SPEX – A SPECTROPOLARIMETER FOR PLANETARY EXPLORATION ONBOARD THE EXOMARS ORBITER

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ABSTRACT

Despite the recent detailed observations of Mars, surprisingly little is known about the microphysical properties (size, shape, composition) of the dust and cloud particles in the Martian atmosphere. Information on these microphysical properties is crucial for understanding the atmospheric radiative and chemical balances, and the weather and climate system. In addition, knowledge on the dust particles is essential for future exploration missions. The Spectrometer for Planetary EXploration (SPEX) that is being developed by Dutch industry and scientists (Dutch Space, SRON, TNO and the University of Amsterdam) is tailored to study atmospheric aerosol (i.e. cloud and dust) particles.

SPEX is aimed for accomodation on the foreseen ExoMars orbiter platform and provides synergy with instruments on the ExoMars rover and lander. As an exploration instrument, SPEX will give crucial "planetary weather" information for the ExoMars rover and lander as well as for future landers. As a scientific instrument, SPEX will provide information on the optical and microphysical properties of the aerosol particles that cannot be obtained with the planned ExoMars ground-based instrumentation.

1. THE EXOMARS MISSION

[1] Establishing whether life ever existed on Mars, or might even be present today, is an outstanding question of our time. It is also a prerequisite to prepare for future human exploration of the red planet. To address this important objective, ESA plans to launch the ExoMars mission in 2011 (with arrival at Mars in 2013). ExoMars will also develop and demonstrate key technologies needed to extend Europe's capabilities for planetary exploration.

ExoMars will deploy two science elements on the Martian surface: the Pasteur rover and the stationary Geophysics & Environment Package (the GEP). The rover will search for signs of past and present life on Mars, and will characterise the water and geochemical environment by collecting and analysing surface and subsurface samples. The GEP will measure geophysical parameters that are important for understanding Mars's evolution and habitability, identify potential surface hazards to future human missions, and study the environment.

The lander part of the ExoMars mission has fully been approved at the European Ministerial conference for the ESA programme at the end of 2005. The orbiter part of the mission has not been approved yet but is believed to be a high probability candidate because of its science merits and especially from an overall mission success perspective, as it safeguards the critical communication link with the rover. Figure 1.1 shows an artist's impression of the ExoMars orbiter with the descent module and the rover.

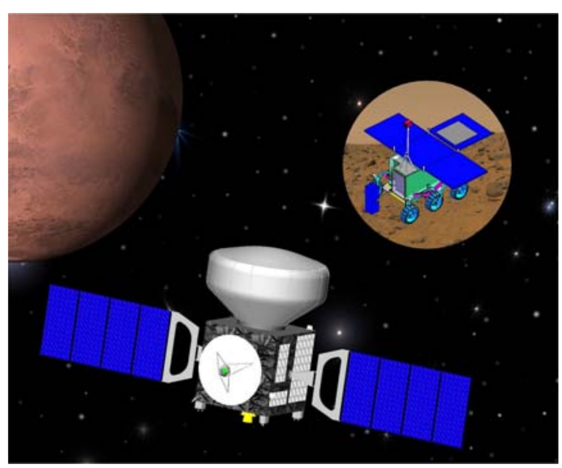

Figure 1.1: Artist's impression of the ExoMars orbiter with descent module and rover (credit: ESA)

The current baseline for communication with the ExoMars rover is NASA's Mars Reconnaisance Orbiter (MRO) which was placed into Mars orbit in March 2006, i.e seven years in advance of the earliest expected arrival of the ExoMars mission, and therefore doubtful for ExoMars service. A decision about the orbiter will be made by the end of 2006.

In support to their search-for-life-experiments, Pasteur and the GEP will have dedicated instrumentation to measure the geological context and the environment. This includes an in-situ dust characterisation experiment and water vapour analysis equipment. The payload(s) on an orbiter should provide synergy with the payload on the surface. As depositing dust could be one of the limiting factors for the lifetime of the rover, it appears to be sensible to propose to measure dust in the Martian atmosphere from orbit during the rover mission.

2. DUST AND CLOUDS IN THE MARTIAN ATMOSPHERE

On Mars, most of the atmospheric aerosol particles are dust particles that are swept up from the surface. Sometimes the airborne dust forms into relatively small, local events, such as the so-called dust devils that can reach altitudes of about 1000 m and that have cross-sections of a few hundred meters. Occasionally, however, regional or even planet encircling dust storms develop within a few days (usually during the Southern spring) that can last for weeks. During such storms, dust particles are lifted up into the Martian stratosphere (i.e. up to altitudes of about 40 km). The amount of airborne dust particles thus varies strongly both in time and in space, causing the colour of the Martian sky to range from bluish (when there is little dust) to orange, as observed by NASA's two Mars Exploration rovers.

Figure 2.1 shows a picture of Martian analogue palagonite particles; dust that was sampled near a Hawaiian volcano by American colleagues at NASA Ames. These particles are considered to be the best representative currently available for dust in the Martian atmosphere and scattering measurements of these particles, performed at the University of Amsterdam, now serve as input for radiative transfer modelling of the Martian atmosphere which include the polarization state of the light.

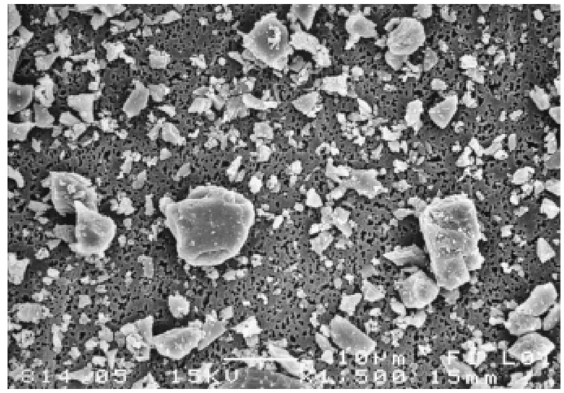

Figure 2.1: Martian analogue palogonite particles

The influence of aerosol particles on a planet and its atmosphere has many facets. To start with, aerosol particles scatter and absorb incoming solar radiation (visual to near-infrared wavelengths), and they absorb and emit thermal radiation, e.g. originating from the planetary surface, (at infrared wavelengths). Through their interaction with radiation, dust particles thus directly influence the planet's radiation and energy balance, as well as its weather and climate. In addition, dust particles can serve as condensation nuclei for atmospheric gases. Most of the clouds that are observed on Mars are cirrus-like ice clouds composed of H_2O-ice crystals. However, clouds of CO_2-ice crystals have also been detected, in particular over the polar ice caps. Figure 2.2 shows CO2-ice particles that formed in a laboratory (they have a bipyramidal shape).

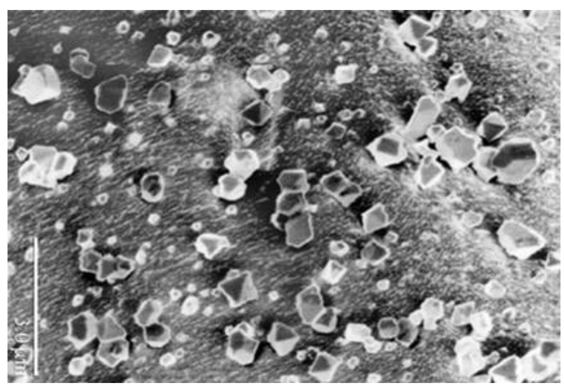

Figure 2.2: CO_2 ice particles (bipyramids)

Even clouds as thin as those found on Mars, play an important role in a planet's climate and radiation balance, because the clouds remove dust and other aerosol particles from the atmosphere. And, just like the aerosol particles themselves, the cloud particles that form on them interact with the radiation in the atmosphere. In addition, clouds provide the vertical and horizontal transport on Mars of condensates, such as water vapour. Interestingly, model studies show that the formation of CO_2 clouds might have limited the development of a greenhouse effect on Mars, a finding that is crucial in understanding the early and current Martian climate.

Aerosol particles and the cloud particles that form on them also influence chemical processes, for example, by providing the surface area for heterogeneous reactions. Recent research has shown that heterogeneous chemical reactions on dust in the Martian atmosphere could significantly decrease the mixing ratio of methane, especially when the dust particles are electrically charged, as happens during dust storms. Without knowledge of the physical properties of the dust particles, methane observations such as those by a PFS-like instrument are thus hard to interpret.

Finally, in view of the Aurora program, studying the Martian dust is important for landing and habitability considerations, as not only the dust storms themselves but also the electrical discharges that can occur in them are potential hazards for human life on the Martian surface

On Earth, the climatic effects of aerosols have been recognized, and the spatial and temporal distribution of aerosol particles, such as soot and Saharan dust, are regularly monitored. Compared to the Earth with its surface pressure of about 1 bar, Mars has a very thin gaseous atmosphere consisting mostly of CO_2 with traces of H_2O: the surface pressure varies between about 0.006 bars during Northern winter to 0.01 bars during Northern summer. In addition, Mars lacks water bodies like oceans, which on Earth are strongly coupled with processes in the atmosphere, and which regulate e.g. temperature changes. As a result, on Mars, aerosol particles are generally thought to have a much larger relative impact on the atmospheric and climate processes than on Earth.

The precise contribution of aerosol particles to an atmosphere's radiation and chemical balances, as well as their role as condensation nuclei in cloud formation processes depends on their number density, their spatial and temporal distribution, and on their microphysical properties, such as their size, shape, and chemical composition or refractive index. A powerful tool for deriving information on the distribution and the microphysical properties of aerosol particles is the observation of sunlight that has been scattered within the planetary atmosphere. On the current Mars missions, there are various instruments that are capable of measuring the reflected sunlight, e.g. PFS and Omega on ESA's Mars Express orbiter. However, these instruments measure only the intensity of the scattered light, not its degree of polarization. The reflected intensity depends both on the amount of particles and on their optical properties, and as such it appears to be very difficult to untangle these two parameters. It should thus come as no surprise that although we now have some knowledge on the optical thicknesses of Martian dust and clouds (mainly derived by using pre-defined aerosol optical properties), there is still very little information on the microphysical properties of the particles.

Despite the important role of dust particles in the Martian atmosphere, surprisingly little is known about their microphysical properties. Consequently, in radiative transfer calculations that are used to interpret observations of Mars, various assumptions are made regarding the dust optical properties. For example, although dust particles on Earth are known to be irregularly shaped (see Figures 2.1 and 2.2), it is common to assume spherical or, more generally, spheroidal shaped dust particles. The optical properties of the particles are then calculated using, respectively, Mie-theory or e.g. the T-matrix method.The optical properties of spheroidal particles, however, differ significantly from those of irregularly shaped particles, even if their composition and/or size distribution is similar. Therefore, assuming spheroidal instead of irregularly shaped particles in radiative transfer calculations that are used to analyse observations, leads to significant errors in retrieved parameters, such as the dust optical thickness and/or the dust particle size distributions.

3. SPECTROPOLARIMETRY

We plan to design our instrument such that we can determine both the spatial distribution and the microphysical properties of atmospheric aerosol particles. We will achieve this by measuring both the intensity and the degree and direction of polarization of the reflected light, for a range of visible to near-infrared wavelengths. In particular the degree of polarization has proven to be very sensitive to the microphysical properties of atmospheric particles. By observing under different angles, we can derive for specific locations, the particle's phase functions in both the intensity and the polarization, the combination of which is very sensitive to the shape and size of the particles. By observing the intensity and polarization across a range of wavelengths, valuable information about the refractive index of the particles will be obtained. The aerosol parameters we will retrieve give information that is unique and complementary to that of other science instruments, both from orbit and on the surface.

Figure 3.1 illustrates the influence of particle shape on the scattered intensity and degree of polarization. The plot on the left shows that for irregularly shaped silicate particles, the dependence of the intensity with the scattering angle is very similar to that for spherical particles. The plot on the right, however, convincingly shows that the scattering angle dependence of the degree of polarization differs strongly between the irregularly and spherically shaped particles. Apparently, polarimetry is a strong and essential tool for reliably deriving the microphysical properties of atmospheric dust and cloud particles.

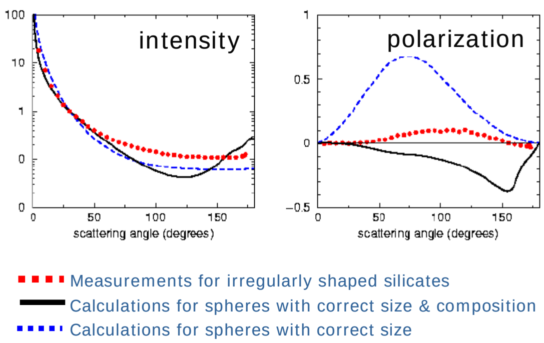

Figure 3.1: Intensity and polarization as function of the scattering angle for irregularly shaped silicates (measurements) and spherical particles (numerical simulations).

4. PRELIMINARY SPECIFICATIONS OF THE SPEX INSTRUMENT

The preferred spectral window for the detection of aerosol particles is the UV-visible. In the 290 nm – 800 nm wavelength region, the optimum conditions are reached both for the reflection of the solar light and for the detection using Silicon-based 2D detector arrays. A compact instrument design can be obtained by employing prisms as dispersive elements, yielding a relatively high spectral resolution of 1.6 nm at 300 nm and of about 26 nm at 800 nm. This resolution strongly limits the data rate in comparison with grating based spectrometers, and avoids overlapping grating orders.

The SPEX optical concept shown in Figure 4.1 consists of three telescopes, placed such to yield maximum angle-dependent information on the aerosol across the scene.

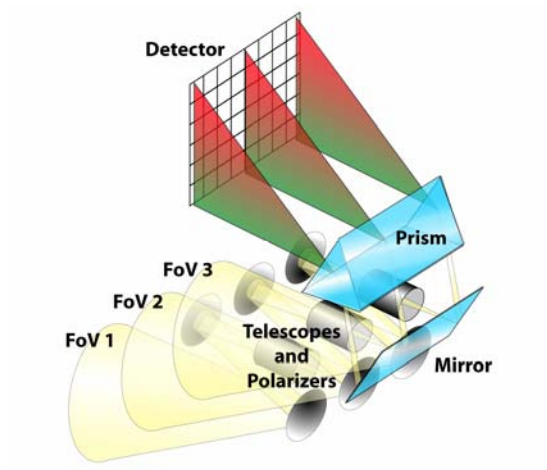

Figure 4.1: Optical concept of the Spectropolarimeter for Planetary EXploration

Each telescope system consists of a primary mirror which provides a telecentric beam on a slit. Behind the slit, efficient polarisation selection could occur by employing a stack of Brewster angle prisms, which, in a very wide wavelength band, effectively transmit light of a particular linear polarisation direction. The beams could next be imaged onto a single collimator for wavelength dispersion.

For detection and readout, a single detector instrument is proposed for the strawman instrument concept. The typical size of the detector would be 1024x1024 pixels. Employing CMOS technology would lead to less read-out electronics compared to CCD technology detectors.

On the square detector, all spectra of the three viewing angles and polarization directions will be imaged. In one image direction, the spatial information will be present, while the other direction will show the wavelength window. Each spectrum will be highly oversampled in the visible part of the spectrum. Co-adding data increases the signal-to-noise ratio, while reducing the data rate. In the spatial direction, the detector allows a swath of some 300 spatial pixels.

The orbit that will be chosen for an ExoMars orbiter will have a significant impact on the exact spatial resolution and coverage that can be accomplished with the SPEX instrument. For high coverage and small groundpixels, a Low Mars Orbit (LMO) is required. This allows a groundpixel resolution of about 5-10 km. Figures 4.2 and 4.3 show some global coverage statistics for sun-synchronous orbits around Mars. Figure 4.2 shows the global coverage time as a function of satellite altitude and total instrument Field Of View (FOV) in a push-broom mode.

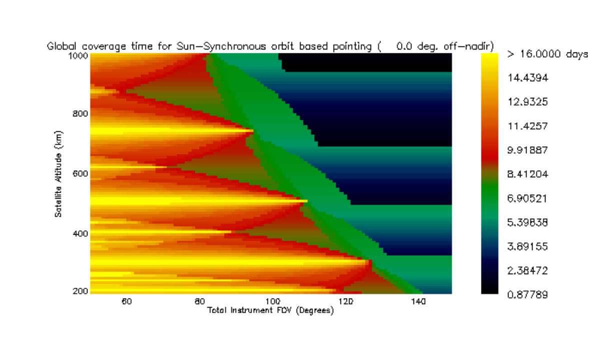

Figure 4.2: Global coverage time for a sun-synchronous circular orbit around Mars as a function of satellite altitude and total instrument FOV in a push-broom mode.

It is clear from Figure 4.2 that a large FOV combined with a high satellite altitude provides the best global coverage time, although it will compromise a compact telescope design and limited aperture, needed for a spatial resolution down to 5 km. Obviously, there are other attractive combinations of satellite altitude and instrument FOV that could be used. For example, at a satellite altitude of 600 km and a total FOV of 80 degrees, a global coverage time of about 4 days can be achieved.

Figure 4.3 shows the daily global coverage percentage as a function of the satellite altitude and total instrument FOV in push-broom mode. It shows that for the previously used example of a satellite altitude of 600 km and a total instrument FOV of 80 degrees, 80 % of the Martian surface can be monitored in a single day.

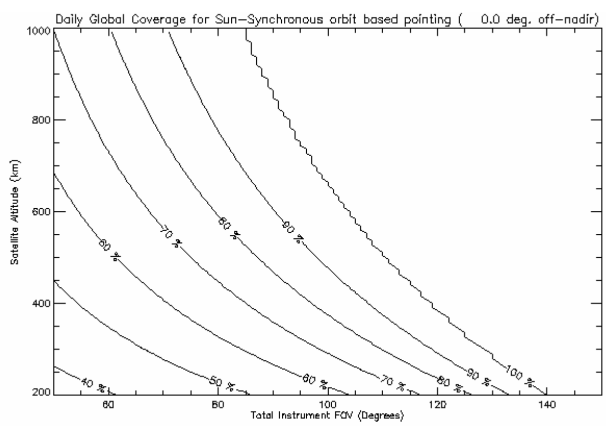

Figure 4.3: Daily global coverage percentage for a sun-synchronous circular orbit around Mars as a function of satellite altitude and total instrument FOV in push-broom mode

Although a circular orbit is advantageous for coverage and spatial resolution, circularizing the orbit from an interplanetary orbit injection is highly demanding for the fuel budget of the spacecraft to be inserted into Mars orbit. Nevertheless, an elliptical orbit (as the Mars Express orbit) could also provide some advantages.

Figure 4.4 shows a picture of a total instrument FOV of only 32 degrees from an apocenter altitude of 9000 km. It is clear that the entire width of the Martian globe can be observed in a single observation.

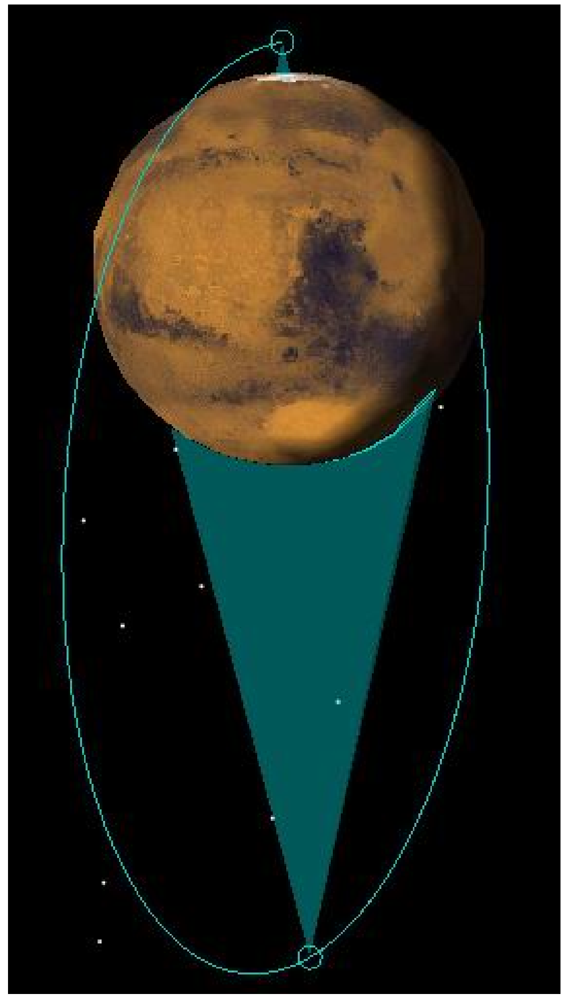

Figure 4.4: FOV of 32 degrees from an apocenter altitude of 9000 km

Using such a highly elliptical orbit, the spatial resolution varies between 3-5 km per ground pixel, when the orbiter is at the pericenter (at an altitude of 300-500 km), and about 100 km, when the orbiter is at the apocenter (at about 10000 km of altitude). Such an orbit would provide both the opportunity to do detailed observations, at either the northern or southern hemisphere, and the option to get a global overview, at the other hemisphere.

5. CONCLUDING REMARKS

SPEX (Spectropolarimeter for Planetary Exploration) is a compact spectropolarimeter to study dust and cloud particles in the Martian atmosphere. SPEX is aimed for accomodation onboard ESA's foreseen ExoMars orbiter.

Without dedicated observations of the dust and clouds in the Martian atmosphere, the weather and climate system of Mars – knowledge of which is essential for both exploration and comparative climatology - cannot be understood or predicted. It is generally recognized that studying other planets helps us to understand our own planet and to answer questions that cannot be solved by looking at only our own planet. This is certainly the case for atmospheric and climate studies. In particular, the Martian atmosphere and surface appear to form a relatively simple, homogeneous system (with a low surface pressure and no oceans) compared to the highly variable Earth's atmosphere and surface. We thus expect that on Mars the role of dust in heating and/or cooling of a planetary atmosphere and surface can be studied in a more straightforward manner than on Earth. The hence obtained knowledge can subsequently help in understanding the role of aerosol (comparative planetology) in the terrestrial climate (comparative climatology). Obviously, the instrumentation we propose to develop within this study can also well be used for atmospheric research of other planets or moons, such as the Earth, Venus and/or Titan.

6. REFERENCES

1. The Aurora programme, Europe's Framework for Space Exploration, ESA Bulletin, number 126, May 2006