematic dust devil searches have been performed[3].

*Figure 2-8: Wind-shaped bedforms on the floor of Endurance Crater imaged by the Pancam on Opportunity. The frame is a few meters across. (NASA/JPL/Cornell)[31].*
**Figure 2-9:** Picture of a dust devil seen from orbit by Mars Global Surveyor. The shadow, the trail, and the dust-filled whirlwind are clearly discernible (NASA/JPL/Malin Space Science Systems)[36].

**Figure 2-10:** Changing dust devil tracks at the Spirit landing site in Gusev Crater. The left image shows all of Gusev Crater with Ma’adim Vallis to the bottom right. The dark areas are areas of strong dust devil activity. On the middle image single dust devil tracks can be discerned, while the changes in the tracks can be seen on the two images to the right. The landing site is marked by the yellow lines on the middle image and is located at the centre of each of the rightmost images (NASA/JPL/Malin Space Science Systems)[31].
Several mechanisms exist for entrainment of dust grains. It requires significant wind speeds to directly lift and entrain dust grains of the small size (~3 microns in diameter) observed in the Martian atmosphere[32] and while these wind speeds might be reached during global dust storms some other process is probably responsible for the entrainment of dust during quieter periods. On Earth entrainment of dust is often caused by moving sand grains, but if the sand is no longer active on Mars this cannot be the process. Another possibility is that dust grains stick together on the surface to form larger aggregates that can be lifted by slower winds (grains around 115 microns in diameter are the easiest to lift[32]), these aggregates would then disperse by collision with rocks or other grains, leaving the dust entrained in the wind. We will return to the subject of aggregation repeatedly in later chapters. Also it has been suggested that the sudden drop in pressure right above the surface caused by the passage of a dust devil is capable of ‘sucking’ loose dust from the surface, not unlike the action of a vacuum cleaner.

2.4.2. Atmospheric Composition

As mentioned in section 2.1 the Martian atmospheric pressure is low, varying between 500-900 Pa depending on season and elevation, a typical value being 700 Pa. Taking for simplicity a typical Terrestrial value for the atmospheric pressure to be 100000 Pa (= 1000 mBar) this means that the pressure on Mars is just ~0.7% of the pressure on Earth. The atmospheric composition as measured by Viking[37] is 95.3% carbon dioxide, 2.7% nitrogen, 1.6% argon and small amounts of oxygen, carbon monoxide, water, ozone and several noble gases. Water and ozone contents vary widely with season and latitude and have consequences for the optical properties of the atmosphere. At times thin water ice clouds form, mostly at high and middle latitudes during winter, as exemplified by figure 2-11 showing clouds above Meridiani Planum. A conspicuous component of the Martian atmosphere having a major influence on its optical properties is of course the dust, which has already been mentioned several times and which we will be describing in more detail in section 2.5.

Since the overwhelmingly dominant atmospheric molecule is CO$_2$, the physical properties of CO$_2$ generally dominate the physical behavior of the atmosphere. As CO$_2$ is heavier than N$_2$ and O$_2$ one consequence of this is that the density of the atmospheric gas is higher for a given pressure, than it would be for a gas of Terrestrial atmospheric composition. This follows from the ideal gas law:

$$\rho = \frac{M}{V} = N \frac{m}{V} = \frac{pV}{kT} = \frac{m}{kT}$$

Where m is the mean molecular mass in the atmosphere. We see that a higher m causes a higher density $\rho$ at a given pressure $p$. Furthermore we see that the lower temperature on Mars also contributes to raising the density relative to the pressure. Another way to express this is by the atmospheric gas constant $R_A = k/m$, which results in the following atmospheric-composition-specific version of the ideal gas law:

$$p = \rho \cdot R_A \cdot T$$

For Mars and Earth respectively we have $R_A$ (Mars) = 188 J/(kg·K) and $R_A$ (Earth) = 287 J/(kg·K)[38]. The final result of the above is that while a typical Martian atmospheric pressure is
~0.7% of the pressure at the Terrestrial surface a typical density is $1.5 \cdot 10^{-2}$ kg/m$^3$; or ~1.25% of the Terrestrial value[38].

![Image by the Navcam on Opportunity showing thin water ice clouds above an outcrop of evaporite deposits in Meridiani Planum (NASA/JPL)[31]](image)

**Figure 2-11:** Image by the Navcam on Opportunity showing thin water ice clouds above an outcrop of evaporite deposits in Meridiani Planum (NASA/JPL)[31]

A typical value for the kinematic viscosity of the Martian atmosphere (at $p = 750$ Pa, $T = 250$ K) is[39] $7.94 \cdot 10^{-4}$ m$^2$/s as compared to a value of $1.46 \cdot 10^{-5}$ m$^2$/s for Earth (ICAO standard atmosphere[40]). This higher kinematic viscosity is primarily a consequence of the lower atmospheric density and has major consequences for the wind-flow at the Martian surface. We will discuss these effects in more detail in **chapter 4**. Wind speeds at the Martian surface are comparable to wind speeds on Earth typically varying between 1-10 m/s although they may rise significantly above this during dust storms. Note however that the low atmospheric density means that the force from the wind is significantly smaller than on Earth. **Figure 2-12** shows wind speed data from the two Viking landers during the first two years of the mission. There are significant seasonal variations between quiet periods with typical wind speeds of 2-3 m/s and more windy periods with large daily variations between 2-10 m/s.

![Wind Speed Data](image)

**Figure 2-12:** Viking wind speed data. The horizontal axis shows sol number[41].
2.5. Dust

2.5.1. Optical Measurements

The ubiquitous atmospheric dust has been studied by cameras on all surface missions to Mars. The most direct manifestation of the dust in the atmosphere is observed by attenuation of incoming sunlight, commonly quantified by the normal optical depth, $\tau$. Normal optical depth is defined by $I = I_o e^{-\tau \cos(i)}$, with $I$ the observed intensity of sunlight at the surface, $I_o$ the intensity of sunlight at the top of the atmosphere and $i$ the incidence angle of incoming sunlight ($i = 0^\circ$ when the sun is at zenith). In practice $\tau$ is measured by imaging the sun several times within a limited time span. Assuming $\tau$ to be unchanged within this time $\tau$ and $I_o$ may be determined from the variation of $I$ with $i$. In the following ‘optical depth’ will always mean the normal optical depth, $\tau$.

Dust is the dominant contributor to the Martian sky optical depth at near ultraviolet, visible and infrared wavelengths. Figure 2-13 shows visible optical depth measurements by the MER rovers; values decrease from just below 1 at the beginning of the mission to just above 0.5 after 100 sols. Values for Spirit are consistently lower than values for Opportunity. A local dust storm was observed in the Meridiani area shortly before landing of the rovers, which explains the higher optical depths at the Meridiani site as well as the general decreasing trend in the optical depths. The storm caused elevated optical depths all over the planet, decreasing gradually towards a ‘normal’ equilibrium value around 0.5, which is consistent with measurements from Viking[42] and Pathfinder[43] showing optical depths around 0.5 in the absence of dust storm activity. Optical depths were also measured in the thermal infrared (9 $\mu$m) on MER; as was the case for visible wavelengths optical depth at this wavelength is dominated by dust. Values for optical depth at 9 $\mu$m were about half the values at visible wavelengths and followed the same downward trend[3]; this is consistent with expectations. Somewhat higher values were measured for mornings than for afternoons, which may be explained by water ice condensing on dust grains at night; Mars Pathfinder also measured elevated $\tau$-values at night (by star observations).

Figure 2-13: Visible optical depths measured by Spirit (red) and Opportunity (blue). Open circles are morning measurements while filled circles are afternoon measurements[3].

The expression is valid only for a ‘plane parallel atmosphere’, i.e., for $i < 70^\circ$. 

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12 The expression is valid only for a ‘plane parallel atmosphere’, i.e., for $i < 70^\circ$.
From measurements of sky radiance at different angular distances from the sun it has also been possible to estimate grain sizes for atmospheric dust grains. These results are somewhat dependent on modeling assumptions about size distribution as well as grain shapes, but give comparable results for all surface missions. For Viking 1 mean grain radius\(^\text{13}\) was determined to 1.52 ± 0.3 \(\mu m\)[44], measured during a dust storm, while for Viking 2 the value was 1.85 ± 0.3 \(\mu m\)[44] at a time of low dust loading. For both Viking landers the best estimate of the variance of the size distribution was 0.5 ± 0.2 \(\mu m\). Pathfinder determined a mean value of 1.65 ± 0.15 \(\mu m\)[45] with 0.35 ± 0.15 \(\mu m\) the variance of the size distribution, while MER has reported 1.47 ± 0.21 \(\mu m\) at Gusev and 1.52 ± 0.18 \(\mu m\) at Meridiani[3] with no data reported for the variance of the size distribution. While all these values are in good agreement – even remarkably good agreement given that grain sizes would not necessarily be expected to be the same at all times and places - different analyses of the same data sets as well as orbiter measurements have yielded larger variations in grain radius[44, 45].

Results from the Phobos orbiter mission[46] give the mean grain radius at an altitude of 25 km as about half the value for an altitude of 15 km, suggesting that grain sizes decrease with increasing elevation as might be expected.

Particle number densities (concentrations) in the atmosphere are not very well known and obviously depend on the weakly constrained grain size distribution. In particular the small-diameter end of the size distribution, which has the largest impact on number density, is not well known. Early in the Viking mission the number density near the Martian surface was estimated to be 1-10 grains per cm\(^3\)[47]. Based on Pathfinder data the number density near the surface could be anything in the range 1-100 grains per cm\(^3\)[45].

2.5.2. Formation

The presence of the dust in the Martian atmosphere is a consequence of the dry conditions, since small particles would be removed from the atmosphere by rain under wetter conditions. This is amply demonstrated on Earth, where the presence of atmospheric dust is mostly known only in dry areas or in dry seasons in areas with seasonal drought. From this, however, we cannot deduce the detailed composition of the dust or its mode of formation.

Dust layers on Mars are generally too thin for determination of dust chemical composition or mineralogy without contribution from underlying rocks and soil. Based on optical spectra the general assumption is that the composition of the dust is not too far from soil compositions as presented in figure 2-2. Measurements on dust sticking to the MER magnets are intended to help resolving this issue.

As mentioned in section 1.2 it was concluded from the magnetic properties experiment on Mars Pathfinder that the Martian atmospheric dust grains are most likely composite particles with a varying component of some highly magnetic material. Moreover from the sweep magnet on the MER rovers it has been concluded that almost all dust grains somewhat magnetic[5]. Whether the grains are cemented composites and formed as such or more loosely bound aggregates (see chapter 6) that may break up and reform continuously is not known.

If the airborne dust has a composition not too far from that of the Martian soil the grains cannot consist entirely of magnetic material since iron oxides contribute no more than about 20% by weight to the soil(fig. 2-2). In order to explain the observed magnetic properties of the dust the

\(^{13}\) Strictly speaking the value reported is the geometric cross-section weighted mean grain radius.
magnetic material must be highly magnetic and this really leaves only magnetite ($\text{Fe}_3\text{O}_4$) or maghemite ($\gamma$-$\text{Fe}_2\text{O}_3$) as possible candidates for this material, maybe with titanium substituted for some of the iron to form titanomagnetite or titanomaghemite respectively.

Both magnetite and maghemite contain iron in the form of $\text{Fe}^{3+}$. In the case of magnetite two out of three iron atoms are $\text{Fe}^{3+}$ and one is $\text{Fe}^{2+}$, while all iron atoms in maghemite are $\text{Fe}^{3+}$. Indeed the reddish-brown color of Mars is a hallmark of $\text{Fe}^{3+}$, and it is generally held that formation of Martian dust and soil from bedrock requires some oxidation of $\text{Fe}^{2+}$ to $\text{Fe}^{3+}$, although rocks in Gusev Crater were shown to contain significant proportions of ferric iron\textsuperscript{14}.

Several pathways for the oxidation of the iron and formation of the magnetic iron-containing composite particles have been suggested, and will be recounted below:

An obvious model\textsuperscript{48} for formation of the magnetic dust is that it is essentially ground-down bedrock, which has undergone little or no modification. The magnetic mineral would in this case be magnetite inherited directly from the basaltic Martian rock, probably with some substitution of titanium. Palagonitic soils on Earth, which are composite soils rich in titanomagnetite produced by breaking down and weathering of volcanic rock, are known to possess mean saturation magnetizations as high as 2.5 Am$^2$/kg. Palagonitic soils also reproduce the spectral appearance of the Martian soil at optical, near IR and thermal infrared wavelengths\textsuperscript{49}; indeed some areas on Terrestrial volcanoes show a striking resemblance to the Martian terrain. Moreover the Mössbauer spectrometer on Spirit identified large amounts of magnetite or titanomagnetite in both rocks and soils in Gusev Crater\textsuperscript{22}. Spirit also determined that the exterior of rocks in Gusev show ratios of ferric to ferrous iron similar to the soil while the interiors of rocks show more ferrous iron suggesting that some oxidation process occurs on the exterior of rocks. This model would be unlikely to produce cemented composite grains but could produce loose aggregates of single-mineral grains. The model has the advantage of utilizing a simple mechanism, which is known to operate on Earth; it does not postulate different formation pathways for soil and dust and, especially after the detection of large magnetite concentrations in Gusev soil and rocks, it must by application of Occam’s razor\textsuperscript{15} be considered the most probable. Further understanding of the oxidation process which seems to have occurred on rock exteriors would, however, be desirable.

Another possibility is that the dust was formed by precipitation in water during a wetter period in the Martian past. On Earth oxidation of iron is often encountered in connection with water, moreover there is geological evidence in the so-called banded iron formations that conversion of $\text{Fe}^{2+}$ to $\text{Fe}^{3+}$ followed by precipitation of $\text{Fe}^{3+}$ happened on a very large scale in the oceans on Earth until around 2 billion years ago. Experiments also bear out that effective conversion of $\text{Fe}^{2+}$ to $\text{Fe}^{3+}$ followed by precipitation can be induced by shining UV-radiation on a solution of $\text{Fe}^{2+}$ in water\textsuperscript{50, 51}, even in the total absence of molecular oxygen. Based on the evidence for widespread water on Mars in an earlier epoch it is conceivable that UV-induced conversion of $\text{Fe}^{2+}$ to $\text{Fe}^{3+}$ in Martian lakes or seas could have led to a large production of ferric minerals. Precipitation in water also naturally produces composite particles as different minerals are mixed together in the liquid solution. The question is just whether this process could produce one of the highly magnetic minerals needed. Formation of the mineral lepidocrocite ($\gamma$-$\text{FeOOH}$) is reported in one experiment\textsuperscript{50} and would on a later dry Mars naturally lead to formation of maghemite.

\textsuperscript{14} ferric iron = $\text{Fe}^{3+}$, while ferrous iron = $\text{Fe}^{2+}$.

\textsuperscript{15} Occam’s razor (William of Occam, 1300-1349) is the general scientific principle that among two models that explain the observed phenomena one should prefer the simplest, and the one which requires the fewest new assumptions.
(γ-Fe₂O₃) by dehydration, but another experiment[51] reports formation of goethite (α-FeOOH) which would lead to later formation of weakly-magnetic hematite (α-Fe₂O₃). Most likely the exact precipitation product is dependent on specific factors such as pH-value of the solution and availability of oxygen. In all cases iron-oxides formed by precipitation in water would be expected to be titanium-free.

In summary UV-induced precipitation of γ-FeOOH in water followed by dehydration to maghemite might well produce composite particles with a high saturation magnetization. Maghemite is yellow-brown and thus fits the visual appearance of the Martian dust, however the proposed formation process is not known from Earth, where maghemite is uncommon and usually formed by oxidation of magnetite. Also, the Mössbauer spectrometer on Spirit detected magnetite, not maghemite, in Martian soils, so this model would require the dust to be mineralogically distinct from the soil.

Other possible formation models exist: The dust has been suggested to originate as volcanic aerosol particles[52]. The lower pressure and lower gravity on Mars would tend to produce volcanic eruptions of a more explosive nature than on Earth; such explosive volcanic eruptions would lift large amounts of dust into the atmosphere with small grain sizes and experiments have suggested that small magnetite grains can nucleate in suspended droplets of melted basalt[53]. Some of this magnetite might later oxidize to maghemite or hematite to account for the brownish-red color of the dust.

Analogously microscopic grains of oxidized iron might form in the hot plumes from major meteor impacts. A layer of iron-rich nano-sized grains with a significant magnetization, which is thought to originate in the major meteor impact at the boundary between the cretaceous and tertiary time periods (CT-boundary)[54], has been discovered on Earth and some similar process might conceivably have produced the dust on Mars. The presence of Ni in meteoritic material could serve to distinguish such a contribution to the Martian dust.

Although the model of Martian dust as largely ground-down bedrock must be said to be the most probable there are, as we see, several different competing models for formation of the dust with accompanying distinct predictions for dust mineralogy. The primary purpose of the MER magnetic properties experiment is determination of the mineralogy of the magnetic phase in the dust, which would facilitate discrimination between different formation models with their differing consequences for our ideas about the past history of Mars.
Chapter 3

Spirit and Opportunity

3.1. The MER Mission

Before returning to discussions of Martian dust we will devote this chapter to a description of the MER mission. Several results and images from the mission have already been discussed in the previous chapter. This was necessary, since the mission has significantly extended our knowledge in many fields of Mars science and discussion of our present knowledge of Mars is practically impossible without mention of MER results. We will now present the design and important scientific results of the MER rovers in a more thorough fashion. This, unavoidably, will also return us to the subject of past water on Mars.

The MER mission to the surface of Mars consists of two identical, mobile, solar-powered rovers named Spirit and Opportunity. Each of the two MER rovers is a six-wheeled robotic vehicle carrying a scientific payload called the Athena payload as well as a set of engineering cameras used for orientation, mobility and hazard avoidance.

The stated overall science objectives of the mission are: to determine the aqueous, climatic, and geologic history of sites on Mars where conditions may have been favorable to the preservation of evidence of possible pre-biotic or biotic processes[55]; or, in an alternative formulation: to explore two sites on the Martian surface where water may once have been present, and to assess past environmental conditions at those sites and their suitability for life[2]. In other words: While the search for possible past or present Martian life remains a major general objective of Mars exploration this mission does not search directly for traces of life, instead it focuses on reading and understanding the geological record in order to better understand whether conditions favorable for life existed in the Martian past, and if so, where and when? In practice this largely means searching for geological evidence of past water activity.

The landing sites for the two rovers were chosen from ~155 original candidate sites based on the probability at a given site of finding clues to the past history of water on Mars as well as on a
number of engineering and safety criteria. For engineering and safety reasons landing sites were
required to be located between $10^\circ$N and $15^\circ$S (for maximum solar power), at least 1.3 km below
the local geoid (sufficient atmosphere for aerobraking and airbag deployment) and were required
to have low winds, few slopes and no more than moderate abundance of large rocks (for safety in
landing) as well as a trafficable and load-bearing surface (for rover mobility)[55]. Also the two
landing sites were required to be separated from each other by a large distance for ease in
operation of, and communication with, the rovers. The two landing sites eventually chosen were
Meridiani Planum (actual landing coordinates: $1.95^\circ$S, $354.47^\circ$E) and Gusev Crater (actual
landing coordinates: $14.57^\circ$S, $175.47^\circ$E), both of which show strong evidence for past water
activity in data acquired from orbit. In the case of Gusev the evidence for past water is
morphological in nature while at Meridiani it is spectroscopic, based on the detection of the
mineral grey hematite.

Gusev Crater$^{16}$[56], the landing site of the Spirit rover, is an old meteor crater with a diameter
of about 150 km (see figures 2-5 and 2-10), which is thought to have been the site of an ancient
lake. The crater is located at the northern end of one of the larger valley networks, Ma’adim
Vallis, which snakes for 900 kilometers through the Martian southern uplands before terminating
at its inflow in Gusev Crater. There is evidence for the existence in the past of a very large lake
basin at the upper end of Ma’adim Vallis. Counting this lake as well as valley networks emptying
into this lake, the area drained by Ma’adim Vallis is one of the largest watershed basins on Mars
with a total area of 7 million square kilometers; comparable to the largest Terrestrial watersheds
such as the Amazon and Congo Basins. The fluvial activity in the Ma’adim basin is thought to
have continued up until the late Hesperian or even early Amazonian 2-3 billion years ago,
probably with gradual freezing and glaciation in its later stages.

Numerous water-related morphological features are observed in Gusev; most evidently in the
channel and delta-like terrain at the inflow of Ma’adim Vallis, but several isolated groups of hills
in the otherwise flat crater also show a sedimentary layered structure. There was therefore
reasonable cause to expect mineralogical traces of water in Gusev soil and rocks, however Gusev
Crater is also located just 250 km south of the sizable volcano Apollinaris Patera and volcanic
material is prominent in the crater, forming the newest and uppermost layers. The above-
mentioned groups of hills are possibly isolated remnants of older sedimentary terrain that had
been eroded and subsequently covered by volcanic material in most of the crater. Wind-related
features are also observed from orbit, both in the shape of numerous dust devil tracks (fig. 2-10)
as well as in the shape of erosional features. Finally a number of smaller craters dot the floor of
the larger Gusev Crater, interestingly some of these exhibit morphologies suggestive of the
presence of near-surface ice.

In contrast to Gusev the landing site of the Opportunity rover in Meridiani Planum$^{17}$[57] does
not exhibit any distinctive morphology indicative of fluvial activity. It is one of the smoothest
places on Mars; a very flat plain of dark sand/dust overlying a complex, brighter unit of ‘etched
terrain’, which is locally visible where it is exposed by impact craters and in other places. The
interest in the Meridiani site stems mainly from the detection by the Thermal Emission
Spectrometer (TES) on Mars Global Surveyor of a large proportion (up to 15% by weight) of the
mineral hematite in the dark, upper unit. These large hematite deposits are unique for Mars and
moreover orbital optical spectra lack the typical distinctive bright red signature of hematite,
which was interpreted to mean that the hematite is present as large-grained gray hematite.

$^{16}$ Named after Russian astronomer Matvei Gusev (1826-1866)
$^{17}$ Named for the location of the plains, close to where the meridian crosses the equator
Hematite is known to be a possible product of oxidation and precipitation of iron in water (see section 2.5.2), and especially gray hematite is on Earth strongly connected with slow precipitation in standing water.

The Meridiani hematite area is regionally located within old, heavily cratered plains that slope gently downward from the highlands to the north-west toward the plains of Arabia Terra and Margaritifer Terra and, ultimately, the northern lowlands. Fluvial structures are common in the wider region and follow the topography arguing that the general tilt of the plains has been unchanged since before the formation of these structures. Both the dark, hematite-bearing unit and the brighter etched terrain underneath postdate the fluvial structures and are thought to have been emplaced around 3.5 billion years ago in the late Noachian or Early Hesperian age, when the general tilt of the terrain was the same as it is at present. Intriguingly this means that there is no evident morphological boundary to the putative lake or sea in which the hematite deposits should have been formed, unless indeed this boundary encloses the entire northern lowlands. The strong support coming from the observations of the Opportunity rover for the theory that the Meridiani hematite deposits were formed in standing water (see section 3.4.3) thus also strengthens the theory of a past Martian ocean covering the lowlands of the northern hemisphere (see section 2.3).

Like in Gusev, aeolian features are widespread in Meridiani Planum. Most notably many impact craters show dark duneforms in their bottom (see figure 2-8) and the bright etched terrain shows evidence of wind erosion in many places.

3.2. Rover Design

3.2.1. Design Overview

The active instruments of the Athena payload[2] are two remote-sensing instruments located on a mast, the Pancam Mast assembly (PMA) and four in-situ instruments located on a robotic arm, the Instrument Deployment Device (IDD): The remote sensing instruments are the Mini Thermal Emission Spectrometer (Mini-TES), a mid-range infrared spectrometer capable of mineralogical investigations of rocks and soil as well as temperature measurements of the ground and the atmosphere, and the Panoramic Camera (Pancam), a high resolution stereo color camera. The in-situ instruments are the Microscopic Imager (MI), for very high resolution close-up imaging; the Alpha Particle X-ray Spectrometer (APXS), which determines the elemental composition of rocks and soils by particle induced x-ray emission spectroscopy, x-ray fluorescence spectroscopy and alpha particle backscattering spectroscopy; the Mössbauer Spectrometer, an instrument for determining the mineralogy of iron-containing minerals and the Rock Abrasion Tool (RAT) for grinding the surfaces of rocks. In addition to this the rover carries a number of engineering cameras: The stereo Navigation Camera (Navcam) on the PMA and a total of four wide-angle Hazard-Identification Cameras (Hazcams), two on the front, two on the rear of the rover body. In addition to the active instruments the rovers carry a set of magnets designed to capture airborne magnetic dust and dust liberated by RAT-grinding for further analysis by the active instruments. These magnets are collectively denoted the Magnetic Properties Experiment

The overall guiding principle behind the design of the Mars Exploration Rovers is that the rovers should be able to act as ‘robotic field geologists’. The rovers move across the terrain surveying their surroundings with the mast instruments and, based on data thus acquired, the science team chooses targets for further investigation by the instruments on the robotic arm. Many of the rover instruments have analogies in the toolset of a field geologist: Pancams and
Navcams are the geologist’s eyes; the MI is his field magnifying glass while the RAT is his rock hammer, providing access to the unaltered interior of rocks. Other instruments provide spectroscopic capabilities not normally available to a geologist outside of a laboratory. These are the Mini-TES, the APXS and the Mössbauer.

The rover design is illustrated in figure 3-1 below. In addition to science instruments and engineering cameras the sketch also shows the power-generating solar arrays, the rover mobility system (i.e., the wheels), the filter and capture magnets and the three communication antennas on the rover.

![Figure 3-1: Design of the Mars Exploration Rover showing the science instruments and magnets of the Athena Payload as well as engineering cameras, antennas, solar arrays and five of the six rover wheels.](image)

Solar arrays cover most of the rover deck and provide power for rover operations and heating either directly or indirectly via the batteries located below the rover deck. The wheels can each be elevated, turned or rotated separately, allowing the rover to turn in place, drive over significant obstacles and drive both forwards and backwards. The front wheels have also occasionally been employed for digging shallow trenches, allowing access to subsurface soil layers. The magnets of the magnetic properties experiment (see section 3.5) are located in three places on the rover. The capture and filter magnets are visible right in front of the PMA on the sketch. The sweep magnet is too small to be visible, but is located right next to the Pancam calibration target, at the rear of the rover deck. The RAT magnets are also too small to be visible. They are located within the RAT structure on the IDD.
The three antennae are all located on the rover deck. The low-gain antenna provides low-bandwidth, but direction-independent, direct-to-Earth communication capability, important for maintaining communications in the event that the rover should lose its orientation. The high-gain antenna provides a higher bandwidth communication direct-to-Earth, but the antenna needs to be pointed in order to make communication possible. This antenna is the preferred route for command upload. The UHF antenna is employed for indirect communication sessions, using the Mars Odyssey or Mars Global Surveyor orbiters as relay stations. The UHF antenna provides the highest bandwidth of the three antennae and is the preferred route for data download.

3.2.2. Mini-TES

The design of the Mini-TES is based on the Thermal emission Spectrometer (TES) instrument carried on the Mars Global Surveyor probe. The instrument itself is a Michelson interferometer located in the main rover body, right below the deck. Thermal radiation enters the PMA through a hole on its rear (i.e., the side opposite the front of the cameras) and via a system of mirrors the radiation is transmitted through the hollow PMA down to the interferometer. The PMA thus in effect acts as a periscope for the Mini-TES. The system can point 360° in azimuth and from -50° to +30° in elevation and acquires 167-point spectra in the wavelength range from 5-29 µm. The instrument can be run in two modes, one with a field of view of 8 milliradians and one with a field of view of 20 milliradians. The disadvantages of the high spatial resolution mode are a lower signal and less spatial coverage. Generally during rover operations the 20 mrad mode was used.

Emission by rocks and soils in the wavelength range of the Mini-TES is dominated by vibrational molecular energies. The emission energies of various materials are controlled by the detailed crystal structures, thus mineralogy of many geologic materials including silicates, carbonates, sulfates, phosphates, oxides, and hydroxides can be determined from Mini-TES spectra. Also since the Mini-TES analyzes infrared radiation in the thermal wavelength region the instrument can be used to remotely determine temperatures of surface rocks and soils as well as temperatures in the atmosphere. Measuring surface temperatures as a function of time of day allows estimation of the thermal inertia of surface materials and thereby allows the Mini-TES to distinguish between areas rich in rocks (high thermal inertia) and areas rich in sand (intermediate) or dust (low thermal inertia). Since the wavelengths investigated are at the high end of the thermal range relative to Martian temperatures the instrument is most effective in the afternoon, when temperatures are highest.

3.2.3. Pancam

Each rover carries two Pancams[58] and two Navcams on a rotating camera bar on top of the PMA, 1.5 m above the Martian surface. The camera bar provides pointing capability over the full 360° in azimuth and ±90° in elevation and the two Pancams are located 30 cm apart providing stereo ranging capability for the rover. Each Pancam has a small filter wheel with eight different filter positions giving a total of 16 different filters for the two Pancams. Two of these filters are high attenuation ‘solar filters’; one position has no filter for maximum signal, while the 13 remaining are narrow band ‘geology filters’.These allow the camera to take 11-point spectra in the wavelength region between 400 - 1100 nm, with two of the geology filters duplicated in the right and left camera providing stereo imaging in two different color bands.

The Pancam has a square field of view of 16.1° by 16.1° and a best focus distance at 3 meters with a depth of field from 1.5 meters to infinity. Like all cameras on the MER mission the
Pancams are digital cameras using a frame transfer CCD detector array of 2048 by 1024 pixels with an active imaging area of 1024 by 1024 pixels. For Pancam this translates to an angular resolution of 0.27 mrad/pixel, equivalent to ~1 mm/pixel at the best focus distance of 3 meters.

The Pancam fulfills several functions on the rover: From an engineering perspective the camera is the primary sun-finding camera, assisting in rover navigation and orientation. Also the Pancam provides the best stereo coverage in the distance and thus complements the Navcam and Hazcams for construction of digital terrain models. From a science perspective the Pancam delivers measurements of optical density through its solar filters and through the geology filters delivers measurements of sky brightness as a function of angular distance from the sun, thus providing constraints on properties of airborne dust (see section 2.5.1). Few-color Pancam panoramas are the main tool for assessing morphology and geologic context of the landing sites and single frame ‘multispectral spots’ provide 11-band spectral information in the visible and near-infrared of selected targets thus assisting with mineralogical determination. Iron oxides and hydroxides tend to have especially distinctive spectra at these wavelengths. From multispectral imaging of the same or similar areas at various viewing geometries (photometry) physical properties (grain sizes) of surface materials may be constrained and finally as the color camera on the mission the Pancam has a central role in the public outreach effort.

The sixteen Pancam filter positions are denominated in shorthand by a letter and a number from 1-8 so that, for instance, L4 denotes the fourth position of the filter wheel on the left Pancam. Figure 3-2 shows the spectral response of the geology filters and of L1, the ‘no filter’ position. The L1 curve is equivalent to the normalized spectral response of the optics and the CCD only. The remaining left Pancam filters cover the region from 440 nm to 750 nm while two right filters duplicate left filters for stereo coverage and the rest of the right filters extend the spectral coverage to 1100 nm. All filters are narrow-band filters except for L7 and R1, which are short-wavelength pass filters and R7, which is a long-wavelength-pass filter. As illustrated by this figure the camera has stereo capacity either at 440 nm (L7, R1) or at 750 nm (L2, R2). The geology filters generally have peak transmissions around 85%. Figure 3-3 shows the spectral response of the two solar filters. The solar filters are narrow band filters similar to the geology filters, but with and additional neutral density metallic film coating providing an additional reduction of a factor of $10^5$ in the signal. The large attenuation makes direct observation of the sun practicable with these filters. The 'bump' near 700-750 nm is a leak in the blue filter (L8) which has been shown in realistic tests to contribute as much to the signal as the primary band pass[3].
Figure 3-2: Normalized spectral response profiles for Opportunity Pancam geology filters as measured during preflight calibration[58]. The curves for the Spirit Pancam are very similar. The curves show normalized total system response, i.e., they include the response of the optics and the CCD.

Figure 3-3: Normalized spectral response profiles for Opportunity Pancam solar filters as measured during preflight calibration[58]. The curves for the Spirit Pancam are very similar. The curves show normalized response for narrow band filters, optics and CCD but do not include the effect of the neutral density coatings.
All MER cameras underwent an extensive preflight test and calibration program. Generally it was found for all cameras that the required flat-field corrections are small and there are only very few bad pixels. The dark current noise is also of low significance at realistic Martian temperatures and sensitivity and spectral response of the cameras changes only little over the relevant temperature range. Frame transfer smear is significant for exposure times less than ~2s. During flight smear correction was performed by subtracting a zero exposure time image of the same scene. None of the MER CCDs have any built in anti-blooming structures. Thus, after a pixel reaches full well, electrons may ‘bleed’ into neighboring pixels. When imaging the Martian sky or surface this is generally not a problem as the scene has relatively homogenous brightness. However it is occasionally problematic when imaging targets on the rover deck - such as magnets - since specular reflections from nearby metallic structures can be very much brighter than the surrounding scene. Magnet observations have occasionally had to be repeated due to blooming problems.

As a supplement to the pre-flight calibration procedures the rovers each carry a Pancam calibration target on the rear of the rover deck for in-flight validation of the pre-flight results as well as for monitoring the stability of the calibration. During the mission the calibration target is imaged routinely as an accompaniment to all Pancam imaging. The magnetic properties experiment (see section 3.5) includes the sweep magnet, which is very small and located next to the Pancam calibration target. All images of the calibration target also show the sweep magnet. Therefore the sweep magnet is imaged almost every sol, often several times in a sol, so that temporal coverage of dust build-up on the sweep magnet is extensive.

### 3.2.4. Engineering Cameras

The rover engineering cameras[59] include two Navcams mounted on the PMA; two front Hazcams mounted just below the rover deck on the front of the rover; two rear Hazcams mounted just below the rover deck on the rear of the rover. In addition to this there is a camera on the lander structure, which was used solely for the purpose of acquiring three images of the landing site during the descent through the Martian atmosphere.

The Navcams are located next to the Pancams on the PMA camera bar and, like the Pancams, can be pointed in all directions. The main differences are that the Navcams are monochrome with a wide-band optical filter and have larger field of view and correspondingly lower angular resolution compared to the Pancams. The Navcams have a square field of view of 45° by 45° and an angular resolution of 0.82 mrad/pixel. The best focus distance is at 1 meter and the depth of field is from 0.5 m to infinity.

The primary purpose of the Navcam is to provide basic context stereo imagery of the local environment. Digital terrain maps based on these images are used for planning rover traverses and Navcam images are used for pointing of Pancam and Mini-TES observations. The large field of view of the Navcam means that full 360° panoramas can be – and are – routinely acquired at a non-prohibitive cost in time and data volume. The mobile nature of the rover means that it often finds itself in unknown terrain. Quickly acquiring a general overview of local obstacles and identifying targets of scientific interest is essential for efficient rover operation. This pressing need is met by the Navcam.

The Hazcams are wide-angle fish-eye cameras, one stereo pair looking forward, one pair looking backward. Each Hazcam has a square field of view of 124° by 124° giving an angular resolution of 2.1 mrad/pixel. The depth of field is from 0.1 m to infinity with a best focus at 0.5 m. The Hazcams complement the Navcams and Pancams in generation of terrain models,
covering the area right in front of and behind the rover, thus ensuring that obstacles right in front of the rover wheels are adequately characterized before driving, both when driving forward and when reversing. The rover’s autonomous navigation and hazard avoidance system (see section 3.3.1) relies on regular imaging of the area right in front of the rover to update the onboard terrain map at short intervals during driving. Terrain maps generated from front Hazcam stereo images are also essential for accurate placement of the robotic arm instruments.

### 3.2.5. Microscopic Imager

In contrast to the PMA instruments and the Hazcams described above the MI and all other instruments on the IDD are in-situ instruments. The IDD is a five-degrees-of-freedom manipulator, which is located on the front of the rover, below the PMA, and has roughly the dimensions and shape of a human arm. There is an elevation actuator and an azimuthal actuator in the ‘shoulder’ of the IDD, an elevation actuator in the ‘elbow’ and two actuators in the ‘wrist’. The four IDD-instruments making up the ‘hand’ of the IDD all have to be brought into close proximity of their target for measurements (or grinding in the case of the RAT). Therefore, in general, these instruments are used less often than Hazcams or PMA instruments as IDD work is a greater operational challenge than remote sensing. This is true from a planning perspective since the IDD has 5 degrees of freedom as against 2 for the PMA instruments and because IDD instruments have to be very carefully positioned for maximum science return. It is true from a safety perspective as well since the IDD brings sensitive scientific instruments into close proximity with rocks and soil, which might potentially damage these instruments if proper care is not exercised.

The main function of the MI is to provide high resolution monochrome images of soil and rock targets of interest. This includes documentation imaging of targets investigated by the APXS or the Mössbauer. By identifying the MI target area in a Pancam image generally one also identifies the target for the APXS or Mössbauer as the IDD is able to rotate and place another instrument on the same target with good precision. Like all IDD instruments the MI can be brought in contact with the capture and filter magnets and provides high resolution images of the dust on these magnets as well.

Technically, the MI is not a true microscope as it operates at a fixed, moderate magnification. The best focus distance is 66 mm from the lens with a depth of field of ±3 mm. This gives the camera a square field of view of 31 mm by 31 mm at the operating distance, which is equivalent to a resolution of ~31 µm/pixel. This moderate resolution is adequate for resolving sand-sized particles but not sufficient for resolving dust grains. The chosen resolution has the important advantage that placing MI images into the context of a Pancam image of the surrounding scene is generally easily achievable. Higher resolution images with smaller fields of view would be harder to place into context.

The limited depth of field means that some part of the MI image will be out of focus when imaging a scene with strong relief. For this reason, and in order to assure that one image is in good focus even if the positioning of the MI is slightly inaccurate, MI images are routinely taken in ‘stacks’ of seven, five or three, moving the IDD 3 mm closer to the target between each image. At least one image in such a stack will generally be in good focus if the scene imaged has only slight relief. If there is larger relief an image with good focus over the entire scene can be generated from a stack of images by the procedure of a ‘focal section merge’. Pseudo-stereo 3D models of the target surface can also be generated from stacks of MI images. Improved stereo
3D-modeling can be achieved by the simple expedient of acquiring an extra stack or just a single image from a position translated 3 mm laterally across the target surface.

![Design of the MI](image)

**Figure 3-4**: Design of the MI. The ball at the end of the contact sensor was removed in the final version[60].

The MI design is shown in **figure 3-4**. The MI is protected by a contact sensor and a dust cover. The contact sensor is a small pole sticking out in front of the camera which protects the camera from contact with a hard target, should an erroneous command be sent. The dust cover protects the lens from airborne dust and is opened by a stepper motor before imaging.

The MI is a monochrome camera with a wide-band optical filter chosen to give a spectral response similar to the response of the human eye. The normalized spectral response of the MI optics and CCD is shown in **figure 3-5** below. It is possible to take MI images through the transparent dust cover on the MI, which shifts the spectral response curve to slightly longer wavelengths. Typically, the effective wavelength shifts from 570 nm without the cover to 582 nm with the cover. From one image with the dust cover open and one with the cover closed a ‘pseudo color’ image of the scene may be generated. Another way to generate MI color images is by merging Pancam color data with MI textural data from the same scene.
Figure 3-5: Normalized spectral response at different temperatures for the MI on Spirit. The curve for the Opportunity MI is very similar[60].

3.2.6. Alpha Particle X-ray Spectrometer

The purpose of the APXS is to determine the elemental composition of soils and rocks at the two MER landing sites. The instrument is an improved version of the similarly named instrument on the small Sojourner rover that was part of the Mars Pathfinder mission. The APXS works by exposing Martian soil and rocks to energetic alpha particles and x-rays from a radioactive $^{244}$Cm source and measuring the energy spectra of backscattered alphas and emitted x-rays. Different elements have different distinctive spectral signatures allowing determination of elemental composition. The field of view of the instrument is a circle 25 mm in diameter[20], comparable to the MI square 31 mm by 31 mm field of view.

Measuring x-ray emissions the instrument is sensitive to elements from sodium and upwards in atomic weight. Elements detected at Gusev include Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Zn and Br[20]. The list from the Meridiani site is similar. Measuring alpha particles the instrument is sensitive to lighter elements, mainly oxygen and carbon, but this requires very long integration times. Normally major element composition from the x-ray mode can be determined in about half an hour, while minor elements require longer integration times of several hours. The instrument is vulnerable to thermal noise in the detectors and is most effective when temperatures are low at night or in the morning.

Like the MI and the Mössbauer the APXS can be brought into close contact with the dust on the capture and filter magnets. APXS spectra of these dust layers have been acquired on both rovers. However, because these dust layers are thin compared to the penetration of x-rays and alpha particles, analysis of the data is different from that of bulk samples[61].
3.2.7. Mössbauer Spectrometer

For radioactive nuclei in solid materials emission or absorption of gamma rays occasionally happens ‘recoil-free’ in the sense that the recoil required by conservation of momentum is absorbed by the entire crystal instead of by motion of the emitting or absorbing nucleus relative to the crystal (crystal vibrations). This is known as the Mössbauer effect. The large mass of the entire crystal relative to the momentum of the gamma photon has the important consequence that an absorbing nucleus has a relatively large probability of absorbing all of the photon energy or conversely, that most of the emitted photons carry all of the energy from the transition in the nucleus. Thus, when scattering of a gamma photon occurs recoil-free the scattered photon has exactly the same energy as the original photon, i.e., the process is essentially lossless and no noise is introduced by recoil of the nucleus. This is called resonant absorption/emission.

Mössbauer spectroscopy utilizes this effect to gain knowledge of mineralogical structure by shining gamma rays from a given transition in some suitable elemental isotope onto a sample containing this same isotope. The energy levels in the target nucleus will be split and shifted very slightly by the effect of the local crystal environment on the energy levels in the nucleus (electrostatic and magnetic hyperfine interactions). This energy split is so tiny (of the order of $10^{-13}$ relative to the total energy of the transition) that normally one would not expect it to be detectable; however the lossless and noiseless nature of the recoil-free absorption allows investigation of these subtle shifts. Commonly the emitting source is placed on a drive vibrating at speeds of mm/s and the Doppler shift in the emission energy is used to scan across the split energy levels in the absorber. By this technique information can be gained about the crystal structure of the target sample.

Several different gamma transitions in radioactive isotopes of common elements have been utilized for Mössbauer spectroscopy. The transition most commonly used, however, is the 14.4 keV transition in $^{57}$Fe. Because of the ubiquitous presence of iron-minerals in Martian surface materials Mössbauer spectroscopy using $^{57}$Fe is a method uniquely well suited for determining the mineralogy of Martian rocks and soil. This is the transition utilized in the MER Mössbauer spectrometer.

From Mössbauer spectra one may identify a number of different iron bearing minerals and determine the relative amount of iron in these minerals. The ratio of ferric to ferrous iron is easily determined allowing insight in past or present oxidation processes; notably products of aqueous oxidation will in general be different from products of other oxidation processes. Magnetically ordered materials have very distinctive Mössbauer spectra so the method is even more powerful for identifying magnetic iron minerals.

Usually, in a laboratory, Mössbauer spectroscopy is performed in transmission geometry, measuring resonant absorption of photons in the sample as a function of the instantaneous drive velocity, but measurements can also be performed in backscattering geometry, measuring photons resonantly scattered from the sample. This is the method used by the MER Mössbauer spectrometer. The spectrometer has a $^{57}$Co source mounted in a velocity drive, which is vibrated at speeds in the range ±12 mm/s. For measurements the spectrometer is brought into contact with, and pressed slightly towards, the target in order to minimize spurious vibrations. The target area is a circular spot of ~15 mm in diameter.

Mössbauer spectra can be dependent on temperature. Especially for small crystal grains of magnetic materials (superparamagnetic materials) the Mössbauer spectrum often shows a strong temperature dependence. For this reason the MER Mössbauer spectrometer saves data in different temperature bins, so that long integrations can be performed across changing temperatures and
information can be extracted from the variation of the spectra with temperature. The Mössbauer spectrometer is not as vulnerable to thermal noise in the detectors as the APXS and adequate Mössbauer spectra can be acquired at any time of day. Some information (e.g., \( \text{Fe}^{2+}/\text{Fe}^{3+} \) ratios) may be extracted from short integrations while long overnight integrations result in more precise mineralogical information.

As with the MI and the APXS the Mössbauer can be brought into contact with the capture and filter magnets. Indeed the primary purpose of these magnets is to allow investigation of magnetic dust by the Mössbauer spectrometer thereby identifying the mineral responsible for the magnetic nature of the Martian airborne dust. For this reason the magnets contain no iron\(^\text{18}\), so that no contribution to the Mössbauer spectrum will come from the materials in the magnets.

3.2.8. Rock Abrasion Tool

Natural rocks commonly have surfaces that are altered in some way from the more pristine rock interiors. For Martian rocks this alteration may range from surficial layers of airborne dust to changes in outer layers of rocks due to mechanical or chemical weathering. Understanding the formation of rocks is often easier if one has access to the unaltered interior while an understanding of weathering processes can be gained from comparing altered rock surfaces to unaltered rock interiors.

The last of the IDD instruments, the RAT, is not an instrument for scientific observation of surface materials as such, rather the purpose of the RAT is to allow other MER instruments access to unaltered rock interiors by grinding away surface layers. The RAT is capable of grinding a hole 45 mm in diameter and at least 5 mm deep in rocks. The instrument has a rotating diamond-tipped grinding head with very low gearing and grinds at a low force. Therefore the power requirements for grinding are low and only little frictional heating is expected, so that no chemical or mineralogical changes should occur in grinded rocks. The downside is that grinding operations take a long time; typically 3-4 hours are required for grinding 5 mm into the hard Gusev basalts while the softer evaporite rocks at Meridiani are easier to grind. The RAT saves data of power and grinding depth as a function of time thus the instrument actually measures rock hardness and the uniformity or heterogeneity of rock hardness.

The grinding process obviously produces a certain amount of debris. This is swept from the RAT hole by a system of two brushes rotating in conjunction with the grinding bit. By grinding with no applied force it is possible to perform a brushing operation with the RAT, just removing loose dust rather than actually grinding. By investigating a pristine rock surface with IDD instruments, brushing, investigating again and grinding followed by a final investigation it is possible to distinguish loose dust from chemically altered surface material and from the unaltered rock interior.

Four small magnets of differing strengths are mounted on the RAT behind the grinding head. These ‘RAT-magnets’ attract magnetic dust liberated from rocks by grinding. Inspection of the RAT magnets by the Pancam allows information to be gained about magnetization and optical spectra of any magnetic materials removed from rocks by the grinding process.

\[^{18}\text{The Sm2Co17 material contains iron impurities, but this material is covered by a layer of 99.999\% pure aluminum, which is 2 mm thick on the Filter magnet and 0.4-1.1 mm thick on the Capture magnet. A small Mössbauer signal is observed on a clean Capture magnet but not on a clean Filter magnet.}\]
3.3. MER Operations

3.3.1. Rover Operations

Due to the time-lag in communications introduced by the distance between Earth and Mars direct control of the rover by an operator on Earth is impracticable. The solution is to instead generate and send a set of commands to the rover once every day. The rover turns on in the morning, receives its command load for the day, and proceeds to execute the commands one by one in the order commanded. It is possible to fix certain rover actions to specific times (used for instance for communications sessions) either requiring the rover to introduce a wait before the action if the previous actions finished early or to break off a series of commands before full execution if execution of the commands is running late.

The generation of the daily command load is a complex puzzle with the objective of getting the largest science return from the available resources. Three different limited resources impose the main constraints. These are energy, time and download capacity. The rover solar cells only generate a limited amount of energy every sol and while it is possible to use more energy during a sol by drawing on the batteries this cannot continue for many sols before recharging is necessary. The rover needs energy for driving, for science observations, for running the CPU and for heating of the central electronics during night. There is obviously also only a limited number of hours in a sol and most rover operations can only be performed during the day. Moreover operations cannot commence at sunrise but must wait until the sun has heated rover joints enough for operation, usually around 9-10 AM. Earlier operation requires extra heating, which is energy-expensive. Finally there is only a finite data download volume available each sol and while more data can be acquired this gradually fills the onboard memory and can only continue for so long.

Several options exist for manipulating these limitations by trading one resource for another. If the rover operates for a shorter time, the shorter CPU on-time will result in more available energy. Similarly canceling a communication session will conserve energy. Commonly several communication sessions are possible during nighttime. Canceling one of these will save both energy for radiating the signal, energy for heating and CPU on-time at the cost of lower download.

Some rover operations are costly in terms of energy and time but not in data volume (i.e., driving, RAT grinding); some are mainly costly in terms of time (Mini TES operation), some mainly in energy (overnight APXS or Mössbauer integrations) while some are mainly costly in terms of data volume (imaging). Choosing a temperate mix of these different operations is crucial for maximizing science return. Also some operations can run in parallel; this is mainly the case for the Mössbauer and the APXS, both of which, once they are placed on a target, may integrate in parallel with PMA work (see section 3.2.1).

Finally there are a number of practical and safety-related constraints that must be taken into consideration: The Mini-TES is most effective in the afternoon, when temperatures are highest. When commanding PMA observations after a drive Navcam images of the surroundings will not be available. For a short drive it may be possible to hit a target with a PMA observation based on previous knowledge of that targets position, after a long drive, however, the PMA pointing will have to be carried out blindly. New Navcam panoramas will typically have top priority in these situations. A consequence of the above is that on drive days the Mini-TES may either be used in the morning, when signal to noise ratios are bad or in the afternoon after the drive, when pointing is bad. IDD operations cannot be commanded until front Hazcam images from the current position are downloaded, which means that the IDD cannot be used after a drive on the same day.
For really good APXS and Mössbauer data an overnight integration is required. Both instruments are capable of integration while the CPU is off, so a common way to do this is to take MI images in the afternoon followed by a placement, usually of the Mössbauer, on the target. The CPU is then turned off and the Mössbauer integrates. In conjunction with a communication session during the night, when the CPU is on anyway, the APXS is then placed on the target and the APXS integrates for the rest of the night. Finally the IDD is stowed first thing after rover wake-up in the morning.

In order to facilitate the easy construction of a set of rover commands that takes all constraints and limitations into consideration a number of generic ‘sol types’ have been identified. The first step in rover planning for a sol, a step that will usually be taken several sols in advance, is to identify the type of sol to plan for. This gives an agreed overall framework for the detailed planning and command generation and saves planning time. Sol types include such concepts as the drive sol, the approach sol (a short drive bringing a specific target into reach of the IDD), the spectroscopy sol (mainly IDD work), the panorama sol (PMA work) and others.

Rover drives can be commanded either ‘blindly’, or with the onboard hazard and obstacle avoidance software active. In a blind drive the drive sequences are generated on Earth using a digital terrain model based on previously downloaded stereo Hazcam, Navcam and Pancam imagery. The rover then executes the uploaded sequences exactly as commanded. A blind drive is only safe when terrain data are reasonably complete. This puts a maximal distance on a blind drive. If there is Pancam data in the drive direction this maximal distance is usually about 40 meters, less if only Navcam data are available.

It is possible to execute a rover drive without adequate terrain data available by using the rover’s onboard obstacle avoidance software. In this mode the rover drives a short distance, acquires a stereo front Hazcam image pair, updates its onboard terrain model and autonomously decides on the next short drive. The only input supplied from Earth is the final target point, towards which the rover should drive. Driving with obstacle avoidance active is very much slower than blind driving, which is why the usual way to command a long drive is by first commanding a blind drive as far as it is safe and follow this by a drive with active obstacle avoidance for the rest of the distance.

### 3.3.2. Camera Operations

All camera observations on the rover are commanded by just a single command having no less than 47 arguments. This command: `capture image`, regulates all aspects of imaging. One argument specifies which camera to use; one argument specifies the downlink priority of the image; one argument regulates exposure time, which may either be specified directly or can be determined by an ‘autoexposure’ routine; one argument species which filter to use for Pancam imaging and so on. Pointing of the PMA camera bar for Pancam or Navcam imaging is also regulated by the capture image command, while for the MI positioning of the IDD must be commanded separately.

Pointing of the PMA camera bar can be specified in several different frameworks: Important examples are `site frame`, which points the camera towards a specified x, y, z point; `rover azimuthal frame`, which points the camera to a specified azimuth and elevation relative to the rover, zero elevation being parallel to the rover deck, zero azimuth straight forward and `level azimuthal frame`, which points the camera to a specified azimuth independent of the rover position and orientation, zero elevation being towards the horizon, zero azimuth north. Navcam
or Pancam panoramas can be generated by stringing series of capture image commands with
different pointings together.

The dominant contribution to rover download data volume comes from imaging. Every MER
CCD has 1024 × 1024 pixels. The raw image has 12 bits to a pixel, meaning that a raw image
takes up 12 megabits. Given that typical daily download volumes are no more than 200-300
megabits it is clear that reducing image data volume is crucial. Several options exist for achieving
this, all of them regulated by the capture image command. These are: Downsampling,
subframing, pixel scaling and compression.

Downsampling (binning) consists in adding pixels together, typically four by four, in effect
converting the CCD from a 1024 pixels × 1024 pixels square array to a smaller array, typically
512 × 512 pixels. Downsampling typically degrades the data more than compression to the same
number of bits, and so is not used much. Subframing consists in just downloading a part of the
image. If it is known that the target of interest fills only part of the image this is an efficient way
to reduce data volume without compromising the data. Pancam observations of the capture and
filter magnets, the sweep magnet or the RAT magnets are examples of Pancam observations that
are routinely subframed before being downloaded. Pixel scaling consists of reducing the number
of bits used in encoding the value for the brightness in a single pixel. Most images are scaled
from 12 to 8 bits using a square root transformation, meaning that more information is lost from
brighter pixels than from darker pixels. Finally compression covers more complex algorithms for
reducing data volume while retaining as much as possible of the information in the images. Two
different compression algorithms are used on the MER mission, both of them developed at JPL.
The LOCO algorithm is a lossless compressor, which is only used for data of extra interest.
LOCO compression typically reduces the data volume for an image from 12 bits/pixels to
somewhere in the range 7-9 bits/pixel, depending on the scene. The vast majority of images are
compressed using the ICER algorithm, which normally compresses to a fixed number of
bits/pixel, specified in the capture image command. Commonly Pancam or Navcam images are
reduced to 1-2 bits/pixel, usually after first reducing the data volume from 8 to 12 bits/pixel by
pixel scaling. MI and Hazcam data is typically reduced to 2-4 bits/pixel. It is possible to run the
ICER compressor in a mode, which compresses to a fixed image quality instead of a fixed
number of bits/pixel. This is the usual choice for MI images, as it has the advantage of
compressing the in-focus images of a stack less than the out-of-focus images, thus making more
efficient use of the available download data volume.

All MER images were subjected to several calibration procedures based on pre-flight
 calibration measurements as well as in some cases in-flight calibration procedures. Corrections
 routinely made onboard the rover include flat-field correction, dark current correction, bias
correction19 and frame transfer smear correction. In addition to this the science camera (MI and
Pancam) images are also converted to units of radiance (W/m²·nm·sr) and Pancam images are
also given as I/F, where I is the radiance and πF is the radiance of sunlight incident on the top of
the Martian atmosphere.

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19 Bias correction is correction for an offset voltage added in the electronics in order to maximize dynamic range
while avoiding undersaturation (zeros).
3.4. MER Results

3.4.1. Introduction

At the time this is written, both rovers have operated successfully on the Martian surface for more than 250 sols. Each rover has returned ~10 gigabytes of data and the MER mission has widened our understanding of Mars and Martian geological history considerably. It is clear, then, that an exhaustive treatment of the entire body of MER scientific results lies far outside the scope of this thesis.

What will instead be presented in the following is a broad overview of each rover’s observations and a general picture of our present understanding of the two landing sites. Image data will be given slight emphasis over other MER data for the simple reason that I was more directly involved with the acquisition of these data and for the same reason primary mission data (first 90 sols of the mission) will be more thoroughly treated. The magnetic properties experiment and its results will be treated separately in section 3.5.

3.4.2. The Spirit Rover in Gusev Crater

The landscape in Gusev Crater is similar in many ways to the landscape encountered at the Viking sites and the Pathfinder site; a dusty, reddish-brown plain, strewn with loose rocks and dotted with small impact craters. Figure 3-6 is a section of the Pancam panorama acquired shortly after landing. This image is pointed almost due east and shows the most obvious large-scale morphological feature visible from the landing site, namely the so-called Colombia Hills.

![Figure 3-6: The Colombia hills seen from the landing site of the Spirit rover. The image is an approximate true color composite made from I/F calibrated Pancam images taken in the L2, L5 and L6 filters. (NASA/JPL/Cornell)](image)

This group of small hills was about 2.5 kilometers from the landing site of the rover and was one of several isolated groups of hills in Gusev showing indications of layered structure in orbital images (see section 3.1). This image is shown at quite low resolution. Viewed at higher resolution these and later Pancam images of the Colombia Hills also show hints of layering in the hillsides.

Figure 3-7 shows a section of the terrain closer to the landing site. On this smaller scale, characteristic features of the terrain are its relative flatness (also compared to the Pathfinder and Viking sites), the many rocks of up to football-size scattered about the terrain and a number of small ‘hollows’: Shallow dusty depressions with few rocks. The closest of these hollows, named ‘Sleepy Hollow’, is visible in the middle right of the picture. The hollow is about 10 meters from the rover and is roughly 5 meters across.
A hollows are generally interpreted as being very small impact craters. Airborne dust has accumulated in these small depressions. However, despite the dust being clearly discernible in optical spectra, loose dust layers were nowhere found to be deeper than fractions of a millimeter, too little for analysis by APXS or Mössbauer spectroscopy. Soil surfaces everywhere show a fine-grained ‘dusty’ texture as is for instance evidenced by figure 3-8, the first MI image taken by Spirit. The surface shown in this MI image could easily be imagined as entirely consisting of loose, fluffy dust aggregates. However the well-defined shape of wheel tracks, as well as the reaction of the soil to manipulation by the wheels (i.e., digging of small trenches, ‘scuffing’) suggests that the upper few centimeters of soil are cemented into a fairly cohesive crust. The shape of imprints from the contact plate in front of the Mössbauer spectrometer supports this. Crusts are also found on the top of ripples[33], supporting the assertion that these sand-related aeolian features are no longer active (see section 2.4.1). Compositionally soils were observed to be similar to Pathfinder soils.
Three rocks were thoroughly investigated during the ‘primary mission’ phase constituting the first 90 sols of the mission. The rocks were investigated with the full Athena payload of scientific instruments (Pancam, Mini-TES, MI, APXS, Mössbauer) followed by brushing with the RAT, another full investigation and finally RAT grinding followed by a final investigation with the full payload. As described in section 2.2.2 the interior composition of these rocks was found to be consistent with olivine-rich primitive basalts with a significant content of magnetite (~5 % by weight). Based on Pancam and Mini-TES data these three rocks seem to be representative of the vast majority rocks in the area around the landing site. All three rocks are covered with a fine dust layer, which is apparent in a strong color change after brushing the rock surface. This is illustrated by Figure 3-9, which shows the last of the three rocks, named Mazatzal, before brushing, after brushing two spots and after grinding one of the brushed spots. Mazatzal is different from the two other rocks in that it has a bright outer coating, but the rock interior is largely similar to the other two rocks. Many other such bright-coated rocks were observed among the generally darker rocks in Gusev Crater. These were often low and flat rocks, and several rocks were observed that seemed to have bright coatings on one side or on the lower part. This suggests that some deflation process has been going on, probably driven by winds or dust devils, slowly removing the upper layers of soil, gradually exhuming rocks and stripping away their outer bright coatings. The Mössbauer spectrometer measured a hematite-like component in spectra of Mazatzal before grinding that was not present after grinding[22]. This component must thus be identified with the bright outer layer.
Figure 3-9: Pancam images of the rock Mazatzal before contact, after brushing, and after grinding. The images are approximate true color composites made from I/F calibrated Pancam images taken in the L2, L5 and L6 filters. (NASA/JPL/Cornell)

Figure 3-10 shows a part of a 4-image MI mosaic of the hole ground in the rock Mazatzal. The MI images show rests of a dark coating that is bounded on both sides by bright layers, strengthening the evidence that this rock has a chemically altered outer coating. In high resolution the image also shows dark megacrysts in the rock interior that are interpreted as olivine crystals. These are present in the other two rocks as well. Finally a fracture in the rock is filled with bright material. One of the other two rocks, Adirondack, also shows fractures filled with bright materials. This bright material is not believed to be dust and is most likely analogous to the bright coatings on Mazatzal and other rocks. It seems likely that the Gusev rocks have undergone some chemical alteration before being exhumed. This alteration may have involved small amounts of water[21]. The energy required to grind the Gusev rocks was also less than for a reference terrestrial unaltered basalt, supporting the assertion that some alteration has taken place[62].

Figure 3-10: MI image of the hole ground in the rock Mazatzal by the RAT. (NASA/JPL/USGS)
The Spirit landing site was just ~300 m from a large ~150 m diameter impact crater. The strategic objective decided by the science team for the initial rover traverse was to reach the rim of this crater, named Bonneville Crater. This goal was reached after ~70 sols. During the traverse to the crater rim the rover transected the crater ejecta material and a clear increase in rock sizes and rock abundances was observed as the rover approached the crater rim. Figure 3-11 shows part of a Pancam panorama acquired at the rim of Bonneville Crater. The crater floor and sides were covered with loose material and no bedrock was exposed in the interior of the crater as had been hoped. Therefore the team decided against entering the crater, as the expected science return was judged to be too small to justify the risks involved. The material in the crater would most likely turn out to be similar to material already investigated, while there was serious safety concerns connected with driving on the rather steep slopes of loose material.

Figure 3-11: Panorama acquired on sols 68-69 at the rim of Bonneville Crater. The Colombia Hills are visible on the right. The image is an approximate true color composite made from IF calibrated Pancam images taken in the L2, L5 and L6 filters. (NASA/JPL/Cornell)

After the end of the primary mission, the picture of the landing site that had emerged was of a plain of primitive volcanic basalt with some chemical alteration of rock surfaces going on underground and rocks being exposed on the surface by meteoritic impacts or wind-deflation of the upper soil layers. Although slight amounts of water are probably involved with the chemical alteration processes it was clear that this is not material from the time of the putative lake in Gusev Crater. Therefore it was decided to drive to the Colombia Hills, 2.5 kilometers away, in the hope that the material in these hills would be of different origin and contain the sought-after evidence from the time of the crater lake. Figure 3-12 shows an overhead image by Mars Global Surveyor of the region traversed by Spirit during the first 155 sols of the mission. A yellow line shows the path of the rover, from the landing on sol 1, over the time at the edge of Bonneville Crater around sol 70 and ending with the rover reaching the first spur of the Colombia Hills on sol 155. It is clear that from the time of the decision to drive for the Colombia Hills around sol 90-100, when the rover was still close to Bonneville Crater, significantly longer drive distances were acquired. This was partly due to a decision to prioritize driving over in-situ investigations, but was also due to an upload of new software that made the rover’s autonomous navigation software more robust (i.e., less ‘scared’ of small obstacles) and due to the increasing routine of the science and engineering teams allowing more efficient use of the available resources. Finally the terrain was also significantly more traversable away from the rock-rich Bonneville Crater ejecta blanket.
At the time this is written Spirit has spent more than 100 sols investigating the Colombia Hills. The materials in the hills have indeed turned out to be very dissimilar from the materials on the plain and for the first time Spirit has found solid bedrock. Since entering the hills several rocks have been investigated and these show strong evidence of alteration by water. The rocks are soft, they have elevated levels of bromine, chlorine and sulfur and strongly hydrated minerals like goethite have been encountered. Rocks have in general also been much softer and many show clear layered structure. Figure 3-13 shows a rock outcrop investigated recently in the Colombia Hills. The layered structure is unmistakable. So it seems likely that the Colombia Hills do indeed hail back to an earlier period than the surrounding plains; a period, when liquid water was more abundant in Gusev Crater than it is at present. Whether this can be interpreted to mean that the hills are remnants of sedimentary rocks formed at the bottom of a crater lake has not yet been determined.
3.4.3. The Opportunity Rover on the Meridiani Plains

From the very first images received it was evident that the landing site of Opportunity was very different from any of the places on Mars previously investigated by landers. Hopping and rolling across the flat surface of Meridiani Planum inside its protective airbags the rover had eventually come to rest inside a small impact crater with a diameter around 20 m. This crater was named Eagle Crater. From the landing site an extensive outcrop of bright, layered rock was visible in the crater ‘wall’ and behind this bright outcrop the dark and extraordinarily flat expanse of Meridiani Planum stretched unbroken to the horizon. A panorama of the scene at the Opportunity landing site is shown in **Figure 3-14** and part of the scene is shown in greater detail in **figure 3-15**.

![Figure 3-13: Pancam image of ‘Tetl’, a rock outcrop in the Colombia Hills, which shows a clear layered structure. The image is a false-color view generated from images taken in the Pancam’s L2, L5 and L7 filters. (NASA/JPL/Cornell)](image)

**Figure 3-14:** Panorama of the scene in Eagle Crater. The bright outcrop section has a horizontal extent of 5-6 m. The image is an approximate true color composite made from I/F calibrated Pancam images taken in the L2, L5 and L6 filters. (NASA/JPL/Cornell)

The bright outcrop instantly attracted very great interest. It is in-situ bedrock, looks very different from anything seen on Mars previously and gave indications of layering already in the
very first images. On closer approach these indications were borne out, as the outcrop rocks were indeed seen to be finely layered.

Figure 3-15: Part of the outcrop rocks in more detail. The extraordinary flatness of the surrounding plain is readily apparent. The image is a RGB composite made from radiance calibrated images taken in the Pancams L4, L5 and L6 filters (NASA/JPL/Cornell).

The Opportunity rover spent more than 60 sols thoroughly investigating the small Eagle Crater where it had landed. Especially the bright outcrop materials were closely scrutinized. As has been already mentioned in section 2.2.2 the eventual conclusion of these investigations was that that these layered outcrop materials are evaporite sediments formed in an ancient lake or sea. This conclusion rests on 5 pieces of evidence:

- Spherules a few millimeter in diameter are observed in the outcrop and in very great numbers on the ground everywhere on the plains. The spherules contain a large amount of gray hematite.
- The outcrop is shot through with ‘vugs’, disk-shaped holes a few millimeter in diameter.
- The outcrop rocks are finely layered. Detailed structure of the layers (‘crossbedding’, ‘festooning’) is reliable evidence for sedimentation in water.
- The APXS measured very high sulfur content in the outcrop rock. Chlorine and bromine levels are also elevated.
- The Mössbauer spectrometer discovered a large concentration of the mineralJarosite, an iron sulfate salt, in the outcrop rock.

The first piece of evidence, the hematite spherules, was evident already before approaching the outcrop. In figure 3-15 the ground both nearby and in the distance is very dark grey in color. In
some places the ground is slightly redder as if the grey material is a surface material on top of redder soil. In close-up this becomes even clearer. **Figure 3-16** shows a monochrome Pancam image of the ground right in front of the lander taken before egress, i.e., before the rover drove off the lander. The round marks on the ground are marks from the airbags as the lander rolled to its final resting place. The lines in the bottom of the image are drag-marks, from when the deflated airbags were dragged under the lander structure. The interesting thing is the rough texture of the ground as opposed to the smooth surface where the airbags touched. This rough texture is due to literally millions of tiny grey-blue spheres, a few millimeter in diameter, that lie strewn all over the Meridiani Plain. Where the airbags impacted, the spherules have been pushed into the soil, leaving a smooth surface.

**Figure 3-16:** Pancam image of hematite spherules on the ground in front of the Opportunity lander. Image is roughly 1 meter across in the foreground. (NASA/JPL/Cornell).

In MI images the individual tiny spherules are clearly visible. **Figure 3-17** shows an MI image on the ground at the floor of Eagle Crater taken on sol 15 of Opportunity’s mission. The image shows the spherules. Some of them half-buried in the soil, others lying on top of the soil. Some of them almost perfectly spherical, others are less symmetric. Comparing this image with 3-16 and 3-15 showing the texture and coloration effects on the ground due to the spherules gives an idea of the truly staggering number of these strewn across the plain.
Individual spherules are not big enough for analysis by the APXS and the Mössbauer spectrometer. However while investigating the outcrop rocks several sites were found, where the spherules had accumulated close together. Figure 3-18 shows a Pancam image of one of these places. At this site spectra were taken of the area to the right of the circular RAT mark, where there is a dense concentration of the spherules and for comparison spectra were taken of the area to the left of the RAT mark, which is empty of spherules. The Mössbauer spectrum of the spherule-rich area showed a strong hematite signal, while the empty area gave only a weak hematite signal. Thus the spherules are identified as the bearers of the grey hematite that had been discovered from orbit. The color of the spherules is consistent with this interpretation. Mini-TES spectra further strengthen the interpretation, showing the weakest hematite signal from the rock outcrop, where there are fewer spherules and the strongest hematite from soil areas rich in spherules.

As mentioned, grey hematite is usually encountered on Earth in connection with precipitation in liquid water. The perfect round shapes are also consistent with crystal growth in a liquid environment rich in ferric iron. The spherules are present randomly distributed inside the outcrop as well as on the ground, which argues for them growing in-situ during or right after formation of the rock as opposed for instance to forming in air during volcanic events, in which case one would expect the spherules to be concentrated in some layers more than others. It is very likely that all the spherules now seen on the plain were once inside rocks like the bright outcrop in Eagle Crater. As the soft outcrop rock slowly eroded over a long time the hematite-bearing spherules were left behind as a dense layer on top of the soil.
The second piece of evidence for a watery origin of the outcrop rocks is illustrated in figure 3-19. This MI image shows a close-up of a section of outcrop rocks. Very prominent in this image are a number of oblong cavities in the rock with random orientations. These ‘vugs’ are common structures in Terrestrial sedimentary rocks formed in briny water, being sites where salt crystals formed during the formation of the rock. Later dissolution of these salts then left the disk-shaped cavities. The mineral gypsum is a common cause of such vugs in Terrestrial rocks but any salt crystals that grow fast in two dimensions and slower in the third could form these structures upon subsequent dissolution. Incidentally, the image also shows two hematite spherules still sitting in the rock.

The third piece of evidence comes from the layering in the outcrop and the detailed structure of this layering. Layered rocks can be produced by various sedimentary processes only some of them involving water; however, the detailed structure of the layering can reveal in what medium and under what conditions the sedimentation happened. In order to get high-resolution imaging of the layering over a sufficiently large area to reliably discern between various origins a panorama of MI images was acquired on sol 41. The generation of this panorama was an extensive IDD operation requiring the acquisition of a large number of MI images and some careful planning. The panorama is shown in figure 3-20.

Careful scrutiny of this panorama and other MI and Pancam images reveals cross-bedding, i.e., some layers are at angles to the main layers. While cross-bedding is also observed in wind-sediments the scale is typically smaller when water is involved. The scale of cross-bedding in these rocks suggests a watery origin. Another telltale piece of evidence in the layers is festooning. Festooned layers have smile-shaped curves produced by shifting of the loose sediment’s rippled curved under a current of water.

The morphological evidence for cross-bedding and festooning is a very important piece of the puzzle as this is the only piece of evidence that unequivocally points to formation of the rocks in
a large standing body of water as opposed to, for instance, underground in groundwater-soaked soil.

Figure 3-19: MI image of a section of outcrop rock showing vugs and hematite spherules within the rock. (NASA/JPL/USGS)

Figure 3-20: MI mosaic of outcrop rock from Eagle Crater. (NASA/JPL/USGS)
The fourth piece of evidence for a watery origin of the outcrop rocks is that the APXS measured a very high concentration of sulfur in these rocks. Concentrations of chlorine and bromine are also elevated. Elevated concentrations of these salt-forming elements are usually connected with the action of liquid water.

Intimately connected with this APXS finding is the fifth piece of evidence, namely the detection by the Mössbauer spectrometer of the mineral jarosite in the outcrop. Jarosite is a hydrated iron sulfate salt and the discovery that a large proportion of the outcrop is jarosite makes perfect sense of the extraordinarily high sulfur content in the rocks.

After thoroughly characterizing the rocks in Eagle Crater the science team decided to drive the rover out of the crater and make for the larger Endurance Crater ~750 meters to the east. An overview of the local terrain is shown in figure 3-21. Right out of Eagle Crater an odd rock was discovered, which upon nearer investigation proved to chemically match the SNC meteorite EETA79001 very well (see section 2.2.2). This rock was lying by itself on the plain and is distinct from other rocks at the site. It may originate as impact ejecta from an impact tens of kilometers away. Thereafter the rover headed toward Endurance Crater. The flat plain is eminently traversable and after stops at a shallow crack in the ground named Anatolia and at a very small crater named Fram Opportunity reached Endurance Crater around the end of the nominal mission on sol 90.

Since then the rover has been thoroughly investigating this ~150 m diameter crater. Except for the scale the general picture here is the same as in Eagle Crater. More jarosite deposits have been found, and due to the larger depth of this crater the vertical extent of these deposits is greater than at Eagle Crater. As a consequence of this more variation has also been found in the Endurance Crater outcrop rocks than at Eagle.
The general picture emerging of Meridiani Planum is that this area was once the floor of a lake or sea; possibly a region of shallow tidal flats\textsuperscript{20} at a shoreline. Minerals washed into the lake or sea from the southern highlands and salt deposits formed in the briny water as salt concentrations rose in response to evaporation. Jarosite was among the dominant minerals formed, but crystals of other salts formed inside the rock eventually leading to formation of the vugs as well as crystals of hematite forming the spherules. The extraordinary flatness of the terrain is consistent with this picture.

A recently published numerical modeling analysis of chemical weathering of basalt\textsuperscript{63} shows that indeed reaction of acidic water with basalt under oxidizing conditions produces jarosite. Interestingly this model also shows production of gypsum, consistent with the vugs observed in the rock. The model also shows that the weathering must stop before more than a few percent of available basalt is altered or the jarosite would be further transformed into other minerals, suggesting that the water was only present for a geologically short time. However it seems evident that the bright outcrop present in Eagle and Endurance Craters can be identified with the bright etched terrain unit identified from orbit (see section 3.1) which is widespread in thick layers in Meridiani Planum, so if the water was only there for a short time production of salt deposits must have been fast while the water was there. To a certain extent we thus re-encounter at Meridiani Planum the overall Martian dilemma of mineralogical evidence arguing for only a limited presence of water while morphological evidence argues for a more extensive water history (see section 2.2.2).

### 3.5. The Magnetic Properties Experiment on MER

#### 3.5.1. Purpose

Having described in overview the design and important results of the MER mission we will now turn to a more detailed description of the magnetic properties experiment [4, 5, 64]. As already mentioned in section 1.3 this experiment takes its inspiration from previous magnetic properties experiments on the Viking and Pathfinder missions, and aims at furthering our understanding of the magnetism of Martian dust. Important questions that the experiment tries to answer are: Are all airborne dust grains magnetic or is the magnetism present only in a subset of the grains? Is the dust simply ground-down (and slightly oxidized) bits of surface rocks or does it have some more complex origin (see section 2.5.2)? And finally, what is the mineral responsible for the magnetism of Martian airborne dust? To this end the experiment consists of three separate elements with each their role. These are the Sweep magnet, The RAT magnets, and the Capture and Filter magnets.

The numerical simulation work presented in this thesis aims at interpretation of results from the Capture and Filter magnets, wherefore these magnets are of special interest to us, but the various elements of the magnetic properties experiment work together synergistically and we will describe the Sweep magnet and the RAT magnets in some detail before concentrating on the Capture magnet and the Filter magnet.

All the magnets of the magnetic properties experiment are permanent magnets made from the same materials. The active magnetic material used is Sm\textsubscript{2}Co\textsubscript{17}, which has a magnetization of $M = 8.75 \cdot 10^5$ A/m at room temperature and a Curie temperature of $T_C = 1190$ K. All the magnets

\begin{footnote}{Tidal flats do not necessarily need tides. Motion of water back and forth may be driven by wind.}

\textsuperscript{20}
have cylindrical symmetry. The magnetic material is glued into an aluminum superstructure, and
on the Capture and Filter magnets the surface where the dust is attracted is covered with a foil of
high purity aluminum. An important point is that the magnets contain no iron\(^{21}\). Therefore it is
possible to measure a Mössbauer spectrum of the dust on the Capture magnet or Filter magnet
without being disturbed by a background signal from the magnet itself.

### 3.5.2. The Sweep Magnet

The Sweep Magnet is a small ring magnet, the magnetic material having an outer diameter of 9
mm, an inner diameter of 4 mm and a height of 5 mm. The magnetic material is placed 0.4 mm
below the aluminum surface and this, together with the small size and compactness of the ring,
means that there is an area of the surface above which the magnetic force repels instead of
attracting. Figure 3-22 shows a vector diagram of the gradient of the magnitude of the magnetic
field above the surface of the Sweep magnet. The force on a magnetic dust grain is in the same
direction as the vectors in the diagram (see section 4.4) and it is apparent that the force is directed
upwards from the centre of the ring structure, thus ‘sweeping’ the central area free of magnetic
dust. Any dust grain with a specific magnetic susceptibility above \( \kappa = \chi / \rho \sim 3 \cdot 10^{-7} \text{ m}^3/\text{kg} \) will be
repelled from the central surface of the magnet meaning that even most paramagnetic grains will
be unable to settle in the centre of the magnet. Any grains settling in this central area will thus be
non-magnetic, i.e., contain no or very little iron. (This will, however, depend slightly on other
factors such as wind speed and grain size as well – see chapters 4 and 8).

![Figure 3-22: Vector plot showing the gradient of the magnetic field in the region above the surface of the Sweep magnet. The length of a vector is proportional to the magnitude of the gradient.](image)

As described in section 3.2.3 the small Sweep magnet is located next to the Pancam calibration
target and is included in all images of the calibration target. This means that the Sweep magnet is
imaged regularly. Standard images of the calibration target are compressed to 1 bit/pixel in order
to reduce data volume. Once in a while, however, a special Sweep magnet sequence\(^{22}\) was run in
which the LOCO-compressor was used, resulting in images of \( \sim 7 \) bits/pixel. These images were
heavily subframed to include only the Sweep magnet, which kept the data volume insignificant.
Figure 3-23 shows an image of the Sweep magnet on Spirit from sol 73 together with three
optical reflectance spectra generated from a series of Pancam images in all the 11 geology filters.
One spectrum is of the area outside the ring magnet; one spectrum is of the dusty ring; and one

\( ^{21} \) The Sm2Co17 material contains iron impurities, but this material is covered by a layer of 99.999\% pure aluminum,
which is 2 mm thick on the Filter magnet and 0.4-1.1 mm thick on the Capture magnet. A small Mössbauer signal is
observed on a clean Capture magnet but not on a clean Filter magnet.

\( ^{22} \) Designed in part by the author
spectrum is of the ‘swept’ are in the centre of the ring. This last spectrum is almost flat, resembling spectra of the pure aluminum surface, and is markedly different from the spectrum of the area outside the magnetic ring, which has been subjected to more or less undisturbed gravitational deposition of dust. Multispectral images of the Sweep magnet on Opportunity show a similar pattern. Based on this analysis the main conclusion from the Sweep magnet experiment is that a large majority of Martian dust grains are at least somewhat magnetic.

Figure 3-23: Pancam image of the Spirit Sweep magnet and optical reflectance spectra from different areas of the image.[5]

3.5.3. The RAT Magnets

The RAT magnets are four very small cylindrical magnets built into the structure of the RAT, each cylinder of magnetic material having an outer diameter of just 4 mm. Two of the RAT magnets are of equal strength, having a maximum magnetic field and field gradient of $B = 0.28$ T and $\nabla |B| = 350$ T/m respectively. The two other magnets are of different, weaker strengths. One has $B = 0.10$ T and $\nabla |B| = 120$ T/m; the other has $B = 0.07$ T and $\nabla |B| = 80$ T/m.

Anytime the RAT is used for grinding rocks magnetic material may be released from the interior of the rocks. Such material will then adhere to the RAT magnets. Information about the type of magnetic material in the rocks may be ascertained by analysis of the amount of dust adhering to the magnets as well as the optical spectrum of the dust.

Figure 3-24 illustrates such an analysis for the RAT magnets on Spirit: The first brushing operation on a rock was performed between the image taken on sol 30 and the image taken on sol 34. The first grinding operation performed by Spirit, was performed on the rock Adirondack shortly after the image on sol 34 was taken. The dust released by this grinding operation was still sticking to the magnets on sol 68. Before the brushing operation some reddish dust is sticking to the magnets. This is airborne dust, which has been attracted to the magnets. After brushing, the dust on the magnets has the same color as before, which is not surprising as loose dust on a rock surface is supposed to be of aeolian origin. Possibly the amount of dust on the magnets is somewhat greater than before brushing, though this is hard to judge. After grinding, however, the magnets have been covered with a large amount of new material, which is much darker than the reddish airborne dust. The color change is underlined by the optical reflectance spectrum shown below the images (figure 3-24). We may conclude from these data that the rock Adirondack contains a significant amount of reasonably magnetic material, which is dark in color. Given that the Mössbauer spectrometer identified ~5% magnetite by weight in the rock Adirondack the dark magnetic material on the RAT magnets may readily be explained.
The RAT magnets on Opportunity also showed a significant accumulation of dust after the first grinding operation. As far as it can be judged from the images the amount was comparable to the amount of dust on the Spirit RAT magnets. However this dust was reddish like the airborne dust. There is some indication from the Mössbauer spectrometer that some amount of hematite is present in the Meridiani outcrop rocks as well as in the spherules. If the hematite spherules grew in situ shortly after formation of the rock it is probably not unreasonable to expect some diluted hematite to be present in the rock matrix also. Weakly magnetic material like hematite, however, would not be expected to cling to the RAT magnets in the amounts observed. Whether hematite under some conditions can accumulate on the RAT magnets in these amounts is being investigated in ongoing simulation experiments.

![Figure 3-24: Pancam analysis of dust on the RAT magnets on Spirit before operation with the RAT(sol 30); after brushing the rock Adirondack (sol 34); and after grinding the same rock(sol 68).][5]

### 3.5.4. Design of the Capture and Filter Magnets

The Capture and Filter magnets are located in front of the PMA, right at its base. Both magnets have their surfaces inclined 45 degrees to the horizontal and the magnets are located next to each other; the Filter magnet above the Capture magnet. The magnets are visible in the sketch of the rover in figure 3-1, marked as: Magnet array (forward). The main purpose of these magnets is that they should capture airborne dust for mineralogical and geochemical investigation by the Mössbauer and APX spectrometers, but the magnets are also accessible to the MI and the Pancam. Both magnets are cylindrically symmetric with an outer diameter of 25 mm for the magnetic material and 45 mm for the aluminum frame. The magnetic material in the Capture magnet is in the shape of a cylinder and three outer rings with alternating magnetization directions. This makes for a strong magnetic force close to the surface of the magnet, which falls off quickly with distance. The magnetic material in the filter magnet is in the shape of a modified ellipsoid, giving a weaker force that falls off more slowly with distance from the magnet. The Capture magnet therefore captures any magnetic dust passing closely above its surface. The Filter
magnet, on the other hand, captures weakly magnetic dust only if it is brought very close to the magnet, but captures highly magnetic dust grains from a larger distance, than does the Capture magnet.

The net effect of this is that if the magnets are exposed to an ensemble of dust grains with varying magnetic properties the dust grains captured on the Filter magnet will be on average more magnetic than the dust grains on the Capture magnet (i.e., the Filter magnet ‘filters’ the dust according to its magnetization, see section 8.3.4). The design of the Capture and Filter magnets are shown in figure 3-25. Graphs and vector diagrams of the magnetic field and gradient of the magnitude of the field across the magnet surface are shown in figures 2-26 and 3-27 for the Capture and filter magnet respectively.

Figure 3-25: Design of the Filter magnet and the Capture magnet. The magnetic material is $\text{Sm}_2\text{Co}_{17}$ glued into an aluminium structure[4].
Figure 3-26: Magnitude and direction of the magnetic field and its gradient across the active surface of the Capture magnet[4].

Figure 3-27: Magnitude and direction of the magnetic field and its gradient across the active surface of the Filter magnet[4].
3.5.5. Results from the Capture and Filter magnets

The accumulated dust patterns produced on the Filter and Capture magnets on Mars are shown below. **Figure 3-28** shows an MI image of the Spirit filter magnet acquired on sol 92 (left) and an MI image of the Spirit Capture magnet acquired on sol 53 (right). The Capture magnet image is slightly out of focus, but is better than the image of the Capture magnet taken on sol 92, which was partly in shadow. **Figure 3-29** shows MI images of the Filter magnet (left) and Capture magnet (right) on Opportunity. Both images acquired on sol 38. The dust layer is evidently thickest where the magnetic force is strongest. The well-defined circular patterns on the Capture magnets are very conspicuous, whereas the dust on the Filter magnets is distributed in a more homogenous pattern with less well-defined edges. This tends to make the Capture magnets look significantly dustier than the filter magnets, however, to a certain extent, this is an illusion. A more quantitative analysis of these, as well as Pancam images, concluded that for both rovers there is roughly twice the amount of dust on the Capture magnet as there is on the Filter magnet.

An interesting difference between the two rovers is that on the Opportunity magnets there are a number of dark clumps visible, apparently randomly distributed across the magnet surface. No similar clumps are observed on the Spirit magnets. Later images of the Opportunity magnets show more of these clumps, which argues against them being clumps of soil that have dropped off of the IDD in a single episode when the IDD was brought close to the magnets. It is possible that there has been several episodes of soil dropping off the IDD but it seems more likely that these clumps are aggregates of smaller dust grains either formed on the magnet or formed in suspension to arrive later on the magnet. **Figure 3-30** shows a close up of some of these clumps or aggregates on the Opportunity Filter magnet.

![Figure 3-28: MI images of the Filter magnet (left) and Capture magnet (right) on Spirit. The left image is from sol 92, the right from sol 53. (NASA/JPL/USGS)](image)
Figure 3-29: MI images of the Filter magnet (left) and Capture magnet (right) on Opportunity. Both images are acquired on sol 38 (NASA/JPL/USGS).

APXS spectra of dust on the magnets indicate that the chemical composition of dust on the magnet is roughly similar to the basaltic composition of surface rocks and soil[64] pointing to a common origin of airborne dust and other surface material.

The amount of dust on the Capture and Filter magnets is only marginally sufficient to acquire a Mössbauer spectrum with an adequate signal. It therefore proved necessary to wait for a long while before sufficient dust had accumulated for Mössbauer analysis. At present only one useful Mössbauer spectrum has been acquired. This spectrum of Spirit’s Filter magnet, which was acquired during sols 244-258 and represents a total of 50 hours of integration time, shows the presence of magnetite, hematite, olivine, other silicates and some nanophase iron oxide material in the dust[64].
It has been shown, then, that there is magnetite present in the Martian airborne dust. This obviously does not mean that there is necessarily no other magnetic material present in the dust, however it seems likely that the magnetic properties of dust grains are dominated by magnetite and, moreover, no other process than gradual mechanical weathering of surface rocks is needed to explain the magnetism of the dust (see section 2.2.2). Some chemical weathering has occurred, however, and the hematite in the dust could conceivably be a weathering product of the magnetite. The weathering might occur on the surface or on dust grains in suspension. The presence of olivine, however, argues against strong chemical weathering and it is also possible that all minerals in the dust are inherited directly from surface rocks and soil with only limited chemical weathering.

Some further understanding of the properties of the dust can be gained from analysis of multispectral Pancam images of the magnets. Figure 3-31 shows such an analysis of the Capture and Filter magnets on Spirit. Reflectance spectra of dust on the Capture magnet are markedly different from spectra of dust on the Filter magnet, a difference that can not be explained merely by a difference in the amount of dust clinging to the two magnets. The dust on the filter magnet has a flatter spectrum than the dust on the Capture magnet, i.e., the dust on the Capture magnet is redder than the dust on the filter magnet. The difference is also marked in the near infrared, where the dust on the Capture magnet is brighter than aluminum while the dust on the Filter magnet is darker than aluminum. Note that the aluminum surface was not fully optically saturated with dust at the time these images were taken, so the difference would be expected to become slightly more marked as more dust accumulates.

The color difference may readily be explained if there is a larger proportion of magnetite in the dust on the Filter magnet than on the Capture magnet. Magnetite is dark and has a flat spectrum, while hematite and many other iron oxides are reddish. Compare with RAT magnet spectra in figure 3-24. That there should be a greater proportion of magnetite in the dust on the Filter magnet is also understandable. The Filter magnet is constructed to preferably attract highly magnetic dust (see section 3.5.4) so if there is a distribution of dust with varying amounts of magnetite in the various dust grains, the grains on the Filter magnet would be expected to be on average more magnetic, i.e., they would on average contain more magnetite and thus would be darker, which is what is observed.
Figure 3-31: Pancam image of the Spirit Capture and Filter magnets and optical reflectance spectra from the two magnets. [5]

So the Pancam images support the assertion from the Mössbauer spectrum that there is magnetite present in the dust and moreover from these images we may conclude that the dust grains are not all alike, but that some dust grains contain more magnetite than others. As described before (see section 2.5.2) the grains may either be solid composites of various minerals or loose aggregates of smaller possibly single-mineral grains.

Further analysis of Pancam images of the Opportunity Capture magnet will be presented later in the text (see chapter 9) after we have introduced conclusions from the numerical simulation analysis. For now, however, we shall turn to the detailed theory of the motion of suspended dust grains, which will be necessary for the introduction of the numerical simulation model.
Chapter 4

Dynamics of Airborne Dust

4.1. The Reynolds Number

The motion of a fluid is governed by the Navier-Stokes equations of fluid dynamics. For the case of incompressible flow, which applies whenever all relevant speeds are significantly below the speed of sound (as is certainly the case for our problem of dust motion in the Martian atmosphere) these equations take the following form:

Mass equation:

\[ \vec{V} \cdot \vec{V} = 0 \]

Momentum equation:

\[ \rho \left\{ \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} \right\} = -\nabla p - \rho \vec{V} \phi + \mu \nabla^2 \vec{V} \]

Here \( V \) is velocity, \( \rho \) is fluid mass density, \( p \) is pressure and \( \phi \) is the gravitational potential. The quantity \( \mu \) in the last term of the momentum equation is the dynamic viscosity (or molecular viscosity), which is a measure of the friction force between two adjacent packets of fluid having different velocities. For the case of a gas \( \mu \) equals the mass exchange per unit time due to random molecular motion between two unit volumes a unit length apart. The mass equation is obviously just the continuity equation applied to mass, while the momentum equation is recognized as Newton’s second law.

It is a well-known fact, which can be found in any textbook on fluid mechanics[65], that these equations may be brought into a dimensionless form by introducing a characteristic length \( l \) and a
characteristic velocity $V$ determined by the geometry of the problem in question. The resulting equations have only one free parameter, called the Reynolds number $R$.

$$R = \frac{\rho \cdot V \cdot l}{\mu}$$

Or alternatively, introducing the kinematic viscosity $\nu = \frac{\mu}{\rho}$:

$$R = \frac{V \cdot l}{\nu}$$

What this means is that two problems with the same topology (boundary conditions) will give identical solutions in the dimensionless coordinates provided they have identical Reynolds numbers. In other words: identical Reynolds numbers give qualitatively identical solutions.

The Reynolds number may be interpreted as the proportional relationship between the viscous force and the inertia of a volume of fluid. Flows dominated by inertia have high Reynolds numbers while flows dominated by viscosity have low Reynolds numbers. When viscosity is dominant the flow tends to be regular and predictable since every little parcel of fluid feels a strong force from all neighboring parcels, smoothing any irregularities. If on the other hand inertia is dominant the flow tends to be chaotic and turbulent with large velocity gradients between neighboring parcels. In other words: Large Reynolds numbers mean irregular and turbulent flow while small Reynolds numbers mean regular, viscous flow.

For gases the dynamic viscosity is largely independent of pressure and only somewhat dependent on temperature. On Earth a typical value is $\sim 1.79 \cdot 10^{-5}$ kg/ms (ICAO standard atmosphere[40]). On Mars a value of $\sim 1.26 \cdot 10^{-5}$ kg/ms is reported at $p = 750$ Pa and $T = 250$ K[39, 40], consistent with tabulated values for pure CO$_2$ ($1.29 \cdot 10^{-5}$ kg/ms at $T = 252$ K[40]). From this it follows that the kinematic viscosity is about 58 times larger on Mars than on Earth due to the lower atmospheric density, typical values being $\nu = 8.4 \cdot 10^{-4}$ m$^2$/s on Mars as compared to $\nu = 1.46 \cdot 10^{-5}$ m$^2$/s for Earth. This means that at the same velocity and length scale the flow will be more viscous and regular on Mars than it would be on Earth, or conversely that the velocity would need to be 58 times larger on Mars in order to produce the same level of turbulence at a given scale.

The larger kinematic viscosity on Mars also means that the boundary layer close to a surface, the region where the velocity is reduced due to the presence of the surface, extends further away from the surface than it would under terrestrial conditions (see section 7.1.2). We may thus expect for a magnet on Mars that there is a larger zone of reasonably still air close to the surface than there would be under terrestrial conditions.

### 4.2. Drag Force

Any solid body moving through a fluid will experience a force directed against the direction of motion of the body relative to the fluid. This is called drag. The motion of a dust grain in the Martian atmosphere is determined by the balance between the forces of drag, gravity and - for our special case - magnetism. It may be that many of the grains are electrically charged and thus
affect each other with an electrical force, but little is known about the electrical properties of Martian dust, and we will neglect electrical effects in our dynamical treatment (see chapter 6 for a discussion of electric forces, though).

The one point where we will be taking electrostatic effects into account is in our treatment of particles hitting a solid surface. We are assuming in the numerical simulation that any dust grain hitting a surface sticks. This is supported by experimental observation in our wind tunnel (see chapter 5) where dust is observed to stick to all surfaces. This sticking is probably due to electrostatic forces, although adhesive (bonding) or magnetic forces could be involved.

The drag force on a body is conventionally written as:

\[ F_d = \frac{1}{2} A \rho V^2 C_d \]

Where \( A \) is the wind-facing area of the body, \( \rho \) is the fluid mass density, \( V \) is the velocity of the object relative to the fluid and \( C_d \), the drag coefficient, is a quantity dependent on the shape of the body and the velocity of the body relative to the fluid. In the low Reynolds number limit the drag coefficient of a sphere may be calculated analytically (\( R < 0.2 \), with the Reynolds number based on sphere diameter and the speed of the sphere relative to the fluid). This leads to Stokes law:

\[ C_d = \frac{24}{R}, \text{ for } R < 0.2 \]

For the case of a spherical dust grain of 3 \( \mu \)m diameter suspended in the Martian atmosphere we find that \( R = 0.2 \) corresponds to a grain velocity relative to the air of 67 m/s. We never expect the dust grains to move as fast as this, and therefore we will take the condition \( R < 0.2 \) to always be fulfilled. Our calculations of terminal velocity and characteristic time in section 4.3 below strongly support this assumption.

Inserting \( C_d = \frac{24}{R} \) and \( A = \pi r^2 \) into the expression for the drag force we find:

\[ F_d = 6\pi \mu r V \]

Note that this force scales only as the radius of the grain, not as the wind-facing area.

Stokes law for the drag force on a sphere is derived on the basis of a model of a continuous fluid, with a velocity that falls to zero at the surface of the sphere. Obviously any physical fluid is composed of atoms and molecules, and the model may be expected to break down at scales sufficiently small. In our case this scale is determined by the relation between the mean free path of molecules in the atmosphere and the diameter of the dust grain. A realistic value for the mean free path in the Martian atmosphere (at 750 Pa, 250 K) is about 7 \( \mu \)m (see section 5.5), which is more than twice the diameter of a 3 \( \mu \)m dust grain, so we may expect to need some correction to the expression given by Stokes law.

The correction factor we need is called the slip factor. A semi-empirical expression for the slip factor is[66]:

\[ S = 1 + \frac{\lambda}{r} \left(1.257 + 0.4 \cdot \exp(-1.1 \frac{r}{\lambda})\right) \]

With \( \lambda \) the mean free path of molecules in the gas.
Our final expression for the drag force on a dust grain thus becomes:

\[ F_d = \frac{6\pi \mu V}{S} \]

For a 3 µm dust grain in the Martian atmosphere and using \( \lambda = 7 \mu m \) we calculate the slip factor to be: \( S = 8.3 \), so it is a significant correction to the drag force. Note that the slip factor is dependent on grain size: If the grain diameter was 10 times larger the slip factor would be just 1.6 and as the grains get larger than this we enter the region where no correction to Stokes law is required. For very small grains the slip factor expression reduces to \( S = 1.657(\lambda/r) \) and the drag force scales in proportion to the wind-facing area of the grain.

The treatment above is only strictly valid for spherical grains. Real dust grains are typically irregular and elongated in shape and will tend to feel a stronger drag force for the same volume grain (greater area-to-volume ratio), however this effect is probably no greater than a factor of 2-3. Lacking precise knowledge about grain shapes as well as an algorithm for calculating this correction factor we will neglect it, consistently assuming spherical grains in our treatment.

### 4.3. Terminal Velocity and Characteristic Time

A dust grain falling in still air under the influence of gravity will accelerate until the drag force balances the force of gravity at which point it will continue moving at a constant speed called the terminal velocity \( V_T \). The terminal velocity may be found by equating the expressions for drag and gravity:

\[ F_g = F_d \]

\[ \frac{6\pi \mu V}{S} = \frac{4}{3} \pi r^3 \rho_{\text{grain}} g \]

\[ V_T = \frac{2St^2 \rho_{\text{grain}} g}{9\mu} \]

Entering the values for our case of a 3 µm dust grain in the Martian atmosphere; Martian gravity and assuming a grain mass density of \( \rho_{\text{grain}} = 3000 \text{ kg/m}^3 \) we get: \( V_T = 3.7 \) mm/s. If the random vertical velocity component of the air due to turbulence is larger than this velocity then the grain is said to be in suspension. This will often be the case (which is why grains of this size are observed in the atmosphere on Mars).

The equation of motion obeyed by a dust grain under the influence of gravity and drag is:

\[ \ddot{\vec{F}}_g + \ddot{\vec{F}}_d = \frac{4}{3} \pi r^3 \rho_{\text{grain}} \ddot{a} \]

The solution to this equation is:
\[ \vec{V}(t) = \vec{V}_T + \vec{V}_0 e^{(t/\tau)} \]

With \( V_0 \) determined by initial conditions and \( \tau \) given by:

\[ \tau = \frac{2 S \rho_{\text{grain}} r^2}{9 \mu} \]

\( \tau \) is a characteristic time for a grain to accelerate from rest to the terminal velocity. \( \tau \) is determined by grain size, grain density and drag force and is not dependent on the force being applied. We might insert a magnetic force in the equations instead of gravity and would find the same characteristic response time, but a different terminal velocity. If we set the outside force to zero, we see that \( \tau \) is also the time for a grain to come to rest relative to the surrounding fluid if it starts with a nonzero relative velocity. Note that for gravity:

\[ \vec{V}_T = \tau \cdot \vec{g} \]

The 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 have low characteristic times and are therefore observed to move relative to the fluid at, or close to, the terminal velocity, which is proportional to the applied force on the grain.

Thinking of such dust grains as steel balls on ballistic trajectories through more or less empty space is a misleading analogy. Steel balls suspended in syrup would be a better picture as the dynamics of grain motion is dominated by drag.

We calculate \( \tau = 0.99 \text{ ms} \) for a 3 micron grain in the Martian atmosphere, and conclude that the behavior of such grains is close to that described above for the limit of small characteristic times. Indeed it is obvious that this should be the case, as the grains need to have low terminal velocities under the force of gravity, or they would not remain suspended in the atmosphere. 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.

4.4. The Magnetic Force

A dust grain placed in a magnetic field and magnetized by this field is subject to a force given by[67]:
\[ \vec{F}_m = m \left( \sigma(B) \times \nabla \right) \times \vec{B} = m \nabla \left( \sigma(B) \cdot \vec{B} \right) \]

Where \( \sigma \) is the magnetization of the grain, which is a function of the magnetic field, and \( m \) is its mass. Assuming the magnetization of the grain to be always oriented in the direction of the local magnetic field this reduces to:

\[ \vec{F}_m = m \sigma(B) \hat{\nabla} B , \quad \text{(With } B = \left| \vec{B} \right| \text{)} \]

The force is thus always directed in the direction of the gradient of the magnitude of the magnetic field. By dividing out the grain mass we can define the acceleration due to the magnetic force \( a_m \):

\[ \vec{a}_m = \sigma(B) \hat{\nabla} B \]

By analogy with the treatment for gravity the terminal velocity becomes:

\[ \vec{V}_T = \tau \cdot \vec{a}_m \]

Obviously in a realistic setting the true terminal velocity will be the vector sum of the terminal velocity due to gravity and the terminal velocity due to the magnetic force. The actual velocity of the grain will then be the vector sum of the terminal velocity and the local velocity of the gas (i.e. the local wind velocity).

For the purpose of the numerical simulations we will express the magnetization of a dust grain by the expression:

\[ \sigma(B) = \sigma_s \cdot \frac{B}{B + \gamma} \]

The magnetic properties of the material in question are thus defined by the saturation magnetization, \( \sigma_s \), and the field at half saturation, \( \gamma \). The specific magnetic susceptibility at low fields may be found as:

\[ \kappa = \frac{\sigma_s}{\gamma} \mu_0 \]

For large fields the magnetization approaches the constant \( \sigma_s \) and the force is proportional only to the gradient of the magnitude of the field (\( F \propto \nabla |B| \)), while for weak fields the magnetization is proportional to the field and the force is proportional to the product of the magnitude of the field and the gradient of field magnitude (\( F \propto B \nabla |B| \)). In all cases the force points in the direction of the gradient of the magnitude of the field.

We wish to make an estimate of the terminal speed of a grain subjected to the force from one of the MER magnets in order to develop a feeling for the dynamics of dust grain capture on the magnets. From figure 3-27 we estimate that a typical field gradient above the surface of the filter magnet is \( \sim 20 \text{ T/m} \). Just above the Capture magnet surface the gradient is significantly larger.
than this, but it falls quickly with distance from the surface. Assuming a grain magnetized to a saturation magnetization of 2.5Am$^2$/kg the force on the grain will be 13.5 times the Martian force of gravity. For a 3 micron dust grain with a mass density 3000 kg/m$^3$ the terminal velocity becomes ~5 cm/s.

If we assume that a grain is carried past a magnet with a speed of 1 m/s and is deflected towards the magnet with a terminal velocity component of 5 cm/s we find that the grain is above the magnet for only 1 m/s $\cdot$ 45 mm (magnet diameter) = 45 ms. During this time the grain is deflected downwards by 45 ms $\cdot$ 5 cm/s = 2.25 mm. So the grain is only captured if it passes less than about 2 mm from the magnet. Although the wind velocity will probably be less than 1 m/s just 2 mm above the array, we may still conclude that a grain needs to pass quite close to the magnet in order to be captured.

### 4.5 Summary

By way of conclusion to these theoretical considerations we observe that the drag force scales as the radius of the grain for grain diameters larger than the mean free path and as the radius squared for smaller grains, whereas body forces like gravity and magnetism scale as the volume of the grain, which is the radius cubed. This means that as the grains get smaller the drag force gets more and more important. For micron-sized dust grains the drag force is extremely important. Even quite large forces on dust grains lead only to relatively low terminal velocities and the stopping time for a grain is very short, which we have illustrated through specific examples.

For these small dust grains, therefore, their velocity is essentially always the sum of the local wind velocity and the terminal velocity of the grain; the terminal velocity being determined by the external force on the grain and the characteristic time of the grain. The motion of a grain is therefore determined by three influences: By the wind velocity field, which depends on geometry and Reynolds number of the specific situation; By the magnetic and gravitational forces, and thereby by the magnetic properties of the grain; and finally by the magnitude of the drag force as expressed by the characteristic time of the grain.
Chapter 5

Experimental Method

5.1. Wind Tunnel Design

The experimental results that will be presented in chapters 6 and 8 were acquired in a wind tunnel at the Mars Simulation Laboratory, Aarhus University. The wind tunnel allows for injection of dust in the wind stream and re-circulates the dust-filled gas, which means that an instrument or magnet is exposed to a dusty environment for several tens of minutes after injection of only a small amount of dust (~1 cm$^3$) into the tunnel. The tunnel can be depressurized, the gas composition in the tunnel can be controlled and the temperature in the tunnel can be lowered below room temperature. This allows for simulation of Martian conditions.

The design of the wind tunnel is shown in figure 5-1. The outer length of the chamber is 3 m. The length of the inner tube (light brown) is 1.5 m and its diameter is 40 cm. The gas enters the inner tube on the left and is drawn through the tube by the action of the fan (red). The gas passes the fan and returns from right to left on the outside of the inner tube. The experiment (magnet or other target) is placed towards the fan-end of the inner tube, where several windows in the tank allow visual monitoring of the experiment. Liquid nitrogen can be led through a pair of cooling tubes (blue) if low temperatures are desired.

Dust is injected through a valve on the top of the tank. A small volume of dust (typically about 1 cm$^3$) is placed in a small closed tube in front of the valve. The tube is filled with gas at high pressure compared to the tank. When the valve is opened, the pressure difference causes the gas in the tube to rush into the tank at high velocity. The high velocity gas carries the dust with it, and the dust is suspended and dispersed through the volume of the tank. Dust concentration is observed to fall exponentially with time as dust falls out of suspension and settles on the sides and floor of the wind tunnel. The time constant $\tau$ of this exponential is inversely proportional to the wind speed $V$ and may be written as $\tau = \frac{K}{V}$, with $K$ a constant having the dimension of length.
Introducing the dust concentration \( n(t) \) (number of dust grains per unit volume) and the dust dose \( N(t) \) (number of dust grains having passed a unit area after a given time) we may write:

\[
N(t) = V \int_0^t n(t') dt' = V \int_0^t n_0 e^{-(\nu' t')} dt' = V \int_0^t n_0 e^{-t' / \nu} dt' = Kn_0 \left( 1 - e^{-t' / \nu} \right)
\]

From which it follows that:

\[
N(t \to \infty) = Kn_0
\]

If we then assume the dust concentration immediately after injection, \( n_0 \), to be independent of wind speed we may conclude that the total dust dose delivered when injecting a given amount of dust and waiting until all dust has fallen out of suspension is independent of wind speed. This means that we can compare dust exposure at different wind speeds with confidence.

Since the sensitivity of the Laser Doppler Anemometer, by which we measure \( n(t) \), is dependent on wind speed (see section 5.2) we cannot with certainty determine if \( n_0 \) is actually independent of wind speed. It seems probable, however, that \( n_0 \) is determined primarily by the amount of dust injected and by the volume of the wind tunnel.
5.2. The Laser Doppler Anemometer

Wind speeds, dust concentrations, dust doses and turbulence levels in the wind tunnel are measured by a commercial\(^{23}\) Laser Doppler Anemometer system. This instrument issues two split laser beams to form a fringe pattern across a small (~1 mm\(^2\)) target area. Dust grains passing through the fringe pattern produce a burst of reflected light whose flicker frequency depends on the fringe spacing and the particle velocity normal to the fringes. Therefore this velocity component can be calculated from the measured flicker frequency and the known fringe spacing.

Since the dust grains move with the wind flow (see chapter 4), the speed of dust grains is identical to the wind speed. The active area of measurement is typically chosen to be at the centre of the wind tunnel, in front of or above the experiment, in order to measure the free-flow wind speed away from obstructions.

After a given measurement time the dust dose can be estimated from the number of counts. Given the wind speed instantaneous dust concentrations can be estimated by measuring the dust dose in a short time (differential of the dust dose, see section 5.1). The mean value of measured dust grain speeds gives the wind velocity component at right angles to the active measurement area. Assuming the wind direction to be known (along the long axis of the tunnel) the total wind speed can be measured directly. Turbulence intensity is quantified by the standard deviation of grain speed measurements expressed as a percentage of the mean value of grain speed measurements. This value is typically 5-10% and increases with increasing wind speed.

As was mentioned in section 5.1 the instrument sensitivity is dependent on wind speed. Therefore dust doses and concentrations cannot be measured in an absolute sense and comparison cannot readily be made between LDA measurements made at different wind speeds. Measurements made at the same wind speed but after injection of different amounts of dust can be meaningfully compared, however.

Figure 5-2 shows an image of the interior of the inner tube of the wind tunnel with the LDA system active. The dust concentration was high when this image was acquired. The beam of laser light is therefore revealed by light scattering on dust grains. The magnets at the bottom are a copy of a Mars Pathfinder magnet array.

![Figure 5-2: The interior of the wind tunnel looking towards the rotating fan and showing the LDA beam.](image)

\(^{23}\) From Dantec dynamics A/S
5.3. The Salten Skov Mars Analogue Dust

The Martian dust analogue used in all the laboratory simulation experiments presented in chapters 6 and 8 is the < 63 μm fraction of a chemical sediment precipitated from iron II bearing groundwater, which is found in Salten Skov, Jutland[68, 69]. The Salten skov dust contains approximately 60% iron by weight with 73% of the iron atoms in goethite, 14% in hematite and 13% in maghemite. The remainder of the mass is made up of silicates and organic material. Note that every dust grain contains (roughly) the proportion of minerals described above; there are no pure goethite, hematite or maghemite grains.

The Salten skov dust is quite magnetic due to the large proportion of maghemite, and has a saturation magnetization at the upper end of the range for Martian dust quoted in section 1.3 of 2.5 ± 1.5 A·m²/kg. Indeed this high magnetization is a primary reason for using this dust as a Mars analogue. Figure 5-3 shows a magnetization curve for the Salten skov dust[70]. The curve was fitted with an expression of the form:

\[ \sigma(B) = \sigma_s \cdot \frac{B}{B + \gamma} \]

(see section 4.4) and from this the saturation magnetization was found to be 3.6 A·m²/kg and the B-field at half saturation (\(\gamma\)) was found to be 42.7 mT. This expression fits the data well, and has accordingly been used to estimate the magnetization curve in the numerical simulations (see section 7.2.6).

![Figure 5-3: Magnetization curve for Salten skov Mars analogue dust[70].](image)

Figure 5-4 shows the size distribution of a sample of Salten skov dust scraped from the wall of the wind tunnel after a run[69]. The size distribution was measured in liquid suspension using a laser diffraction instrument24. The distribution shows a dominant peak at 2 μm and a smaller peak at 30 μm interpreted as aggregates of smaller particles. Whether the aggregates are as prominent

24 Sympatec laser diffractometer
in the suspended dust as in the wall sample, or whether they primarily form on the wall of the wind tunnel is not known. The curve shows volume density (i.e. volume of dust per volume of liquid); in a curve showing concentration (number of dust grains per volume of liquid) the small grains would be far more dominant.

Figure 5-4: Grain size distribution for a sample of Salten skov Mars analogue dust as measured by laser diffraction in liquid suspension[69].

5.4. Quantification of Amounts of Deposited Dust

The same method for measuring dust deposition was used in the dust charging experiments (chapter 6) and in the magnetic capture experiments (chapter 8). The surface of interest (electrode or magnet) was covered with a 0.12 mm thick acetate transparency film, which was fastened to the metal surface using double-sided adhesive strips (0.07 mm thick). The surface was then exposed to the dust flow in the wind tunnel and dust was deposited on the film.

After dust deposition the film was removed from the metal and scanned in an optical transmission spectrophotometer. The transmission of the film at a wavelength of 400 nm was measured, from which the absorbance of the film could be calculated as the negative logarithm of the transmission: \( A = -\log(T) \). Subtracting the absorbance of the clean film we obtain the absorbance of the dust. The spectrophotometer integrates over an area of 1 mm × 10 mm. Measurements were made at different positions, this gives us the variation in dust deposition across the magnet or electrode.

If dust deposition is stochastic, i.e., the position of each new grain is independent of the position of previous grains, we have:

\[
T \propto e^{-\alpha m} \quad \Leftrightarrow \quad \alpha m \propto -\log(T) = A
\]

with \( m \) the total amount of dust deposited and \( \alpha \) a constant. Total amounts of dust deposited are thus expected to be proportional to the absorbance of the deposited dust. If dust layers are thin enough to be still largely transparent (i.e., if absorbances are low) this is true also for non-stochastic deposition.

25 Perkin-Elmer Lambda 1 UV-VIS spectrophotometer
Other relationships between m and A can be envisioned, however. If, for instance, dust deposition on the surface occurs by construction of three-dimensional aggregates (see chapter 6) that are large enough to be opaque, the area covered by one of these structures grows only as \( m^{2/3} \) and, as a result, we have: \( A \propto m^{2/3} \).

Figure 5-5 shows experimental dust absorbances measured on a neutral and a charged (300 V) electrode as a function of the injected dust mass. The dust masses represent 1, 2, 3 or 4 separate injections, so injected dust concentrations have been unchanged. The two data sets have been fitted by power laws of the form \( A \propto m^{2/3} \) and seem to obey this relation well.

![Graph showing dust absorbance as a function of injected dust mass at unchanged injected dust concentration](image)

Figure 5-5: Dust absorbance as a function of injected dust mass at unchanged injected dust concentration

This would seem to indicate that the dust settles on surfaces by construction of aggregates. The data are sparse, however, and the data sets above could probably equally well have been fitted by a linear relation with an offset, although the physical meaning of such an offset would be unclear. In lieu of a clearer picture of the dust deposition process, I will generally present dust absorbances and take them as proportional to masses of deposited dust. Most conclusions would be unaltered by a transformation of \( m \rightarrow m^{3/2} \), although the values calculated for central fractions in chapter 8 would be modified.

5.5. Equivalent Pressures

The experiments presented in this work were all performed at ambient temperature and with a gas of terrestrial atmospheric composition. The wind tunnel tank was evacuated to a pressure of 900 Pa before dust injection. Dust injection then raised the pressure to 950 Pa. When several dust injections were performed the pressure was reduced to 900 Pa before each injection, so that dust deposition always occurs at a pressure of 950 Pa.

There are several ways to compare conditions in the wind tunnel to conditions on Mars: One way is by setting atmospheric mass densities equal. At room temperature (293 K) a pressure of 950 Pa gives a mass density of \( 1.13 \cdot 10^{-2} \text{ kg/m}^3 \) by the ideal gas law. The Martian atmosphere at 250 K would need to have a pressure of \(~530\) Pa in order to reproduce this mass density (see section 2.4.2).
Another way to compare conditions in the wind tunnel to conditions on Mars is by setting kinematic viscosities equal. Identical kinematic viscosities means identical Reynolds numbers for the same wind speed and geometry and thereby identical aerodynamic behavior (see section 4.1).

The kinematic viscosity in the wind tunnel is equal to the dynamical viscosity divided by the mass density. Using \( \mu = 1.79 \cdot 10^{-5} \text{ kg/ms} \) we get:

\[
\nu = \frac{\mu}{\rho} = \frac{1.79 \cdot 10^{-5} \text{ kg/ms}}{1.13 \cdot 10^{-2} \text{ kg/m}^3} = 1.58 \cdot 10^{-3} \text{ m}^2/\text{s}
\]

On Mars, setting the kinematic viscosity to this value and using \( \mu = 1.26 \cdot 10^{-5} \text{ kg/ms} \) gives a density of:

\[
\rho = \frac{\mu}{\nu} = \frac{1.26 \cdot 10^{-5} \text{ kg/ms}}{1.58 \cdot 10^{-3} \text{ m}^2/\text{s}} = 7.97 \cdot 10^{-3} \text{ kg/m}^3
\]

By the ideal gas law this is equivalent to a Martian atmosphere at a pressure of \(~375 \text{ Pa}\) and a temperature of \(250 \text{ K}\).

Finally we could compare conditions in the wind tunnel to conditions on Mars by setting the mean free path of atmospheric molecules equal. Identical mean free paths means identical slip factors, which would mean identical drag forces on dust grains, except for a factor of \(~1.4\) introduced by the higher dynamic viscosity in the Terrestrial atmosphere. The mean free path of molecules for a gas of Terrestrial atmospheric composition at a pressure of \(101300 \text{ Pa}\) is \(6.63 \cdot 10^{-8} \text{ m}\) (ICAO standard atmosphere[40]). Given that the mean free path is inversely proportional to the pressure and directly proportional to the temperature we can calculate the mean free path in the wind tunnel:

\[
\lambda = 6.63 \cdot 10^{-8} \text{ m} \cdot (101300 \text{ Pa} / 950 \text{ Pa}) \cdot (288 \text{ K} / 293 \text{ K}) = 6.95 \mu \text{m}
\]

The mean free path in the Martian atmosphere (at \(p = 750 \text{ Pa}, T = 250 \text{ K}\)) is reported as \(6.87 \mu\text{m}\) [39]. Calculating the mean free path in a pure \(\text{CO}_2\) atmosphere at \(p = 750 \text{ Pa}, T = 250 \text{ K}\) based on tabulated values[40] we find a comparable value: \(\lambda = 6.99 \mu\text{m}\). Using \(\lambda = 6.87 \mu\text{m}\) we can calculate the pressure needed to reproduce the mean free path value in the wind tunnel by the inverse proportionality between pressure and mean free path:

\[
p = 750 \text{ Pa} \cdot 6.87 \mu\text{m} / 6.95 \mu\text{m} = 741 \text{ Pa}
\]

So the mean free path of molecules in the wind tunnel is equivalent to the mean free path of molecules in a Martian atmosphere at a pressure of \(~740 \text{ Pa}\) and a temperature of \(250 \text{ K}\). For identical drag forces the equivalent Martian atmospheric pressure is slightly above \(740 \text{ Pa}\), the exact number being dependent on grain size.

It is clear that we cannot perfectly reproduce all aspects of the Martian atmosphere with a gas of Terrestrial atmospheric composition. With regard to the drag force on dust grains we are simulating in the wind tunnel a typical Martian atmospheric pressure in the middle of the pressure range (500-900 Pa) quoted in section 2.4.2. With regard to kinematic viscosity and thereby aerodynamic behavior, however, the wind tunnel conditions are equivalent to Martian atmospheric gas at a pressure (~375 Pa) somewhat below the typical range 500-900 Pa.
5.6. Experimental Geometry

The experimental arrangement for the magnetic deposition experiments (see chapter 8) is shown as a sketch in figure 5-6. The sketch shows a vertical section along the long axis of the cylindrical inner tube of the wind tunnel. The arrow on the left shows the wind direction. Four magnets are placed on the experimental structure to the right; a Capture magnet and a Filter magnet facing 45° above horizontal and a Capture magnet and a Filter magnet facing 45° below horizontal. For comparison the Filter and Capture magnets on the MER rovers both face 45° above horizontal. A metal plate extends in front of the structure that carries the magnets. Compare this figure with the geometry of the numerical model shown in figure 7-2. Three images of the magnets inside the wind tunnel are shown in figures 5-7, 5-8 and 5-9.

Figure 5-6: Vertical section along the long axis of the cylindrical inner tube of the wind tunnel. The vertical extent of the sketch is 40 cm, the diameter of the inner tube, and relative scales are correct. The horizontal extent of the sketch is ~120 cm, somewhat less than the full 1.5 m length of the inner tube. The arrow shows the wind direction (the fan is to the right).

Figure 5-7: Experimental set-up looking through the inner tube of the wind tunnel towards the fan, which is not in motion in this image.
Figure 5-8: Same scene as previous figure. This image is taken shortly after dust injection at a low (< 1 m/s) wind speed. A semi-permanent dust-free vortex is visible to the left of the magnets.

Figure 5-9: Same scene as previous figure. This image is taken some time after dust injection at a high (> 1 m/s) wind speed. Dust patterns are visible on the magnets.
Chapter 6

Charging and Aggregation

6.1. Electrical Charging of Dust Grains

While the central subject of this thesis is the motion of suspended dust grains under the influence of a magnetic force there is obviously no reason to suppose that dust grains could not also be subject to electrical forces. Electrical forces on dust grains is a wide field in its own right and we can do no more than scratch its surface in this treatment, but it has effects that have a direct influence on the dynamics of dust deposition, mainly through the phenomenon of dust aggregation. In this chapter, therefore, we discuss electrical effects in broad terms and present some experimental results that have a bearing on this discussion.

The build-up of static electric charges between two objects brought into physical contact is known as triboelectricity or contact electrification[71, 72]. The term triboelectricity generally implies some kind of relative sliding, rubbing or collisional motion between the two objects, while contact electrification is used for exchange of electrical charge between two objects in physical contact for a more prolonged time. The microscopic effects involved are, however, the same in the two processes, the differences arising instead from details in the time available for charge exchange and extent of the surface areas involved. I shall therefore use exclusively the term contact electrification to denote any charge exchange between dust grains and not discuss further the nature of the microscopic processes involved.

Electrical fields as well as magnetic fields caused by moving charges have been measured in connection with terrestrial dust devils[73]. An obvious explanation for this observation is that dust and sand grains acquire charge by contact electrification during collisions and such a process would be expected to operate in Martian dust devils as well. The dry environment on Mars would also be expected to facilitate the acquisition and retention of static electric charges.
6.2. Laboratory Simulation Experiments

A series of laboratory simulations[74] were performed in the wind tunnel facility at the Mars Simulation Laboratory, Aarhus University (see chapter 5). These experiments were designed to investigate the charge state of suspended dust grains and its dependence on various factors. A number of electrodes were exposed to a fixed dust dose in the wind tunnel. The electrodes were covered by a transparent plastic film and subsequently the optical absorbance of the dust on the film was measured as described in chapter 5. Images of some of these electrodes after exposure to the dust are shown in figure 6-1. It is immediately apparent that the dust deposition is not uniform but has been influenced by the presence of the electric field.

Figure 6-1: Images of two sets of electrodes exposed to the dust flow. Left image shows a prototype set-up. Image is about 12 mm across. Right image shows the set-up used in generating the data presented in figures 6-2, 6-3 and 6-4. This image is about 12 cm across.

Results from such a series of measurements of absorbance as a function of electrical potential on the electrodes are shown in figure 6-2:

Figure 6-2: Absorbance of dust deposited on electrodes at various voltages. The long horizontal dashed line shows the best estimate of absorbance due to dust deposition at zero electric field (background deposition).
It is observed both for negative and positive potentials that dust deposition rises with rising potential. Measured absorbance as a function of potential follows a linear relationship quite well for high potentials. This makes sense if the absorbance is linearly related to the amount of dust deposited: The amount of dust will be linearly related to the terminal velocity of dust grains towards the electrode. The terminal velocity is linearly related to the electric force, which is proportional to the electric field, which is proportional to the potential. Thus we would expect a linear relationship between potential and measured absorbance.

However this relationship breaks down at low potentials and it seems that deposition is lowest at potentials around ± 30 V; lower even than the deposition at zero volts. This may be understood if the main effect of a low positive potential is to repel positively charged grains and similarly for negative charge. Only at potentials above ± 100 V does attraction of grains of opposite polarity become equally significant as repulsion of grains of like polarity.

This means that from somewhat above ± 30 V an electrode is only effected by neutral grains and grains of opposite polarity. Grains of the same polarity are repelled and do not settle on that electrode. Making a linear fit to the data points at positive voltages we may then tentatively interpret the intersection of this line with the zero-volt line as the background deposition of neutral and negatively charged grains (i.e., how much deposition of negative and neutral grains would happen, if there was no electric field). Conversely making a linear fit to the data points at negative voltages we can determine the background deposition of neutral and positively charged grains. We can also measure the total background deposition as the deposition at zero volts. From these three measurements it was determined that 46 ± 6 % of the grains carry a negative charge and 44 ± 15 % of the grains carry a positive charge. In other words: Most of the dust grains are charged and there are roughly equal amounts of positively and negatively charged grains.

The equal amount of positively charged and negatively charged grains suggests that the grains charge by interactions with each other as opposed to charging by interactions with the wind tunnel walls or other aspects of the environment. We do not yet know, however, whether this charging happens continually while in suspension, or whether it mainly happens during injection of the dust. Two series of measurements were performed in order to answer this question. The first series consists of three measurements designed to determine whether the charge state of the dust changes in time: In the first measurement the voltage on the electrodes was on at injection and was turned off after a third of the total dust dose had passed the electrodes. In the second measurement the electrodes were turned on after a third of the dose had passed and turned off at two-thirds of the total dose. The last measurement had the electrodes on during the passage of the last third of the dust dose. Results from this series measuring deposition on a 300 V electrode as a function of the fractional dust dose passed are depicted in figure 6-3:

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26 It is not immediately clear how figure 6-2 can be reconciled with figure 5-5, as they seem to lead to two different conclusions about the relationship between dust mass and absorbance.
The vertical axis of the plot shows the relative dust absorbance, defined as $A_r = (A_V + A_b)/A_b$, with $A_V$ the absorbance of dust deposited on the electrode and $A_b$ the background absorbance of dust deposited on electrically neutral surfaces. The horizontal axis shows the fractional dust dose $F(t)$, defined as (see chapter 5):

$$F(t) = \frac{N(t)}{N(t \to \infty)} = 1 - e^{-t/\tau}$$

The main point in understanding figure 6-3 is that an equal amount of dust passed the electrode when measuring the first, second and third bar of the bar chart. The inescapable conclusion is that the charge state of the dust falls with time. This could either be because the dust charges and discharges continually by collisions, with the charge state being related to the dust concentration, i.e., the dust being more charged at high concentrations. Alternatively it could be that the dust charges only at injection and discharges over time either by grain-grain interactions or by interactions with the environment (gas and wind tunnel walls). A second experiment, which investigated the relation between dust concentration and dust charge, will help us discern between these possibilities. Data from this experiment are shown in figure 6-4:
Figure 6-4: Relative dust absorbance $A_r$ as a function of inverse dust mass concentration in the wind tunnel right after injection.

The horizontal axis shows the inverse of the dust mass concentration (mass of dust grains per volume) in the wind tunnel immediately after injection. This number was estimated from the known injected dust mass and is proportional to the concentration. What this plot surprisingly shows is that dust deposition on charged surfaces is higher when dust concentration is low, i.e., that the dust is more electric when dust concentration is low. This suggests that the fall in charge state with time observed in figure 6-3 is not related to the fall in dust concentration, rather the dust charges only at injection and gradually discharges with time. Moreover, figure 6-4 suggests that the process by which the dust discharges is more effective when dust concentrations are high.

6.3. Aggregation

An obvious process by which the dust could discharge is by the formation of larger, less electrically charged, aggregates. Since dust grain motion is generally dominated by drag, the relative motion of two dust grains suspended in the same air stream is limited, and the electric attraction between grains of opposite charge has time to move the grains toward each other. This process would be more effective at higher dust concentration (smaller grain separation), as is observed.

There is other, more direct evidence, for the formation of aggregates. Figure 6-5 shows a scanning electron microscope image of dust deposited on a surface exposed to the dust flow in the wind tunnel. This dust grain looks to be formed from aggregation of a number of smaller dust grains. We regularly observe the formation of these sorts of structures in the wind tunnel both on this scale and on larger scales. While we do not know whether aggregates like this are held together by electric forces, by adhesive (bonding) forces or by magnetic forces, it seems likely that electric forces play a role in their formation. Other workers have also observed the formation of aggregates under simulated Martian conditions[75]. Figure 6-6 shows a large aggregate formed from micron-sized particles under simulated Martian conditions. Observations from Mars also suggest the presence of aggregates of dust grains as discussed in section 3.5.5. Although it is
not clear how much of the aggregate formation observed in these sorts of experiments actually occurs in suspension as opposed to on a surface after deposition, it seems likely (based also on the results presented in section 6.2) that at least some of the process occurs before deposition.

Figure 6-5: Scanning Electron Microscope (SEM) Image of a dust aggregate deposited in the wind tunnel.

Figure 6-6: Scanning Electron Microscope (SEM) image of a large aggregate formed from micron-sized dust grains in a simulated Martian environment[75].
6.4. The Dust Cycle on Mars

The theoretical maximum charge carried by a micron-sized grain in the Martian atmosphere is \( \sim 10^5 \) e. Grains charged higher than this lose charge by spark discharge to other grains or by a corona-like discharge directly to the atmosphere\[76\]. Nonetheless this charge is still more than enough to cause aggregation and have a major influence on grain motion. Based on comparisons between dust deposition on a charged electrode and background dust deposition in the wind tunnel the charge on grains in the wind tunnel has been estimated to be close to the maximal charge of \( \sim 10^5 \) e\[74\].

The general picture emerging of the aggregation process in the wind tunnel is therefore that the dust grains charge up to the maximal value upon injection, gradually form aggregates while in suspension and subsequently deposit on the walls and floor of the wind tunnel as electrically largely neutral grains. Note that aggregate formation will generally cause a rising characteristic time of the grains, which means that aggregates will be more susceptible to the force of gravity (and to a magnetic force) than are single grains and aggregates will thus be more likely to fall out of suspension.

The cycle of dust lift-off and subsequent deposition on Mars could be analogous to this. Whether grains are lifted by dust storms or by dust devils they will experience a situation of above-normal dust concentration and turbulence around the time of lift-off. This could cause the grains to acquire charge by contact electrification or it might simply be that the dust lies on the ground as electrically neutral aggregates consisting of charged single grains. These aggregates would then break up during lift-off, freeing their charged, constituent grains to form new aggregates. By whichever process: The newly lifted dust would be electrically charged.

Dust concentration in the Martian atmosphere is significantly lower than in the wind tunnel, so aggregate formation would be much slower, however it is still very much true that formation of aggregates would raise the characteristic time of the grains, thus raising the terminal velocity under gravity of the grains and raising the likelihood for the grains to fall out of suspension. Thus aggregate formation could be an important step in the deposition process on Mars.

We must note, however, that the significant UV flux on Mars might modify the process outlined above, since dust grains could exchange charge with atmospheric molecules under the influence of UV radiation. This could skew the charge state of the dust grains population, so that more grains had one polarity than the other, which would inhibit aggregate formation.

The main effect of this picture as regards suspended dust in the wind tunnel or on Mars is that a major part of the dust could be in the form of aggregates. This means that the mass density of grains (the quantity \( \rho_{\text{grain}} \) introduced in section 4.3) can easily be significantly lower than the bulk mass density, thus lowering the characteristic time of the grains and lowering their terminal velocity under gravity or a magnetic force. Conversely, however, the link between aggregate formation and fall-out means that the mean diameter of grains arriving at the magnet surface could easily be significantly larger than the mean diameter of grains in suspension, which would mean a rise in characteristic times.

We must therefore regretfully conclude that neither in the wind tunnel nor in the Martian atmosphere do we have firm knowledge about grain characteristic times and we must generally treat this quantity as a variable in our numerical model.
Chapter 7

The CFD Model

7.1. General Method

7.1.1. CFD

Computational fluid dynamics (CFD) is an expanding field, driven by the continual increase in computer power. However, like any tool, CFD has its limitations. If it was possible to model the motion of every single gas molecule separately we could have absolute confidence in the results of CFD calculations, but this approach is prohibitively expensive in terms of calculation time and will remain so for a long time yet. Therefore any CFD calculation relies on a set of assumptions about the flow being modelled; one generally assumes that the fluid obeys the Navier-Stokes equations; possibly also one assumes incompressibility and typically some model for the effect of turbulent motions. Obviously one must be careful to choose these assumptions in such a way that the essential characteristics of the real problem are preserved in the simplified model, which is solved numerically. For this reason laboratory simulation experiments are important as checks on the results from CFD.

Experimental simulations typically incorporate complexities that are neglected in a CFD model. However, the CFD model often gives more detailed results. The CFD model used for this work, for example, is only 2-dimensional, which is obviously a simplification; but the model calculates the tracks of individual dust grains, which are not available from experimental data.

Also there may be questions that are not easy to test experimentally but can be answered by CFD. An obvious example of this is the question of whether the difference between Martian and Terrestrial gravity has a major influence on the magnetic capture of dust grains. Simulating Martian gravity experimentally is difficult, but it is easy to change the acceleration of gravity in a numerical model.
Many different CFD codes exist. The one I have used is a commercially available code called STAR-CD. This code is described in more detail in section 7.1.3

7.1.2. Example: Wind Profile Above a Flat Plate

It was stated in section 4.1 that the high kinematic viscosity in the Martian atmosphere results in wider boundary layers than under Terrestrial atmospheric conditions. This is exemplified by the wind profile above a flat surface; a well-studied problem, which may be found in many textbooks on fluid mechanics[65]. Here I present a numerical calculation of the wind profile above a flat plate made with STAR-CD and compared to experimental data from wind tunnel experiments.

As mentioned this problem has been well studied and I present these results mainly as verification that, at least for this simple problem, my CFD results are consistent with experiments. It also serves as a demonstration of the difference between the Martian and Terrestrial aerodynamic environments.

Figure 7-1 shows simulation results and experimental data for two cases: Air at a pressure of 100000 Pa (Earth) with a wind speed of 1.2 m/s and air at a pressure of 950 Pa (Mars-equivalent conditions in the wind tunnel, see section 5.5) with a wind speed of 1.0 m/s.

The calculations reproduce the experimental data quite well: There was no ‘tweaking’ of the numerical model; the calculations were performed based only on knowledge of the experimental geometry, the measured free-flow wind speed and the measured pressure.

Under Martian conditions the boundary layer stretches about 2 cm away from the plate, while under Terrestrial conditions the thickness of the boundary layer is more like 3 mm. Admittedly the wind speed is not exactly the same in the two cases, but the two wind speeds are close enough that there is no doubt our conclusions would be similar if the two wind speeds had been identical.

7.1.3. The STAR-CD Code

STAR (Simulation of Turbulent flow in Arbitrary Regions) is a commercially available27 CFD code based on the FORTRAN programming language. In the following I shall describe the main features of the code as it relates to the problem at hand. I will not be going too deeply into specific details about the workings of the code or about CFD theory. For this I refer to the STAR

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27 Available from CD-Adapco (www.cd-adapco.com)
user guide and methodology volumes as provided by the vendor or to a textbook in computational fluid dynamics[77].

STAR uses the finite volume method for ‘discretization’ of the governing equations. The computational domain is divided into a number of cells and values for quantities such as velocity, pressure or turbulent energy are calculated at a computational node located at each cell centre. The main advantage of the finite volume method is that mass conservation is explicitly enforced by the method of discretization.

The STAR-code also allows choice between several so-called ‘differencing schemes’ for determining the values of computational quantities in a cell based on the values at neighbouring cells. The scheme I use is a second order accurate scheme called MARS (Monotone Advection and Reconstruction Scheme)[28].

Fluid flow calculations may be performed either as transient or steady state calculations. Because of calculation time constraints the steady state mode has been used whenever possible. In this mode the governing equations are solved iteratively until the flow field converges to a steady (i.e., time-invariant) solution. STAR uses under-relaxation to force faster convergence. This consists in replacing a quantity \( Q_i \) not with the full value calculated for the next iterative step \( Q_{i+1} \), but with a value \( Q'_{i+1} \) somewhere between the value calculated for the next step and the present value. That is: \( Q'_{i+1} = \alpha \cdot Q_{i+1} + (1-\alpha) \cdot Q_i \), with \( \alpha \) an under-relaxation factor between 0 and 1. Under-relaxation tends to remove fluctuations and thereby causes faster convergence, the danger is that one might find a solution where no true steady solution exists.

For cases where no time-invariant solution can be found it is necessary to perform the calculation in a transient (i.e., time-dependent) mode. In this mode the calculation cycles through a fixed number of time steps. For each time step relevant aerodynamical quantities (wind speed, pressure, etc) are updated in each calculational cell based on the neighboring cells. There is no under-relaxation in a transient simulation as the objective here is not to find a converged time-independent solution, but rather to map the time-dependence of the quantities of interest over a reasonable time-span. The transient calculation mode is the most precise but it is costly in terms of calculation time, and has therefore only been used when no steady solution could be found.

In both the steady-state and transient modes small scale turbulence is modelled by a so-called ‘low Reynolds number’ k-\( \varepsilon \) model; k-\( \varepsilon \) models are described in many CFD textbooks[77]. ‘Low Reynolds number’ signifies that no special treatment is given to near-wall cells. The wide boundary layers allows us to resolve the velocity variation close to the wall without having to use unreasonably small cells, so no extra modelling (wall function) is required. The k-\( \varepsilon \) model is a statistical treatment of small scale turbulence, which introduces k (the turbulent kinetic energy per unit mass) and \( \varepsilon \) (the dissipation of turbulent energy per unit mass and unit time) as new modelling quantities. The main effect of the turbulence model on the flow solution is to increase the viscosity, which makes sense based on our understanding from section 4.1 of viscosity as a measure of mass exchange due to random molecular motions. We are simply adding a term representing mass exchange due to small-scale turbulent motion. Large scale turbulence, however, can only be handled by a calculation in the transient mode.

The dust grains are treated in a lagrangian formalism partially coupled to the flow field; ‘partially coupled’ means that while the air influences the motion of the grains; the influence of the grains on air motion is neglected. In the steady state mode the procedure is to first obtain a converged steady solution for the airflow and then generate the tracks of the dust grains by

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28 That these four letters also spell the name of a certain planet is sheer coincidence, the scheme was chosen based on a recommendation by someone not working in planetary science.
stepping them through the solution domain one by one, modifying grain velocity at each step by
the influence of the forces of drag, gravity and magnetism. The main calculation is therefore
essentially a Monte Carlo simulation of a large number of dust grains moving through a
previously generated flow field under the influence of drag, gravity and a magnetic force.

In the transient mode a number of dust grains are introduced at each time step; dust grain
positions and velocities are then updated every time step in parallel with updates of wind speed
and other aerodynamical quantities, and dependent on these.

The effect of small-scale turbulence on the motion of dust grains is modelled by adding a
random perturbation based on a gaussian probability distribution with a mean of zero and a
standard deviation of $\sqrt{2k/3}$ to the air velocity experienced by the dust grain. The timescale for
changing the random velocity term is based on an estimate of the length- and timescales of
turbulent motion.

The magnetic force term is calculated from the expression given in section 4.4 and introduced
through the user-coding capability in STAR-CD by modifying the user subroutine dromom.
Introduction of the slip factor is handled through the same subroutine.

Calculation of the magnetic force term requires acquisition of data for the magnetic field and its
gradient at every time-step. This is accomplished by reading in a large table of magnetic field
values at the beginning of the calculation, controlled by the user subroutine posdat. In the
transient mode the numbers and positions of dust grains introduced at each time step are defined
in the user subroutine droico.

7.2. Specific Model Conditions

7.2.1. General Considerations

The overall objective of the CFD model presented here is, as described in section 1.4, to gain a
better detailed understanding of the process of magnetic capture of dust grains and of the
dependence of this process on various parameters of interest. The intention is to compare results
from the CFD model with data from the Capture and Filter magnets on the MER rovers on Mars.
Comparison with laboratory simulation experiments (see chapter 5) is performed in order to
verify and support CFD results.

The intention is thus to set up the geometry and parameters of the CFD model in such a way as
to approach as closely as possible conditions in the wind tunnel and on Mars. However, for a
number of reasons, there are several discrepancies. Most discrepancies are of minor importance,
but some are more significant.

One obvious cause of discrepancies is the difference between the wind tunnel experiments and
conditions on Mars. Neither in terms of geometry nor in terms of aerodynamic parameters (see
section 5.5) is the wind tunnel simulation a 100% precise reproduction of magnetic capture
processes on the MER rovers. Whenever there is a difference between rover conditions and
conditions in the wind tunnel I have therefore had to make a choice of CFD parameters which
leads unavoidably to a discrepancy, either with conditions on Mars or with conditions in the wind
tunnel. This choice has not been made consistently in favour of one side or the other, rather in
each instance convenience has played a part in choosing whether to model more closely
conditions on Mars or in the wind tunnel.

Another obvious and essentially unavoidable discrepancy between the CFD model and
conditions both on Mars and in the wind tunnel is caused by the dimensionality of the CFD
model. In order to reduce calculation time I chose to make the CFD model 2-dimensional rather than 3-dimensional. If the model had been 3-dimensional I would have had to either make the computational grid much coarser thereby reducing the precision of the calculations or else the generation of a converged steady solution for the flow field would have become very time-consuming and transient calculation would have become too costly to be practicable. Moreover, in order to truly reproduce the 3-dimensionality of the rover environment, it would have been necessary to perform several CFD calculations with different wind directions, which in this case would raise the cost in calculation time even further. The geometry of the CFD-model is therefore a 2-dimensional approximation to the 3-dimensional geometry in the wind tunnel, which again differs from the precise geometry of the magnets on the MER rovers.

Some discrepancies also arise from simplifications that were chosen for convenience in designing the CFD model or in subsequent data analysis. An example is that for each calculation in the CFD model every dust grain is identical, spherical and with a fixed mass density, fixed diameter and fixed magnetic properties; whereas both in the wind tunnel and on Mars the population of dust grains vary in size, shape and magnetic properties. Dust properties are varied, however, between calculations, so this discrepancy may be viewed as an advantage of the CFD model, namely that dust properties can be isolated and controlled in a way that is impossible in an experimental situation.

Finally some minor discrepancies arise from slightly unfortunate choices of aerodynamical parameters made early in the process of designing the CFD model. Once a number of CFD calculations had been performed with such slightly unfortunate parameters I opted for keeping these parameters unchanged for ease of comparison between CFD calculations. Examples of this are kinematic viscosity and mean free paths in the CFD model, which are not entirely identical to the values quoted in chapter 4 as the best ‘Martian values’ (see section 7.2.5). Another example of a similar situation is that the experimental arrangement in the wind tunnel was changed after a number of CFD calculations had been performed. This is the reason that figure 5-6 and figure 7-2 are not identical. However the differences were not judged to be sufficiently significant to warrant re-starting the series of CFD calculations with the new geometry.

7.2.2. Model Geometry

The geometry of the CFD model is shown in figure 7-2. Compare this with the geometry of the wind tunnel experiments shown in figure 5-6. As mentioned the two geometries are not identical due to a late change in the experimental arrangement. However, as regards the environment close to the magnet, the two geometries are alike. The horizontal plate in front of the magnet has a length of 20 cm from the front edge to its intersection with the inclined surface, on which the magnet itself sits. This surface (and thus the magnet surface as well) is inclined 45° to the horizontal, as is the MER magnets and the magnets in the wind tunnel.

29 Calculations were performed on a single (large) PC
Figure 7-2: Geometry of the full 2-dimensional CFD model. The vertical extent of the model is 40 cm, equal to the diameter of the inner wind tunnel tube. The horizontal extent of the computational domain is ~120 cm, somewhat less than the full 1.5 m length of the inner wind tunnel tube. The arrow shows the overall wind direction.

7.2.3. Computational Grid

The computational grid is shown in figure 7-3. It has been constructed to have the finest cells in the area close to the magnets and generally in the bottom part of the domain, where the tracks of dust grains that pass close to the array will be located. The upper part of the grid is coarser because there is less variation in this area, and we are not interested in dust grains passing this far above the magnet.

Figure 7-3: The computational grid

Figure 7-4 shows a magnified view of the central region of the computational domain while figure 7-5 shows a further magnification of the region close to the magnet. The region immediately above the magnet surface was resolved with an extra-fine computational grid in order to monitor the generation of dust patterns on the magnet with sufficient resolution. There are a total of 80 computational cells along the surface of the magnet, which means that the side of one of these cells has an extent of 4.5 cm / 80 = 0.56 mm.
Figure 7-4: Central region of the computational domain

Figure 7-5: The region immediately above the magnetic surface
Figure 7-6 shows a magnified view of the leading edge of the horizontal plate. Under some conditions refinement of the grid in this region was found to be necessary in order to avoid losing an unrealistic amount of dust grains by collision with the edge of the plate. At a wind speed of 1 m/s refinement of these grid cells was also found to cause faster convergence to a steady solution.

Figure 7-6: Magnified view of the region close to the leading edge of the vertical plate.

7.2.4. Boundary Conditions

Ideally the flow solution should be independent of the design of the grid, so the task in grid design is to maximize efficiency by making a grid fine enough to give a sufficiently precise solution while not so fine as to be prohibitively costly in terms of calculation time. Deciding on a set of boundary conditions on the other hand is a more fundamental choice, since different boundary conditions obviously lead to different solutions. The physical conditions in the model are largely introduced through specification of the boundary conditions.

STAR-CD allows choice of a number of different types of boundary conditions, but each of them in some way represents an idealisation, so that it may not be possible to choose a perfectly realistic set of conditions. However as long as the boundary is far enough away from the area of interest this need not cause undue worry.

In our case the simulation domain is bounded by three different boundaries. An inlet boundary at the left side, a pressure boundary at the right side and wall boundaries representing the magnet array and plate as well as the top and bottom of the wind tunnel.

At the inlet boundary the fluid velocity is specified as well as the density and the turbulence parameters (k and ε) of the inflowing air. At the pressure boundary the pressure is specified. Air may flow either in or out of the domain at a pressure boundary. In case the solution should show inflow somewhere along the pressure boundary the air density and turbulence parameters also have to be specified. The same values as for the inlet have been used.

At a wall boundary the wind velocity is specified to be zero, which, through the viscosity, reduces the velocity at the near wall cells. As mentioned (see section 7.1.3) the high kinematic viscosity at Martian conditions causes wide boundary layers and allows resolution of the
boundary layer without making unreasonably small cells, so no special treatment of the near-wall cells are needed. The model also specifies that any dust grain hitting a solid surface sticks and stops moving, which is consistent with observations in the wind tunnel.

7.2.5. Fluid Properties

The fluid density in the model is a constant since the flow is incompressible (wind speeds much lower than the speed of sound), but the value of the density is still important through its effect on the kinematic viscosity. The value chosen was $1.5 \cdot 10^{-2}$ kg/m$^3$, consistent with the density of the Martian atmosphere at $T = 248$ K, $p = 700$ Pa (see section 2.4.2). Obviously other sets of pressure and temperature could give the same density as well. For instance it could be seen as the density of the Martian atmosphere at $T = 293$ K, $p = 826$ Pa. The pressure is specified to be 700 Pa both at the inlet and at the outlet (pressure boundary), but the absolute value of the pressure really has no influence on the flow, only pressure differences are important, so any other reasonable pressure value would give the same result. The temperature does not directly influence the flow either.

The dynamic viscosity was set at $1.5 \cdot 10^{-5}$ kg/m·s, consistent with some authorities[38], however not entirely consistent with the favored value $1.26 \cdot 10^{-5}$ kg/m·s, which was used for calculations in chapter 4 and section 5.5[39]. This discrepancy arises from an unfortunate choice early in the process of designing the CFD model (see section 7.2.1), however the discrepancy is not large and neither is the value used entirely unrealistic. It is consistent with the tabulated value for a pure CO$_2$ gas at 293 K[40] and thus the model may self-consistently be seen as modelling the Martian atmosphere at $\rho = 1.5 \cdot 10^{-2}$ kg/m$^3$ $T = 293$ K, $p = 826$ Pa, although these values, admittedly, are at the high end of the range of Martian values for temperature and pressure.

7.2.6. Dust Properties

Dust grain properties in the standard case were taken from the measured parameters for the Salten skov Mars analogue dust used in the wind tunnel (see section 5.3). Grain diameters were set at 2 µm (as opposed to 3 µm in the Martian atmosphere - see section 2.5.1). Grain mass density was set at 3000 kg/m$^3$. The true grain mass density is not known as this may be influenced by aggregate formation (see section 6.3). Slip factors were calculated based on a mean free path of 8 µm, another case of an unfortunate discrepancy, as a value of 6.87 µm was used for calculations in chapter 4 and section 5.5, this being the value consistent with a fluid mass density of $1.5 \cdot 10^{-2}$ kg/m$^3$.

However, both grain diameter, grain mass density and mean free path enter the calculations only through the characteristic time (see section 4.3), and I will generally refer to characteristic times. The characteristic time for a standard grain with a diameter of 2 µm and a mass density of 3000 kg/m$^3$ in a gas with a mean free path of 8 µm is $\tau = 0.61$ ms, a value which is very reasonable both for Martian dust grains and for grains in the wind tunnel. It could for instance equally well be taken as the characteristic time for an aggregate grain with a diameter of 3 µm and a mass density of 1800 kg/m$^3$ in the Martian atmosphere (mean free path = 6.87 µm).

Magnetic properties of the dust grains have also been taken from measurements on the Salten skov dust. Magnetization of the dust grains are modelled by the equation:

$$\sigma(B) = \sigma_s \left( \frac{B}{B + \gamma} \right)$$
(see sections 4.4 and 5.3), for which a fit to the measured magnetization value for Salten skov
dust gave the parameters $\sigma_s = 3.6 \text{ Am}^2/\text{kg}$ and $\lambda = 42.7 \text{ mT}$. Values used in the standard modeling
case were $\sigma_s = 3.5 \text{ Am}^2/\text{kg}$ and $\lambda = 42.7 \text{ mT}$. The discrepancy is unnecessary, but unimportant. By
the equation:

$$\kappa = \frac{\sigma_s}{\gamma \mu_0}$$

the magnetic susceptibility at zero field is, for the standard case, $\kappa = 1.03 \times 10^{-4} \text{ m}^3/\text{kg}$.

### 7.3. Calculated Flow Field Data

#### 7.3.1. Wind velocity

Three parameters have been varied independently in the CFD calculations. These are: Inlet wind
speed, dust grain characteristic times and dust grain magnetic properties. Of these parameters
only one, the wind speed, influences the flow field. The others only influence the motion of dust
grains (see chapter 8).

The general practice has been to choose a single standard case and then vary one parameter at a
time, keeping the others constant at the standard values. Generally at or below 1 m/s convergence
was achieved in 1500-2000 iterations with a calculation time of 3-4 hours. Above 1 m/s no steady
solution could be found. This inlet wind speed was therefore chosen to be the standard. Thus,
although it is at the low end of the range of expected Martian wind speeds, most calculations
were made at 1 m/s in order to conserve calculation time.

Figure 7-7 shows 4 colour-coded plots of velocity fields from three different cases. The top
plot shows the time-invariant solution for $v = 0.2 \text{ m/s}$. The second plot from the top shows the
time-invariant solution for the standard case $v = 1 \text{ m/s}$. The two bottom plots show the time-
dependent solution for $v = 9 \text{ m/s}$ at two different times. Note that the scales are different for the
three different inlet wind speeds.

Generally these velocity fields do not show any particularly surprising or complex features. A
common feature of all the situations is that the maximum velocities are reached at, or
immediately after, passage of the magnet, when the gas is forced through a narrower passage and
is therefore forced to move at higher velocity. The most conspicuous difference between the
different velocities is the width of boundary layers, which decreases with increasing velocities.
This comes about because higher wind velocity means higher Reynolds number (see section 4.1),
that is: Higher inertia of gas packets relative to the force of viscosity. As the inlet velocity rises
the change in width of boundary layers caused by the decreasing importance of viscosity is
evident at the top of the domain; in the region immediately above the magnet; and most evidently
in the narrow passage below the horizontal plate. At 0.2 m/s only a small amount of the gas
passes below the horizontal plate as the viscosity makes it difficult to push gas through this
narrow passage. At 9 m/s, in contrast, wind velocities below the plate are as high below as above
the magnet; the higher velocity of the gas forces it through narrower passages.

The region behind the magnet also shows a clear variation as the velocity rises. In fact this
model provides a demonstration of the development of ‘vortex shedding’ in 2-dimensional flow
past an obstacle. Many sources [78] describe this well-known phenomenon, which is widespread
in nature in situations when a fluid flows past an obstacle in an approximately 2-dimensional
geometry (e.g., water flowing past a vertical pole).
Figure 7-7: Steady solutions for the velocity field at an inlet wind speed of 0.2 m/s (top) and 1 m/s (second from top) as well as the time-varying solution at 9 m/s shown at two times 10 ms apart (two bottom plots). The color code shows the magnitude of the wind velocity in m/s as a function of position.
At low Reynolds numbers \((V = 0.2 \text{ m/s})\) there is a region of still air, which does not extend very far behind the obstacle, since the viscosity makes the velocity ‘spread out’ after passage of the obstacle. As the Reynolds number rises \((v = 1 \text{ m/s})\) two slow vortices develop behind the obstacle, although the asymmetry of the geometry makes one vortex more prominent than the other in contrast to the standard, symmetrical situation. The region of slow-moving air also extends farther and farther behind the obstacle until, eventually, the situation becomes unstable and a steady solution to the equations can no longer be found. At 1 m/s the situation is only marginally stable; as the wind speed, and thereby the Reynolds number, rises further, a harmonic fluctuation develops behind the obstacle, in which vortices form, grow, and are shedded to move downstream with the general fluid flow, thereby forming a vortex street.

This is demonstrated by the two bottom plots of figure 7-7 showing the time-varying situation at 9 m/s at two different times. The bottom plot shows a time 10 ms later than the second plot from the bottom. In the second plot from the bottom two vortices are clearly visible behind the magnet (dark blue spots). In the bottom plot the two vortices have moved slightly downstream and are starting to merge. The asymmetry of the geometry means that the vortex formed at the upper edge and the vortex formed at the lower edge tend to collide and dissolve; in a more symmetric situation vortices would shed from the lower and upper edge by turns, leading to formation of a longer ‘vortex street’ downstream of the obstacle.

It is evident from these two plots that the velocity field varies in time, which is why no steady solution can be found. Although the main time-variation occurs in the zone behind the magnet the velocity in other parts of the domain varies harmonically as well, in step with the vortex formation and shedding and specifically the extent of the boundary layer above the magnet also pulses up and down in step with the vortex shedding.

Figure 7-8 shows a magnified view of the region immediately above the magnetic surface in the steady solution for an inlet velocity of 1 m/s. There is a distance of 2-3 cm perpendicularly from the centre of the magnet out to the zone where the wind velocity is 1 m/s or higher (yellow color). This boundary layer obviously assists the magnetic capture of dust grains, since the slow wind velocity immediately above the magnetic surface gives the magnetic force more time in which to attract passing grains. Therefore, as we will see in chapter 8, the aerodynamic environment (i.e., the inlet wind speed) has a major influence on the dust capture process.

**Figure 7-8:** Magnitude of the wind velocity as a function of position. Magnified view from the solution for an inlet wind speed of 1 m/s. See figure 7-7, second plot from the top, for the color code legend.
7.3.2. Turbulence and Pressure

The turbulence parameters $k$ and $\varepsilon$ are specified at the inlet. In practice the quantities specified are the intensity of turbulent motions $I = u'/V$, with $u'$ the mean speed of turbulent motions and $V$ the inlet wind speed; and the length scale $l$ of turbulent motions. $k$ and $\varepsilon$ are then derived by the STAR code from $I$ and $l$. The $l$-value was chosen to be 4 cm in all cases, as 4 cm is 10% of the diameter of the inner wind tunnel tube. $I$-values are chosen based on the measured turbulence intensity in the wind tunnel at a given wind speed (see section 5.2). At 0.2 m/s $I$ is 0.03, at 1 m/s it is 0.04, while at 9 m/s it is 0.08.

Figure 7-9 shows a color plot of the kinetic energy of turbulence, $k$, as a function of position for the standard 1 m/s case, while figure 7-10 shows a magnification of the same plot. Levels of turbulent kinetic energy are generally highest away from solid surfaces. Generation of turbulence happens mainly in two places: At the leading edge of the horizontal plate and behind the top edge of the inclined plate, on which the magnet is placed. From the velocity plots in figure 7-7 it is evident that these are places where there are high wind speeds close to solid surfaces.

The turbulence plots provide some support for the choice of the turbulence parameters $I$ and $l$ (or $k$ and $\varepsilon$). If the parameters chosen had been very far from realistic values there would have been a strong gradient in $k$ across the computational domain, as the unrealistic inlet values decayed; this is not observed.

Figure 7-9: Turbulent kinetic energy, $k$, as a function of position for an inlet wind velocity of 1 m/s. The unit is J/kg.
Figure 7-10: Magnified view of part of figure 7-9. See that figure for the color code legend.

Figure 7-11 shows a plot of the relative pressure as a function of position for an inlet wind speed of 1 m/s. The pressure distribution is very regular, decreasing towards the left in order to provide a pressure differential to offset the drag force on the gas from the solid surfaces. The pressure variations are small, however, less than 0.3 Pa in total difference between the minimum and maximum values in the computational domain as set against an absolute value somewhere in the range 500-900 Pa.

Figure 7-11: Pressure as a function of position for an inlet wind velocity of 1 m/s. The unit is Pa.
Chapter 8

CFD Dust Capture Results

8.1. Introduction

We have now finally reached the point where we can attempt to answer the questions posed in section 1.4: Which parameters are of importance for the dust capture process, and how does the capture process depend on these parameters? The theoretical considerations of chapter 4 have given a good starting point for building this understanding. Based on this I present in this chapter dust capture data from the CFD model in comparison with laboratory simulation data and draw qualitative and quantitative conclusions from these data. Eventually in chapter 9 I compare selected data from the MER mission with the CFD data and analyze these MER results in light of the conclusions from the CFD-model.

We saw in section 4.5 that there are three factors determining the motion of dust grains; namely the wind velocity field, the drag force, and the external forces (gravity and magnetism). Accordingly model calculations have been performed while varying each of these three factors separately.

The wind velocity field has been varied by varying the inlet wind speed in the model as described in section 7.3.1. The velocity field could also have been varied by varying the kinematic viscosity of the gas, i.e., by changing any of the other parameters that contribute to the Reynolds number. However the kinematic viscosity in the Martian atmosphere is well known and probably does not vary more than by a factor of 2. Variations in the velocity field are therefore expected to arise mainly from wind speed variations.

The drag force has been varied by altering the characteristic time, \( \tau \), as this single parameter expresses the effect on the drag force of dust grain size, grain mass density, dynamic viscosity of the gas and mean free path in the gas.

The external forces have been changing mainly by varying the magnetic properties of the dust grains through varying the magnetic parameters \( \gamma \) and, primarily, \( \sigma_s \); specifically the magnetic
properties of dust grains have mostly been expressed through the magnetic susceptibility at zero field, $\kappa$, which is derived from $\gamma$ and $\sigma_s$. Separate calculations have been performed with the magnetic field of the Capture magnet, with the magnetic field of the Filter magnet, and with no magnetic field. Most calculations were performed using the Martian acceleration of gravity (3.7 m/s$^2$). As a separate issue I have investigated the effect of changing the force of gravity from the Martian to the Terrestrial value, which is of relevance for comparison between numerical calculations performed at Martian gravity and simulation experiments performed at Terrestrial gravity. The effect of changing the sign of the gravity vector (i.e., turning the magnet upside down) has also been investigated.

In general the calculations have given as output deposition rates on the Capture or Filter magnet as well as deposition patterns across the magnets. I have then studied the dependence of these outputs on wind speed, characteristic time and grain magnetization. Since it is impractical to numerically model all possible variations of these three parameters I investigated the dependence of dust deposition on each parameter individually and performed empirical fits to quantities of interest in order to allow extrapolation to the complete parameter space. Typically an exponential function of the form $a \cdot e^{(b \cdot x)} + c$, where $x$ is the variable parameter and $a,b,c$ are fitting coefficients, provided an adequate fit to the data. In section 8.6 a general empirical formula is derived based on these fitting functions.

Data from the numerical model have been compared with laboratory data wherever feasible.

### 8.2. Dust Grain Paths

Figure 8-1 shows direct results from the calculation of the standard case: Salten Skov dust ($\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\kappa = 1.03 \cdot 10^{-4}$ m$^3$/kg, $\tau = 0.61$ ms – see section 7.2.6) passing at a wind speed of 1 m/s across the surface of the MER capture magnet. 120000 dust grains are introduced into the flow at a distance of ~45 cm from the magnet, spread evenly over an area 12 mm vertically by 1 mm horizontally and the tracks of the grains are calculated. Such a calculation takes ~11 hours in the steady state mode, ~72 hours in the transient mode.

The plot shows the tracks of 1200 grains. Some grains pass below, some above the horizontal plate. Of the grains passing above the plate a certain fraction settle on the upper surface of the plate under gravity, while some pass on and are magnetically captured on the magnet and some pass above the entire structure. Notice the two stable vortices behind the plate and magnet. The centre of a vortex tends to be free of dust. (see the image of a vortex in figure 5-8). Figures 8-2 and 8-3 show magnified views of the grain tracks. It is apparent from figure 8-3 that the magnet only captures dust from a narrow layer above the magnet surface in agreement with the theoretical considerations in section 4.4. It is also apparent that most dust grains are captured on the front edge (left side) of the magnetic surface.

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30 The fits presented in this section are not weighted fits, i.e., $\sigma$-values have not been taken into account when determining the fitting parameters.
Figure 8-1: Tracks of 1200 dust grains through the computational domain. Wind speed of 1 m/s, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.

Figure 8-2: Magnified view of dust grain tracks above the horizontal plate and magnet. Wind speed of 1 m/s, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.

Figure 8-3: Further magnified view, showing dust grain tracks passing above the magnet surface. Wind speed of 1 m/s, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.
**Figure 8-4** shows the percentage probability of a grain being captured as a function of the vertical position of its starting point both for a calculation with the magnetic force included and for a reference calculation with no magnetic force (nonmagnetic grains). Several interesting facts emerge from this plot. One is that the maximal chance of ‘hitting’ the magnet with a dust grain starting at a distance of 45 cm is about 14%. Another is that the width of the peak (2σ) is about 3 millimeters. Taken together this reveals that the magnet is not emptying the dust from a wide cross section of the air, rather the dust grains are captured from a very narrow layer above the magnetic surface as was already concluded from **Figure 8-3**. From the size of the peak we can calculate the number of grains per second captured on the capture magnet, given an estimate of the number density of grains in the air. Assuming that the 2D-model can be taken as accurate for a 1 cm–wide area across the centre of the magnet and given a dust concentration in the air of 1 grain/cm$^3$ we calculate that 5.4 dust grains hit this area per second compared to only 0.3 dust grains per second if no magnetic force was present. Note that these deposition rates should not be taken as accurate in an absolute sense, since dust concentrations are not well known (see section 2.5.1); viewed as relative numbers, however, they are instructive.

The vertical position (y – coordinate) of the point of introduction of the grains as well as the width of the grain distribution in the y-direction was determined for each case from inspection of the type of plot shown in **Figure 8-4**. A range of y-values were chosen. If the full peak was not captured in the y-values chosen, the calculation was redone with grains introduced over a modified range of y-values. The lower surface of the horizontal plate is at $y = 0$ mm. The horizontal distribution of injection points (x-coordinates) was the same for all sets of calculations.

**Figure 8-4:** Probability of capturing a given dust grain on the capture magnet as a function of the vertical coordinate of its introduction point. Vertical error bars are ±1σ based on a binomial distribution while the horizontal bars denote the width of a bin. Parameters: Wind speed of 1 m/s, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.

### 8.3. Dust Capture Rates

#### 8.3.1. Deposition as a Function of Wind Speed

The curves and results shown and described in section 8.2 are the standard output from each calculation. Several series of such calculations have been performed while varying the different
parameters. The results from one such series, varying the wind speed while keeping characteristics of the dust grains unchanged, are shown in **Figure 8-5**. The graph shows calculated deposition rates on the filter and capture magnets as a function of wind speed. Deposition rate denotes the number of grains per second captured on a 1 cm-wide area across the surface of the magnet given a number density in the air of 1 grain/cm$^3$. It is apparent from this graph that for both magnets the total deposition grows significantly with the wind speed. This means that on a magnet exposed to a dust-filled Martian atmosphere with varying wind speeds, most of the dust deposition will occur during periods of high wind. Moreover these results show that the deposition on the capture magnet increases faster with increasing wind speed than the deposition on the filter magnet, so that for low wind speeds (below ~1 m/s) the deposition is greater on the filter magnet while for high wind speeds (above ~1 m/s) the deposition is greater on the capture magnet.

![Figure 8-5: Numerically generated deposition rates on Capture and Filter magnets as a function of wind speed. Error bars are $\pm 3\sigma$. $\sigma_i = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.](image1)

![Figure 8-6: Deposition on Filter magnet relative to Capture magnet for modeling data as well as laboratory simulation data. Error bars are $\pm 1\sigma$. Parameters for numerical model: $\sigma_i = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms, Martian gravity.](image2)
Figure 8-6 shows deposition on the filter magnet relative to deposition on the capture magnet as a function of wind speed both for the numerical modeling data and for data from laboratory simulations. The laboratory data show the same general trend as the data from the numerical model, namely deposition on the filter magnet relative to the capture magnet falling with rising wind speed. However the relative deposition on the filter magnet is somewhat smaller in the laboratory data than in the numerical simulations. As discussed below (see section 8.3.2) this could be caused by a lower characteristic time for the grains in the wind tunnel as compared to the standard modeling case. Both curves were fitted to an expression of the form: \( R = a e^{(bv)} + c \). For numerical data the best fit was found with parameters \( a = 1.86 \), \( b = -1.00 \) s/m, \( c = 0.40 \) while the laboratory data gave the best fit: \( a = 1.39 \), \( b = -0.81 \) s/m, \( c = 0.22 \). Note that roughly twice as much dust was observed on the capture magnets relative to the filter magnets on the MER rovers (see section 3.5.5) figure 8-6 therefore suggests that local wind speeds have been generally above 2 m/s at the two landing sites.

8.3.2. Deposition as a Function of Characteristic Time

Figure 8-7 shows results from a series of calculations varying the characteristic time. In order to facilitate comparison with experiments these calculations were performed under Terrestrial gravity. By changing the sign of the gravity vector in the numerical model calculations were made both for the magnet facing upward and facing downward. For low characteristic times the magnet captures the same amount of dust whether facing upward or downward, while for higher characteristic times the difference is marked, and above a certain level no dust gets captured on the downward facing magnet. A set of magnets facing upwards and downwards could conceivably be used on a future mission as a means to determine grain characteristic times (see section 10.3).

The standard case of 2 micron particles with a density of 3000 kg/m\(^3\) corresponds to a characteristic time of 0.61 ms, so based on these calculations we would not expect to see any deposition on the downwards facing magnet. Nevertheless simulation experiments using magnets facing both upward and downward have shown deposition levels on the upward facing magnet of only slightly (~15 %) more than the deposition on the downward facing magnet for Salten skov dust at a wind speed of 1 m/s. One possible interpretation is that at a large fraction of the suspended grains in the wind tunnel have significantly lower characteristic times than 0.61 ms, i.e. they are either significantly smaller than 2 microns or more likely aggregates of significantly lower density than the bulk density of the material (see chapter 6). We have observed in the numerical model that lower characteristic time results in lower deposition on the filter magnet relative to the capture magnet, so this would also be consistent with the observation in section 8.3.1 above that deposition on the filter magnet relative to the capture magnet is lower in the laboratory data than in the numerical results.

If all grains in our wind tunnel were identical and had the same magnetization as the mean magnetization of Salten Skov dust then figure 8-7 and the observed deposition rates would suggest that the grains had characteristic times of around 0.1 ms or less, since this gives a deposition rate on the upward facing magnet of only slightly more than the deposition rate on the downward facing magnet.
Another set of calculations was performed, in which characteristic times were also varied. These calculations were performed at Martian gravity and included calculations for no magnetic force. Results from this series of calculations are shown in Figure 8-8. ‘Full deposition’ denotes the deposition on the Capture magnet at a given characteristic time. ‘Reference’ is the deposition in the same case, but with no magnetic force (i.e., nonmagnetic grains). ‘Corrected deposition’ is simply the difference between the full deposition and the reference, and shows how much of the deposition is due to the presence of the magnet. The largest characteristic times are equivalent to grains with a diameter of 50 µm and a mass density of 3000 kg/m³. The curve shows that for characteristic times of 0.61 ms and less the contribution to the deposition due to gravity is insignificant, meaning that simulation experiments at Terrestrial gravity would be expected to reproduce Martian conditions well. At large characteristic times (for large grains) the full deposition rate curve seems to approach a straight line and the effect of gravity grows increasingly important for the deposition as evidenced by the growth of the reference curve. At the limit of large grains we would expect the deposition to be mainly controlled by the terminal velocity of the grains under gravity, which (as long as Stokes law is valid) is proportional to the characteristic time. The linear relation between deposition and characteristic time is therefore explainable.
8.3.3. Deposition as a Function of Gravity

Figure 8-8 demonstrates that, at least for larger grains, gravity has an important role to play in the deposition process as does, in another sense, figure 8-7. Another short series of calculations was performed in which the magnitude and sign of the gravity vector was varied. Results from these calculations are shown in figure 8-9. Calculations were performed at zero gravity; at positive and negative Martian gravity (magnet facing upwards or downwards) and at positive and negative Terrestrial gravity. Based on figure 8-7 it comes as no surprise that there is a large difference between deposition rates with upwards and downwards facing magnets. Interestingly, however, for zero and both positive gravity values the corrected deposition rate is constant within the error indicating that the contribution to the deposition due to gravity can be treated as independent of the contribution due to the magnetic force.
8.3.4. Deposition as a Function of Magnetic Properties

Results from a set of calculations, varying the magnetization properties of the dust, while keeping wind speed and characteristic time constant, are shown in figure 8-10. The calculation was performed for seven different sets of magnetization parameters.

The leftmost data point corresponds to $\gamma = 2.01$ T, $\sigma_s = 1.05$ A·m$^2$/kg, values that were obtained by a fit to measurements on a hematite sample. The five central points have identical $\gamma$-values, $\gamma = 42.7$ mT, obtained from measurements on a sample of Salten Skov dust, while saturation magnetization for the central point was also taken from measurements on Salten Skov dust $\sigma_s = 3.5$ A·m$^2$/kg, and the points around have $\sigma_s$-values equal to 0.2, 0.5, 2 and 5 times this value. Finally the rightmost data point corresponds to $\gamma = 53.7$ mT, $\sigma_s = 82.4$ A·m$^2$/kg, obtained from measurements on a maghemite sample.

Since the model for the magnetization $\sigma(B)$ of a dust grain operates with two free parameters, $\sigma_s$ and $\gamma$ or alternatively $\kappa$ and $\gamma$ (see section 4.4), we have to make a choice of which of these parameters to plot on the horizontal axis. Arguably $\kappa$ is the most important parameter for determining the influence of the magnetic field on dust motion, since the grains only approach saturation close to the magnet, when they are effectively captured already and far away from saturation $\sigma = \kappa B$. I therefore chose $\kappa$ as the parameter on the horizontal axis.

For each case the curve shows both the rate of dust deposition on the Capture magnet and the rate of deposition on the Filter magnet. As the magnetization rises the deposition on the filter magnet rises relative to the deposition on the capture magnet and even for moderately magnetic grains there is greater deposition on the filter magnet than on the capture magnet. This occurs because the magnets are constructed so that the filter magnet causes a weaker magnetic force than the capture magnet in the region close to the magnetic surface, but causes a stronger force than the capture magnet at greater distances. Thus, for highly magnetic grains, the filter magnet is capturing dust from greater distances than the capture magnet.

These calculations support the claim (made in section 3.5.4) that the filter magnet preferentially captures stronger magnetized dust grains (i.e. ‘filters’ the dust), while the capture magnet to a larger degree captures all magnetic dust. If the Martian dust is magnetically inhomogenous, the dust on the filter magnet will be on the average more magnetic than the dust on the capture magnet.

Figure 8-10 also clearly shows that, if other parameters are known, the amount of dust on the capture magnet relative to the filter magnet can be used as a diagnostic of the magnetic properties of the dust. The Mars Exploration Rover Spirit measured about twice as much dust on the capture magnet as on the filter magnet[5]. Taking figure 8-10 at face value this would indicate that the Martian airborne dust has a magnetization significantly less than half the value for Salten Skov dust. However several other effects could cause the observed deposition rates with dust of a higher mean magnetization. Higher wind speed than 1 m/s, lower dust mass density than 3000 kg/m$^3$ or a wide distribution of magnetization values among dust grains would all be expected to result in higher deposition on the capture magnet relative to the filter magnet. (See discussion in section 8.6).

The data points for the Capture magnet deposition rate have been fitted with a power law with an exponent of 0.336. This curve fits the data well.
Chapter 8 – Magnetic Dust Capture

Another series of calculations were performed varying the magnetic properties of dust grains while keeping the inlet wind speed at 3 m/s instead of 1 m/s. These data are shown in figure 8-11 together with the Capture magnet deposition rate at 1 m/s (which was also shown in figure 8-10). All calculations for \( v = 3 \text{ m/s} \) were made at \( \lambda = 42.7 \text{ mT} \), while \( \sigma_s \) was varied. As was the case at \( v = 1 \text{ m/s} \) the Capture magnet deposition rate at 3 m/s fitted a power law well, with an exponent of 0.384. Whether the difference in value between the exponent at \( v = 1 \text{ m/s} \) and the exponent at \( v = 3 \text{ m/s} \) can be taken as significant is doubtful.

Figure 8-11: Numerically generated Capture magnet deposition rates for various materials of differing magnetic properties at wind speeds of 3 m/s and 1 m/s. Error bars are \( \pm 3\sigma \), \( \tau=0.61 \text{ ms} \), Martian gravity.
8.4. Dust Deposition Patterns

In addition to registering the total deposition rate the CFD calculation also registers where on the magnet each grain impacts, giving a profile of dust accumulation across the magnetic surface. These data are plotted in figure 8-12 (left) for the standard case ($\tau = 0.61$ ms, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\kappa = 1.03 \times 10^{-4}$ m$^3$/kg, $v = 1$ m/s). The entire magnet housing has a diameter of 45 mm, so the horizontal axis has an extent equal to the extent of the housing. However the magnet itself has a smaller diameter (25 mm), which is obvious from the pattern of the dust grains. For this case most grains stick to the forward edge of the active magnetic surface. This is not always the case however, as we will show in examples below (see section 8.5), and we will see that the pattern on the magnet reflects wind speed, grain magnetization and characteristic time.

![Figure 8-12: Dust profiles in the standard case. Left curve shows modeling results for relative deposition rate as function of position on the magnet. Right curve shows the symmetrized version generated by averaging the curve on the left with its mirror image in the 0 mm line. Both curves are normalized to have an integral of 1. Error bars are ± 1σ. Wind speed of 1 m/s, $\sigma_s = 3.5$ Am$^2$/kg, $\lambda = 42.7$ mT, $\tau = 0.61$ ms Capture magnet, Martian gravity.

The pattern on the magnet in this model is generally highly asymmetric, which is obviously an effect of the fixed wind direction. In a real exposure of a magnet to the Martian atmosphere there will be a varying wind direction, especially on a rover that changes its orientation from day to day. Therefore one expects a more symmetric pattern on the magnets, and indeed this is what is observed on Mars (see section 3.5.5). In order to attempt a better simulation of changing wind directions I symmetrize the graph by averaging it with its mirror image. The result is shown in figure 8-12 on the right. This graph shows a dust pattern with more dust on the outer parts of the magnet than in the central area. The dotted lines on the graph indicate the integration limits used in the definition of the Central Fraction in section 8.5.1.

Plots of dust deposition as a function of position on the magnet may also be generated from the laboratory simulation data. Such a plot is shown in figure 8-13 on the left. Two curves are shown on the graph: The blue, solid curve is the symmetrized profile measured parallel to the wind direction, while the red, dotted curve is the symmetrized profile measured at right angles to the wind direction. The two curves are not exactly identical, but come quite close, which supports the assumption that the symmetrized profiles generated by the CFD model (parallel to the wind direction) can be taken as a reasonable representations of the pattern generated on a magnet exposed to a varying wind direction, as is the case on Mars. Comparing these curves (figure 8-13, left) with the CFD-generated curves for the standard case (figure 8-12) we see that the two curves do not match very well, as the central peak in the laboratory curve is somewhat higher
than in the CFD-generated curve, as compared to the edges. However as discussed below (section 8.5.3) this may be explained as caused by the characteristic times of the dust grains in the wind tunnel being lower than the characteristic times of the grains in the numerical model. That is, the numerical model does not fully take into consideration the fact, that the grains in suspension are low density aggregates of smaller grains. On the right figure 8-13 shows a numerically generated profile for the same case as figure 8-12, except the characteristic time is reduced from 0.61 ms to 0.24 ms. This profile comes closer than figure 8-12 to reproducing the result of the laboratory simulation.

Figure 8-13: Left curve shows absorbance of dust deposited on the film as function of the position on the Capture magnet for a laboratory simulation. Wind speed of 1 m/s, Salten Skov dust. Right curve shows a CFD generated profile for $\sigma_s = 3.5 \text{ A m}^2/\text{kg}$, $\lambda = 42.7 \text{ mT}$, $\tau = 0.24 \text{ ms}$ Capture magnet, Martian gravity.

8.5. The Central Fraction

8.5.1. Definition of the Central Fraction

We saw in section 8.3.4 that the deposition rate on the Filter magnet relative to the Capture magnet may be used as a diagnostic of the magnetization of the dust. Another such diagnostic quantity is the deposition rate on the centre of the Capture magnet relative to the deposition on its edges. This is illustrated clearly by figure 8-14 showing the dust profiles across the Capture magnet for a model calculation with parameters $\gamma = 2.01 \text{ T}$, $\sigma_s = 1.05 \text{ A m}^2/\text{kg}$, corresponding to weakly magnetic hematite (left) and a calculation with parameters $\gamma = 53.7 \text{ mT}$, $\sigma_s = 82.4 \text{ A m}^2/\text{kg}$, corresponding to strongly magnetic maghemite (right). For weak magnetization we see more deposition in the central part of the magnet than on the edges, while for strong magnetization there is practically no deposition on the central part of the magnet, almost everything gets captured on the edges. The peaks at +/- 22 mm for weak magnetization are an aerodynamic effect at the downwind edge of the magnet that only shows up when the magnetic force is weak. Compare these figures also with the pattern corresponding to Salten Skov dust shown in figure 8-12, which shows a pattern intermediate between the one corresponding to hematite and the one corresponding to maghemite.
These observations may be put in a more quantitative form by calculating the area of the central peak (the integral from -2.5 mm to 2.5 mm) and expressing it as a fraction of the total area under the curve (the integral from -17.5 mm to 17.5 mm). We call this quantity the \textit{Central Fraction (CF)}. Figure 8-12 (right) has dotted vertical lines marking the integration limits used in the calculation of the central fraction.

\textbf{8.5.2. Central Fraction as a Function of Wind Speed}

Figure 8-15 shows the effect of wind speed on the central fraction both for laboratory data and for numerically generated data. The general trend of both data sets is the same, namely that rising wind speeds result in rising central fractions, but the laboratory data show central fractions larger than the ones for the CFD data by about 0.045 on average. The laboratory data were fitted to an expression of the form $\text{CF} = a \cdot e^{(b \cdot v)} + c$. This expression was chosen as a simple function which approaches a constant value both for high $v$ and for low $v$, however it should only be taken as an empirical curve, as there is no particular theoretical basis for assuming a curve of exactly this form. The laboratory data fit this expression remarkably well. The numerical simulation data were also fitted to an expression of this form, however the $b$–value was fixed at the value found from the laboratory data, so only the values $a$ and $c$ were used as free parameters. The resultant curve has the values $a = -0.228$, $b = -0.904$ s/m, $c = 0.23$ and it fits the data reasonably although by no means as good a fit as was the case for the laboratory data. From this curve we calculate $\delta\text{CF}/\delta v = 0.083$ s/m at $v = 1$ m/s. As described in section 7.3.1 all calculations with inlet wind speeds above 1 m/s were performed as transient calculations, whereas calculations at wind speeds below 1 m/s were performed as steady state calculations. The two data points shown at $v = 1$ m/s are the results of a transient (bottom point) and a steady state calculation (top point). The two values are not too far from each other, although the difference is probably slightly larger than can be explained by statistical variation alone. Only the transient calculation was taken into account when calculating the parameters for the fitted curve.

The deviations at higher wind speed from the simple expression used in the fit probably reflect a real variation (see section 8.5.4) caused by the large-scale time-variability of the solutions. Why the numerical modeling results show this structure, when the experimental results do not is not known. A likely explanation is that the 2-dimensionality of the numerical model allows for
easier development of a strong, harmonic time-variability, whereas the time-variability in the experimental flow is more random, smoothing out any effects caused by regular harmonic variations.

![Central Fraction as a Function of Wind Speed](image)

**Figure 8-15:** Central fractions as a function of wind speed both for laboratory data and for numerically generated data. Error bars are ±1σ. $\sigma = 3.5 \text{ Am}^2/\text{kg}$, $\lambda = 42.7 \text{ mT}$, $\tau = 0.61 \text{ ms}$, Martian gravity.

### 8.5.3. Central Fraction as a Function of Characteristic Time

Seeing the effect of the characteristic time demonstrated in figures 8-7 and 8-8 one might assume that a variation in the characteristic time would have an influence also on the central fraction. Indeed this is so as is demonstrated by figure 8-16, which shows the central fraction as a function of the characteristic time. A higher characteristic time results in lower deposition on the central area of the magnet. This could explain the higher central fractions observed in laboratory data relative to numerically generated data. A characteristic time of 0.2 ms instead of the 0.61 ms used in the numerical model could explain the offset of about 0.045 between the two curves in figure 8-15 above. Based on the difference in deposition rates between upwards and downwards facing magnets we estimated $\tau < 0.1 \text{ ms}$ in the wind tunnel in section 8.3.2. This value is lower than the one estimated from consideration of the central fraction, however the trend is the same, namely that the characteristic times in the numerical model are higher than the true characteristic times of grains in the wind tunnel. For spherical 2 micron grains $\tau = 0.2 \text{ ms}$ corresponds to a mass density of 1000 kg/m$^3$.
Figure 8-16: Calculated central fractions as a function of characteristic time. Error bars are ± 1σ. Some of these data were generated assuming Martian gravity (τ > 0.61) while others were generated assuming terrestrial gravity (τ < 0.61). However this gravity difference is not expected to have a large effect, which is supported by the near match of the two datasets at τ = 0.61. Parameters: σ = 3.5 Am²/kg, λ = 42.7 mT.

In analogy to the case for wind speed the data points have been fitted to an expression of the form $CF = a e^{b\cdot\tau} + c$, with calculated parameters $a = 0.134$, $b = -1.08$ (ms)$^{-1}$, $c = 0.092$. There is significant scatter in the data at low characteristic times, which is most likely due to bad statistics. From the fitted curve we calculate $\frac{\delta CF}{\delta \tau} = -0.075$ (ms)$^{-1}$ at τ = 0.61 ms.

8.5.4. Central Fraction as a Function of Magnetic Properties

Figure 8-17 shows a plot of the central fraction as a function of the specific magnetic susceptibility of the dust. The blue, filled circles are data for a wind speed of 1 m/s, the red, empty circles are for 3 m/s. This graph confirms our qualitative assertion above that higher magnetization of the dust correlates with a lower fraction of the dust deposited in the central area of the magnet. The data points for 1 m/s were fitted to an expression of the form $CF = a e^{b\cdot\kappa} + c$, and the best fit was found with the values $a = 0.2$, $b = -4500$ kg/m$^3$, $c = 0.0336$.

As was the case for figure 8-10 the leftmost and rightmost data points (corresponding to parameters for hematite and parameters for maghemite) have different values of γ than the rest of the points. Because of this and because of the large error bar the leftmost point (hematite) was ignored when determining the fitting parameters. The bad match between the fitted curve and the rightmost point (maghemite) can be attributed to the different γ - value. From the fitted curve we calculate $\frac{\delta CF}{\delta \kappa} = -565$ m$^3$/kg at $\kappa = 1.03 \cdot 10^{-4}$ m$^3$/kg (Salten Skov dust).

The points for 3 m/s are compared to a curve generated by displacing the curve for 1 m/s upwards according to an expression including all three parameters (see section 8.6). The value of the displacement (0.077) was found as the difference between 1 m/s and 3 m/s for $\kappa = 1.03 \cdot 10^{-4}$ m$^3$/kg (see figure 8-15). The points follow the curve reasonably on average, but there is some additional structure in the variation of the central fraction with magnetization at 3 m/s not present at 1 m/s. I attribute this to time variation in the large-scale airflow at 3 m/s which is absent at 1 m/s.
Obviously based on this curve one might relate an observed dust pattern on a magnet to a degree of magnetization of the dust. We must however stress that, as is illustrated by figures 8-14 and 8-15 above, conclusions regarding the magnetization of the dust can only be drawn based on these kinds of plots provided that other relevant parameters are known.

Figure 8-17: Calculated central fractions for various materials of differing magnetic properties. Error bars are ±1σ. \( \tau = 0.61 \) ms. Wind speed are 1 m/s or 3 m/s, Martian gravity.

### 8.6. Discussion

We have demonstrated that three main factors determine dust pattern generation and deposition rates when capturing airborne dust on permanent magnets. These factors are wind speed, dust magnetization and characteristic time. In a qualitative sense we may moreover state that increasing grain magnetization has the same effect as increasing characteristic time. This is understandable when we consider that stronger magnetic force and larger characteristic time both manifest themselves as a larger terminal velocity. Thus, in regions where the magnetic force dominates over gravity, strengthening the magnetic force will have the same kinematic effect as increasing the characteristic time.

With regard to the dust pattern on the capture magnet and the relative deposition rates on the capture versus the filter magnet we may also state that lowering the wind speed has the same effect on the pattern as raising the dust magnetization, at least in a qualitative sense. This may be understood from a consideration of the local velocity of dust grains. As discussed in chapter 4 dust grains effectively travel at terminal velocity at all times. The instantaneous velocity of a grain is the vector sum of the local wind velocity and the terminal velocity of the grain due to gravity and magnetic force. Therefore the path of a grain is decided not so much by the magnitude of its velocity but by the direction of its velocity relative to the magnet. Lowering the wind speed effectively reduces the grain velocity component in the direction along the magnet surface; in general this has a similar effect as increasing the magnetization – i.e. increasing the grain velocity component towards the magnet surface.

For the central fraction we may give a more quantitative description. As described in section 8.5 we have obtained empirically generated exponential expressions for the central fraction as a function of wind speed, characteristic time and grain magnetization. We cannot from these single-variable expressions derive the general function \( CF(\kappa, v, \tau) \). However we can attempt an
approximation to this function in the region of parameter-space close to our standard case point $\kappa = 1.03 \cdot 10^{-4}$ m$^3$/kg, $v = 1$ m/s, $\tau = 0.61$ ms. A simple way of generating such an approximation is just to add the three single-variable expressions. The resulting expression is:

$$ CF(\kappa, v, \tau) \sim 0.2 \cdot \exp(-4500 \text{kg/m}^3 \cdot \kappa) - 0.228 \cdot \exp(-0.904 \text{s/m} \cdot v) + 0.134 \cdot \exp(-1.08 \text{(ms)}^{-1} \cdot \tau) + 0.04 $$

with the final constant chosen so as to make this expression give a central fraction of 0.15 in the standard case as was observed for the steady state calculation. The data points for $v = 3$ m/s in figure 8-17 provide some validation for this expression, however it must be remembered that this is an extrapolation from empirical data, which can not be expected to be valid for parameters far from the standard case parameters.

In the next chapter I will derive values for the central fraction from images of the capture magnet on Opportunity and subsequently use the above expression to draw quantitative conclusions about properties of the Martian dust.
Comparison to MER Data

9.1. Image Analysis

It is possible from images taken by the MER Pancam to estimate the relative amount of dust deposited at various distances from the magnet centre (i.e., the dust profile). This profile may then be compared to profiles generated by laboratory simulation experiments or by numerical modelling and a central fraction may be calculated for the dust profile on the magnets on Mars.

This analysis introduces four quantities that may be derived from analysis of the images. The first quantity is the relative reflection profile $R(d, \lambda)$, defined as the average diffuse reflection at a distance $d$ from the centre of the magnet relative to the diffuse reflection from a dust-free aluminium surface. The second quantity is the diffuse reflection from a dust-free aluminium surface $b(\lambda)$, which is estimated from early images of the aluminium surface away from the magnetic region. We also introduce the diffuse reflection from an infinitely thick dust layer $r(\lambda)$ and the fractional dust coverage, or covering fraction$^{31}$, $\alpha(d)$.

Following a treatment previously used in analyzing data from the magnets on Mars Pathfinder [35] we assume that the dust-covered magnet may be modelled as consisting of a dust-free-area having reflectance $b(\lambda)$ and a dust-covered area having reflectance $r(\lambda)$. This leads to the equation:

$$R(d, \lambda) = \alpha(d) \frac{r(\lambda)}{b(\lambda)} + (1 - \alpha(d))$$

$^{31}$ Not to be confused with the Central Fraction, which is something else entirely
By performing a fit to observed intensity distributions this model can be used to determine the fractional dust coverage, $\alpha(d)$, and reflectivity of the dust, $r(\lambda)$. This simple form was successfully used to analyse the observations of dust deposition on the Magnet Array on Mars Pathfinder [35]. For low dust deposition ($\alpha(d) << 1$) the fractional dust coverage may be taken as proportional to the amount of dust on the magnet. Based on the observation that $1-R$ increased linearly with time for the first part of the mission we expect this assumption of non-saturation to be valid for analysis of images from early in the mission.

In our analysis of laboratory simulation data we took the absorbance $A$ of the dust as proportional to the amount of dust. In a slightly more sophisticated model than the one above the absorbance relates to the fractional dust coverage by:

$$A = \log(1-\alpha) \quad (\sim \alpha, \text{for } \alpha << 1).$$

Which means that for low dust deposition $\alpha$ and $A$ are equivalent.

Comparisons between dust on the Capture magnet and on the Filter magnet have revealed differences in optical spectra as discussed in section 3.5.5. Specifically the dust accumulated by the filter magnet is seen to be darker (less reflective at longer wavelengths) than that on the capture magnet (see figure 3-31). From the CFD model the darker dust on the filter magnet is expected to be more magnetic than the dust on the capture magnet as discussed in section 8.3.4. Furthermore, if there are correlated variations in magnetization and optical properties of the airborne dust we would expect there to be observable variations across the surface of the capture magnet as highly magnetic dust tends to stick on the edge of the magnetic area while less magnetic dust is more likely to stick to the centre (see figures 8-14 and 8-17).

Indeed the dust on the capture magnets on the two rovers does show color variations between the centre and the edges of the dust pattern. This means that the simple model that was adequate for analysis of the Mars Pathfinder data is not adequate for data from the MER capture magnets. The presence of different magnetic and optical components in the dust requires, for these magnets, the application of a more complex model than the single component dust model presented above.

Figure 9-1 shows the relative reflection profile observed on the Opportunity capture magnet at six different wavelengths. The wavelengths shown cover the observed variation. These curves cannot all be fitted by the same single-component model since for different wavelengths we derive different curves for the covering fraction $\alpha(d)$; instead they have been fitted by an analogous two-component model:

$$R(d, \lambda) = \alpha_1(d) \frac{r_1(\lambda)}{b(\lambda)} + \alpha_2(d) \frac{r_2(\lambda)}{b(\lambda)} + (1 - \alpha_1(d) - \alpha_2(d))$$

By fitting this expression to the observations from MER, values for the reflectivity of the two components ($r_1(\lambda)$ and $r_2(\lambda)$) and their fractional dust coverage ($\alpha_1(d)$ and $\alpha_2(d)$) have been obtained. It is evident from figure 9-1 that this model fits the data well. I will here restrict the analysis to these Opportunity data, however data from Spirit show a similar two-component pattern and lends itself to an analogous analysis.
Figure 9-1: Relative reflection profile for dust on the Opportunity capture magnet observed at six different wavelengths. The data are fitted with a two component model. Only radial distributions are shown. Note that at wavelengths < 700 nm, where the dust reflects less than aluminum, dust coverage results in a relative reflectance < 1 and conversely for wavelengths > 700 nm, where the dust reflects more than aluminum.

From the fit we obtain for two dust components the covering fractions $\alpha_1(d)$ and $\alpha_2(d)$ as well as the reflection spectra $r_1(\lambda)$ and $r_2(\lambda)$. Many solutions exist that give equally good fits. In general, however, they all show a component which is bright at red and infrared wavelengths and is concentrated at the centre of the magnet and a darker component which is more concentrated at the edges of the magnetic surface. Figure 9-2 shows $\alpha_1(d)$ and $\alpha_2(d)$ for a typical fit. Overlaid on the curves are estimates of the covering fractions found from two different optical filters of the Pancam by application of the single-component model. Incidentally these two sets of data points demonstrate forcefully that the single-component model cannot fit data from different optical filters with the same fit (i.e., the optical spectrum of the dust is not identical all over the surface of the magnet).
Figure 9-2: Estimates of dust covering fractions. Left plot shows $\alpha_1(d)$ from the two component fit overlaid on $1-R(754\text{nm},d)$ derived from the Pancam’s R2 filter. Right plot shows $\alpha_2(d)$ from the two component fit overlaid on $1-R(602\text{nm},d)$ derived from the L4 filter. All curves are normalized to an integral of 1.

The two sets of observational data from the R2 and L4 filters (shown as points in figure 9-2) match the two components (curves) in the two-component model reasonably. Data sets from the other filters generally fall between these two distributions. This can be explained by inspection of figure 9-3, which shows the optical reflection spectra of the two components $r_1(\lambda)$ and $r_2(\lambda)$, as derived from the fit, relative to the spectrum $b(\lambda)$ for a clean aluminium surface. Note that only the relative distance from 1 of the various points has meaning in this graph as $R(d,\lambda)$ is unchanged under the transformation $(\alpha_1, (r_1-b)) \rightarrow (x\alpha_1, (r_1-b)/x)$.

Component number 1 has a reflectance very close to that of aluminium in the L4 (602 nm) band and so this component is essentially invisible in this filter. Thus filter L4 shows only component number 2. Conversely component number 2 is invisible in the R2 (754 nm) band and so this filter shows only component 1. The other filters generally show some combination of the two components.

Figure 9-3: Optical reflectance spectra derived for the two dust components in the fit. Compare this curve with figure 3-31.
We have thus learnt from analysis of images of the Opportunity capture magnet that the dust on the magnet is not homogenous, but consists of at least two components that have distinctive optical properties and different spatial distributions. Variations in spatial distribution can be caused by variations in magnetic properties, in characteristic time or in wind speed. However in this case the cause is most likely a variation in magnetic properties. It is easy to envision how a variation in magnetic properties could correlate with a color variation, but less evident, perhaps, why a variation in characteristic time should correlate with a color variation. This last possibility can not be entirely discounted, however.

The two (or more) components are not necessarily discrete; but could both be present in every dust grain in varying amounts. This would mean that there is a continuous distribution of dust grains with varying spectral and magnetic properties and the two components derived above would then represent ‘typical’ grains from each extreme of the distribution.

Calculating a central fraction from the distribution of material 1 (or component 1) we find a value of $0.230 \pm 0.001$ (derived from the R2 data points), which suggests a weakly magnetic material. For material 2 (or component 2) we get a central fraction of $0.110 \pm 0.003$, which suggests a significantly more magnetic material (uncertainties here are based on photon counting statistics only). Note that since these central fractions are derived from a direct analysis of data from two Pancam filters these conclusions are essentially independent of the two-component fitting procedure described above.

Based on the presence of magnetite on the Spirit Capture magnet we can tentatively identify the dark material number 2 as dust grains with a high content of magnetite and the brighter material number 1 as dust grains more dominated by hematite or some other bright, weakly magnetic, iron oxide. This is consistent with the picture developed in section 3.5.5 based on the difference in optical spectra between Filter and Capture magnets as well as on the Mössbauer and APXS data.

### 9.2. Consequences

From the data for the dust pattern observed on Opportunity’s capture magnet (figure 9-2) I calculated a central fraction of 0.23 for material number 1 and a central fraction of 0.11 for material number 2. I will now try to analyze these results in light of the expression for $CF(\kappa, v, \tau)$ derived in section 8.6:

$$CF(\kappa, v, \tau) \sim 0.2 \cdot \exp(-4500 \text{ kg/m}^3 \cdot \kappa) - 0.228 \cdot \exp(-0.904 \text{ s/m} \cdot v) + 0.134 \cdot \exp(-1.08 \text{ (ms)}^{-1} \cdot \tau) + 0.04$$

Clearly many different combinations of the three variables $\kappa, v$ and $\tau$ can give the observed central fractions, however all of the variables can be restricted to some degree based on data from other sources. I will therefore approach the problem by fixing the value of two of the variables based on previous data and investigating what can be derived about the third variable. In other words, I will treat two of the variables as input and calculate a value for the third variable as output based on the central fractions derived in section 9.1. I will here treat the wind speed and the dust grain characteristic times as input and derive values for the magnetic susceptibility, $\kappa$.

For the wind speed parameter 3 m/s can be regarded as a lower limit based on data from Viking showing wind speeds varying around 5 m/s (see section 2.4.2). We have seen (section 8.3.1) that dust deposition rises with rising wind speed, and the value we are really interested in is the mean wind speed weighted with the rate of dust deposition, which will be dominated by the higher wind speeds. Also the observed deposition on Capture magnets relative to filter magnets suggests wind speeds above 2 m/s (see section 8.3.1). Note that the difference in derived central fractions
from \( v = 3 \, \text{m/s} \) to \( v \to \infty \) is only 0.015, meaning that calculations on the basis of \( v = 3 \, \text{m/s} \) are roughly valid for \( v > 3 \, \text{m/s} \) as well.

As for the characteristic times: Taking dust grain diameters to be 3 microns[3], the standard case value of \( \tau = 0.61 \, \text{ms} \) results in a grain mass density of 1800 kg/m\(^3\), consistent with our expectations that the grains are aggregates of lower density than the bulk density. If the grains in the atmosphere have a wide distribution of sizes, the magnets will preferably capture the larger grains (see figures 8-7 and 8-8) giving a mean diameter greater than 3 microns for grains captured on the magnets. However, densities of grains could also be considerably lower than 1800 kg/m\(^3\) if the grains are loose aggregates of smaller particles. Characteristic times could therefore easily be anywhere in the range 0.1 ms – 2 ms. In the wind tunnel we have derived grain characteristic times of less than 0.2 ms (see sections 8.3.2 and 8.5.3), however these grains could well be smaller and/or less dense than Martian grains.

Taking \( v = 3 \, \text{m/s} \) and \( \tau = 0.61 \, \text{ms} \) I derive \( \kappa = 3.6 \times 10^{-5} \) for the weaker magnetic component 1 and \( \kappa = 2.2 \times 10^{-4} \) for the stronger magnetic component 2. Taking \( \gamma = 42.7 \, \text{mT} \) this is equivalent to \( \sigma_s = 1.2 \, \text{A} \cdot \text{m}^2/\text{kg} \) and \( \sigma_s = 7.6 \, \text{A} \cdot \text{m}^2/\text{kg} \) respectively. Given that the mean saturation magnetization of Martian dust has previously been estimated as 1-4 A\cdot m\(^2\)/kg these values are slightly high although not unreasonable as typical values from each extreme of a continuous distribution. If the magnetization derives from magnetite with a saturation magnetization of 92 A\cdot m\(^2\)/kg this translates to a 1.3 % magnetite content for material 1 and 8.3 % magnetite for material 2.

Based on the power law-relationship derived from figure 8-11 we estimate that grains with \( \kappa = 2.2 \times 10^{-4} \) will be captured roughly twice as efficiently as grains with \( \kappa = 3.6 \times 10^{-5} \). Thus, the distribution of grains in suspension will have a correspondingly greater proportion of the weaker magnetic material 1 relative to the distribution of grains on the magnet.

Assuming a higher characteristic time than 0.61 ms would cause us to derive lower magnetization values. A higher \( \tau \) could come about if the captured grains are larger than 3 microns in diameter. At \( v = 3 \, \text{m/s} \) and \( \tau = 2 \, \text{ms} \) we get \( \sigma_s = 0.13 \, \text{A} \cdot \text{m}^2/\text{kg} \) and \( \sigma_s = 3.28 \, \text{A} \cdot \text{m}^2/\text{kg} \). This corresponds to 0.14% and 3.6% magnetite content respectively.

Interestingly we can, if we continue to assume \( v = 3 \, \text{m/s} \), put a limit on the characteristic time of material 2 grains without assuming anything about their magnetic properties. These grains must have characteristic times of more than 0.4 ms or they will be too weakly affected by the magnetic force to reproduce the low central fraction observed. Whether this means that grains with high magnetite content tend to be bigger or denser than grains with less magnetite or whether it just means that most grains have characteristic times greater than 0.4 ms is not clear.

Certainly if the magnetite in the grains is undergoing slow oxidation to hematite or some other weakly magnetic mineral there are several ways to explain a correlation between grain characteristic time and grain magnetization. It could be that the oxidation process causes the grains to become less dense or even to break up into smaller grains. Smaller or less dense grains also have larger surface to volume ratios and so are more vulnerable to oxidation.

If, on the other hand, all grains are electrostatic aggregates that continually break up and reform while in suspension, as was suggested in chapter 6; then the process that determines grain size would presumably be largely independent of magnetite content and we would conclude that most grains have characteristic times larger than 0.4 ms.
Conclusion and Outlook

10.1. Parameters Controlling Dust Dynamics

Based on theoretical considerations I have proposed that the parameters controlling the process of magnetic dust capture can be summarized by three quantities. These are: The local aerodynamic environment, which for a given geometry and fixed kinematic viscosity is determined by the wind speed, $v$. The size, shape and mass density of dust grains as summarized by the characteristic time, $\tau$ and the magnetic properties of dust grains, which we have been expressing mainly by the magnetic susceptibility at low magnetic field, $\kappa$.

I have successfully developed a CFD model of the capture of magnetic dust grains on a magnet, and verified that the model agrees qualitatively and in most cases quantitatively with results obtained in wind tunnel experiments. I have thus developed a consistent picture of the dynamic behavior of the airborne magnetic dust grains and the effect of wind speed, dust grain characteristic times and dust grain magnetic properties on the capture process.

From this model it is a firm conclusion that dust deposition rates and patterns on magnets are determined not solely by the magnetic properties of the dust grains but by the aerodynamic environment and the size and mass density of dust grains as well. Drawing conclusions about the magnetic properties of the grains therefore requires consideration of these other parameters as well.

With regards to deposition rates on magnets it can be stated with confidence that the deposition rate increases with increasing wind speed; a conclusion from the CFD model, which was not obvious beforehand. The deposition rate increases with increasing characteristic times as well, since this means larger terminal velocities. Also the deposition rate increases with increasing magnetic susceptibility, which is unsurprising.

Absolute deposition rates can be hard to quantify experimentally, whether in the laboratory or on Mars. I have therefore also studied several relative quantities, which are easier to measure
experimentally. These quantities are the deposition on the filter magnet relative to the capture magnet and the deposition in the center of the capture magnet relative to the full deposition on this magnet (the central fraction). These two quantities have been used for comparisons between theoretical modeling, wind tunnel simulations and data from the MER mission.

It has been found for both these relative quantities that increasing wind speed has qualitatively the same effect as decreasing characteristic time or decreasing magnetic susceptibility. This may be understood by considering the patterns on the magnets as arising from the relationship between the speed of dust grains parallel to the magnet surface, which is determined by the wind speed; and the speed of dust grains towards the magnet, which is determined by the balance between drag and the magnetic force.

10.2. MER Data Analysis

By analyzing images of the MER capture and filter magnets in light of results from the CFD model it has been possible to put bounds on both wind speeds, grain characteristic times and grain magnetic properties at the MER landing sites. These conclusions rest on the assumption that results from the 2D numerical model are valid for the MER–magnets in their 3D environment on Mars. Even though the large scale environments are dissimilar, I expect the situation close to the magnetic surface to be similar in the two cases and expect the differences to cause at most a minor modification of the quantitative bounds derived.

For the wind speed it can be concluded from the relative deposition observed on the Capture versus the Filter magnets on Mars that most of the dust is deposited at wind speeds above 2 m/s. This does not preclude the possibility that there are quiet periods, during which dust deposition would be reduced, but it indicates that wind speeds are often above 2 m/s. This is consistent with expectations based on Viking wind speed data. I have not here studied wind speeds above 9 m/s, but I do not expect such studies to change these conclusions.

Analysis of dust patterns on the Capture magnets reveals that the dust grains are not all identical, but fall in a distribution with varying color. The darker grains are organized in a pattern with a low central fraction, while brighter reddish grains are organized in a pattern with a high central fraction. This color difference is also observed between the Capture and Filter magnets on both rovers, the dust on the Filter magnets being darker than the more reddish dust on the Capture magnets. Observations of magnetite in rocks and soil as well as the observation of magnetite on Spirits filter magnet suggest that this pattern variation can be explained by grains having a greater or smaller proportion of magnetite. The grains with high magnetite content would then be darker and more magnetic, hence the low central fraction of the pattern. Conversely grains with less magnetite would be brighter and less magnetic.

For the characteristic times it can be concluded from consideration of the central fraction that at least the more magnetic fraction of dust grains have characteristic times above 0.4 ms, in contrast to the situation in the wind tunnel, where we estimate \( \tau < 0.2 \) ms for all grains. Assuming the Martian dust grains to be spherical with a diameter of 3 microns \( \tau > 0.4 \) corresponds to a mass density of at least 1200 kg/m\(^3\). In wind tunnel experiments we have found several independent indications that the dust grains in the wind tunnel are in fact aggregates of smaller grains and have significantly lower mass density (\(< 1000\)kg/m\(^3\)) than the bulk mass density of the material. This is consistent with previous simulation experiments suggesting that the grains are electrically charged and form electrostatic aggregates while in suspension. Such a process might be operating on Mars as well. The characteristic time derived here for Martian dust could be consistent with
relatively dense aggregates, or with very loose aggregates if they are significantly larger than 3 microns in diameter.

Regarding the magnetic properties of Martian dust grains I derive saturation magnetizations of $\sigma_s = 0.13 - 1.2 \text{ A} \cdot \text{m}^2/\text{kg}$ for the less magnetic grains and $\sigma_s = 3.28 - 7.6 \text{ A} \cdot \text{m}^2/\text{kg}$ for the more magnetic grains. This means that the grains have a distribution of magnetizations with a minimum value that could be quite low and a maximum value of $3.3 - 7.6 \text{ A} \cdot \text{m}^2/\text{kg}$. Assuming the magnetization to derive exclusively from the presence of magnetite this gives a maximal magnetite content in the dust grains of $3.6 - 8.3\%$ by mass. These values are consistent with the previously derived mean saturation magnetization of $1-4 \text{ A} \cdot \text{m}^2/\text{kg}$ for the Martian dust.

10.3. Future Perspectives

Several possibilities for future work emerge from this study. Following the model presented here for the Capture and Filter magnets on the MER rovers, similar CFD modeling of the sweep magnet on MER as well as the magnet array on Mars Pathfinder would be of great value, providing an independent check on these results and possibly new constraints on the values of $v$, $\tau$ and $\kappa$. Specifically studying the sweep magnet by CFD should yield a lower bound on $\kappa$.

For future Mars missions permanent magnets may be designed that offer new ways of disentangling the three involved parameters $v$, $\tau$ and $\kappa$. This could take the form of magnets with different orientations relative to the gravity vector, analogous to the experiment presented in figure 8-7, or more directly it could involve combining permanent magnets with an instrument for measuring wind speed as well as dust grain sizes and concentration. Such instruments have been proposed[79, 80].

In conjunction with this, a capability for monitoring dust deposition dynamically (i.e. not just from images) would allow correlation of deposition rates with varying wind speeds, and would increase the precision of measurements of dust deposition rates as well as possible dust removal by high winds or the passage of dust devils. Such instrumentation has also been proposed [81].
Bibliography


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