THE MEDUSA (MARTIAN ENVIRONMENTAL DUST SYSTEMATIC ANALYSER) EXPERIMENT FOR THE MONITORING OF DUST AND WATER VAPOUR IN THE LOWER ATMOSPHERE OF MARS

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Introduction:

Dust and water vapour are fundamental components of Martian atmosphere. In view of tracing the past environmental conditions on Mars, that possibly favoured the appearing of life forms, it is important to study the present climate and its evolution, on which dust and water vapour have (and have had) strong influence. Moreover, in view of the exploration of the planet with automated systems and, later, by manned missions, it is of primary importance to analyse the hazard conditions linked to the quantity and physical-chemical properties of dust and abundance of water vapour dispersed in atmosphere and their exchange with surface. The instrument MEDUSA (Martian Environmental DUst Systematic Analyser) has been designed to measure directly and quantitatively in situ the cumulative dust mass flux and dust deposition rate, the physical and electrification properties, the size distribution of intercepted particles and the water vapour abundance versus time, a goal that has never been reached so far. MEDUSA is suitable to be accommodate in the payload of a rover or a lander of a space mission on Mars (e.g. Exomars).

Why studying water vapour in the lower atmosphere :

Although water vapour is a minor constituent of the Martian atmosphere it plays a fundamental role and it is important as indicator of seasonal climate changes. Moreover, the interest about the water cycle on local and global scales is linked to the fundamental function that water could have played in relation to the existence of living organisms on Mars. The presence of liquid water on Mars surface is improbable nowadays, as the typical value of the pressure at the surface is close to the triple point, making it difficult even a temporary persistence of liquid water at surface level. Despite the low abundance (0.03% volume fraction in atmosphere), water vapour often reaches the saturation point, due to the cold environment, that reduces the water vapour retention capability of the atmosphere. Thus, water vapour condenses to the solid state directly (due to the surface pressure close to 6.1 mbar, the triple point of water). The atmosphere layer immediately above the surface can warm up considerably due to solar radiation, equalling a typical spring day temperature on Earth. However, temperatures are sub-freezing just a few tens of centimetres above the surface, due to the low thermal conductivity of atmosphere, and water vapour, confined in the warm air layer above surface, reaches saturation. As long as the temperature increases with solar elevation, the surface water ice may melt, but its evaporation is restricted by the status of the overlying atmosphere. These conditions may imply the temporary presence of liquid water on the surface. Finally, as the atmospheric temperature increases further (with Sun elevation), the remaining water and ice evaporate. Actually, high-resolution images by the MGS - Mars Orbiter Camera (MOC) showed evidence of geomorphic features that can be explained by processes associated with "recent" groundwater seepage and surface runoff of liquid water (Malin and Edgett, 2000). Despite this scenario, most probably the soil has not been moistened with enough water to sustain micro-organisms. Martian "life" might, however, be / have been deep under surface or near the most recent volcanic areas where liquid water might be / have been present in hot springs or hydro-thermal systems. In this context it is of paramount importance:

- to study the evolution of the water vapour content close to the surface;
- to relate atmospheric water vapour content to surface sources and sinks.

This information is required in order to clarify the mechanisms of interaction and exchange of H_2O between surface and lower atmosphere, in view of the existence of a possible "humus" favourable for the life existence. An innovative approach that can provide quantitative information is performing in situ measurements of water vapour abundance as a function of time.

Why studying dust in the lower atmosphere:

Martian atmosphere contains a significant load of suspended dust, whose amount varies with seasons, but never drops entirely to zero (constant haze). Airborne dust impacts on the climate of Mars and, probably, it played a role in the past evolution of climatic conditions and surface characteristics. Its amount and distribution affects the thermal structure and circulation of atmosphere on diurnal, seasonal and annual time-scales.

The cycle of dust on Mars determines the dynamic and thermodynamic evolution of atmosphere and is strongly correlated to the seasonal variations of CO_2 and water vapour. Atmospheric grains are likely to act as catalysts in the condensation of water and CO_2 in the atmosphere and water ice cloud formation. Aerosol dust influences the thermal behaviour of the troposphere by absorbing/scattering solar radiation and reduces the diurnal thermal excursion, by increasing the atmospheric thermal inertia. The occurrence of dust storms is somehow controlled by the surface pressure and CO_2 variations. Dust storms ignition requires a feedback from atmospheric dust, in terms of dynamics and heating. Dust devils are another interesting atmospheric phenomenon associated to vortical winds capable to lift surface dust. Several of these vortices were identified by the Viking Lander and have been observed by Mars Pathfinder (Metzger et al, 1999). Several open questions concern physical and dynamic properties of atmospheric dust, that impact on Martian climate and, thus, on the boundary conditions that could have brought to the preservation of life forms.

Moreover, aeolian erosion, redistribution of dust on the surface and weathering are mechanisms which couple surface and atmospheric evolution. The exchanges occur in the planetary boundary layer, i.e. the turbulent region from surface to a few hundred meters height. Dust suspended in the atmosphere is a major agent of atmospheric motions at all scales and had great influence on the morphological evolution of the Martian surface. In the present Martian environment, the most active surface modifying agents are the wind and the windblown dust. The mechanisms are driven by the wind intensity and the grain size distribution. So far, only qualitative information has been obtained on dust injection, transport and removal mechanisms that control atmosphere - surface exchanges. Particles moved by the wind range from sub-micron sizes, for suspended dust, to perhaps as large as 1 cm in diameter. The data available so far do not allow us to identify the efficiency of mechanisms proposed for lifting dust. The particle size most easily moved on Mars is the fine sand with diameters of about 100 µm. The observation of dunes and thermal IR spectroscopic data indicate that sand-sized particles are actually present over much of Martian surface. Wind causes these grains to lift off the surface and bounce back several times (saltation) (White, 1979). Saltating sand grains may strike larger grains (< 1 cm) and push them along the surface in creep. Saltation may also "trigger" the injection of smaller particles (suspension) via impacts. Sand-sized aggregated particles can be broken down into smaller particles by collisions. Dust size distribution and abundance are fundamental parameters that influences all mechanisms in which dust is involved (thermal regulation, atmosphere evolution, atmosphere - surface exchanges).

It should be noted that information about the size distribution of atmospheric dust on Mars has been mainly retrieved from light scattering measurements. Results obtained by several authors are summarised in Figure 1 and appear sometime controversial. Several uncertainties affect the obtained results. Remote measurements of dust properties are affected by the presence of diurnally varying ground fogs and higher level water ice hazes (Pollack et al., 1977; Colburn et al., 1989), as well as extensive and possibly more persistent high level ice hazes (Leovy et al., 1972; Anderson and Leovy 1978; Jaquin et al., 1986; Kahn, 1990). In addition, remote sensing measurements made in different parts of the spectrum are sensitive to different particle size ranges and sample different depths in the atmosphere, even for similar viewing geometries and constant climatic conditions.

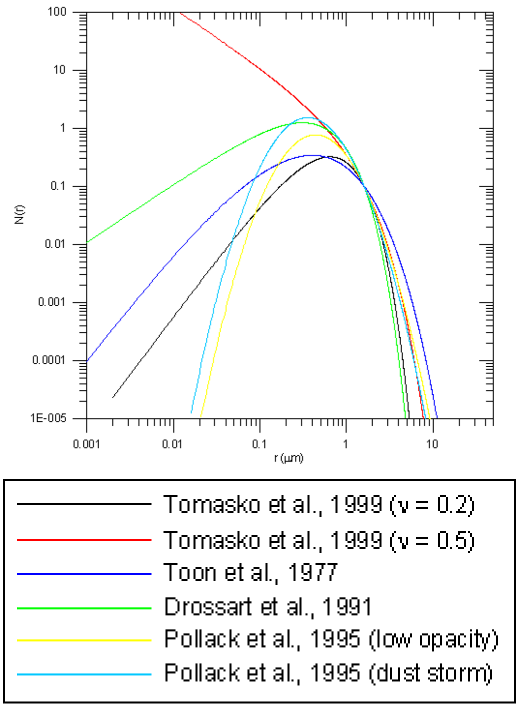

Figure 1. Comparison of dust size distributions in the Mars atmosphere as derived from various authors. Curves are scaled to have N = 0.1 at grain radius r = 1.6 µm.

It should be also noted that the parameters of the size distribution laws are determined from optical data based on assumptions, mainly about the shape of the size distribution (assumed ad hoc) and the optical and morphological properties of the dust. For example, the frequent assumptions of homogeneous composition and spherical shape of particles are

questionable.
As far as the number density of particles in the constant haze is concerned, Moroz et al. (1993) quoted it as n = 1 - 2 cm^{-3} near the Mars surface. This number varies between 1 and 0.2 cm^{-3} in the range of altitudes 15 - 25 km. Above the altitude of about 25 km the dust number density declines sharply. The dust mass density of the Martian atmosphere in standard conditions has been quoted as $1.8 \cdot 10^{-7}$ kg·m^{-3} (Metzger et al., 1999). During a dust devil, instead, the mass concentration rises to $7 \cdot 10^{-5}$ kg·m^{-3} (Metzger, 1999). Also in this case the available data derive from remote observations and information relative to the layers close to the surface are nearly not existing.
It is evident that information available so far about Martian dust size distribution and abundance is rather uncertain (if not lacking) and that only direct in situ measurements can provide a "jump" in their quantitative knowledge.
The role of dust on Mars (and in the atmosphere, in particular) should also be considered from another point of view. In fact, dust is a relevant agent that may interact / interfere with any instrument / system delivered to Mars surface for on ground activities.
Finally, on a longer perspective, a safe human mission to Mars cannot be properly planned without a preliminary proper characterisation of all possible aspects of hazard: dust is among the first elements of concern in this respect. Information on dust properties such as size distribution, abundance and electrification in different atmospheric conditions is essential to evaluate hazard conditions for future missions to Mars surface.
In conclusion, MEDUSA:

- is capable to provide an independent verification of the scientific outcome derived from cameras, spectrometers and analytical instruments about the properties of dust and water vapour content.
- does not directly contribute to the “search for life”, but gives information about climatic (water vapour and dust) conditions and evolution, essential to support search for life.
- addresses problems related to environmental and climatic conditions connected with life on Mars.
- contributes to the identification of hazards to future manned and unmanned missions, related to dust physical and electrification properties and dynamics.
- increases knowledge of the geological evolution at the sites the rover will visit by studying water vapour and dust close to the surface.

Instrument concept:

General requirements to be considered in selecting promising techniques for in situ monitoring of Martian atmospheric dust and water vapour are based on the following criteria:

- heritage and previous experience (e.g. the GIADA instrument aboard ESA Rosetta mission; see Palumbo et al., 1997, Bussoletti et al., 1999, Colangeli et al., 2003; 2004);
- compatibility with a space mission and automated procedures;
- possibility to use in Mars environment;
- optimisation with reference to the science requirements;
- resources minimisation.

Beside meeting all the above criteria, the techniques listed below allow simple and direct detection or measurement of some important dust and volatiles parameters:

1. optical detection
2. impact detection
3. mass measurement for solid or condensable volatiles
4. charge measurement

In support to the above measurements, techniques for proper atmospheric dust sampling and selection have to be considered. The aim of these devices is to avoid biasing effects on sample collection or to select particle dimensions.
As a result, the following basic choices have been taken for MEDUSA:

- A sampling device is used to avoid biasing effects on sample collection and to select particle dimensions;
- A five-stages dust cascade collector is considered integrating an optical detection device, an impact (momentum) sensor and four dust cumulative mass measurement systems. The stages are sensitive to different, subsequent size intervals to cover the required detection range; this configuration allows the best sensitivity coverage, ranging over more than 3 orders of magnitude in grain size (0.01-10 μm).
- Water vapour is detected with high sensitivity through devices similar to those used for dust cumulative mass measurement.
- Dust deposition rate and electrification are determined using six laser-optoelectronic systems measuring the effects of dust electrification and gravity. Dust removal, electrical retardation and wind speed are also measured.

Each of the used techniques used in MEDUSA returns directly important physical parameters of grains and water vapour in the Mars atmosphere as reported in Table 1.

Sensor	Primary output	Derived Output
Optical detector (OS)	Light scattering	Grain shape; grain size; grain optical properties
	Time of flight	
Impact sensor (IS)	Released momentum	Grain mass
OS + IS	Time of flight	Grain speed
Micro-balance (MB)	Dust mass in size range	Grain mass in size range
MB for water	Collected water	

6 lasers + photodiodes + electrical field	Wind; deposition of dust	Wind speed; electrification of dust

Table 1: Output from MEDUSA sensors and derived physical quantities

Starting from the quantities directly measured by MEDUSA, important information is derived about dust and water vapour environment in the lower atmosphere of Mars, as illustrated below.

- *Atmospheric dust particle size distribution*

MEDUSA shall measure the size of atmospheric dust in the wide size range of interest: from 0.01 to 10 µm; complementary techniques covering different size ranges shall be coupled. It shall be possible to detect optically and by impacts single particles ≥ 1 µm in size and to measure the cumulative mass of sub-micron grains selected in pre-defined size ranges. A statistical analysis of the results obtained in a typical run of the instrument shall provide the results reported in Figure 2.

- *Number density of particles vs. size*

This measurement is related to the previous result through the sampling operations. Once particle counting and/or mass measurements have been performed, dust number density can be derived, since the volume sampled by the system is known. From the operational point of view this requires a careful control of the atmospheric volume that is sampled. Due to the poor knowledge of the actual values for dust size distribution and number densities in Martian atmosphere, the instrument has to be versatile and must consider sufficient margins to cope with a wide range of dust properties.

- *Water vapour abundance in the atmosphere*

This measurement is basically independent from the previous ones. The cumulative mass measurement of water vapour condensed on the sensing device in a defined time interval and environment conditions (p, T) provides the water abundance monitoring.

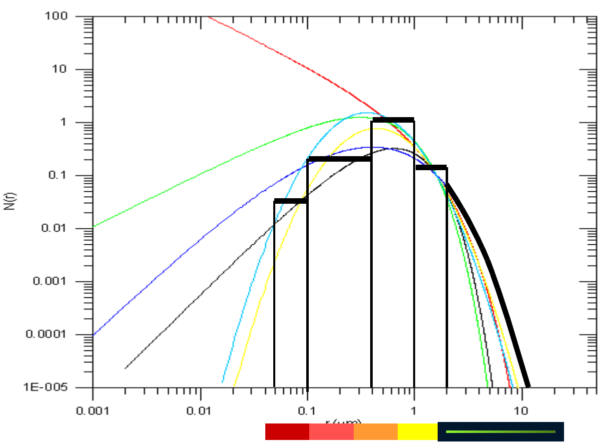

Figure 2: Typical result expected from the statistical analysis of MEDUSA optical, impact and cumulative dust detection. The hypothetical size distribution (normalised grain number N(r) versus grain size r (µm) derived from MEDUSA (black thick line) shall be able to constrain model predictions (colour curves) on size distribution.

- *Dust deposition rate and electrical properties*

Dust deposited on accumulation surfaces is measured by detecting scattered light. Electrical fields are applied to the dust accumulator surface to derive information on dust electrification. As a by product, the wind is derived from light signal variation produced by blowing grains crossing the patterned beam produced by the light sources.

- *Time evolution of the former quantities on long terms (seasons) and short term due to local events (e.g. winds, dust storms)*

This implies mainly operation requirements. The system shall repeat the sampling and analysis of variable amounts of atmosphere. Different environment conditions could result in different dust number densities by orders of magnitude. A sufficient number of sampling runs shall be guaranteed in order to test various Mars conditions.

In addition, the experiment shall be able to perform:

- *Atmospheric dust sampling for other analytical measurements*

The sampled atmospheric dust shall be delivered to other analytical experiments for characterization of chemical and physical dust properties, to be complemented with MEDUSA results.

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