A PROPOSAL FOR CONTROL SYSTEM OF A WIND ENERGY CONVERTION SYSTEM FOR SPECIAL PURPOSES

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ABSTRACT. Nuclear energy sources have been widely used in the past decades in order to power the spacecrafts, nevertheless their use has attracted controversy because of the risk of harmful material released into the atmosphere if an accident were to occur during the launch phase of the mission. As compared to solar cells, wind turbines have a great advantage on Mars, as they can continuously produce power both during dust storms and at night-time.

This paper focuses on the design of a wind energy conversion system (WECS) considering the atmospheric conditions on Mars. Wind potential on Martian surface has been estimated, as well as the average energy requirements of a Martian probe or surface rover. Finally, the expected daily energy output of the WECS has been computed on the basis of both the swept area of the rotor and the average wind speed at the landing site, as well as the characteristic curves of the turbine to be implemented in the control system for optimal rotor operation.

I. Introduction and Background

The beginning of the space exploration can be placed in 1957, when the Soviet Union launched the first artificial satellite, Sputnik 1. Since then, there has been a series of launches, which enabled the world to achieve a series of successes: from the first human flight around the Earth until the conquest of the Moon with Apollo 11. Exhausted the lunar exploration, the field of investigation was extended to the Sun, planets and minor bodies, with expeditions which made possible to map Mercury, Venus and Mars and also to study objects such as comets and asteroids.

The exploration of Mars by humans began with the launch of two probes called "Mars1960A" and "Mars1960B" by the Soviet Union in October 1960. The launch was the beginning of dozens of expeditions for the exploration of the Martian soil, carried out by both NASA (which gained the greatest successes, notwithstanding several failed expeditions) and the Soviet Union.

Among the most important expeditions to Mars, it is important to point out the first nine probes of NASA’s "Mariner" program (launched between 1964 and 1970, which provided the earliest images of the planet) in parallel with the Russian program "Mars" which included seven shipments, all unsuccessful except for the fifth one ("Mars 5"), which sent 60 pictures before the breakdown of the telecommunication system. In 1976, thanks to NASA's Viking probes, the first successful soft landing on Mars took place and it was thus possible to acquire more scientific information about the planet, in particular its data on the temperature and the atmospheric pressure, together with detailed observations on seasonal sandstorms. However, the first completely successful expedition by the United States and the first absolute success of the exploration of Mars were obtained thanks to the probe "Mars Global Surveyor", launched into the orbit on 7th November 1996. This probe studied the whole surface of the planet, with the particular aim of seeking a possible presence of water. Following, there were many other expeditions and probes which explored the Red Planet. Noteworthy among them is "Mars Pathfinder" (landed in July 1997 which sent important chemical analysis of the rocks and also information on the wind and other atmospheric factors), "Mars Odyssey" (launched in April 2001, confirmed the presence of ice in the subsoil) and the "Mars Exploration Rovers", including a pair of twin rovers launched within a month of each other: "Spirit" (on 10th June 2003) and "Opportunity" (on 7th July 2003). At the present time they must be considered fully operational, along with "Mars Reconnaissance Orbiter", which entered into the Martian orbit on 12th March 2006. This leads to the last full-finished expedition by NASA, the "Phoenix Mars Lander", whose realization was entirely entrusted to the University of Arizona and ended in November 2008: the probe gave specific evidence of the evaporation of water ice on the site of the landing. It made chemical analysis of the soil, revealing its composition and also identifying the presence of perchlorate.

We can therefore say that the exploration of Mars was not easy, in particular for its high financial costs also added to a high number of failed expeditions which are roughly the two-thirds of the total ones realized. This high rate of failures can be attributed to a large number of factors which may affect the exploration, most of which are still unknown.

One of the most important problems for the realization of the expeditions was the power of the probes and in particular of the rovers used for the exploration and the analysis of the Martian soil, which was often the cause of the total failure of the expedition, due to the impossibility of the movement of the rover itself or to the lack of sending of both data and information. A rover requires power to operate, without power it cannot move, use its scientific instruments or communicate with the Earth. The first probes sent to Mars (the Viking I and II are the best examples) used nuclear energy power for their travels and movements, thanks to a small reactor which generated radioactive isotopes from the decay of plutonium. However, with the subsequent expeditions, it was decided to change to solar energy, used both for the power of the probes themselves and also for the rovers working on the Martian surface as the solar energy was considered less risky and invasive towards the Martian environment. The results were particularly satisfactory, in particular for the contamination of the soil, unlike it had before happened with nuclear reaction landers generation. Despite that, the photovoltaic arrays working on the surface of Mars showed different operational problems compared to the same arrays on the Earth or in orbit. On several Martian expeditions, the performance of the solar arrays presented the main difficulty as regards the right site to land, the amount of power available for scientific operations and the duration of the efficiency of the instruments day by day. The environmental conditions on the surface of Mars are very different from the orbital environment, where space solar panels normally work. The differences of the efficiency of the solar arrays working on the Martian surface and those ones on the Earth orbit are due to several factors:

• lower solar intensity due to a greater distance of Mars from the sun;

• suspended atmospheric dust, which modifies the solar spectrum and reduces the solar intensity;

• low operating temperatures;

• deposition of dust on arrays;

This last aspect caused a lot of problems for some shipments: because of sand deposition on the solar panels, the production of electric energy decreased of more than 70%. In particular, the efficiency of the Spirit rover was reduced to 50 minutes a day for a long period, as only the 25% of the solar rays could go through the layer of dust. The problem was fortunately resolved by a particular Martian breeze which swept the dust off the panels, thus allowing the rover to resume almost all its autonomy.

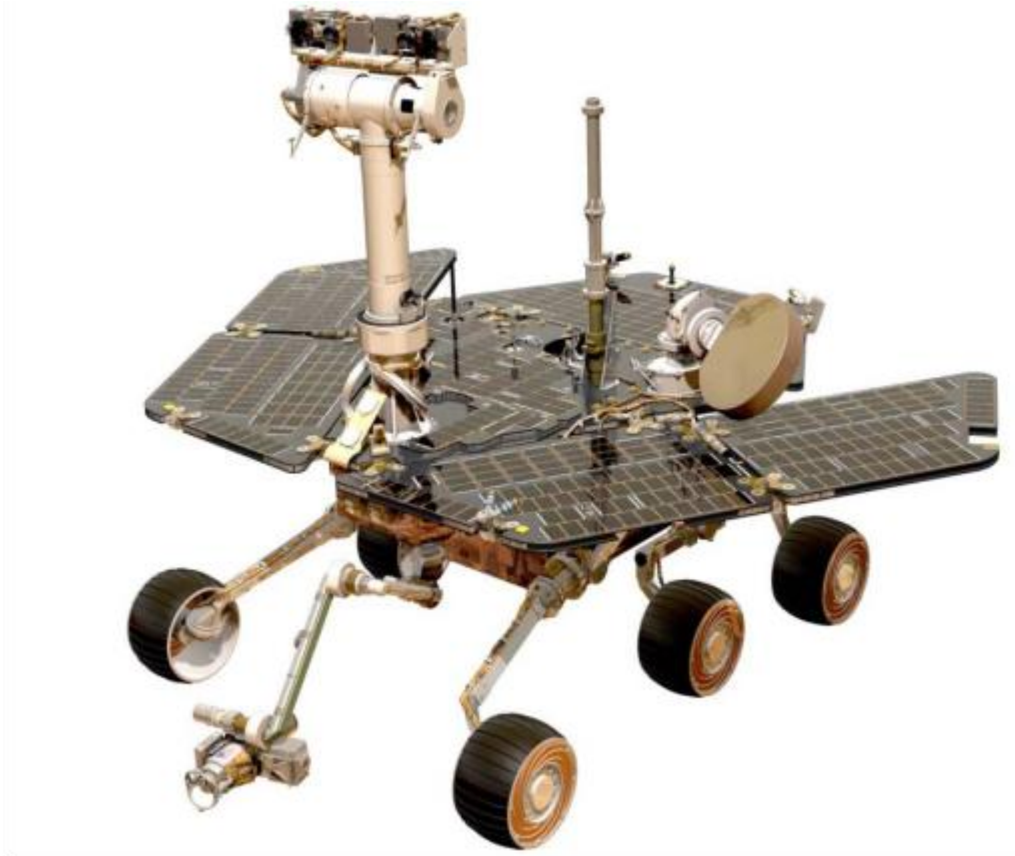

Fig.1 - *Solar Array of the Spirit rover.*

Compared to solar cells, wind turbine systems used on Mars should have the advantage of producing continuously power both during dust storms and at night. In particular, Kumar et al. [1] designed a 500 W Darreius-type straight-bladed vertical-axis wind turbine (S-VAWT), taking into consideration the atmospheric conditions on Mars. The study of specific wind turbines for a possible use on Mars was object of interest also by James et al. [2] who published a treatise on a special buoyant wind turbine, designing the shape and size after a precise investigation of the profile of the wind.

The wind profile on Mars

The wind is the main cause of the ever-changing of the surface on Mars. The presence of the wind on Mars was supposed even before spacecrafts explored the surface. Astronomers observed changes in the brightness of the planet suspecting that the dust lifted by the wind was responsible to darken the atmosphere. The presence of winds was overwhelmingly confirmed when Mariner 9 landed on Mars in the middle of a huge dust storm. The Mariner and Viking spacecrafts also revealed the features of the surface, including various types of dunes, which are widespread on Mars and are very similar in appearance to the dunes on the Earth. They change in the course of time and can indicate the main wind direction. However, the assumptions on the actual presence of the wind on the Martian surface were confirmed subsequently, when, thanks to following expeditions, it was possible to analyze in detail the movements of the dust through special photographic devices.

An important factor to be taken into account is that the force of the wind is lower on Mars, because of its low density (of about a factor of 100) compared to that one on the Earth. Mars has a tenuous atmosphere with a pressure which is less than one-percent with respect to Earth. The MRO used a special high resolution camera (HiRISE - High Resolution Imaging Science Experiment), which provided the best images of the Martian soil. Thanks to these photographs, the scientists were able to establish the actual presence of the wind, eliminating any doubt about the cause of the particular dunes and whirlwinds which constantly change the surface, creating special "drawings" of sand. The process of the modification of the surface by the wind is a process taking constantly place, as pointed out by the photographs of the atmospheric dust storms, whirlwinds and perhaps even tornadoes.

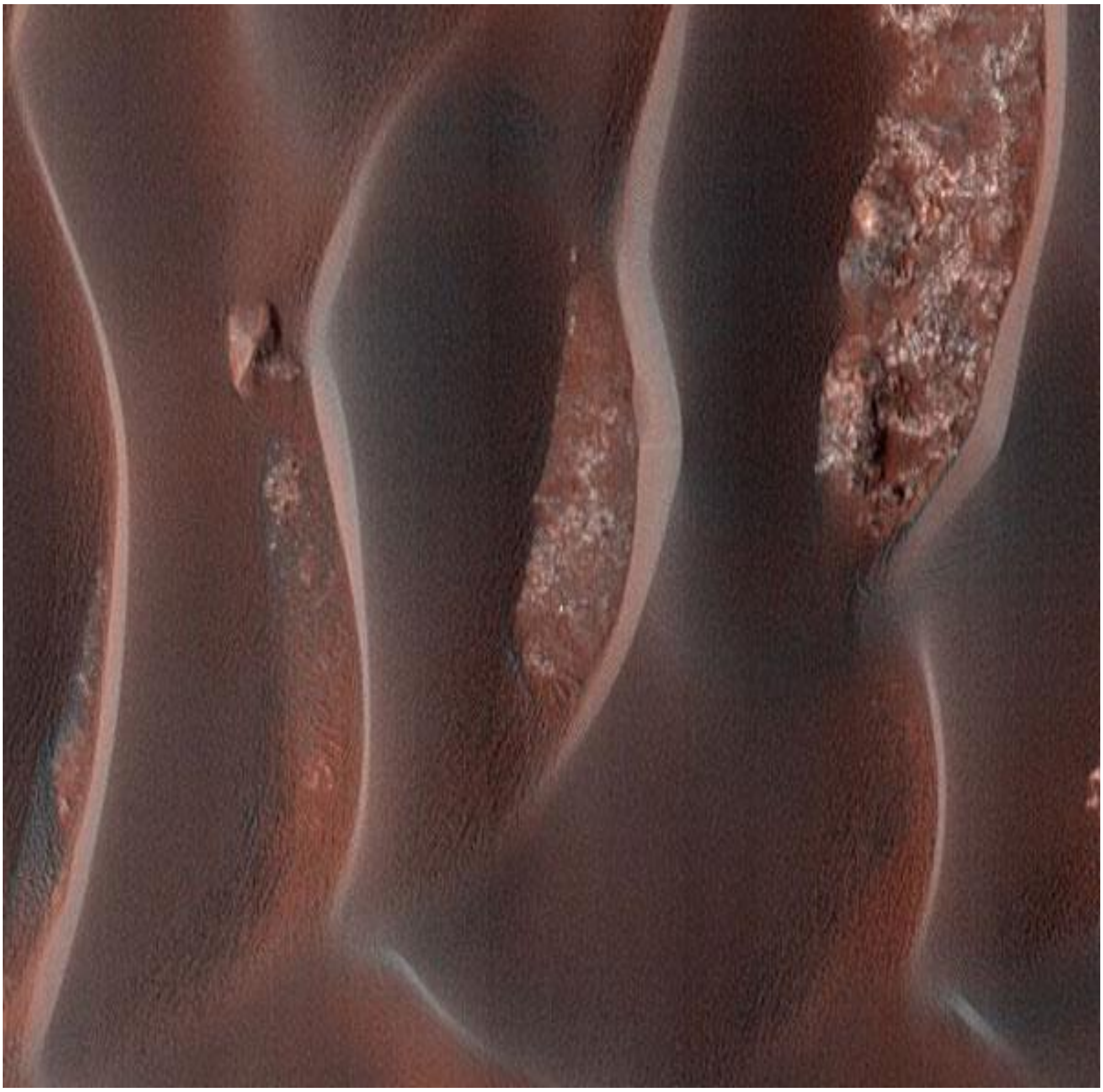

Fig. 2 -*The HiRISE camera took this picture of a dune field within a crater southwest of Hershel Crater on 1st July 2007.*

II. Energy power for rover

The first expeditions to Mars were made with probes mainly powered by nuclear energy, which resulted particularly effective for the purposes and tasks required. Thanks to a system able to generate radioisotopes, the Viking 1 and 2 probes could make shifts in the Martian atmosphere and land onto the soil surface making significant scientific analysis in total autonomy for at least three years. Inside them, there was a radioisotope thermoelectric generator (RTG, RITEG), that is an electrical generator which obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples (a thermocouple is composed of two kinds of metal, or semiconductors, which can both conduct electricity: they are connected to each other by a closed loop; if the two junctions are at different temperatures, an electric current will flow in the loop). RTGs use thermoelectric couples to convert heat from radioactive material into electricity. Thermocouples, though very reliable and long-lasting, are very inefficient; efficiencies above 10% have never been achieved and most RTGs have efficiencies between 3 and 7%. Thermoelectric materials which have been used up to now in space expeditions included silicon germanium alloys, lead telluride and tellurides of antimony, germanium and silver (TAGS). Studies have been done so as to improve their efficiency using other technologies to generate electricity from heat. Achieving higher efficiency would mean the necessity to produce less radioactive fuel for the same amount of power, and therefore a lighter overall weight for the generator. This is a critically important factor to point out, taking into consideration the costs of spaceflight launches. RTGs can be considered as types of battery and have been used as power sources in satellites, in space probes without crew and in unmanned remote facilities, such as a series of lighthouses built by the Soviet Union in the Arctic Circle. RTGs are usually the most desirable power sources for robotic or unmaintained situations, for systems which need at least a few hundred watts (or less) of power for too long spans of time which could not be supported by fuel cells, or batteries, or economical generators or for equipment working in places where solar cells cannot be used.

The Viking probes used plutonium-238 (238-Pu) for the decay inside the generator, and it became the most widely used fuel for RTGs, in the form of plutonium (IV) oxide, (PuO_2). 238-Pu has a reasonable power density and an exceptionally low gamma of the levels of neutron radiation. This type of plutonium has a half-life of 87.74 years, in contrast to the 24,110 year half-life of plutonium 239 used in nuclear weapons and reactors. A consequence of the shorter half-life is that plutonium 238 is about 275 times more radioactive than plutonium 239. The real problem of radioisotope thermoelectric generators is that they may pose a risk of radioactive contamination: if the container holding the fuel leaks, the radioactive material may contaminate the environment. As regards spacecraft, the main concern is that if an accident were to occur during a launch or during the passage of a spacecraft close to the Earth, harmful material could be released into the atmosphere. For this reason their use in spacecraft and elsewhere has attracted controversy.[3]

There have been at least six known accidents involving RTG-powered spacecraft, and to minimize the risk of the release of radioactive material, the fuel is stored in individual modular units with their own heat shielding. The units are surrounded by a layer of iridium metal and encased in high-strength graphite blocks and they result to be corrosion- and heat-resistant. Plutonium fuel is also maintained in a ceramic state that is heat-resistant so as to minimize the risk of vaporization.

However, although the incidents in the nuclear power probes were not so serious (and found to be small), NASA decided to abandon the radioisotope generators, opting instead for a type of much more ecological source of energy. One of the main reasons of the abandonment of nuclear energy was in fact given by the risk of contaminating the landing site. In later expeditions, it was decided to change the fuel to other systems which could have no effect on the planet. In particular, a perfect example of this decision is the Mars Exploration Rover exploration, landed on Mars without using of nuclear energy, but only by an innovative system of airbags that cushioned the fall.

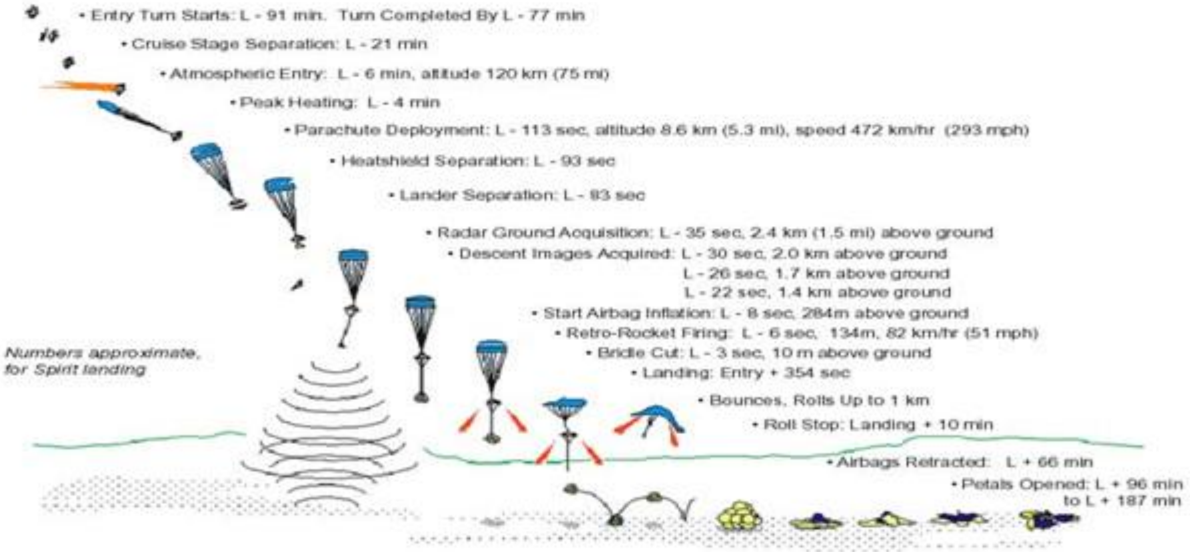

Fig. 3 – *Spirit entry descent landing*

Anyway, both expeditions were realized thanks to the use of powerful solar panels, capable of giving both the lander and rover enough energy to play all major functions provided, including movements, soil analysis,

When fully illuminated, solar panels generated about 140 watts of power for a maximum of four hours per sol (a Martian day). A rover needed about 100 watts to drive. Comparatively, the solar arrays of the Sojourner rover used in the 1997 Pathfinder expedition could supply around 16 watts of power at noon on Mars. Sojourner was also equipped with non-rechargeable lithium batteries, which could provide an output of 300 watt hours, mainly as each night situation required. In 1997 there were not available rechargeable batteries with the reliability required for a space expedition in weight and cost limits imposed by NASA's Discovery program [4].

The electrical power provided by a solar panel of 0.3 m^2 is over 14 W on Mars, during the four hours around noon [5]. Nevertheless, the efficiency of the solar energy on the Martian surface depends on the amount of dust in the atmosphere [6]. The suspended atmospheric dust in Martian atmosphere consists of both a long-term dust and also dust storms, which temporarily add a large loading of dust into the atmosphere. Dust storms can be local storms, of a few days, regional storms, covering a larger area, or "global" storms, which spread from the southern hemisphere during the southern hemisphere summer and can last for several months.

Dust deposition on the solar arrays was measured during the performance of the Pathfinder expedition at a rate of 0.28% per sol during the initial 30 sols of the expedition [7]. Further measurements were carried out on the MER expedition [8].

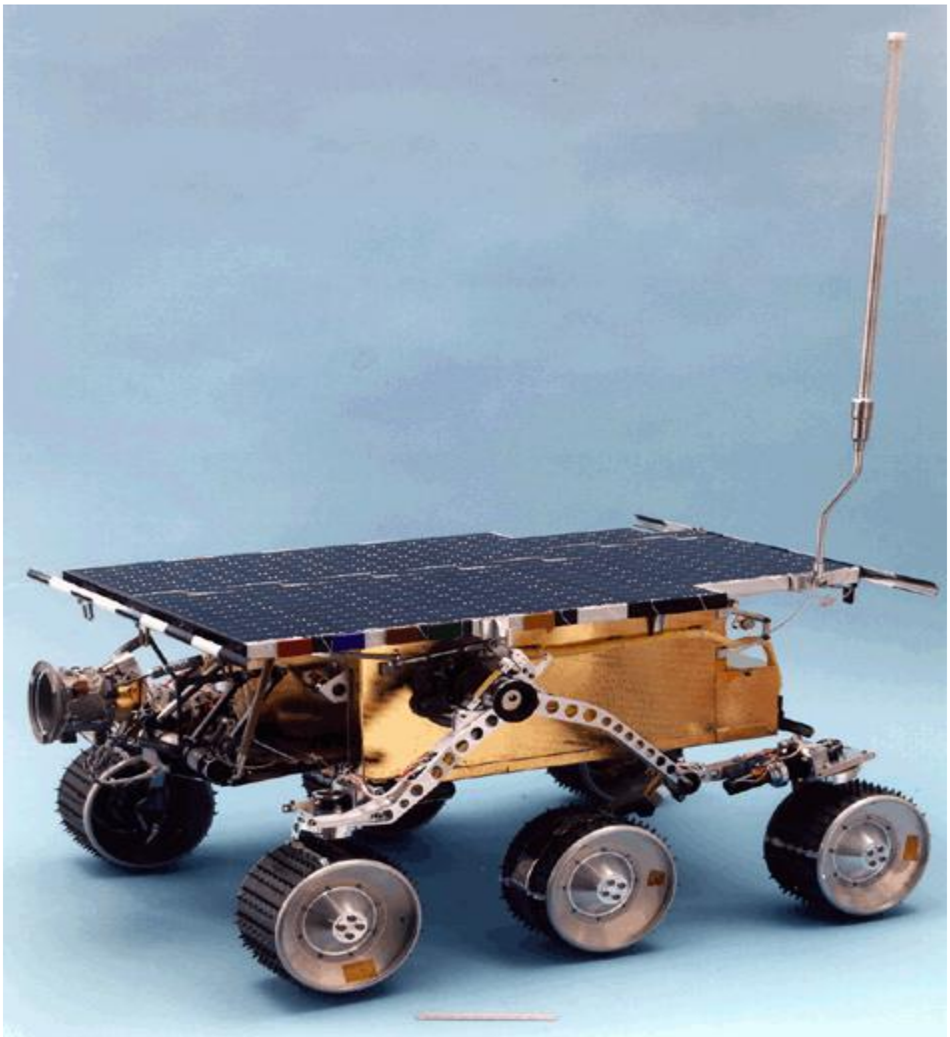

Fig. 4 – *Sojourner*

The power system of the Mars Exploration Rover included two rechargeable batteries, weighing 7 kg each, which would have to recharge by solar power, so the rover could operate even in extreme conditions with little presence of light (at night or in presence of strong dust storms). Scientists were not sure about the degradation of the batteries, because the lower energy of the solar panels - covered with dust - could not fully charge the batteries. They believed also in the ability of the solar panels to generate energy after 90 sols provided for the Martian expedition would probably be reduced to about 50 watts of power, precisely because of the layer of dust which obscured the panels from the sun (as it happened on the Mars Pathfinder Sojourner rover). Indeed, NASA scientists had predicted that the duration of the entire expedition was approximately of 90 days, whereas both the rover Spirit (MER-A) and Opportunity (MER-B) could not overcome the third month of its activity. These specifications have been largely superseded as Spirit continued to operate on the Martian surface for all 2006 (the probe had landed on Mars in January 2004). On 4th January 2010 the rover Spirit celebrated the 6 years of its activity on the Martian surface, showing an amazing resistance to weather conditions that occurred on the planet. Spirit was in contact with the Earth until 22nd March 2010. Operation Spirit was then declared closed by Nasa on 25th May 2011, unlike the rover Opportunity, which is still actually active, being considered as the expedition with the longest operation on the planet Mars. The success of this mission is mainly due to the excellent solar panels, capable of storing energy and recharging the batteries even in unfavourable weather conditions (sand deposited on the panels during storms).

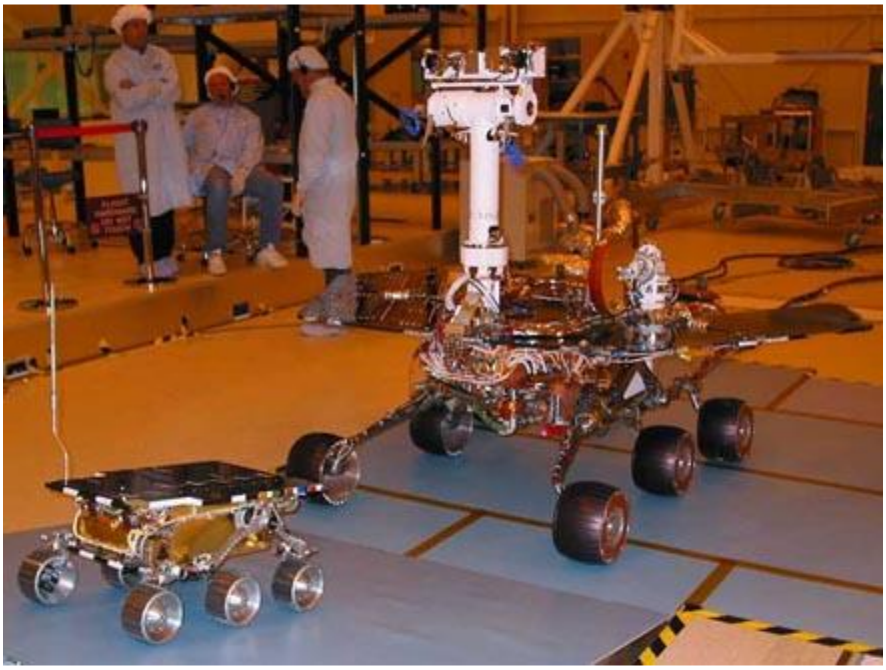

Fig. 5 - *Sojourner and Spirit*

Next Martian expedition (the landing of the probe containing the rover Curiosity is planned for the first months of 2012) is called the Mars Science Laboratory. It will mark the return of nuclear power, with a new landing system. In fact, the considerable weight of the rover (about 900 kg, unlike Spirit and Opportunity which weighed 185) has forced scientists to abandon the idea of a landing using rockets, airbags and parachutes for deceleration, due to a too thin atmosphere for effective use of these braking systems [9].

Curiosity will be powered by radioisotope thermoelectric generators (RTGs), as used by the successful Mars landers Viking 1 and Viking 2 in 1976 [10] [11]. Curiosity's power source will use the latest RTG generation built by Boeing, called the "Multi-Mission Radioisotope Thermoelectric Generator" or MMRTG.[12] Based on classical RTG technology, it represents a more flexible and compact development step [12] and is designed to produce 125 watts of electrical power from about 2000 watts of thermal power at the start of the mission [10][11]. The MMRTG produces less power over time as its plutonium fuel decays: at its minimum lifetime of 14 years, electrical power output is down to 100 watts [13][14]. The MSL will generate 2.5 kilowatt hours per day compared to the Mars Exploration Rovers which can generate about 0.6 kilowatt hours per day [15].

Fig. 6 – *The MMRTG that will power Curiosity*

III. Martian atmospheric density

The Red Planet is substantially exposed to the hardest elements of space weather. Unlike the Earth, which is inside a protective magnetic bubble called magnetosphere, Mars does not have a global magnetic field to protect itself from solar flares and cosmic rays. While the causes of this phenomenon are not still clear, scientist agree on the fact that that the internal magnetic dynamo of the planet turned off about 4 billion years ago. After that, the solar wind gradually has been eroding the Martian atmosphere up to now, making it less than 1% as thick as the Earth's.

Mars' atmosphere is composed by 95% of carbon dioxide, by nearly 3% of nitrogen, and by nearly 2% of argon with trace quantities of oxygen, carbon monoxide, water vapor, ozone, other trace gases. Because of its chemical composition, the atmosphere doesn’t protect the planet from energetic protons. The Martian air density at "sea level" is roughly equivalent to that of the Earth's atmosphere at 70,000 feet altitude.

The variations of the atmospheric properties on mars extend upward from the surface. The sun heats the surface and some of this heat warms the gas near the surface. The heated gas starts to spread in the atmosphere. Thus, the gas temperature is highest near the surface and decreases as altitude increases. In fact, as well as on the Earth, the atmospheric pressure and density decrease with altitude.

The analysis and observations carried out by Mars Pathfinder on density, temperature and pressure of the planet Mars made it possible for many scientists to reconstruct with precision the general profile of the atmosphere, describing it with great accuracy and detail. In particular, Schofield et al. [16] analyzed the data reported by Mars Pathfinder probe (measured from the ground to 160 km above the surface) and compared them with the same values reported by Viking 1: very similar results were registered, except for higher altitudes (over 80 km), where the Mars Pathfinder atmospheric density showed a lower value (for at least a factor of 10) than Viking 1.

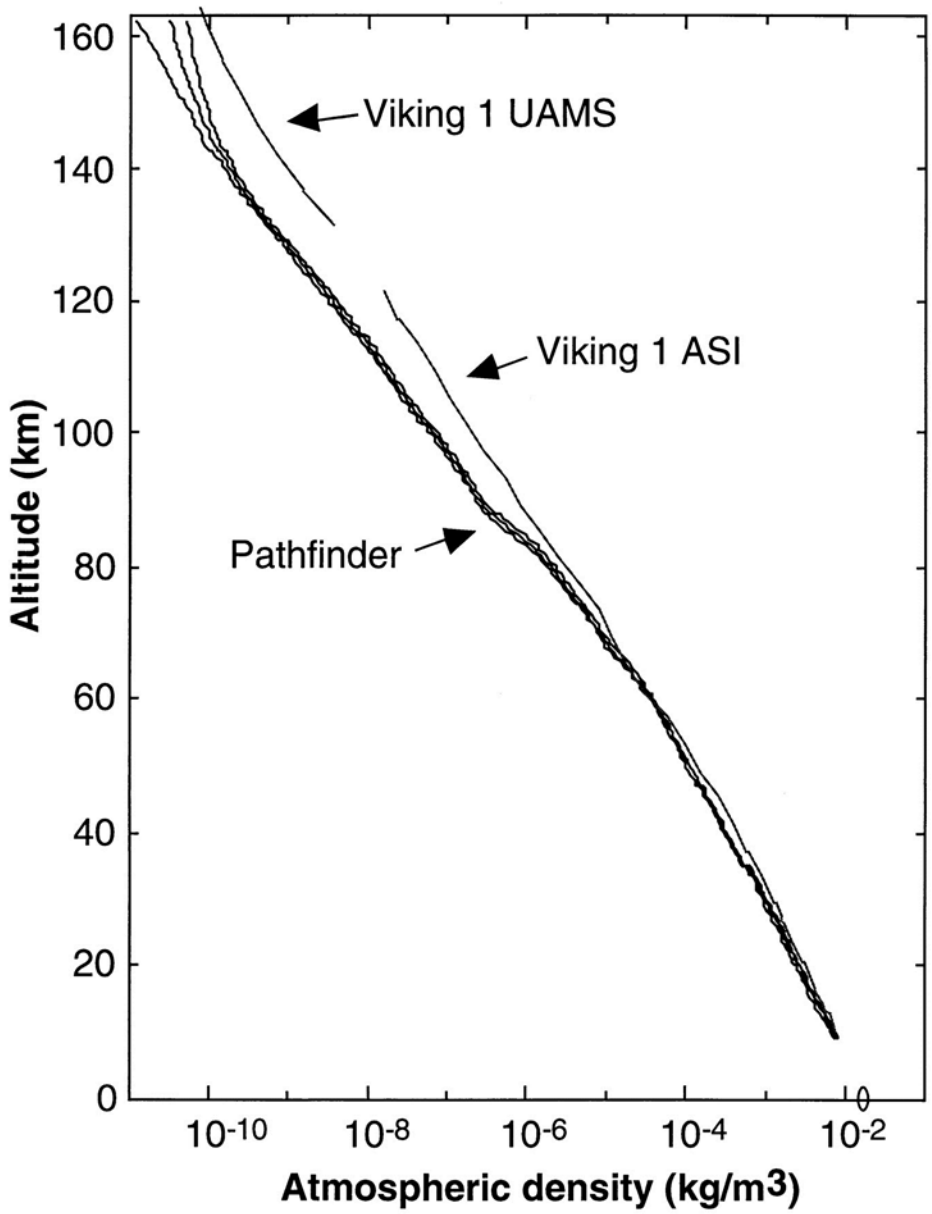

Fig. 7 - *The atmospheric density profile The solid lines give the mean atmospheric density profile derived from the accelerometer data and profiles reflecting ±2σ uncertainties in density based on uncertainties in the entry velocity and the finite digital resolution of the instrument*.

These values can vary on the surface of Mars, due to the range of temperatures (from 27 ºC in summer during the day to –133 ºC in winter at the pole).

In 1998, Tracadas at al. [17] presented a measurement of the density of the Martian atmosphere between 170 and 180 km above the surface for a period of 6 months, when the solar cycle was beginning to rise up from the minimum of its activity. These measurements were made during the orbital decay of the Mars Global Surveyor (MGS) spacecraft, during its Science Phasing Orbits (SPO) (from April to September 1998) using X band Doppler tracking observation. The registered data showed that, depending on the measurement period and also on the site where the measurement was made, at a height of 175 km above the surface, the density of the atmosphere varied between 0.018 and 0.025 kg/km^3.

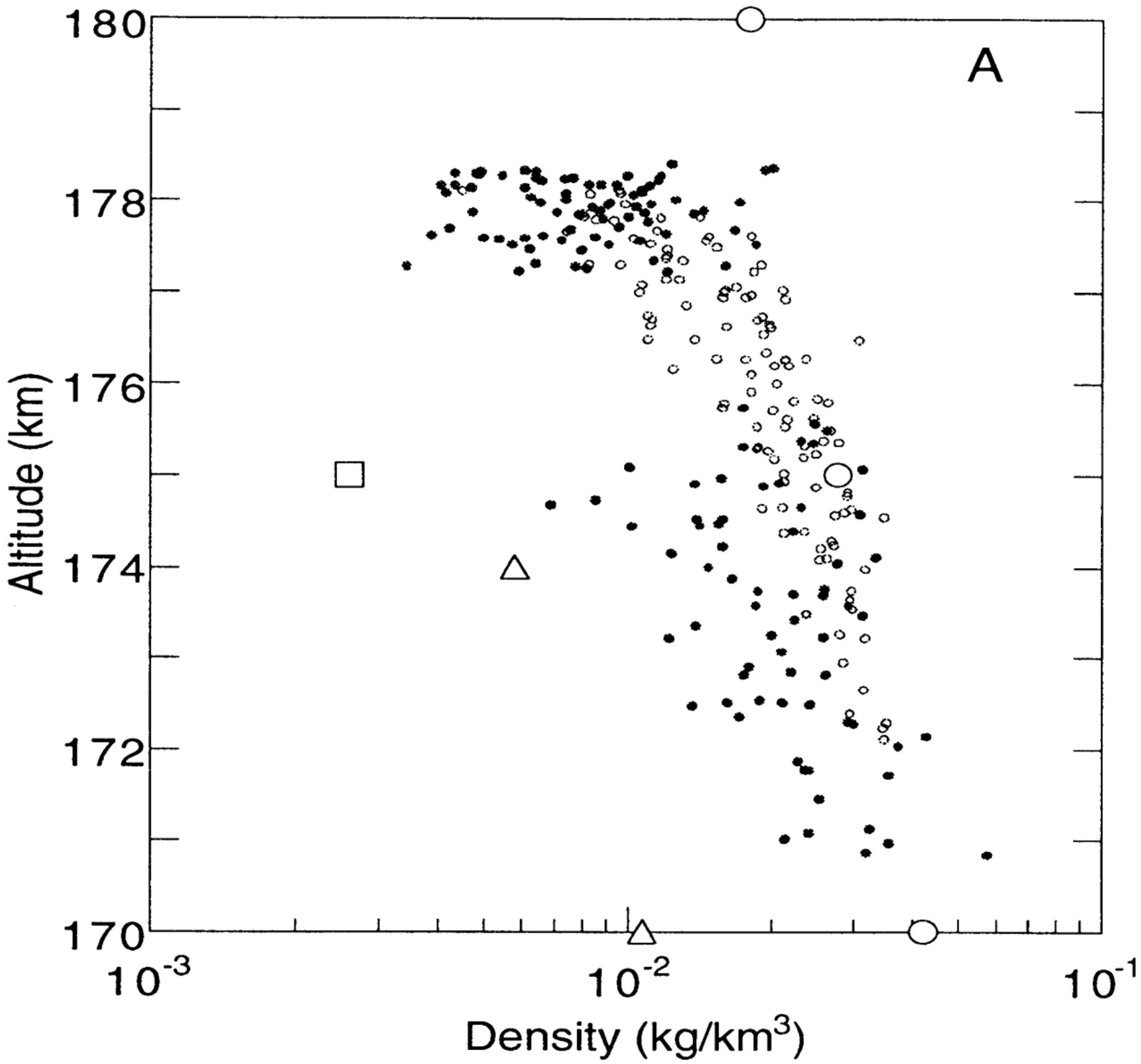

Fig. 8 - *Measured density structure of the Martian thermosphere (from[17])*

Jerolmack et al. [18] suggested a value of around 0.02 kg/m^3 for Martian air density and performed several analysis of the Martian wind, based on the shape of sand dunes and depressions on the surface of the Red Planet.

Using Matlab (see on following pages), we reported on a graph the calculations made by NASA about the changes in density with increasing height from the ground [19]. To help designers of spacecraft, scientists defined a mathematical model of the Martian atmosphere in order to understand the effects of changes in altitude. The model was developed thanks to the measurements acquired in the Martian atmosphere from Mars Global Surveyor in April 1996. Based on these calculations, it was possible to trace the values of temperature, pressure and density altitude, evaluating two different levels of altitude above and below 7,000 meters.

The model has two zones with separate curve fits for the lower atmosphere and from the upper one. The lower atmosphere runs from the surface of Mars to 7,000 meters. In the lower atmosphere, the temperature decreases linearly and the pressure decreases exponentially. The rate of temperature decrease is called lapse rate. For the temperature T and the pressure p, the metric units of the curve fits of lower atmosphere are:

- $T = -31 - 0.000998 * h$
- $p = 0.699 * \exp(-0.00009 * h)$

where the temperature is given in Celsius degrees, the pressure in kilo-Pascals, and h is the altitude in meters. The upper stratosphere model is indicates the values for altitudes above 7,000 meters. Also in this model, as in the lower atmosphere, the temperature decreases linearly and the pressure decreases exponentially. The metric units curve fits for the upper atmosphere are:

- T = -23.4 - 0.00222 * h
- p = 0.699 * exp(-0.00009 * h)

In each zone the density r is calculated with the equation of state:

- r = p / [0.1921 * (T + 273.1)]

We can therefore say, that the calculations confirm the data above-mentioned: in fact, near the ground (considering an altitude of 1 meter from the surface), the results of the Nasa model reveal an atmospheric density of 0,015 kg/m^3, very similar to the values already considered by Jerolmack et al. [18] and above-mentioned (0.02 kg/m^3).

IV. Wind speed on Mars

Since the sending of the first space probes on the Red Planet, the study of wind speed on Mars has been at the centre of many debates by researchers and scientists. Several assumptions have been made in this regard, often with completely different results.. In fact, the study of Martian wind has never been the main aim of any Martian exploration campaign, because the main interest of NASA (but also of the Soviet Union) has always been addressed to the analysis of the soil, in particular to look for the presence of water. None of the rover sent on the planet has ever been equipped with an anemometer aimed to measure with precision the actual speed of the wind, therefore the information obtained about wind are mainly hypothetical, derived from calculations made in laboratory and not directly on the Martian surface.

However, it is only thanks to the several images sent by the various probes equipped with camera that it has been possible to verify the real presence of the wind on the surface: the spacecraft sensors have often photographed the dust storm and tornadoes, which occur frequently, as well as clearer images of the ground, which show a planet covered in large part by sand dunes similar to those of the deserts of the Earth, and altered by the wind.

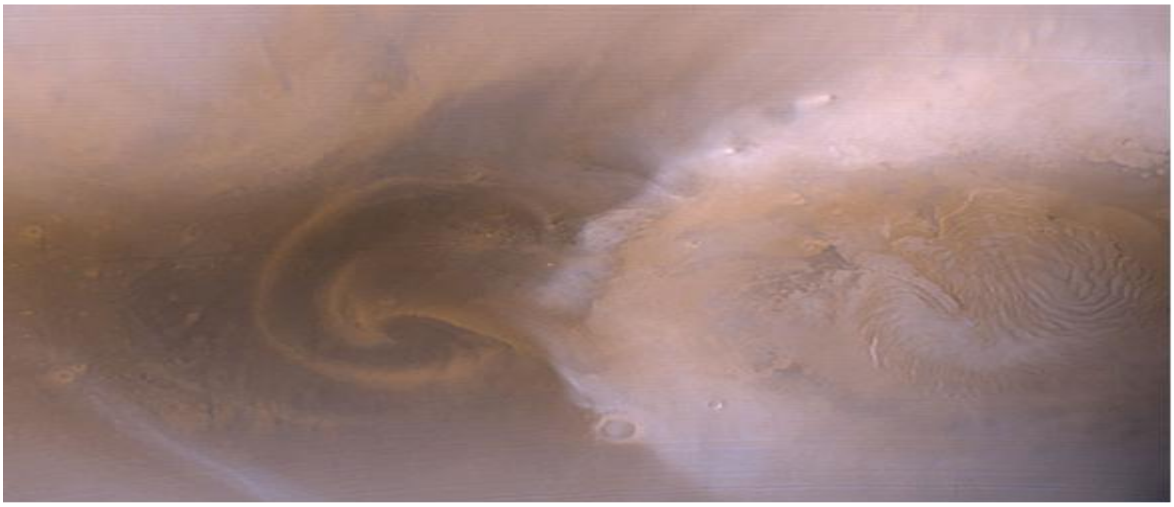

Fig. 9 - *A polar Martian dust storm photographed by Mars Global Surveyor while it was erupting out from the north polar cap of Mars. Such dust storms are not uncommon as summer comes in the north. The white material is frozen carbon dioxide which covers much of the extreme north. A strong central jet, about 900 kilometers long, which is creating symmetric swirling vortices is visible in the storm (from: [20]).*

As already mentioned in the previous chapter, atmospheric density of Mars is about 1% of the atmospheric density of the Earth, mainly because the Martian atmosphere is almost entirely composed of carbon dioxide, while the Earth's atmosphere is a mixture of 78% nitrogen and 21% oxygen. That means the wind on Mars has to be blowing a 100 times faster than the wind on Earth to have the same momentum, being the momentum of the wind the product of its density (the mass of the molecules in the wind added together, in reality) and its velocity.

Many Martian storms have passed by rovers and landers. In fact, some of them have helped their missions, as they removed dust settled on solar panels, particularly during planet-wide dust storms. Mars is dryer and colder than the Earth, and in consequence dust raised by these winds tends to remain in the atmosphere longer than on Earth as there is no precipitation to wash it away. The surface of Mars has a very low thermal inertia, which means it heats quickly when the sun shines on it. Typical daily temperature swings, away from the polar regions, are around 100 K.

On Earth, winds often rise in areas where thermal inertia changes suddenly, such as from sea to land. There are no seas on Mars, but there are areas where the thermal inertia of the soil changes, leading to morning and evening winds similar to the sea breezes on Earth.

When the Mariner 9 probe arrived at Mars in 1971, the world expected to see extremely clear new pictures of surface details. Instead they saw a planet-wide dust storm with only the giant volcano Olympus Mons showing above the haze. The storm lasted for a month, and scientists observed that during those global dust storms the diurnal temperature range narrowed sharply, from fifty degrees to only about ten degrees. On the contrary, wind velocities appear to change very at a considerable high rate: in fact, within only an hour of the storm's arrival they increased to 17 meters per second, with gusts up to 26 meters per second.

The landscape seen by Opportunity (Mars Exploration Rover) at Meridiani Planum (a plain situated near the equator of Mars) was dominated by aeolian (wind-blown) ripples at intervals, with a surface basically composed of hematitic spherules and fragments. These ripples show an ordered grain size, with well sorted coarse grained crests and poorly sorted finer grained troughs. These ripples were the most common bed form encountered by Opportunity in its passage from Eagle Crater to Endurance Crater, and they differ from more common aeolian features for having crests made of very large grains while troughs consist of much finer material.

Fig. 10a - *Coarse-grained ripples at Meridiani Planum (from: [18]).*

Fig. 10b - *Image showing typical coarse-grained ripples (from: [18]).*

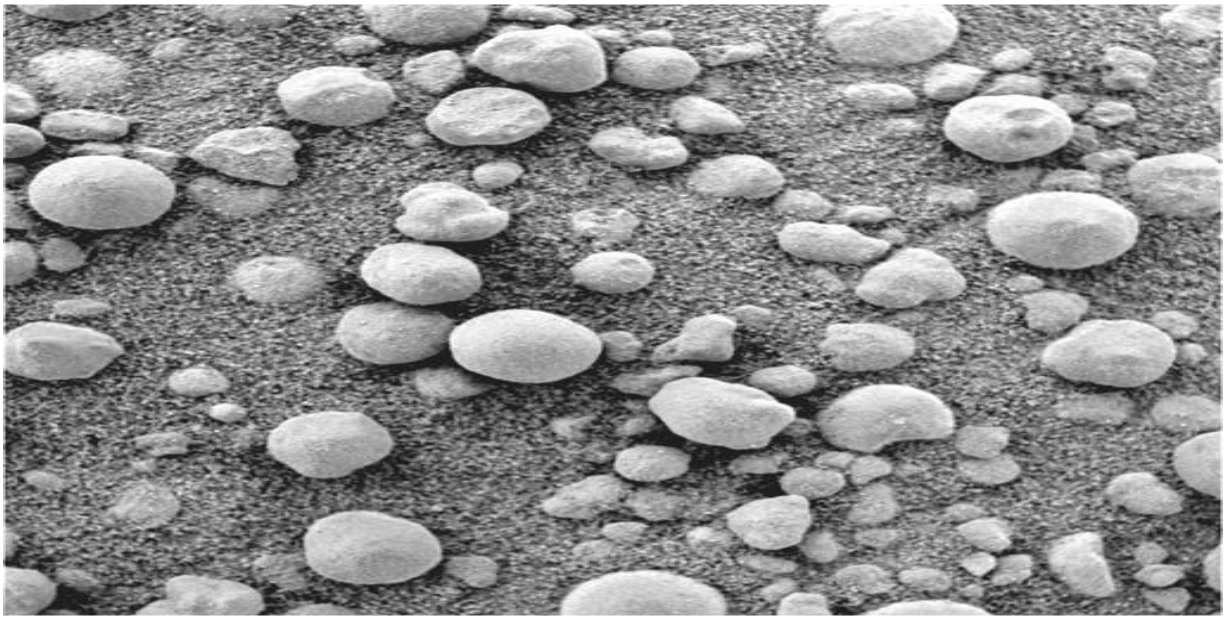

Fig. 10c - *Image of typical inter-ripple zone showing hematitic spherules and fragments, and basaltic sand matrix (from: [18]).*

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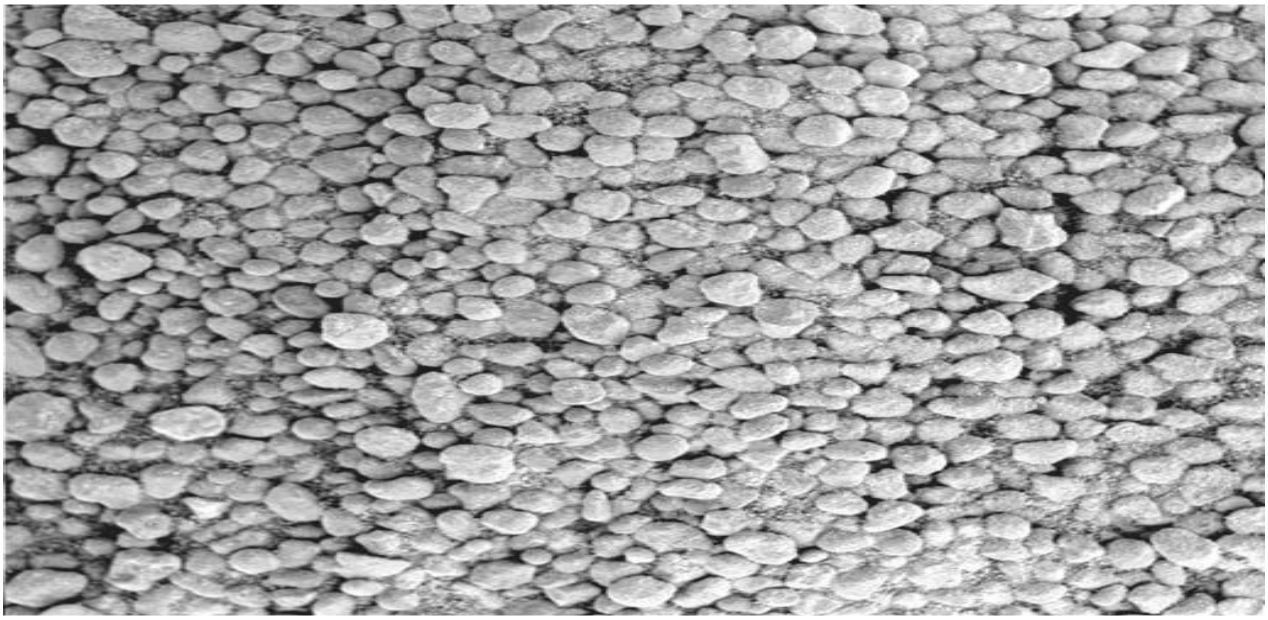

Fig. 10d - *Image of typical coarse-grained ripple* crests *showing monolayer of hematitic fragment. (from: [18]).*

On the basis of the work of Jerolmack et al. [18] it has been possible to determine how surface deposits of coarse-grained ripples can be used to obtain information on wind conditions on Mars surface. Opportunity’s track between Eagle and Endurance craters has revealed that the concentration of fragments and hematitic sediment may not just be the result of simple breeze; rather, these particles seem to create marked and different forms on the surface, suggesting that lateral transport has been an additional, or even dominant, factor in their organisation. Hematitic spherules are quite still owing to their large size, and hence don't migrate to ripple crests: in fact, ripple crest grains have a diameter 6 times higher than the largest basaltic grains in ripple troughs, which therefore can't move without strong winds. At the Opportunity landing site, wind moved particles erasing the edges of the craters and filling them with loose sediment, sculpting moreover bedrock because of the exposure to sandblasting. Open field measurements were performed at White Sands National Monument (New Mexico), showing that shaping Meridiani Planum coarse-grained ripples requires a wind speed of 70 m/s (at a reference elevation of 1 m above the surface). From the images by the Mars Orbiter Camera (MOC) of dust streaks, scientists estimated that surface winds reach a speed of at least 40 m/s and hence may form these ripples just occasionally. Also the conditions that would be required to move the hematitic spherules situated in the inter-ripple zones have been considered, estimating a wind velocity of at least 108 m/s.

Greeley et al. [21] analyzed the wind processes on Mars through the use of a special wind tunnel. In particular, it was proved that it is necessary a wind speed of at least 111 m/s to move the grains of sand on flat surfaces, while lower velocities would be required in regions of high surface roughness, which could be zones of origin for some Martian dust storms.

In conclusion, it can be assumed that, although Martian atmosphere is very rarefied, winds are capable of high velocities, driven by temperature differences between sunny and dark areas, as well as winter and summer regions. Mars is definitely a windy planet: winds are created by air being heated near and around the surface, then rising and moving towards the poles. This is the same general pattern for winds on the Earth. The planet's rotation causes the Coriolis effect which deflects the winds so that they blow around the planet, parallel to the equator in particular. From satellites, orbiting around Mars and rovers on the surface, clouds can be clearly seen, as well a storms, which blow across large parts of the planet. Martian landscape shows signs of wind erosion and, thanks to the explorations, it was possible to observe the shape of shifting dunes and filled-dust craters. Small tornadoes or whirlwinds, known as dust vortexes, frequently move throughout the planet's surface. Regular small local dust storms, similar to those observed in the deserts of Earth, often grow into enormous tornadoes which invade the planet for months.

References

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