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Mars Science Laboratory

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Definition

Mars Science Laboratory is a large instrumented vehicle (rover) built by ► NASA that landed on Mars in August 2012 (launched November 2011) and will operate for more than 1 Martian year (i.e., 2 Earth years). This rover, also called Curiosity, characterizes and interprets the geology of the landing region at all scales, assesses the biological potential of encountered targets, investigates planetary processes of relevance to past habitability, and characterizes radiation arriving at Mars' surface. Aboard MSL, an analytical laboratory is especially devoted to atmospheric analysis and search for organics in the ground.

Overview

Ancient Martian history, from its formation up to about three billion years ago, looks close to Earth's (Hadean-Archaeon on Earth, ► Noachian-Early Hesperian on Mars). We may then ask, was it possible for life to appear on Mars? One faces three possibilities: (a) life appeared and is extinct, but organic remnants or biominerals can be found; (b) only ► complex organic molecules, "bricks of life," were formed, and some of them still exist; and (c) Mars has been absolutely sterile from the beginning.

Viking Results

In 1976, ► NASA sent the ► Viking orbiters and landers to Mars. On landers Viking 1 and 2, instruments were devoted to the search for biosignatures and molecular analysis of the ground. They were (1) a gas exchange experiment: nutrients were brought to the soil, variations in concentrations of O₂, CO₂, CH₄, etc. were searched for (Oyama and Berdahl 1977); (2) two experiments using radioactive 14-C: CO₂ exchanges between atmosphere, soil, and nutrient were monitored (Horowitz et al. 1977) (Levin and Straat 1977); (3) a pyrolysis-gas chromatograph-mass spectrometer (GC-MS) experiment: Mars soil was heated and analyzed (Bieman et al. 1977).

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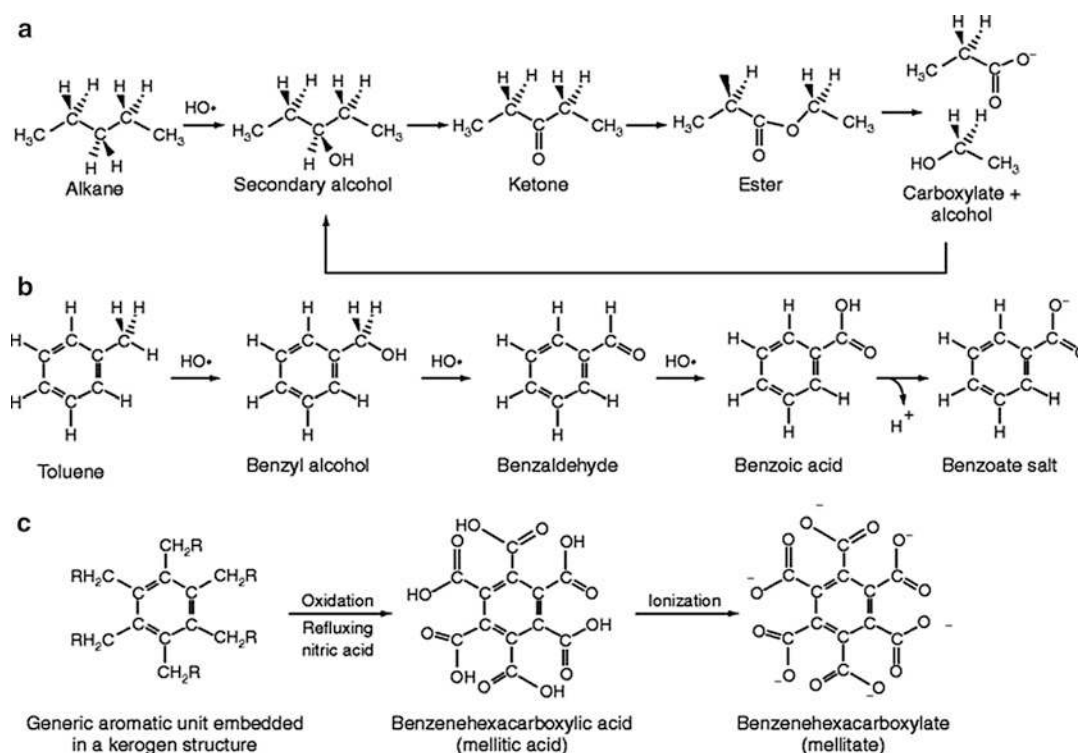


Fig. 1 Oxidative degradation of the generic alkane (represented here by pentane) to acetic acid (a), toluene to benzoic acid (b), and kerogen to benzenhexacarboxylic acid (mellitic acid) (c) (From Benner et al. 2000, Copyright National Academy of Sciences, USA)

Ambiguous responses to the first three experiments were understood as due to the presence of nonbiological reactants rather than metabolic activity. One knows, now, that Mars' atmosphere contains gaseous oxidants, such as H_2O_2 , due to atmospheric photochemistry (Atreya et al. 2006; Zanhle et al. 2008) and that oxidizing compounds may also be present in the soil: Phoenix lander, when characterizing Mars soil near the North pole, observed the presence of perchlorates (ClO_4^-) (Hecht et al. 2009).

Concerning the ► pyrolysis-GC-MS experiment, no organics were detected, except, at low level, chlorohydrocarbons (CH_3Cl , and CH_2Cl_2) the source of which was understood as terrestrial: chlorinated solvents, traces of methanol and HCl brought from Earth (Bieman et al. 1977), although they were not detected at the same level in the blank runs. Nevertheless, organic matter is brought to the Martian surface by micrometeorites ($\sim 10^{-3} \text{ mg/cm}^2/\text{year}$, Flynn 1996), and the question was, then, about its observability. Benner et al. (2000) showed that, in harsh environments, organic complex molecules degrade into refractory species (e.g., benzene-carboxylic acids) (Fig. 1). So, pyrolysis at moderate temperatures (500°C in Viking ovens) could not produce any volatile organic compound. Later, Navarro-González et al. (2010) took into account Phoenix observations and, from the pyrolysis of Mars-like soils (Atacama desert) mixed with perchlorates, obtained the same chlorohydrocarbons as observed by the Vikings. So, organics, at low levels, could be present on Mars surface and revealed by pyro-GC-MS analysis in presence of perchlorates, and this could be an alternative explanation to Bieman et al. results. Following this, exchanges of views occurred between the two teams (Bieman and Bada 2011; Navarro-González and McKay 2011).

Consequently, (i) the analytical laboratory of Curiosity, SAM, has been built (2005–2009) taking into account the fact that detection of organic matter by pyro-GC-MS needs higher temperatures or some

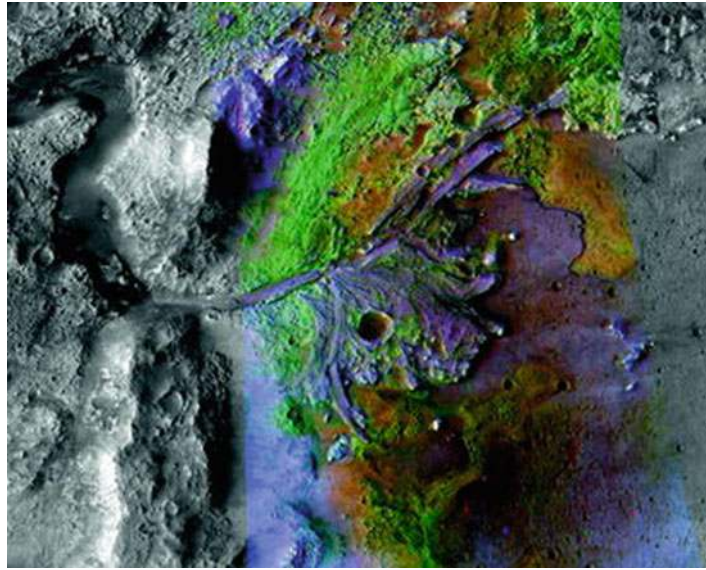


Fig. 2 Color-enhanced image of the rim of Jezero Crater (40 km diameter). Ancient river (meander at *left*) carried phyllosilicates (shown in *green*) into a lake, forming a delta. CRISM instrument aboard MRO, 2008 (Credits: NASA/JPL/JHUAPL/MSSS/Brown University)

preparation before pyrolysis; (ii) the potential production of chlorohydrocarbons has to be kept in mind during the analysis processes that occur at Mars surface, during MSL/Curiosity's activities.

Water on Mars

Since Viking, many orbiters (► Mars Express, MGS, ► Mars Odyssey, MRO, etc. (Bibring et al. 2006; Murchie et al. 2009)) observed Mars and returned strong indications that water circulated on Mars' surface during the ► Noachian period (Fig. 2). Spectral analyses show that carbonates, hydrates, sulfates, and phyllosilicates are present on Mars, linked to what could be riverbeds, deltas, or alluvial cones (Wray et al. 2009), which could be associated with life or its beginning.

Likewise, instrumented vehicles (rovers) have also explored Mars since 1997. Pathfinder-Sojourner (1997) and the MERs (Mars Exploration Rovers) Spirit (2004–2011) and Opportunity (2004-present) were mainly designed to identify geological patterns (panoramic cameras, microscope) (Fig. 3) and to analyze rocks using APXS (Alpha Particle X-Ray Spectroscopy), Mössbauer spectrometry, and TES (thermal emission spectrometry). Again, one can quote the detection of the same minerals as above (Squyres et al. 2004).

Mars Science Laboratory

From 1999, MEPAG (Mars Exploration Program Analysis Group, NASA) defined four goals linked by the motto “follow the water”: (1) Life, (2) Climate, (3) Geology, (4) Human exploration. In this frame, MSL (Mars Science Laboratory) was developed and launched in November 2012 (the vehicle to be landed on Mars surface was named “Curiosity”). MSL project has, in particular, for objectives to assess the past and present habitability, to characterize carbon cycling in its geochemical context, and to assess whether life is or was present (Grotzinger et al. 2012).



Fig. 3 (artificial colors: ‘Earth illumination’) Cape St Vincent, on the rim of crater Victoria, as seen by **MER Opportunity** (June 2007), vertical height ~ 8 m (Credits: MER Mission, Cornell, **JPL**, **NASA**)

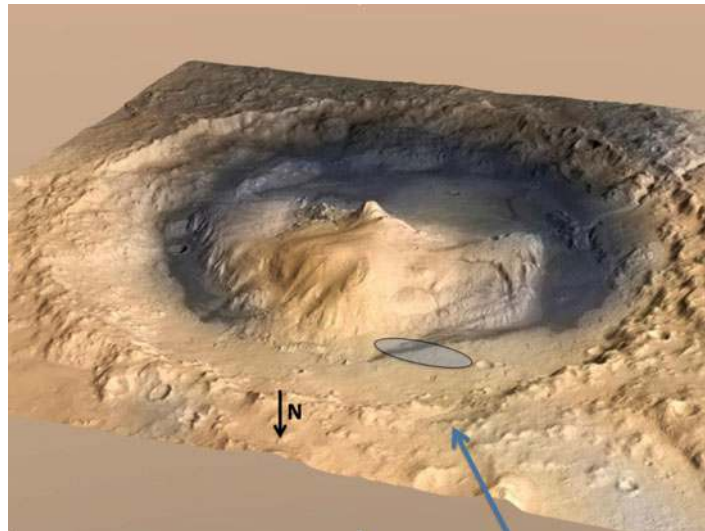


Fig. 4 Gale Crater, 3D reconstituted from MRO orbiter images. The landing ellipse (7×20 km) is shown on the crater floor; the *blue arrow* indicates Peace Vallis, on the rim of the crater (Credit: NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS)

From numerous (≈ 50) candidates for MSL landing (cf. Golombek et al. 2012), taking into account engineering constraints, and after five science workshops, Gale crater was selected in 2011 (Fig. 4). This crater (150 km diameter) was formed, from a meteoritic impact, about 3.8 Gy ago (Late Noachian to Early Hesperian) (Anderson and Bell, 2010). At the center of the crater, Aeolis Mons (aka Mount Sharp) culminates at more than 5 km. Scientists consider that this mound might be the remnant of sedimentary layers that deposited for some 100 My inside the crater, then were eroded (Thompson et al. 2011; Wray 2013). Data analysis show clay-bearing units interstratified with sulfate-bearing strata, indicative of aqueous activity.

Curiosity was successfully landed on the crater’s floor in August 2012, at the extremity of what appears to be an alluvial cone, brought to a potential lakebed by the river that drew “Peace Vallis,” incised into the crater’s rim (Fig. 5).

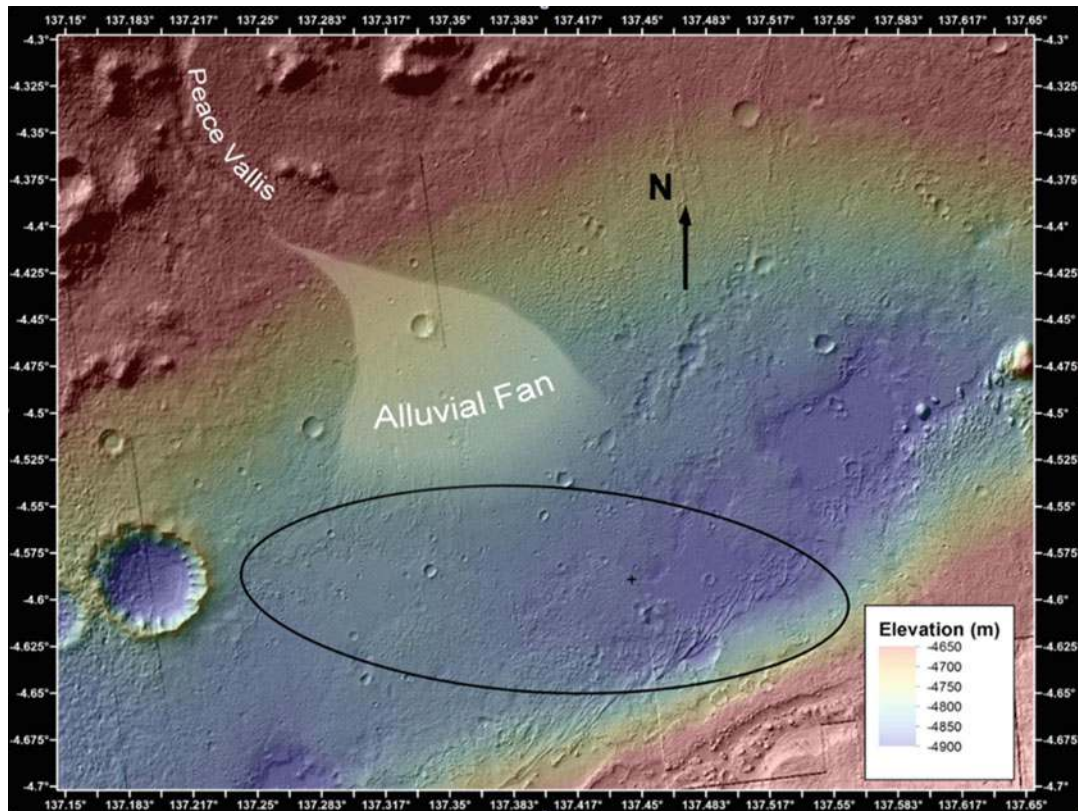


Fig. 5 (false colors: elevations) Curiosity's landing ellipse, on the floor of Gale crater. The landing point ("Bradbury") is figured by a *black cross*. Mount Sharp foothills begin at the *bottom right* (Credits NASA/JPL_CalTech/UofA)

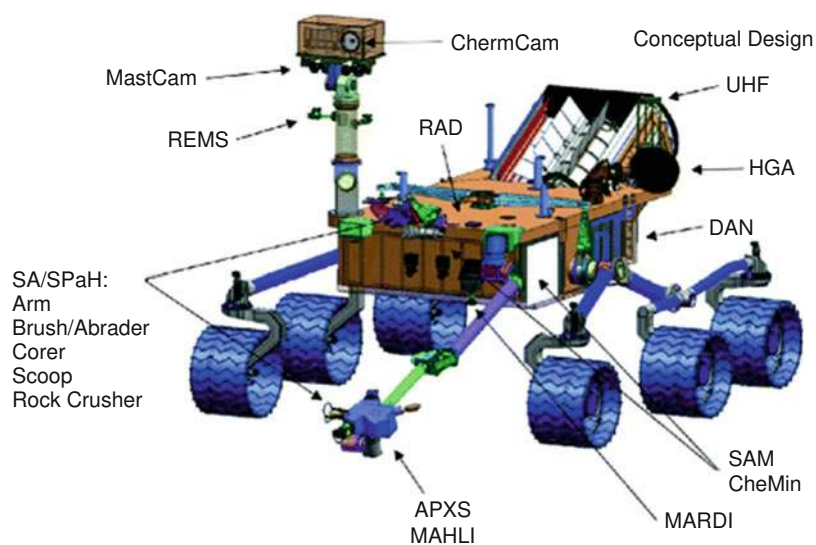


Fig. 6 An artist view of MSL (Credits: NASA/JPL)



Fig. 7 Landing of MSL (artist view): at ~ 20 m above the surface the rover is lowered on a tether from the descent stage ($v < 1$ m/s), and placed directly on the Martian surface (Credits NASA/JPL-Caltech)

Basic Methodology

MSL for 2012

This rover (Fig. 6) is larger ($2.75 \times 3.05 \times 2.13$ m) and heavier (900 kg) than Sojourner (11 kg) or MERs (174 kg each); from 2012, after landing (Fig. 7), its goal is to operate for more than 1 Martian year (~ 669 sols = ~ 687 terrestrial days) and navigate some tens of kilometers, from the landing point -inside the landing ellipse- to the first layers of Mount Sharp. On a sandy flat surface, the velocity of Curiosity lies between 140 m/h for blind drive and 20 m/h for hazard avoidance with visual odometry. It is powered, as were Viking 1 and 2, by radioisotope thermoelectric generators (RTGs; 2.5 kW-h/sol) and is heavily instrumented. Its 80 kg science payload is composed of ten instruments (Grotzinger et al. 2013). They are devoted to (1) observation: cameras or microscopes (MarDI, descent imager; MastCam, on the mast; MAHLI, at contact with the samples); (2) environmental studies: an instrument (RAD) to characterize the broad spectrum of radiation near the surface and a pulsed neutron source and detector (DAN) for measuring \blacktriangleright hydrogen or \blacktriangleright ice and \blacktriangleright water at or near the Martian surface (less than 1 m), a meteorological station and UV sensor (REMS); (3) mineralogy and geochemistry of rocks and soil: APXS (Alpha Particle X-Ray Spectroscopy, at contact with the sample), CheMin (X-Ray diffraction on sampled powders), ChemCam (on the mast, UV to near-IR spectroscopy of gases issuing from laser impacts on targets); (4) molecular analysis of atmosphere and soil samples: SAM for MS, \blacktriangleright GC/MS, and IR spectroscopy (see below). Some of these instruments are on the mast (MastCam, ChemCam) or at the end of the 1.9 m length robotic arm (APXS, MAHLI). This arm also carries the scooping or drilling instruments (Anderson et al, 2012) that feed with mineral powder (< 150 mm diameter, about 50 mg per dosing) the sample preparation devices for SAM and CheMin, which are located inside the rover.

Operations began as soon as the rover was deposited on Mars surface (see Fig. 7). It can be noticed that the way Curiosity is operated leads to quasi-daily downlink (data from Mars to Earth) or uplink (commands from Earth to Mars), seven days on seven at the beginning and, later, limited to working days; note that operations are linked to the Martian diurnal cycle (the “sol”) that slips of about 40 min each “Earth” day. During the first three months (i.e., commissioning), teams were operating exclusively from JPL, then they came back to their laboratories. Results from Curiosity’s science payload are embargoed until MSL project decides/authorizes to release them (Press conferences from NASA, international conferences, papers in peer-reviewed journals, for example).

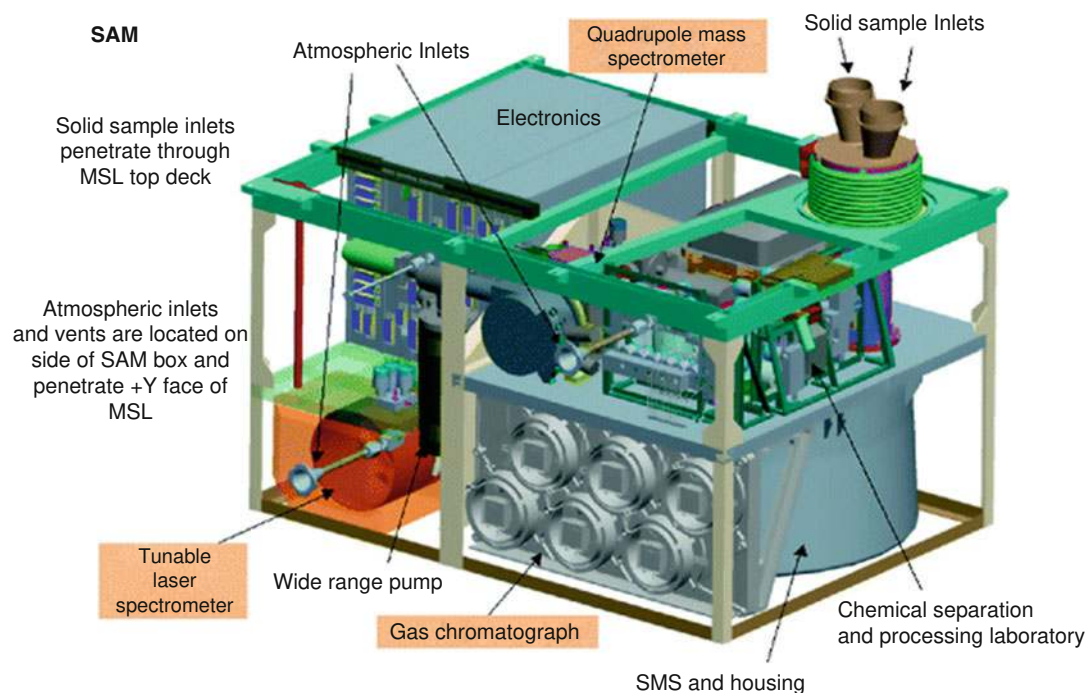


Fig. 8 An artist view of SAM (Credits NASA/GSFC)

Exobiology Aboard MSL: SAM

A large part of the MSL instruments is devoted to the examination of ground samples, and SAM (Sample Analysis at Mars) is one of the most complex and the most relevant for ► astrobiology. It belongs to the family of analytical laboratories following Viking (1978) and Huygens (2005), such as COSAC (Rosetta, 2004–2014), GAP (► Phobos-Grunt, 2011-failure), and MOMA (► ExoMars, foreseen for 2018). This heavy (~40 kg) laboratory is developed by ► NASA (SAM-PI: P. Mahaffy, GSFC/NASA, Mahaffy et al. 2012) and incorporates three scientific units (Fig. 8). These are a quadrupole mass spectrometer (MS, under GSFC/NASA responsibility, Mahaffy 2008), a tunable IR laser spectrometer (TLS, under JPL/NASA responsibility, Webster and Mahaffy, 2012), and a stand-alone gas chromatograph (GC) (under Univ. of Paris/CNES/CNRS responsibility, Cabane et al. 2004; Rodier et al. 2005). The goals of SAM are to (1) analyze the atmosphere, search for minor species (e.g., CH₄, ► noble gases), abundances, and isotopic ratios; (2) analyze ground samples, search for organics and their possible ► chirality, structural gases in mineral species (CO₂, H₂O, SO₂, etc.); (3) measure isotopic ratios.

Six different gas chromatographic modules can be used, which cover a range from low-mass permanent gases or low carbon number (C1-C5) hydrocarbons to high masses (> C15), with the possible use of a “chiral” column to search for ► enantiomers. Specific detectors (thermal conductivity detectors, TCDs) are used that can measure down to some 10⁻¹⁰ mol of a given species in a He flow. The Quadrupole Mass Spectrometer precisely identifies molecular compositions: the mass measurement ranges from 2 to 535 Da, with a detection limit ~ 1 ppm (~1 pmole in a He flow) and isotope ratios down to 1 per mil for ► noble gases. In the case of GC analysis, the MS can be used as detector to lower the detection level (some pmoles for GC-MS compared to some 10⁻¹⁰ mol for GC-TCD). The cell of Tunable Laser Spectrometer instrument can detect down to 2 ppb of CH₄ and 2 ppm of water without enrichment and measure down to <10 per mil isotope ratios for C and O. Isotope measurements from TLS and MS will, in particular, help to solve the methane concern (Lefèvre and Forget 2009): what are the origins and sinks of the Martian CH₄, some tens of ppbs observed using teledetection (cf Atreya et al. 2007), that could originate from well-defined places?

Gases sampled in the atmosphere are pumped through GC-MS-TLS; on their path, the Chemical Separation and Processing Laboratory (CSPL: getters, scrubbers, cold traps) may help to eliminate/separate some species (CO_2 , H_2O) or to concentrate the sample.

Soil or rock powder need to be sieved (diameter $<150\text{ }\mu\text{m}$) before introduction into SAM's inlets. They can be heated up to $1,000\text{ }^\circ\text{C}$ (74 cells potentially reusable, in the Sample Manipulation System, SMS), and exhausted gases are analyzed; in the case of GC analysis, an He flow (pressurized tanks onboard) goes through the oven and pushes the mixture toward GC columns. In case of refractory species, some cups are equipped for wet chemistry (► derivatization): a chemical reagent transforms the molecule into a vaporizable one, while preserving the structure (Buch et al. 2009). Combustion of samples in O_2 atmosphere (pressurized tank onboard) may be also used to determine the isotopic ratios.

Gases from heating of the sample can be directly analyzed by the MS, using the EGA (Evolved Gas Analysis) mode: the release of typical molecules (H_2O , CO_2 , O_2 , SO_2) is monitored by the MS when the temperature of the cell that contains the sample is varied. Then, in a function of temperature, molecules show up and disappear, corresponding to their release from the sample at given temperatures. They can be adsorbed molecules, easily released at low temperatures, or weakly bonded molecules (e.g., H_2O from Gypsum $\text{CaSO}_4(\text{H}_2\text{O})_2$), or they can be molecules that come, at higher temperatures, from a breakup (e.g., CO_2 from CaCO_3) or a dehydroxylation (e.g., H_2O from kaolinite $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$). Monitoring organic molecules when heating the sample is very useful, as far as it allows a better understanding of the processes and reactions that can release and/or modify the structure of organic molecules. Moreover, a precise investigation on the temperature of release could help to decide on the (a)biotic origin of some minerals (Stalport, 2005; Stalport, 2007). During the heating process, for a given temperature range, one can decide to send gases to TLS or GC-MS for further analyses.

In order to have a complete understanding of the results that are obtained on Mars, using GC and/or MS and/or TLS, devoted experiments intended to check the possible pathways are performed on Earth. For this purpose, teams can use, in their laboratories, separate instruments, most of them presenting the same characteristics (e.g., spare models) as the ones that are used on SAM; a complete spare model of SAM is also used, as a full testbed, at NASA/GSFC, in Martian conditions.

Key Research Findings

Curiosity landed safely on Mars surface (landing site was named “Ray Bradbury”) on August 5, 2012 and, from then, performed measurements, using all the instruments of the Science Payload and moving on Mars surface. The embargo policy does not allow quoting nonvalidated results; Nasa's websites (e.g., ► <http://mars.jpl.nasa.gov/msl/>) allow to follow Curiosity in its progress and results.

The main idea, before landing, was to drive out the landing ellipse, quite rapidly, in direction of sulfate- and phyllosilicate-bearing strata (lower part of the mound). Curiosity was deposited near the center of the landing ellipse (see Fig. 5), and it appeared that, at short distances (less than 300 m), there were targets that were worth the visit, in full agreement with the expectations that the team had, from Gale's choice. It took from August 2012 to June 2013 to carry out this task. Here are described the main results, obtained during the first 6 months, that are linked to Astrobiology; other results (Meteorology, Mineralogy, Geology, etc.) may be found on devoted websites and science papers.

Conglomerates

After leaving “Bradbury,” on sol 22, Curiosity approached “Link” (sol 27), then “Hottah” (sol 39) (see Curiosity traverse on Fig. 9), and images were obtained from Mastcam (Figs. 10 and 11). One observes that these outcrops are sedimentary conglomerates composed of rounded gravels cemented

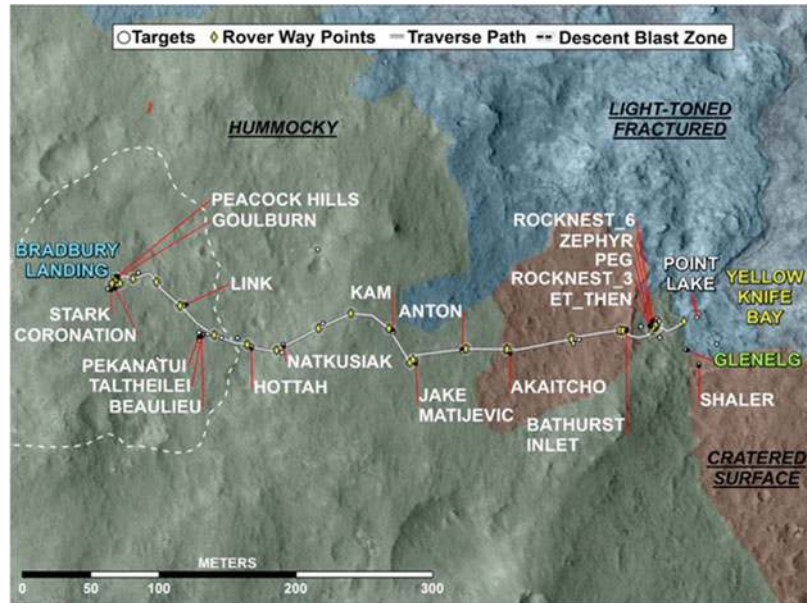


Fig. 9 Traverse path of Curiosity from Bradbury landing site to Glenelg. False colors correspond to the various terrains observed from orbit (Credits NASA/JPL-CalTech/UofA)



Fig. 10 The conglomerate Hottah; the gravel clast circled in white is about 2 cm across. Erosion of the outcrop results in the gravel pile at left (Credits: NASA/JPL-CalTech/MSSS)

together. The size of the rounded stones is not compatible with aeolian processes (these pieces of rock are too big to be moved by the wind), and only flowing water can explain what is observed (Newsom et al. 2013; Williams et al. 2013): pebbles transported for a minimum distance of a few km, by a water flow of velocity from .2 to .75 m/s and depth .03 to .9 m.

Obviously, this conclusion is compatible with the position of Curiosity at this time, at the end of an alluvial fan from Peace Vallis (see Fig. 5), and it strengthens the idea of water flowing on Mars, some billion years ago, in a mild and dense atmosphere.

Atmosphere

SAM used its TLS instrument to search for CH_4 in the atmosphere and compare with the previous results of 10 ppb or more (Kerr 2012) that were obtained from remote observations. Measurements of TLS show a very low level of CH_4 : 0.55 ± 1.46 ppb, at the 1-sigma level (Webster et al. 2013), which allows to

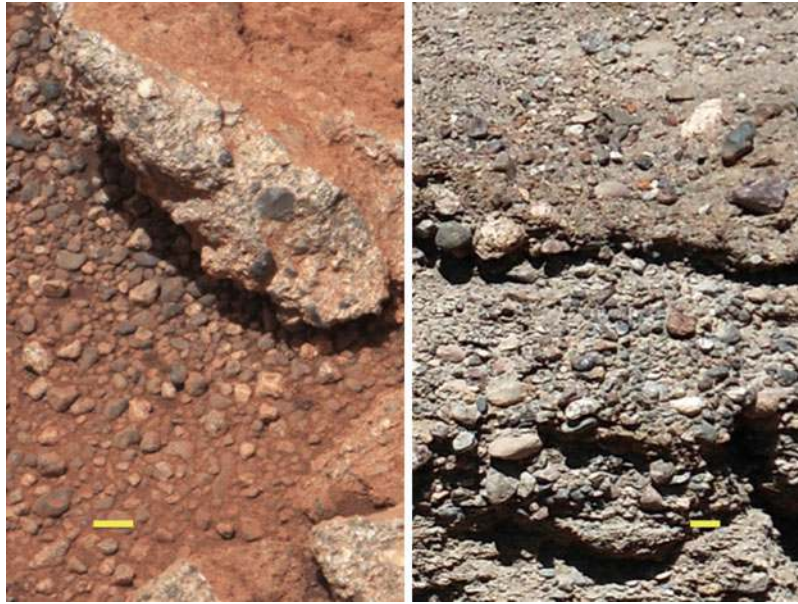


Fig. 11 Comparison between conglomerate Link –on *left*- and an Earth conglomerate –at *right*-. The *yellow bar* corresponds to 1 cm in both cases (Credits: NASA/JPL-CalTech/MSSS)



Fig. 12 The sand dune Rocknest (*middle right*) at the lee side of a rock outcrop (Credits: NASA/JPL-CalTech/MSSS)

think that, if CH_4 is present, it has a concentration that is well below the ones that one could expect from teledetection. Concerning atmospheric escape that helped to lead to the present 7 mbars, SAM observed a decrease of $^{36}\text{Ar}/^{38}\text{Ar}$, compared to Solar or Earth values, that is fully compatible with the values observed for Martian meteorites and corroborates the theories of a dense atmosphere for the first billion years of Mars history. The same trend was obtained by measuring D/H ratio in the atmosphere or from H_2O released when heating soil samples (at Rocknest, see below).

Sand

On her path to the site labeled Glenelg (see Fig. 9), Curiosity stopped (sol 56) at Rocknest, a sand dune (Fig. 12). This allowed the first scooping of Mars soil by Curiosity and analysis by SAM pyro-GC-MS

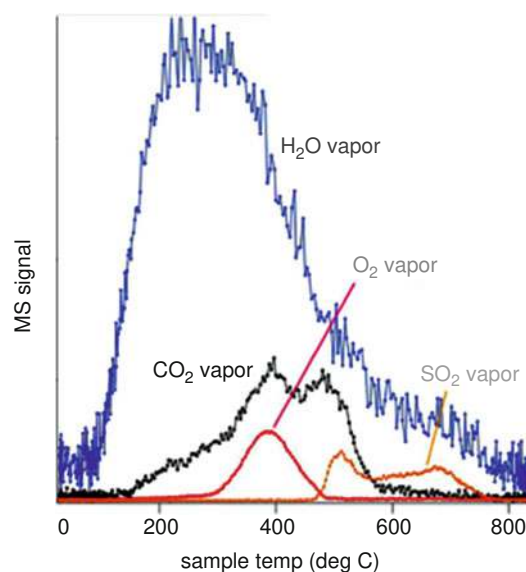


Fig. 13 An example of Evolved Gas Analysis (EGA) performed by SAM on a Rocknest sand sample (signal from the mass spectrometer in function of sample temperature), see also Mahaffy et al. 2013. When T is increased, various molecular species appear when the heating energy allows their release. (Credits NASA-GSFC/JPL-Caltech)

chain (Leshin et al. 2013). EGA (Evolved Gas Analysis) was used for some analyses of the samples, and the release of typical molecules (H_2O , CO_2 , O_2 , SO_2) was monitored using the MS (see an example on Fig. 13).

Chemin observed (Vaniman et al. 2013) that all of the identified crystalline phases it identifies are volatile free; H_2O , SO_2 , and CO_2 volatile releases are then associated with the amorphous or poorly ordered materials. Water vapor is released at rather low temperatures, corresponding to a mixture of adsorbed or weakly bonded water for the lowest part of the spectrum and more or less tightly bonded water for the highest part. Oxygen release can be attributed to the decomposition of perchlorates. CO_2 comes, at low temperatures, from adsorbed molecules, and at high temperatures from carbonates decomposition, a source for CO_2 may be the action of O_2 on organic matter. Using GC-MS, low amounts of CH_3Cl and CH_2Cl_2 are detected, which might correspond to action of perchlorates on organics either present in the samples or brought from Earth. The complexity of the results, the interaction of various species between themselves, leads to cautious interpretations; laboratory experiments are in progress, in order to reproduce and explain the results observed on Mars.

Rock

From sol 157, Curiosity explored a small depression, “YellowKnife Bay,” where another kind of rocks was observed (Fig. 14). When shooting at light-toned veins with its laser, and analyzing the emitted light, ChemCam concluded to the presence of elevated levels of calcium, sulfur, and hydrogen. This may correspond calcium sulfates as Gypsum $\text{CaSO}_4(\text{H}_2\text{O})_2$ or Bassanite $\text{CaSO}_4(\text{H}_2\text{O})_{0.5}$. These minerals form when stagnating “salty” water infiltrates rocks and fills cracks with mineral deposits. SAM-EGA Analysis applied to the rock powder that was obtained by drilling the rock John Klein (down to about 6 cm, Fig. 15) showed the same molecules as in the case of Rocknest and gave the same patterns for O_2 , SO_2 , and CO_2 . But concerning H_2O , the pattern is rather different: instead of culminating when the temperature is about 250 °C, as seen for Rocknest, it appears (see an example on Fig. 16) that water is also delivered for temperatures from 400 °C to 700 °C.

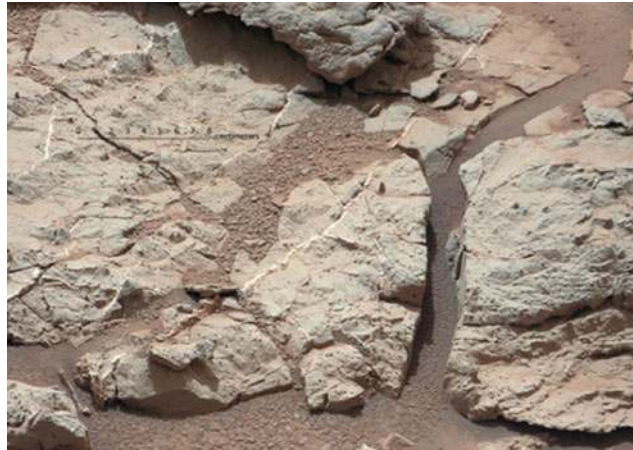


Fig. 14 An outcrop at the Sheepbed locality, the veins are filled with whitish minerals, which can be interpreted as calcium sulfates (gypsum, bassanite) (Credits: NASA/JPL-CalTech/MSSS)



Fig. 15 At the center: the hole (diameter 1.6 cm, depth 6.4 cm) drilled by Curiosity into the rock John Klein; the shallower (2 cm depth) hole, on the *right*, corresponds to a test performed earlier, to test the drill. One can observe the difference between the red-brownish oxidized surface of the rock and the gray-greenish exhumed powder (Credits: NASA/JPL-CalTech/MSSS)

This may correspond to phyllosilicates, as far as much more energy is needed to obtain H_2O from hydroxyl radicals in their chemical formula to deliver H_2O . The same observation came from CheMin where diffraction patterns of phyllosilicates appeared when bombarding the rock powder with X-Rays (Fig. 17).

Concerning sulfur, it was concluded to the presence of hydrogen sulfide (H_2S , reduced S) and sulfate (SO_4 , oxidized S). Similarly to Rocknest, chlorohydrocarbons are observed by GC-MS, and laboratory experiments are in progress for a better understanding.

One can say, as it was declared at a NASA Press Conference in March 2013, that in this plain, near an alluvial cone, what was found around John Klein, at Yellowknife Bay, is fully representative of what is defined as a past habitability of Mars, that is to say, a rather neutral watery environment (Fig. 18), oxidized and reduced atoms, carbonates and clays, etc.

After the conjunction event, in April 2013, when Mars and Earth were separated by the Sun, Curiosity drilled again, from sol 275, a set of holes in Cumberland rock, not so far from John Klein, in order to finalize its study of Yellowknife Bay, before the beginning of her trip to Mount Sharp (see on Fig. 19 Mount Sharp's panorama as seen by Curiosity).

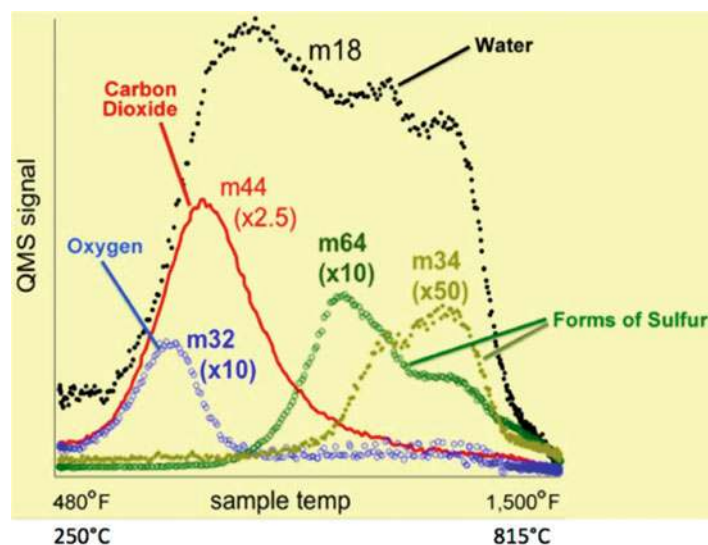


Fig. 16 Major gases released from heating the powder obtained from John Klein's drilling, an example. The signal from the mass spectrometer is shown in function of sample temperature (EGA). This may be compared to Fig. 13, one notices that the major difference appears in the release temperatures for H₂O. In the present case, at high T, this corresponds to H₂O released by phyllosilicates (clays), see also Fig. 17 (Credits NASA-GSFC/JPL-Caltech)

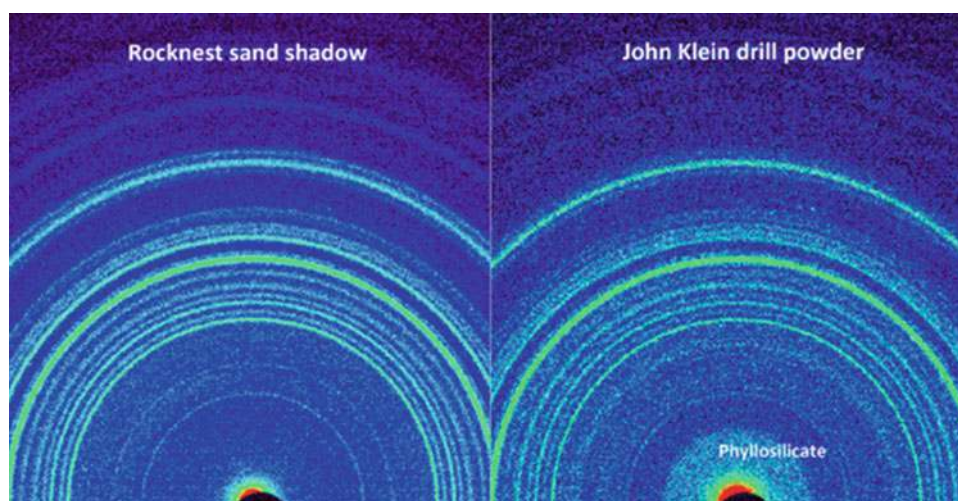


Fig. 17 Comparison between diffraction images obtained by CheMin experiment for Rocknest and John Klein samples. Phyllosilicates appear clearly for the rock sample; compare also results of EGA in the two cases in Figs. 13 and 16 (Credits NASA-GSFC/JPL-Caltech/Ames)

Future Directions

NASA's Mars Atmosphere and Volatile EvolutionN (MAVEN) mission is scheduled for launch in late 2013. One of the goals of this orbiter is to determine the role that losses of atmospheric gases (e.g., CO₂, N₂, H₂O) to space played in changing the Martian climate through time, giving insights into the history of Mars atmosphere and climate, liquid water, and planetary habitability.

In the frame of its Exomars program, and in cooperation with RosCosmos, ESA will launch, in 2016, the trace gas orbiter, TGO, devoted to spatial and temporal localization, and possible sources of methane and other light hydrocarbons or nitriles but also of nitrogen and sulfur compounds, O₃, HCl, HO₂, etc.,



Fig. 18 On *left*: Wopmay rock as seen (11–2004) by Opportunity rover in Endurance crater (Meridiani Planum). On *right*: rocks of the “Sheepbed” unit in Yellowknife Bay (Gale Crater), as seen by Curiosity. Both rocks were formed in the presence of water, but the water at Wopmay was highly acidic and salty, while the water at Sheepbed had a more neutral pH and lower salinity (Credits: NASA/JPL-Caltech/Cornell/MSSS)



Fig. 19 Image taken by 100 mm PanCam aboard Curiosity, looking at S-SW, on August 25 2012. In the proximity, one observes a band of dark dunes (cf Fig. 5) and, further on, layered hills at the base of Mount Sharp. The *top ridge* is about 15 km away from the rover (Credits NASA/JPL-Caltech/MSSS)

with required detection sensitivities down to 1 ppt. An Entry Descent and Landing demonstrator module will be associated, which could perform some science measurements. In the same frame, ESA will land, in 2018, the Exomars Rover, Pasteur, equipped with a drill, able to collect samples down to 2 m below the surface, and a science payload mainly devoted to astrobiology. Pasteur will explore Mars for one or more seasons; a surface platform should be associated to Pasteur to investigate Martian environment.

To continue its Mars Exploration program, NASA has in mind to send to Mars, in 2020, a rover with almost the technical capabilities as Curiosity and an enhanced drilling system. The mission would provide an isotopic datation of Mars terrains (instead of ages obtained from craterization rates) and address key questions about the potential for life on Mars. The mission would also provide opportunities to gather knowledge and demonstrate technologies that address the challenges of future human expeditions to Mars. The rover could acquire rock cores with a core drill and place the cores in a cache. The cache would be left on the ground, while the rover would continue exploring the planet. This could be the first step of an exploration leading ultimately to the arrival, at Earth, of Mars Sample Return mission.

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