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Optical depth and its scale-height in Valles Marineris from HRSC stereo images

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ABSTRACT

We measured the optical depth of the Martian atmosphere as a function of altitude above two opposing scree walls of the Valles Marineris, from stereo images that were taken with the High Resolution Stereo Camera (HRSC) of Mars Express on June 3, 2004, during orbit 471. The optical depths were measured from contrast differences between the stereo images with the so called "stereo method". For 7 regions in the northern wall of the Valles, we estimated the optical depth and found values between 1.0 and 1.6. These regions span more than 6 km in altitude and the results show a clear relation with altitude. A fit on these results yielded a scale-height for the optical depth of 14.0 km + 1.3/−1.1 km. The expected local pressure–scale height is smaller: 11.5–12.0 km. The difference is most likely explained by small (around 1.5%) offset errors in the intensity calibration of HRSC images. We also selected 9 regions in the opposing southern wall and from these we measured values of optical depth in the range 1.3–1.5. Our result suggests the presence of clouds above this part of the Valles because the optical depth appears almost independent of the surface altitude. Possibly these are banner clouds, forming at the edge of the canyon, that contain dust that is blown over the canyon by winds from the high plains to the South.

1. Introduction

The optical depth of the Martian atmosphere in the visible is almost fully determined by the amount of aerosols it contains. Usually it is above 0.3, and regularly it is larger than 1.0. Knowledge of the amount of the aerosols, of their distribution through the atmosphere, and of their composition, is important for understanding the Martian environment. Aerosols determine how much insolation reaches the surface and how much is absorbed in the atmosphere, thus having a big influence on the climate, the weather, the circulation patterns, and on Aeolian processes. Most aerosols, at least those in the lower atmosphere, are particles of reddish dust that can act as condensation kernels for vapors, invoking white hazes when they become sufficiently covered with ice. Their ability to absorb volatiles and the reaction surface they offer for chemical processes make them important for the atmospheric chemistry.

Knowledge of the aerosols is also important for interpreting observations of Mars since these have a big impact on much of the remote sensing data; e.g., they diminish the contrast and spatial resolution of images and the light they scatter creates a strong and diffuse reddish illumination of the surface so that the Martian surface appears redder than it actually is. Interpretation of (surface) images and spectra should consider such effects.

The impact of the airborne dust partly depends on where it resides in the atmosphere, and thus on its vertical distribution. Often it is more or less homogeneously mixed into the air so that the dust invokes an opacity scale-height (or: scale height of optical depth) that is comparable to the pressure scale-height of the atmosphere; this has been found and published by many authors and below we cite several. On the other hand, one may expect that topography and the weather can influence this. For example, what should one expect near big mountains and deep valleys that often create their own weather? This paper intends to contribute to a better understanding of such questions. It describes a stereo method analysis (Hoekzema et al., 2007; Hoekzema et al., in preparation) of two opposing walls of the Valles Marineris. The images were taken with the High Resolution Stereo Camera (HRSC) onboard Mars Express (MEX), the European remote sensing satellite that orbits Mars since December 2003.

During the last decennia, several authors investigated the distribution of aerosols in Mars' atmosphere. More in particular, they estimated the scale height of optical depth. For example, Jaquin et al. (1986) used limb scans from the Viking orbiters. The authors observed discrete, optically thin, detached haze layers between 30 and 90 km altitude that may have consisted of ice. Below about 50 km they observed a continuous, reddish haze that extended all the way to

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the surface. In the 30 to 45 km altitude range, the scale height of the reddish haze was typically 5 to 7 km, while its color implies that it was mostly dust. The authors cannot offer much useful information on the lowest 10 to 15 km of the atmosphere, since these regions are optically thick, and thus featureless, when viewed in the limb.

Chassefière et al. (1995) used observations from various instruments onboard the Phobos 2 mission to study dust in the lower atmosphere of Mars. They determined that the average particle size of airborne dust is probably in the range 1–2 µm. Furthermore they found a scale-height of optical depth of 8–9 km above Tharsis.

Kahn et al. (1981) analyzed the changing sky brightness during the Martian twilight as observed by the Viking landers. They concluded that the dust is exponentially distributed in the lowest 30 km, with a scale-height close to that of the atmosphere. The spectral distribution hinted that the particles low in the atmosphere differ from those higher up.

The Pathfinder mission yielded new observations and new estimates. Thomas et al. (1999) used egress observations of Phobos. Their data best fit models with opacity–scale-heights of 10 to 15 km, but they remark that a scale-height that decreases with increasing altitude would provide a better fit.

From 2004, measurements in 9 µm by the Planetary Fourier Spectrometer of Mars Express began yielding estimates of the opacity scale-height. For a very low region, the Hellas basin, Grassi et al. (2007) gives several values between 8 km and 12 km (with errors of 2 or 3 km) that are all compatible with the pressure scale height. Over very high surface, the flanks of several of the big volcanoes, Zasova et al. (2005) similarly measured a value close to the expected value of the pressure scale-height for these regions around noon: 11.5 ± 0.5 km.

Lemmon et al. (2004) used observations of the setting Sun by the Spirit rover in Gusev crater to derive a local opacity scale height. They found 11.6 ± 0.6 km, while they mention a local pressure scale height at that moment of 11.1 km.

Since 2004, the stereo imagery of HRSC and the Digital Elevation Models (DEMs) that are derived from these, can be used to measure the optical depth of the Martian atmosphere and to study its relation with altitude. By retrieving the optical depth from several areas that differ sufficiently in elevation, the relation between optical depth and altitude can become visible, and the scale height of optical depth can be estimated. This technique has some limitations: each retrieval provides the total optical depth from surface to space, thus it cannot resolve any vertical structure above a given location. Thus, for example, if an important fraction of the dust were contained in a single layer, it would not be easy to find evidence of this via this method. Also, the method merely allows measuring scale-heights of optical depth between the lowest and the highest surface in the image. Moreover, since it depends on comparing (nearby) regions at various elevations it will be hampered by horizontal fluctuations in the concentration of aerosols.

Hoekzema et al. (2007) used the stereo method to measure the opacity scale-height on the flanks of the volcano Pavonis Mons and found 10.8 +0.9/−0.8 km, which is similar to the expected local pressure scale-height of the atmosphere. This is another indication that commonly the dust is almost homogeneously mixed into the atmosphere and it also is an indication that the stereo method can yield accurate results. This paper reports on a stereo method analysis of a much lower region: Valles Marineris. Images of this region cover a wide altitude range which allows studying the relation between optical depth and altitude. We choose HRSC images from MEX orbit 471 taken on June 3, 2004, since these do not show any obvious dust storm activity, and neither any thick bright haze of the sort that quite often covers the floor of the canyon, and then makes the floor almost invisible (see Inada et al., 2008).

In Sections 2 and 3 we present basic information on the HRSC camera and the theory behind the stereo method respectively. Section 4 presents the data. Section 5 offers results and discussion, and Section 6 our conclusions.

2. Instrument

The HRSC camera onboard Mars Express has been developed and build by DLR in Berlin (Neukum et al., 2004; Jaumann et al., 2007). It is a multiple line pushbroom scanning instrument. As the spacecraft moves along its orbit, its nine CCD line detectors acquire superimposed image tracks. The line detectors, with 5184 pixels each, are mounted in parallel inside one optical system. Four of them are equipped with color filters between blue and near infra red. The other five are panchromatic (675 ± 90 nm) and are used for stereo imaging. During standard observations the panchromatic line-detectors observe at −18.9°, −12.8°, 0°, 12.8°, and 18.9° as measured from the nadir channel. The nadir channel is never fully nadir looking, there usually is a small offset, and sometimes it is large (e.g., for limb-sounding). The curvature of the planet and the swath of the camera of ±6° make that the emission angles for locations imaged by the outer stereo channels are always significantly larger than 18.9°. While HRSC was taking the images of the Valles Marineris region that we use for the present analysis, the offset varied within a few degrees from zero, and the emission angles for the forward and backward looking images are between 24° and 31°.

3. Theory

3.1. The stereo method

The observed contrast in remote sensing images depends on the optical depth of the underlying atmosphere. Usually, the surface invokes almost all of the contrast since the atmosphere generally shows much lower contrast than the surface. More in particular: with increasing atmospheric optical depth the surface becomes less visible and the apparent contrast decreases. E.g., Thorpe (1979) used contrast variations between Viking images of standard regions to map changes in optical depth of the Martian atmosphere.

Let μ be the cosine of the emission angle with the nadir. Whereas an inclined view (meaning: $\mu<1$) has a longer path–length through the atmosphere than a nadir view ($\mu=1$), and will thus show a stronger atmospheric contribution, the forward and backward looking images of a stereo sensor will on average display smaller contrasts than nadir looking images. The differences are a measure of the optical depth. This principle is e.g., used in some of the optical depth retrieval algorithms for the Earth orbiting MISR stereo cameras (http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/docs/MISR/atbd-misr-09.pdf). Below we offer basic information on the so called “stereo method”, a version of such an algorithm developed for HRSC images of Mars by Hoekzema et al. (in preparation).

We name the observed image $I(i,j)$. $B(i,j)$ is the radiation reflected upward by the surface in the direction of pixel i,j of the observed image $I(i,j)$. If there were no atmosphere, or if the image would be taken inside the atmosphere at such a low altitude that there were no significant atmospheric scattering between the surface and the camera, then $B(i,j)$ would be equal to $I(i,j)$. However, in reality not all of the radiation contained in $B(i,j)$ will reach the camera because a certain fraction will be scattered in the atmosphere during its way up. The size of this fraction depends on the optical depth of the atmosphere τ.

An important part of the photons that enter the camera did not have their last interaction with the surface but in the atmosphere, usually with an aerosol and in rare cases with a gas molecule. If the aerosols have properties as published by e.g., Markiewicz et al. (1999) or Tomasko et al. (1999) then generally, most of these photons have been reflected upwards by the surface, scattered on a particle of airborne dust once during their way up, and on average changed direction by some 20°–25°. Some of the photons have been scattered twice or more times before reaching the camera, but during periods of average atmospheric optical depth these form a minor fraction.