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Study of clouds and dust aerosols in the Martian atmosphere

H. Chen-Chen[1], S. Pérez-Hoyos[1], and A. Sánchez-Lavega[1]

[1] Departamento de Física Aplicada I, ETS Ingeniería UPV/EHU, Bilbao, Spain (hao.chen@ehu.eus)

Abstract

Observation of Mars' atmosphere has evolved to a state of permanent monitoring of its main components. In this work, we focus on the study of clouds and dust aerosols in the Martian atmosphere by means of spacecraft observations, particularly VMC on-board Mars Express, and surface vehicles, mainly cameras on the MSL rover. Orbiting instrument observations provide a general view of the planet, which allows covering a huge area in a short time. This is very interesting, for example, to study global dust events in Mars. On the other hand, ground-based instruments are better suited to analyse local properties of dust particles from in-situ acquired first hand data.

1 Introduction

During the last three decades, the observation of Mars' atmosphere has changed from a stage where the purpose was to retrieve the main characteristics of the atmospheric components and understanding the main processes to a phase where the main constituents (water, dust, clouds) are permanently surveyed to understand their cycles [16]. Thanks to this permanent monitoring status, vast data sets containing among others planetary images obtained by different instruments have been built up and made available.

The main elements of interest in the characterisation of the Martian atmosphere are the meteorological variables temperatures, surface pressure, wind speed, aerosol optical depth and properties and the variability. These quantities change with time and location and the main objective of spacecraft observations is to quantify the spatial, diurnal, interannual and seasonal variations [19].

In this work, we comment on the available spacecraft observations for clouds and dust phenomena, covering both orbit and ground-based observations and we introduce our current studies within this subject.

1.1 Dust

The atmosphere and climate on Mars is strongly governed by the amount of dust lifted and transported in the atmosphere. Its presence has a significant impact on the thermal structure of the atmosphere and it is the main driver of atmospheric circulation at all spatical scales [4]. The main feature of the annual cycle is the intermittent occurrence of regional or planetary-scale dust storms [3]. Although there may be variations, it is well known that the amount of suspended dust in the atmosphere is higher during Southern hemisphere summer (L_s=180° to 360°), when overall surface and atmospheric temperature are higher, with an annual cycle approximately repetitive. These events occasionally grow up to planetary-scale encircling events and increases the dust optical depth to values exceeding the unity. Other sources that permanently lift dust into the atmosphere are the dust devils and the convective episodes.

1.2 Cloud condensates

Aerosols in form of condensate clouds made up of water ice and CO_2 ice have been observed and are a frequent event, as the water vapour in the Martian atmosphere is controlled by saturation and temperature. Because of the colder thermal environment, water content in Martian clouds is much less than terrestrial, so optically thick clouds on Mars are less common than on Earth. Martian clouds appear to form more frequently in the northern hemisphere than in the southern, and during autumn and winter rather than spring and summer [4].

Clouds of CO_2 ice has been detected since the early observations made by Mariner 6 and 7 and its presence has been inferred at atmosphere altitudes where temperatures are cold enough for CO_2 to condense.[14]

2 Spacecraft observations

The main feature for observations made with orbiting instruments is their capacity to provide a general view of the planet, covering large areas in short times, which results very interesting to study global-scale events in Mars, such as planet-encircling dust storms. The primary tools for atmospheric observation from orbiting spacecraft have been thermal infrared sounding, radio and UV occultations, near infrared spectroscopy and visible and near infrared imaging. The instruments and retrieval methods used to determine the optical depths for water ice aerosols and dust are mostly the same.

The *Mariner 9* IRIS thermal infrared spectrometer retrieved first the optical depth of water ice condensates and monitored the decay of a planet-encircling dust storm [1] [5]. The *Viking* missions used the IRTM infrared thermal mapper to monitor the dust optical depths, including 2 planetary scale dust storms, as well as mapping and imaging clouds [10] [22]; and the *Mars Global Surveyor* (MGS) instruments TES infrared spectrometer and MOC camera mapped the dust optical depth for 3 Martian years and retrieved the seasonal and longitudinal distribution of water ice clouds [19].

The current orbiting instruments monitoring Mars atmosphere are *Mars Odyssey* THEMIS broadband infrared imager [18], *Mars Express* PFS and SPICAM spectrometers [24] [16] and

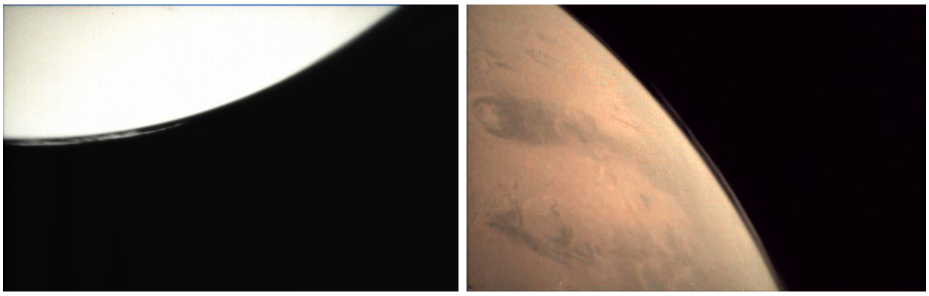

Figure 1: Limb layered detached clouds captured by VMC-MEX: events on 09-349 06:49:25 (left) and 13-066 22:50:46 (right)

Mars Reconnaissance Orbiter (MRO) MCS(climate sounder), CRISM (spectrometer) and MARCI (color imager) instruments.

2.1 Visual Monitoring Camera on Mars Express

The Visual Monitoring Camera (VMC) on-board *Mars Express* (MEX) is a small camera (65x60x108 mm, mass 430 gr) designed to provide visual telemetry feedback of the separation of the Beagle-2 lander [13]. Once this was completed, the camera was turned off and then re-activated 3 years later in 2007 for providing educational and public outreach services. The wide field-of-view of the camera, its capability of obtaining full planet-disk image with sufficient spatial resolution and its flexibility has proven unique weather observation capabilities in Mars. The first scientific results from our team have been recently reported [17].

In our current study, we have reviewed the publicly available image data sets from VMC (from 2007 to 2015, ∼19,000 images) searching for relevant events (e.g. dust storms, detached layered clouds, etc.) at limb. These features are then catalogued, navigated and measured. Several cases of limb layered detached clouds (see Figure 1)have been identified and their altitudes have been estimated, retrieving values within the 40 to 80 km range. These events have been mapped seasonal and areographically [17], and will be reported elsewhere.

3 Dust measurements from surface vehicles

The primary surface observation tools include in such a case the direct Sun and sky imaging, UV and thermal infrared sounding and the collection of meteorological data from Mars surface sensors [19].

Information about the size and shape of dust aerosols is most easily obtained by evaluating the light scattering and absorption by dust particles at different wavelengths, being its size distribution defined by two parameters: the effective radius (r_{eff}) and the dimensionless variance (v_{eff}) [6].

The obtained results have been fairly consistent between a variety of different instruments. Estimations from the *Viking* [15], *Pathfinder* [23] and Mars Exploration Rovers (MER) missions [7] by imaging at visible wavelength the sky brightness from surface as a function of the angular distance to the Sun constrained the particle size values to r_{eff} = 1.5 – 1.65 μm and v_{eff} = 0.2 – 0.3. A complete review of the determination of these parameters from both ground-based and spacecraft observations of Martian dust is given on reference [2].

3.1 MSL Engineering Cameras

The Mars Science Laboratory (MSL) *Curiosity* rover is equipped with a set of 12 cameras built under the same design as previous Mars Exploration Rovers (MER) [8]. The objective of these cameras is to support surface operations of the rover by providing views of the near-range surrounding terrain; detect, monitor and avoid hazards and retrieving the rover position and orientation; as well as supporting the robotic-arm and sample-delivery operations [9].

The Hazard Avoidance Cameras (*Hazcam*) are two stereo pairs of engineering cameras with fish-eye lenses located at the front and rear ends of the rover. They provide a primarily near-field image both in front of and behind of the vehicle and they are used to determine the safe driving directions, as well as supporting science tasks by selecting near field objectives [9].

The MSL Navigation Camera (*Navcam*) consist of four mast-mounted cameras with 45-degree field of view and a broadband response span of 600-800 nm approximately. It is primarily used for navigation purposes and general site characterisation, including 360° panoramic images [9].

Complete technical specifications for the MSL Engineering Cameras can be found in [8] and [9].

Although not designed for this specific purpose, the images taken by the MSL Engineering Cameras can be used for retrieving the dust optical depth and physical properties [12] [20].

3.2 Line-of-sight extinction

The line-of-sight extinction at MSL Location (*Gale Crater*) has been estimated using a sub-set of *Navcam* images according to the methodology in reference [11]. These data are 1024x512 size images pointing North and taken around local noon time. For the line-of-sight optical depth calculation, the spectral irradiance values at the sky, crater rim and near-ground are extracted and evaluated at different sampling directions as in [11]. We have extended this analysis period up to MSL Sol 1292, corresponding to Ls 120 in MY33 (see Figure 2).

3.3 Sky radiance

Navcam and *Hazcam* images were used to retrieve the sky brightness and obtain the scattering properties of the airborne dust(see Fig. 3). The *Navcam sky surveys* cover a wide range of angles from the Sun and were designed to determine the scattering properties of the atmosphere. In addition to these data, MSL *Hazcam* images have also been used to

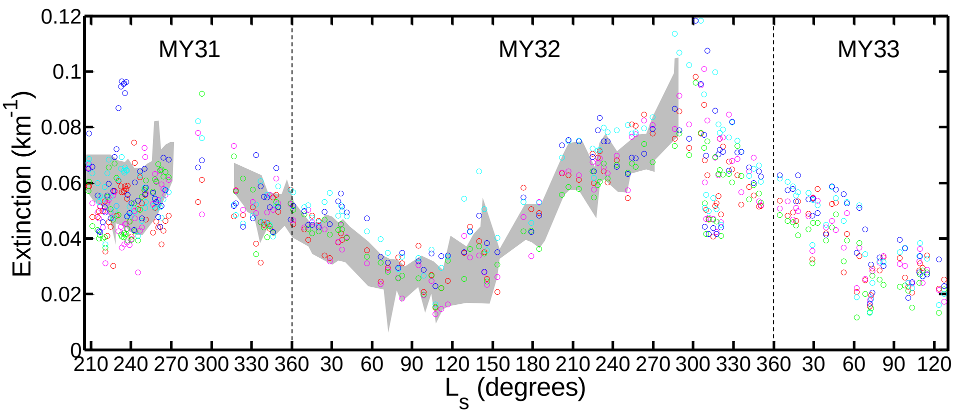

Figure 2: Line-of-sight extinction from MSL at *Gale Crater* during MY31-MY33 and comparison with Moore *et al.* (2016) [11]. (grey envelope)

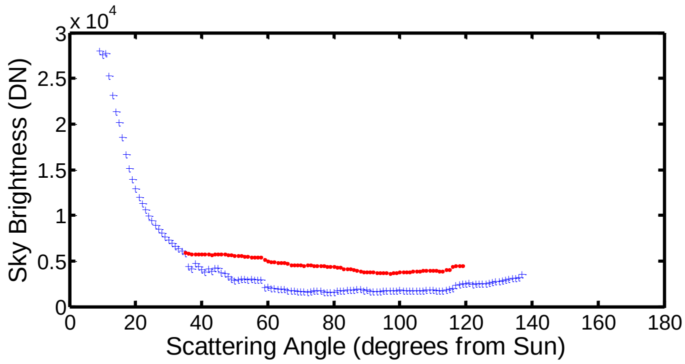

Figure 3: Sky brightness survey obtained by MSL Navcam (cross) and Hazcam (dots) during MSL Sol 669.

complement the evaluation of the scattering phase function. Once this is obtained, the information regarding the dust and aerosol particle size and shape can be derived by computing the phase functions with several models and comparing the retrieved parameters [20]. This work is currently under development.

4 Summary

The spacecraft observations of the clouds and dust in the Martian atmosphere from orbiting spacecraft and ground-based vehicles have been presented. The instruments and techniques used in orbit observations provide a general view of the planet and result for characterising and mapping seasonal and global variations of dust and cloud aerosols; while ground-based observations mostly consist in sky and Sun imaging for retrieving aerosol physical properties. We have used the VMC instrument on *Mars Express* for studying aerosols phenomena in the atmosphere. Limb layered detached clouds have been identified, navigated and measured, obtaining altitudes within the 40–80 km range. The characterization of the dust on Mars can be obtained using the Engineering Cameras on-board the MSL rover. The dust line-of-sight extinction has been evaluated, the sky brightness is retrieved from these images for computing the phase function and fitting the data to the relevant model.

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