Magnetic Properties Experiments on the Mars Exploration Rover Spirit at Gusev Crater

P. Bertelsen,[1]* W. Goetz,[1] M. B. Madsen,[1] K. M. Kinch,[2] S. F. Hviid,[3] J. M. Knudsen,[1] H. P. Gunnlaugsson,[2] J. Merrison,[2] P. Nørnberg,[4] S. W. Squyres,[5] J. F. Bell III,[5] K. E. Herkenhoff,[6] S. Gorevan,[7] A. S. Yen,[8] T. Myrick,[7] G. Klingelhöfer,[9] R. Rieder,[10] R. Gellert[10]

The magnetic properties experiments are designed to help identify the magnetic minerals in the dust and rocks on Mars—and to determine whether liquid water was involved in the formation and alteration of these magnetic minerals. Almost all of the dust particles suspended in the martian atmosphere must contain ferrimagnetic minerals (such as maghemite or magnetite) in an amount of ~2% by weight. The most magnetic fraction of the dust appears darker than the average dust. Magnetite was detected in the first two rocks ground by Spirit.

The history of liquid water on Mars may be reflected in the magnetic minerals present in the surface materials on Mars today: If liquid water is present in an oxidizing environment, Fe^{2+} ions in solution will oxidize to Fe^{3+}, and new minerals will form. In general, the magnetic minerals in the (<3-μm-diameter) atmospheric dust particles will provide information on the formation and alteration processes that have taken place globally on Mars. The Viking Landers (1976) and the Mars Pathfinder Lander (1997) carried permanent magnets (*1*–*3*) designed to investigate the magnetic properties of the martian soil (*4*) and the dust particles suspended in the atmosphere. The main conclusion of these investigations was that the martian soil and dust on average must contain about 2% by weight of a strongly magnetic (ferrimagnetic) mineral. This mineral could be maghemite (γ-Fe_2O_3, saturation magnetization $\sigma_s = 70$ A m^2 kg^{-1}), or magnetite (Fe_3O_4, $\sigma_s = 92$ A m^2 kg^{-1}). Each of the Mars Exploration Rovers carries seven permanent magnets (*5*). The Magnetic Properties Experiments (MPEs) on the rovers are designed to (i) identify the magnetic mineral(s) in the dust on Mars; (ii) establish if all airborne particles contain magnetic minerals; and (iii) provide qualitative information of the magnetism of a few selected rocks (*5*–*7*).

[1]Center for Planetary Science, Danish Space Research Institute and Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, DK-2100 Copenhagen, Denmark. [2]Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus, Denmark. [3]Max Planck Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany. [4]Department of Earth Sciences, University of Aarhus, DK-8000 Aarhus, Denmark. [5]Cornell University, Department of Astronomy, Ithaca, NY 14853, USA. [6]U.S. Geological Survey Branch of Astrogeology, Flagstaff, AZ 86001, USA. [7]Honeybee Robotics Ltd., New York, NY 10012, USA. [8]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. [9]Institut for Inorganic and Analytical Chemistry, Johannes Gutenberg-University, D-55099 Mainz, Germany. [10]Max-Planck-Institut für Chemie, D-55020 Mainz, Germany.

*To whom correspondence should be addressed. E-mail: preben@fys.ku.dk

Four small cylindrical magnets are integrated into the Rock Abrasion Tool (RAT) on the rover. The purpose of the RAT magnets is to detect magnetic minerals in the abraded rock material. The two strongest RAT magnets are identical (both named 1), and the maximum value of magnetic field and magnetic field gradient is $B = 0.28$ T and $\nabla|\mathbf{B}| = 350$ T m^{-1}. The remaining two magnets are weaker: $B = 0.10$ T and $\nabla|\mathbf{B}| = 120$ T m^{-1} for type 2, and $B = 0.07$ T and $\nabla|\mathbf{B}| = 80$ T m^{-1} for type 3, respectively. The weak magnets can only attract and hold particles that have a high magnetization.

Before operations of the RAT, the RAT magnets attracted reddish magnetic particles from the atmosphere, and the spectrum of the attracted dust from sol 30 (*8*) is similar to the spectrum of bright surface soil (Fig. 1). After brushing of the rock Adirondack (*9*), more dust is present on the RAT magnets, but the color is still reddish (the rock was covered with a thin layer of reddish dust). After grinding of the rock Humphrey, the dust attracted to the magnet is much darker and nearly black. The spectrum is consistent with the presence of magnetite and dark basaltic rock material. Because even the weak magnets have attracted a large amount of dark dust, we conclude that the rocks must contain at least a few percent of a dark ferrimagnetic mineral, probably magnetite. The result is corroborated by the Mössbauer spectra of the rocks Adirondack and Humphrey (*10*), which show the presence of magnetite.

The capture and filter magnets are placed at the front of the rover near the base of the Pancam mast. The two magnets attract atmospheric dust, which can be analyzed by the Pancam and by the instruments on the robotic arm (*7*). An image of the capture magnet acquired with the Microscopic Imager shows the dust pattern in detail (*11*). Both magnets (Sm_2Co_{17}) have a diameter of 25 mm and are embedded in an aluminum structure with a

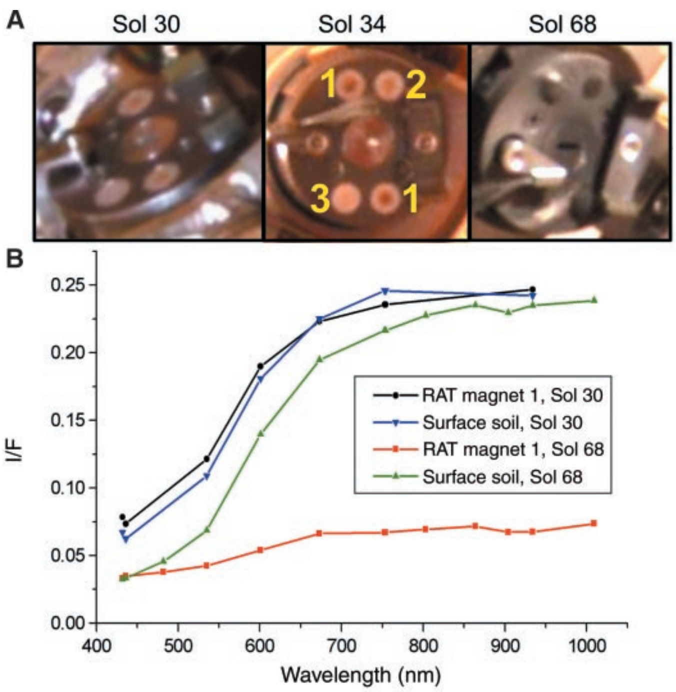


Fig. 1. The RAT magnets. (**A**) Pancam images from sol 30 (before any RAT operations), sol 34 (after brushing the rock Adirondack), and sol 68 (after grinding the rock Humphrey). The location of the individual magnets (type 1, 2, and 3) is shown with numbers. (**B**) Spectra of bright surface soil and dust on RAT Magnet 1 from sol 30 and sol 68. The ordinate is the calibrated reflectance.

diameter of 45 mm (*5*). The capture magnet (Fig. 2A, top) is very strong, with maximum values of the magnetic field and field gradient of $B = 0.46$ T and $\nabla|\mathbf{B}| = 550$ T m^{-1}. The filter magnet (Fig. 2A, bottom) is weaker: $B = 0.2$ T and $\nabla|\mathbf{B}| = 34$ T m^{-1}. The capture magnet is strong enough to attract and hold all paramagnetic and ferrimagnetic particles. The filter magnet, however, will (almost) only attract particles with a high value of magnetic susceptibility ($\chi > 10^{-4}$). Therefore, the dust particles in the atmosphere will be "filtered" according to their magnetic properties.

The amount of dust on the capture magnet is higher than the amount of dust on the filter magnet (Fig. 2A) by a factor of ~2 (a rough estimate based on the absorption at 440 nm early in the mission). This observation supports the view that the airborne particles have a saturation magnetization of about $\sigma_s \sim 2$ A m^2 kg^{-1} (*5*). Furthermore, small differences are observed in the visible–near infrared spectrum of the area where dust has accumulated on each magnet (Fig. 2B). The filter magnet is not yet optically saturated with dust, so the reflectivity at 440 nm is relatively high. At wavelengths above 750 nm, the dust accumulating on the filter magnet has lower reflectance than the aluminum surface, whereas the opposite is true for the material accumulating on the capture magnet. This shows that the dust on the filter magnet is intrinsically darker than the dust on the capture magnet. The darker particles thus have higher magnetization.

The sweep magnet is on the solar panels close to the Pancam calibration target (*5*, *7*), where it attracts dust from the atmosphere. It is a ring magnet (Sm_2Co_{17}) with an outer diameter of 9.0 mm, embedded in an aluminum structure. The maximum value of the magnetic field and field gradient at the surface of the magnet is $B = 0.42$ T and $\nabla|\mathbf{B}| = 450$ T m^{-1}. The size and direction of the magnetic field and field gradient prevent particles with magnetic susceptibility larger than 10^{-6} m^3 kg^{-1} from settling in the circular area inside the ring, called the sweep area (*5*). The sweep magnet is visible in many images of the Pancam calibration target acquired daily during the mission (Fig. 3A). The sweep magnet ring was optically saturated with red dust around sol 25 (at 440 nm). The dust on the ring shows an absorption spectrum (Fig. 3B) similar to the spectrum of the reddish bright soil on Mars (*12–15*). The main absorption features are due to the charge transfer band in an Fe^{3+} compound. The lack of structure in the spectrum supports the view that the martian dust and soil are magnetic composites of multiple phases.

Outside the magnet, no magnetic force is present, and this surface will collect an amount of dust corresponding to the general sedimentation taking place everywhere. The spectrum of the area outside the magnet (Fig. 3B) shows an amount of reddening that is consistent with the reddening observed on the Pancam calibration target (*12*). The third spectrum—of the circular area inside the ring—is similar to the spectrum of a clean aluminum surface of the magnet. No (discernible) dust has settled in the sweep area. Indeed, this little region may be the "cleanest" part of the entire rover deck. Therefore, all airborne dust particles must be sufficiently magnetic that their paths near the magnet be controlled by the magnetic force. We note that a specially designed magnet like this could be used to keep (small) calibration targets clean in future missions.

Although we cannot yet determine which mineral is causing the magnetism of the dust particles, we can assess whether the magnetism of the suspended particles could be caused by hematite (α-Fe_2O_3) alone. Hematite is a canted antiferromagnet above 260 K ($\sigma_s = 0.4$ A m^2 kg^{-1}), and is antiferromagnetic below 260 K. On the basis of alpha particle x-ray spectroscopy (APXS) elemental analysis of the dust, the maximum possible content of α-Fe_2O_3 in a given particle is about 18% by weight (*16*). Mössbauer spectroscopy of soil at the Columbia Memorial Station site shows that less than half of the iron is present as iron oxides (*10*). A substantial part of the iron in the soil is located in paramagnetic silicates, mostly olivine [$(Mg,Fe)_2SiO_4$]. Even if all the iron were present in hematite, the bulk magnetization would still be less than 0.08 A m^2 kg^{-1}, and particles with such a low magnetization would not stick to the filter magnet in the amount shown on Fig. 2B. We therefore infer that hematite cannot be the dominant source of the magnetism present in the airborne particles.

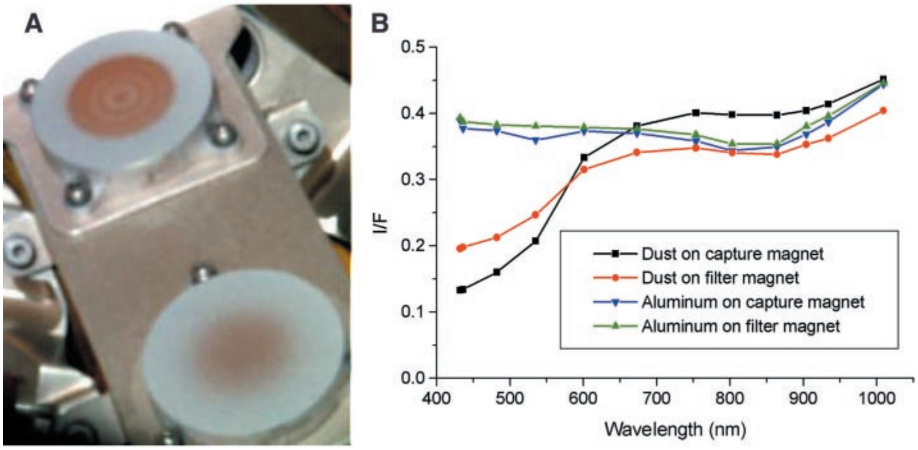
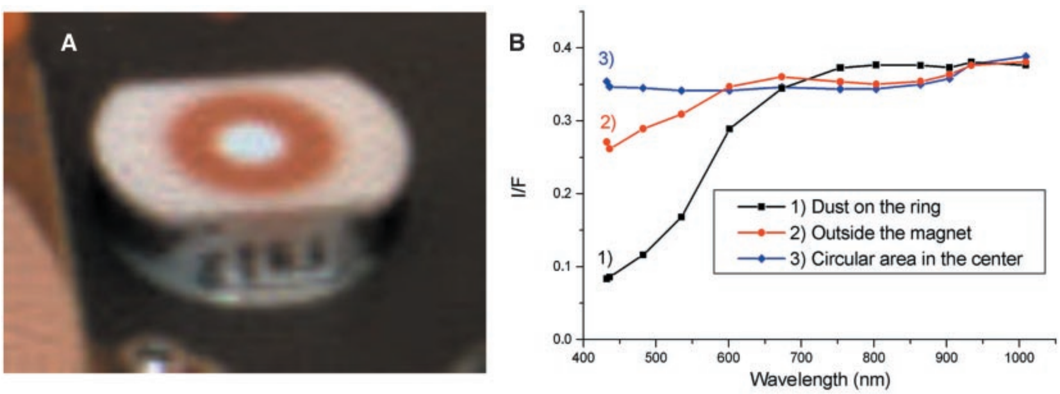


Fig. 2. The capture and filter magnets. (**A**) Pancam image recorded on sol 71. (**B**) Spectra of the area where dust has accumulated on the two magnets, and of the aluminum surface. The ordinate is the calibrated reflectance.

Fig. 3. The sweep magnet. (**A**) Pancam image recorded on sol 73. (**B**) Spectra from three areas: 1, the dust on the ring; 2, the dust outside the ring; and 3, the dust inside the ring. The ordinate is the calibrated reflectance.



Furthermore, Mössbauer spectra of soils at the Spirit site show the presence of magnetite (*10*). A small fraction of magnetite in the dust particles could easily explain the strong magnetization of the dust and the dust on the filter magnet being darker than that on the capture magnet.

APXS measurements and Mössbauer measurements of the dust on the filter and capture magnets will take place later in the mission in order to uniquely identify the ferrimagnetic phase in the composite particles (*5*).

References and Notes

1. R. B. Hargraves, D. W. Collinson, R. E. Arvidson, C. R. Spitzer, *J. Geophys. Res.* **82**, 4547 (1977).
2. P. H. Smith *et al.*, *J. Geophys. Res.* **102**, 4003 (1997).
3. M. B. Madsen *et al.*, *J. Geophys. Res.* **104**, 8761 (1999).
4. The term "martian soil" is used here to denote any loose, unconsolidated materials that can be distinguished from rocks, bedrock, or strongly cohesive sediments. No implication of the presence or absence of organic materials or living matter is intended.
5. M. B. Madsen *et al.*, *J. Geophys. Res.* **108**, 8069 (2003).
6. S. Gorevan *et al.*, *J. Geophys. Res.* **108**, 8068 (2003).
7. S. W. Squyres *et al.*, *J. Geophys. Res.* **108**, 8062 (2003).
8. A sol is a martian day. Sol 1 is the day of landing. A martian solar day has a mean period of 24 hours 39 min 35.244 s and is referred to as a sol to distinguish it from a roughly 3% shorter solar day on Earth. A martian sidereal day, as measured with respect to the fixed stars, is 24 hours 37 min 22.663 s, as compared with 23 hours 56 min 04.0905 s for Earth. See www.giss.nasa.gov/tools/mars24/ for more information.
9. Names have been assigned to areographic features by the Mars Exploration Rover (MER) team for planning and operations purposes. The names are not formally recognized by the International Astronomical Union.
10. R. V. Morris *et al.*, *Science* **305**, 833 (2004).
11. K. E. Herkenhoff *et al.*, *Science* **305**, 824 (2004).
12. J. F. Bell III *et al.*, *Science* **305**, 800 (2004).
13. J. F. Bell III, T. B. McCord, P. D. Owensby, *J. Geophys. Res.* **95**, 14447 (1990).
14. R. V. Morris *et al.*, *J. Geophys. Res.* **94**, 2760 (1989).
15. R. V. Morris, D. C. Golden, J. F. Bell III, H. V. Lauer Jr., J. B. Adams, *Geochim. Cosmochim. Acta* **57**, 4597 (1993).
16. R. Rieder *et al.*, *Science* **278**, 1771 (1997).

17. We are grateful for help from the skillful and dedicated Pancam team, particularly M. J. Johnson, J. Proton, H. M. Arneson, and E. McCartney. The "rover drivers" C. Leger, S. Maxwell, and E. Baumgartner made invaluable contributions to imaging of the RAT magnets. We also thank DELTA Danish Electronics, Light & Acoustics, who performed vibration testing and qualification certification of our flight instruments at no cost to the project, and the Danish Science Research Agency and the Thomas B. Thrige Foundation for the financial support that made our participation possible. We thank our colleagues at our own laboratory, particularly at the workshop, for their undivided dedication to this project.

10 May 2004; accepted 7 July 2004

REPORT

Chemistry of Rocks and Soils in Gusev Crater from the Alpha Particle X-ray Spectrometer

R. Gellert,[1,2]* R. Rieder,[1] R. C. Anderson,[3] J. Brückner,[1] B. C. Clark,[4] G. Dreibus,[1] T. Economou,[5] G. Klingelhöfer,[2] G. W. Lugmair,[1] D. W. Ming,[6] S. W. Squyres,[7] C. d'Uston,[8] H. Wänke,[1] A. Yen,[3] J. Zipfel[1]

The alpha particle x-ray spectrometer on the Spirit rover determined major and minor elements of soils and rocks in Gusev crater in order to unravel the crustal evolution of planet Mars. The composition of soils is similar to those at previous landing sites, as a result of global mixing and distribution by dust storms. Rocks (fresh surfaces exposed by the rock abrasion tool) resemble volcanic rocks of primitive basaltic composition with low intrinsic potassium contents. High abundance of bromine (up to 170 parts per million) in rocks may indicate the alteration of surfaces formed during a past period of aqueous activity in Gusev crater.

The alpha particle x-ray spectrometer (APXS) on the Spirit rover is an improved version of the APXS on the Sojourner rover that measured compositions of soils (*1*) and rocks during the 1997 Mars Pathfinder mission (*2*). A description of the instrument, the methodology, and an outline of the calibration procedure can be found in (*3*). Despite increased background count rate, because of the radioactive sources of the nearby Mössbauer spectrometer (MB) (*4*) and cosmic radiation, the increased sensitivity of this instrument relative to the Pathfinder APXS allowed us to determine the abundances of trace elements such as Ni, Zn, and Br, in addition to the major and minor rock-forming elements (Fig. 1) of circular spots 2.5 cm in diameter.

The internal control software of the APXS automatically splits the measuring time into several intervals. Repeatability and statistical significance, especially for the trace elements, was evaluated using these individual spectra. Data reduction was performed with a least-squares-fit routine developed during calibration. The in-

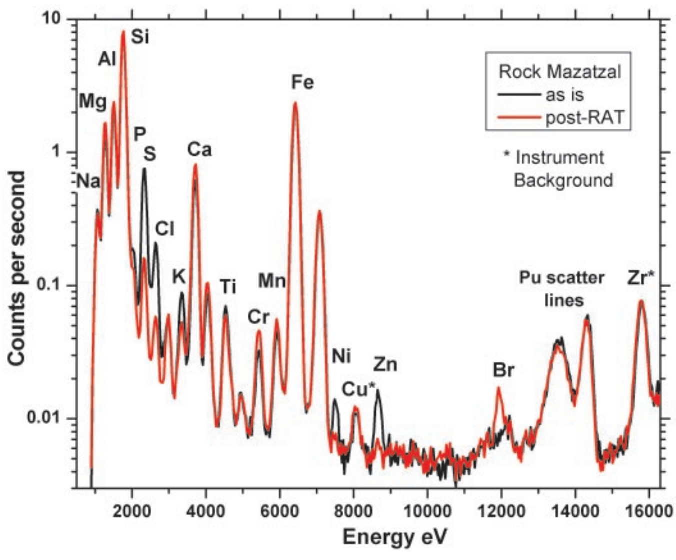


Fig. 1. X-ray spectra of rock Mazatzal before and after abrading with the RAT.

[1]Max-Planck-Institut für Chemie, J. J. Becher-Weg 27, D-55128 Mainz, Germany. [2]Institut für Anorganische und Analytische Chemie, J. Gutenberg-Universität, D-55128 Mainz, Germany. [3]Jet Propulsion Laboratory, Pasadena, CA 911091, USA. [4]Lockheed Martin Corporation, Littleton, CO 80127, USA. [5]Laboratory for Atmospheric and Space Research, Enrico Fermi Institute, Chicago, IL 60637, USA. [6]Johnson Space Center, National Aeronautics and Space Administration (NASA), Houston, TX 77058, USA. [7]Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853, USA. [8]Centre d'Etude Spatiale des Rayonnements, F-31028, Toulouse, France.

*To whom correspondence should be addressed. E-mail: gellert@mpch-mainz.mpg.de.