MARS EXPLORATION ROVER MISSION: AN INTRODUCTION TO THE ROVER PAYLOADS AND AN OVERVIEW OF THE RESULTS OBTAINED AT GUVER CRATER, MARS[1]

Paulo Antônio de Souza Júnior [2]
and The Athena Science Team

Abstract

Spirit landed on the floor of Gusev Crater and conducted some operations on soil covered, rock-strewn cratered plains underlain mainly by olivine-bearing basalts. Plains surface rocks are covered by wind-blown dust and show evidence for surface enrichment of soluble species as vein and void-filling materials and coatings. The surface enrichment is the result of a minor amount of transport and deposition by aqueous processes. Layered granular deposits were discovered in the Columbia Hills, with outcrops that tend to dip conformably with the topography. The granular rocks are interpreted to be volcanic ash and/or impact ejecta deposits that have been modified by aqueous fluids during and/or after emplacement. Soils consist of basaltic deposits that are weakly cohesive, relatively poorly sorted, and covered by a veneer of wind blown dust. The soils have been homogenized by wind transport over at least the several kilometer length scale traversed by the rover. Mobilization of soluble species has occurred within at least two soil deposits examined. The presence of mono-layers of coarse sand on wind-blown bedforms, together with even spacing of granule-sized surface clasts, suggest that some of the soil surfaces encountered by Spirit have not been modified by wind for some time. On the other hand, dust deposits on the surface and rover deck have changed during the course of the mission. Detection of dust devils, monitoring of the dust opacity and lower boundary layer, and coordinated experiments with orbiters provided new insights into atmosphere-surface dynamics.

Key words: Rovers, Mars, Mineralogy.

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[2] *Departamento Gertão Ambiental e Territorial, Companhia Vale do Rio Doce, 20030-900, Rio de Janeiro, R.J.*

INTRODUCTION

The rover *Spirit* (MER-A) landed within the ~ 160 km diameter of the Gusev Crater (14.5692’S, 175.4729’E) on 3 January 2004. *Spirit* landed in a flat plain in Gusev Crater with local undulations at meters scale. Some hills reach ~ 150 m elevation to the east of the landing site (LS). Numerous small depressions are visible from LS referred as ”Columbia Memorial Station” (CMS, Figure 2).(1) Floors are partially filled with finer-grained, high albedo material. (2)

Figure 1. Boing - Delta II rocket carring on Spirit rover in a seven months flight to Mars.

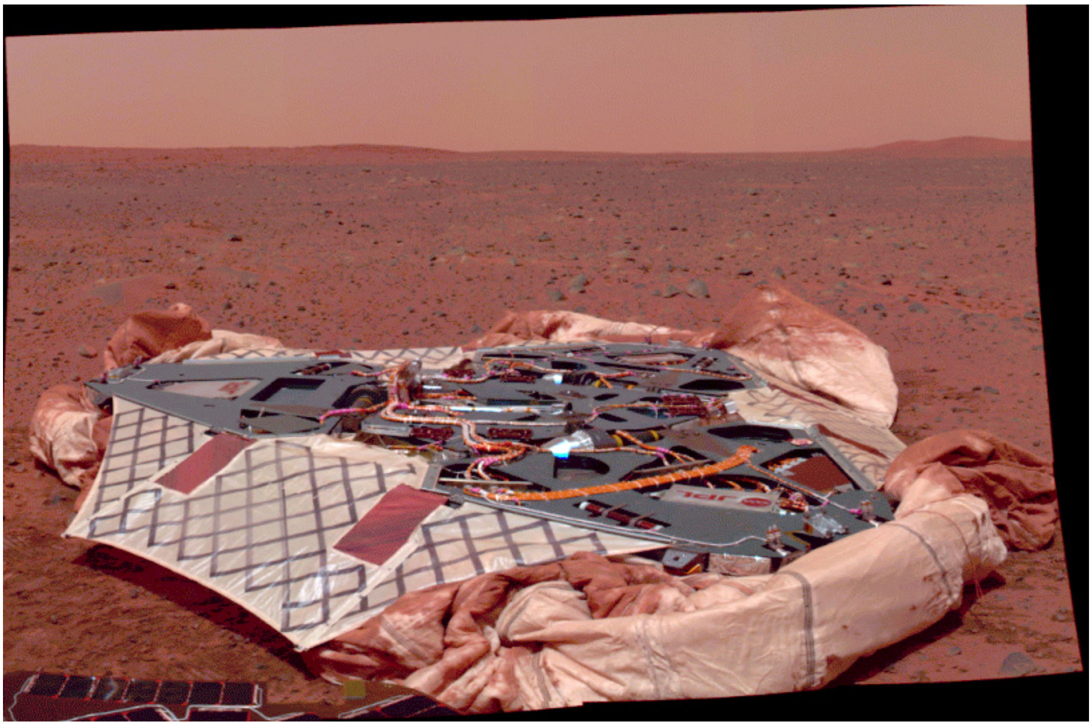

Figure 2. Pancam image of the Columbia Memorial Station, landing site for Spirit at Gusev Crater, Mars (14.5692’ S, 175,4729’E).

The floor of the plain consists of notably smaller rocks than in the three previous landing sites of Viking landers 1 and 2, and Pathfinder. The shape of the rocks at the CMS range from rounded to angular. The first soil observation yields results showing resistance to deformation by applied forces associated with deployment of the IDD and the rover wheels. Other soils, particularly beneath and around rocks like

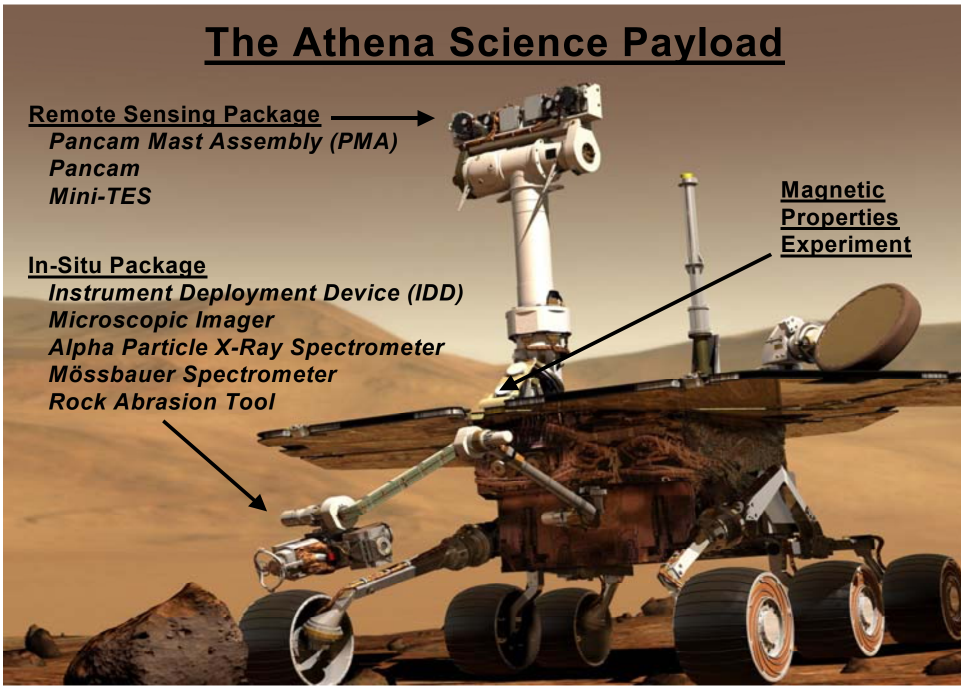

Figure 3. The Athena Science Payload.

Table 1. Engineering Camera Descriptions and Athena payloads.

Instrument	Key Parameters
Mast-	
Pancam: Panoramic Camera	Twelve bands (0.4 to 1.0 μm) for stereoscopic imaging with 0.28 mrad IFOV; 16.8 deg by 16.8 deg FOV. Stereobaseline separation of 30 cm. External calibration target on rover deck.
Mini-TES: Thermal Emission Spectrometer	Emission spectra (5 to 29 μm, 10 cm-1 resolution) with 8 or 20 mrad FOV. Internal and external blackbody calibration targets.
IDD-for *In-Situ* Experiments	
APXS: Alpha Particle X-Ray Spectrometer	^{244}Cm alpha particle sources, and x-ray detectors, 3.8 cm FOV.
MB: Mössbauer Spectrometer	^{57}Fe spectrometer in backscatter mode; Co/Rh source and Si-PIN diode detectors; field of view approximately 1.5 cm^2.
MI: Microscopic Imager	30 μm/pixel monochromatic imager (1024x1024) with 6mm depth of field.
RAT: Rock Abrasion Tool	Tool capable of preparing 5 mm deep by 4.5 cm wide surface on rocks.
Magnets for dust sampling	
Filter	Located front of rover within Pancam FOV. Weak magnet to cull suspended particles from atmosphere and examined by MI, APXS, MB.
Capture	Located front of rover within Pancam FOV next to filter magnet. Strong magnet to cull suspended particles from atmosphere.
Sweep	Located next to Pancam calibration target. Intended to separate magnetic from non-magnetic particles. To be examined by Pancam.
RAT	Four magnets of different strengths in RAT. To be examined by Pancam when IDD points RAT toward cameras.
Engineering Cameras	
Navigation Cameras (Navcam)	Mast-mounted panchromatic stereoscopic imaging system with 0.77 mrad IFOV; 45 deg FOV, and 20 cm stereobaseline separation. For planning sequences.
Hazard Avoidance Cameras (Hazcam)	Front and rear-looking panchromatic stereoscopic imaging systems with 2 mrad IFOV; 123 deg FOV, 10 cm stereobaseline separation. For path planning and hazard avoidance during traverses.

Adirondack rock, for example, are darker, have a pebbly appearance, and also appear cemented. There are evidences for aeolian action at CMS such as high albedo wind tails behind rocks. Variable dust covering likely accounts for the appearance of lighter rocks and all observed so far are propositionally consistent with olivine basalts.(3)

MARS MINERALOGY

The mineralogy of the surface materials on Mars has been directly measured in situ by NASA rovers.(4) The mission goals are to determine the aqueous, climatic, and geologic history of sites on Mars where conditions may have been favorable for the preservation of evidence of possible biotic processes. Martian lithosphere has been investigated by spacecraft accessing its age, structure, chemical composition, and petrogenesis.(3)

Before this mission, by the use of various indirect approaches, including chemical correspondence to the surface analysis, spectral analogies, simulation of Viking lander experiments, some predictions on mineralogy were made. The direct analysis of the soil of Mars surface were performed by Viking landers (1 in Chryse Planetia - 13 samples; and 2 in Utopia Planetia: 8 samples). The sum of oxides is considerably less than 100% (table 6.5). Several reasons for this difference can be stated: light elements ($Z < 12$) could not be detected and therefore, absorbed water, some hydroxides, carbonates, and nitrate minerals; certain elements such as Na, P, and Mn could not be detected because of interferences from major Mg, Cl, and Fe peaks in the X-ray fluorescence spectra; grain size and mineral heterogeneities cause lower-than-expected peak heights for major elements because of weathering rings or coating of large grains by smaller ones (3, and references therein).

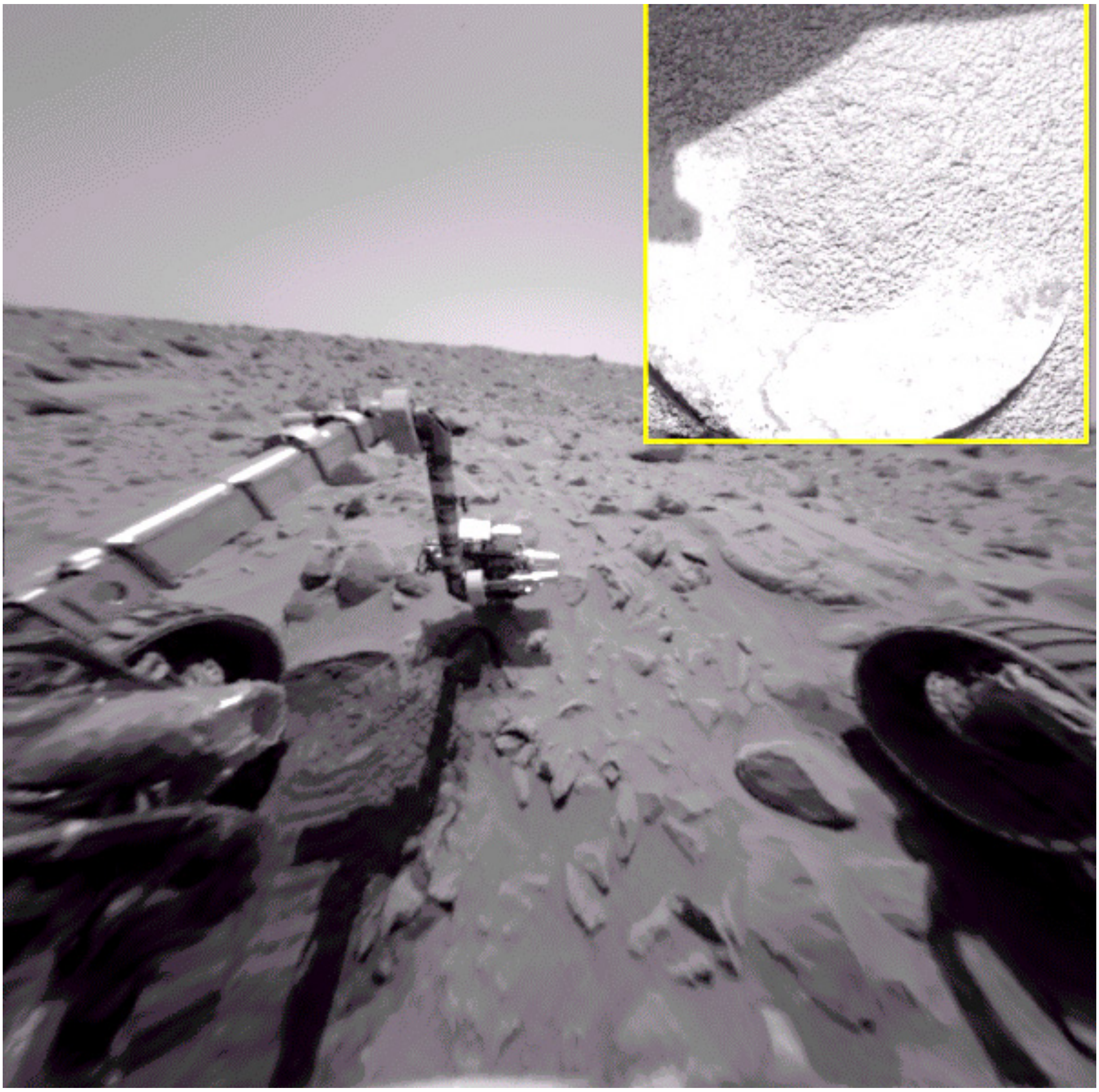

Figure 4. Front HazCam image recording the IDD placement in a soil spot on Sugar Loaf flats. A microscope image of the MIMOS II nose print is presented in detail.$^{(5)}$

The very high iron content coupled with low levels of expected trace elements and low K/Ca ratio pointed to a *mafic or ultramafic* source material. The sulfur concentration is two orders of magnitude higher than typical igneous rock. Viking and Pathfinder missions could not collect lithic fragments that would not contain S and Cl. It was suggested that the S and Cl content result from the addition of these elements as volcanic gases. Correcting the Viking fluorescence data in this manner produces a much different igneous composition, which closely matches the Shergotty meteorite, as first pointed out by many authors (3,6, and references therein).

In addition to chemical results obtained by Martian landers, studies on Martian meteorites are also important. Nevertheless, the question of what is Martian and what is terrestrial contamination in SNC meteorites is still not resolved. A compilation of candidates of minerals proposed by studies based on chemical correspondence with the elemental analysis of the soil, the remote sensing of spectral observations on Mars, simulations of Viking biology and other Viking lander experiments, Pathfinder, *Spirit* and *Opportunity* results, and various thermodynamic modeling efforts were and still being reported by many authors. The presence of clays on Mars is quite controversial. Smectites were considered by some authors (e.g., (3)); nontroniteswere assumed to be part of Martian mineralogy. Beidelite was suggested also as a Martian surface mineral.(3) Iron oxides were proposed as an important Martian mineral phase,(7) both amorphous and cryptocrystalline (08, and references therin). Silicates were suggested.(3) Sulfates, calcium rich sulfates, and sulfates of sodium or magnesium were also proposed. Jarosite was suggested by Burns (Bur 86). Sulfide such as pentlandite ($(Fe;Ni)_9S_8$), pyrite (FeS_2), and pyrrhotite ($Fe_{1-x}S$) were reported (e.g., (3) and references therein). Carbonates were also considered.

Weathering processes can be traced and inferred from the characterization of mineral phases. The physical and chemical weathering have been an important subject of Mars investigation. Physical weathering processes include frost riving, temperature cycles and wind abrasion (dust and ice projectiles). The chemical weathering process, on the other hand, includes oxidation (uptake of oxygen to form oxides or more highly oxidized silicates), hydration (uptake of water to form minerals with structural $OH¡$ or H_2O), carbonation (uptake of CO_2 to form carbonate minerals), and solution (dissolving of minerals in water).

Soil,(9) rock alteration by water(10) and martian dust compostion(11) investigated by Spirit payload instruments were detailed reported.

AUTOMATION IN DATA ANALYSIS

The spectral analysis (e.g., of a Mössbauer spectrum) can be time-consuming and may be subject of a specialist. In the usual analysis procedure the ASCII spectrum file (raw data) is tested against a fitting hypothesis. This hypothesis holds a given set of sub-spectral lines (for ^{57}Fe Mössbauer spectroscopy; singlets, doublets and sextets). Each sub-spectrum can be represented by a given set of parameters (e.g., peak position, full width at half maximum (FWHM), peak area) that can be iteratively improved by a least-squares fitting routine. Depending on the obtained results, a new hypothesis has to be considered. In this case, the initial fitting hypothesis (e.g., number and position of combined basic lines) has to be rebuilt; and the whole process is repeated. The obtained refined parameters should be compared with standard published parameters or with a standard sample. In mineralogy, frequently other technical data are used to support a given hypothesis. It should also be considered that, in a particular case, the published information could be a result of misinterpretation. This may be a problem for the mineral identification.

Literature, data base or standard samples should be and are generally used for comparison and identification purposes. In some cases, there are mineral phases with the same Mössbauer parameters at a given temperature (e.g., for room temperature Mössbauer measurement: akagan´eite β-*FeOOH* and lepidocrocite γ-*FeOOH*). In this situation, new measurements (e.g., different sample temperature) are required. This experimental setup produces differences in the Mössbauer spectrum of the studied sample making possible its correct identification. In some cases, data from other analytical techniques are required.

Since the fitting and the identification processes are time and effort consuming, and considering the large number of iron-bearing minerals already studied by Mössbauer spectroscopy, a complete suite for data analysis was implemented using genetic algorithms, fuzzy logic, and artificial neural networks. The sequence of this chapter describes general aspects of these automatic systems. The detailed implementation, application and results are discussed through the rest of the text. The use of artificial intelligence make possible the use of Mössbauer spectroscopy by non-specialists or in problems where the data analysis has to be done quickly; like in industry and in daily real-time surface operations of a mission to Mars. In the first case, the industry needs a fast analysis for their production process control. A mission like Mars Exploration Rover has a daily interaction with their payloads and need quick data analysis. The planning of a next sol activity is done in a few hours and the decision about the activity rover agenda considers the analysis of the data obtained in the ”yestersol”. The entire analysis has to be done as fast as possible.

These optimization processes, both the least-squares and testing fitting hypotheses using some well-known expert systems are discussed in detail.(3) The implementation of data analysis systems based on these techniques was helpful for the proposed outdoor terrestrial and extraterrestrial applications.

The exploration of the planet Mars is one of the major goals within the Solar system exploration programs of the US-American space agency NASA and the European Space Agency ESA. In particular the search for water and life and understanding of the history of the surface and atmosphere will be the major tasks of the upcoming space missions to Mars. The miniaturized Mössbauer spectrometer MIMOS II(1) has been selected for the NASA Mars-Exploration-Rover Twin-mission to Mars in 2003 and the ESA 2003 Mars-Express Beagle 2 mission. It was developed in Germany by Dr. Klingelhöfer research group in Mainz. Reduced in size and weight, in comparison to ordinary laboratory setup, the sensorhead just weights approximately 400g, with a volume of (50x50x90) mm^3, and holds two gamma-ray sources: the stronger for experiments and the weaker for calibrations. The collimator (in sample direction) also shields the primary radiation off the detectors. Around the drive four detectors are mounted. The detectors are made of Si-PIN-photodiodes in chip form (100 mm^2, thickness of 0.5 mm). The control unit is located in a separate electronics board. This board is responsible for the power supply, generation of the drive’s velocity reference signal, read of the detector pulses to record the spectrum, data storage and communication with the host computer (3, and references therin).

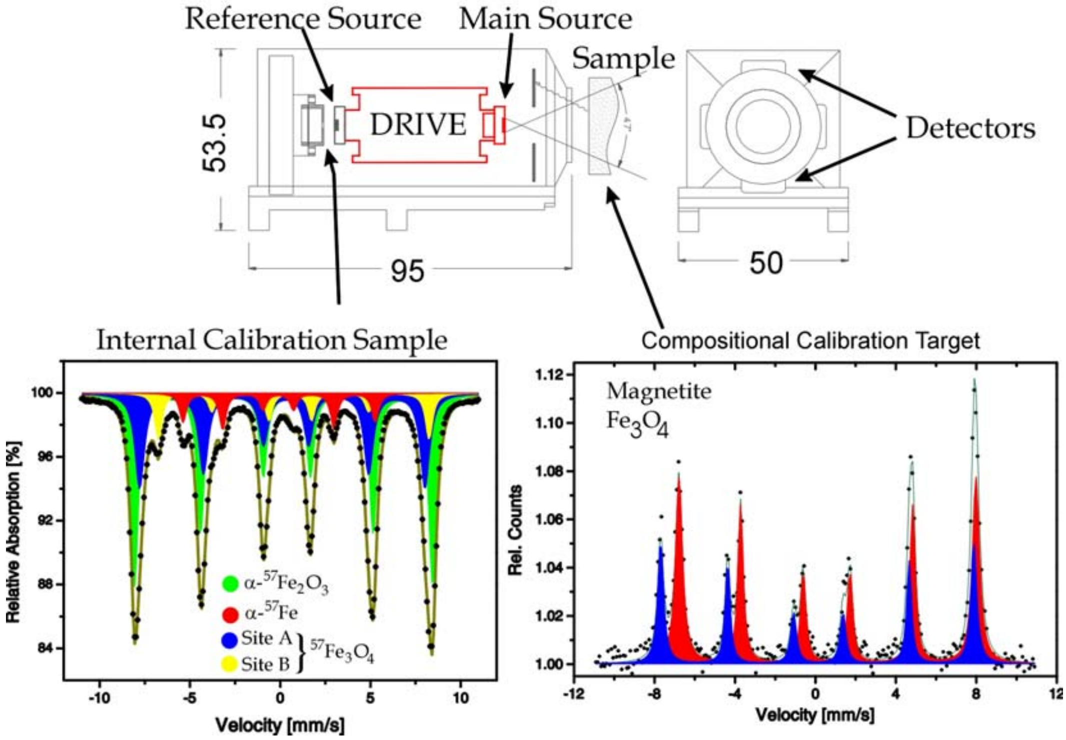

Figure 5. Drawing of the MIMOS II and a spectrum from the Compositional Calibration Target (CCT, magnetite) for the Mössbauer spectrometer on board of the Mars Exploration Rovers (MER) and a spectrum obtained in transmission geometry from an internal calibration sample placed inside the instrument.(3)

After more than four decades from the discovery of the Mössbauer effect, more than 400 minerals were studied at different temperatures. Their Mössbauer parameters were reported in the literature, and have been recently collected in a data bank.(3) Previous Mars-missions, namely Viking and Mars Pathfinder revealed Si, Al, Fe, Mg, Ca, K, Ti, S and Cl to be the major constituents in soil and rock elemental composition of the red planet. More than 200 minerals already studied by Mössbauer spectroscopy contain significant amounts of these elements. A considerable number of Mössbauer studies were also carried out on meteorites and on Moon samples. Looking backward in the studies of the whole Mössbauer community, we have build a specific library containing Mössbauer parameters of those possible Mars minerals. The selected minerals, their Mössbauer parameter values (min. max. s.d and number of available data), main site.substitution, behaviour as a function of temperature and a ranking as expected to be found on Mars were organized. Mars-analogue Fe-bearing minerals not studied by Mössbauer spectroscopy are being collected and investigated. In addition, it was implemented an identification system based on Artificial Neural Networks which is able to make a fast and precise mineral identification from the experimental Mössbauer parameters at a given temperature.(3)

Processing the Information

Minor differences on Mössbauer parameters can seen be a result of all the properties described above and, also, imprecision, misinterpretation of the Mössbauer spectra(3) or even mistyping on papers. Despite of these small disadvantage, still all information useful. An implemented software based on artificial neural networks is robust to minor differences and can, without any additional information, identify Mössbauer phases from its parameters. From a proper learning process, the ANN extract all relevant information from a given set of data (published Mössbauer parameters) forgetting most of the deviations coming from misinterpretations, imprecision and mistyping on reports.

Data Base. A Mössbauer data base was compiled from published Mössbauer parameters on minerals, at different temperatures. All minerals containing the elements found on previous Mars missions were selected. Since temperature on Mars varies from - 100°C to 10°C, only room and liquid nitrogen temperature were selected. Literature on the selected Mars-analogue minerals were investigated considering the following aspects:

Chemical Formula and Mineral Identification. The chemical formula is given for each selected mineral. Those minerals were classified according to the standard mineralogical pattern, as: a) oxides and (oxy)hydroxides; b) Fe-S-bearing minerals; c) phosphates; d) carbonates; e) rich-Mn minerals; f) silicates (nesosilicates, sorosilicates, cyclosilicates, inosilicates, phyllosilicates, tektosilicates); and g) minerals not studied by Mössbauer spectroscopy.

Statistical analysis on the recorded Mössbauer data. The average value, the standard deviation, the minimum and maximum values of a given site were calculated.

Behaviour as funtion of temperature and grain size. The studied mineral may suffer magnetic transitions as a function of temperature and grain sizes. Also, the Mössbauer parameters of isomer shift, quadrupole splitting and internal magnetic field may change as function of temperature or, including the line width, its crystallinity.

Changes as a function of site substitution (e.g. α-$Fe_{2-x}Al_xO_3$) and vacancies. There are rich literature describing the effects of isomorphic substitution of cations in iron sites. This substitutions lead to changes in the Mössbauer parameters well defined at the literature.

Genesis. The Mössbauer spectrum of a given mineral may change according to the formation process. This situation, when pertinent, is reported and described on the basis of previous studies (e.g. 5, 6).

Other Fe-bearing phases usually reported join the considered mineral. Smectites (e.g. montorilonite and notronite) are usually found together with hematite and/or goethite). The weathering process of palagonites leads to Fe-rich smectite phases and oxyhydroxide and ferric oxide. This may be a supporting information during the analysis process of a Mössbauer spectrum.

Final Remarks. Some minerals were reported at the literature with a single site up to, for example, four. This difference may be a result of differences among the analyzed samples, analysis method, spectrum statistics, etc. When such situation is detected, a specific note is registered at this mineral records. Finally, color, common impurities, other iron-free mineral phase reported, as so on. This information may be useful, specially considering the cameras and other scientific instruments carried out by the Mars landers.

Tentative Ranking. Previous lander and orbiter missions to Mars obtained relevant information on the mineralogy of the neighbor planet. Each mineral is being assign to a rank according to the available information on the its possibility to be found on Mars (e.g based on SCN meteorites, previous Mars landers and orbiters data and Martian analogue sample studies). Additional minerals, not found as studied by Mössbauer spectroscopy, are being collected and studied from room temperature down to –100°C. Up to now, over 2,600 references are stored and classified according to the criteria described above. Is the intention of the authors to make available the whole data set and programs by the end of the Mars missions.

Fast Mineral Identifcation

A hybrid artificial neural network,(2,3) associated with the data base, was implemented. The program, written in C++ language, consists in a *learning vector quantization* (LVQ) network. Specific trainings were performed using Mössbauer parameters at room and at liquid nitrogen temperature. The neural identification is robust to minor changes at the reported parameters. This capability comes from its ability to see through noise. After the adequate training, the ANN could successfully and quickly identify the studied Fe-bearing mineral from its Mössbauer parameters.(12)

CONCLUSIONS

A very specific Mössbauer data base were build taking into consideration the needs of the Mars Missions. The information published at the literature were carefully analyzed. The most relevant variables that may lead to changes of the Mössbauer parameters of each mineral were reported in the data base records. The stored Mössbauer parameters were used to train an artificial neural network making possible a fast and save mineral identification from its measured Mössbauer parameters. Before the first Mössbauer spectrum being obtained on Mars surface, early in 2004, several and exhaustive tests are planed to be carried out. Very detailed calibration and data validation is an important upcoming issue in the present investigation.

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