Martian Upper Tropospheric Twilight Clouds: First-time observation from India's First Mars Orbiter Mission (MOM)

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Abstract

MOM completed nearly 8 years in the Mars Orbit (2014-2022). During this period Mars Colour Camera (MCC) captured images of different types of clouds formed in the Martian Atmosphere. In present work, we mainly concentrate on the clouds appearing in the morning and evening terminator or in short seen at twilight. We considered 15 cases of clouds observed at twilight, in which the geometry of the observations allows us to derive the minimum altitude of the clouds, revealing that many of these clouds are in the upper troposphere (above 25 km and up to 45 km). The majority of these upper tropospheric clouds were detected in mid-latitudes (30N - 60N) during the Martian autumn and early winter season (Ls 20 to 90 deg). In this mid-latitude region, we also reported a detached layer of dust and water ice cloud in our previous work (*Kalita et al., 2021a; 2021b*). We propose a plausible mechanism that enhances the probability of the formation of a high-altitude cloud through temperature variation. Our selection process is manual and based on the contrast enhancement through GIMP. Image geometry confirms the incidence angle in the range of 95 to 105 degrees for evening clouds and 75 to 85 degrees during morning and further, using the angle values we estimated the height of the twilight clouds. Further verification with MCS data concretizes our finding regarding upper tropospheric cloud formation.

1. Introduction

During the observed period, i.e., at twilight, the sun is below the horizon. However, the incoming light can still reach clouds or mountains high above the surface. Thus, it makes these feature brighter on the dark background. This effect is sometimes seen on noctilucent clouds on Earth, and also in the mountains on the Moon (*Bernal et al., 2020 Gadsden & Schröder, 1989*). Martian bright patches at the terminator were first observed in 1890 using telescopic observations (*Campbell, 1894; Douglass, 1895; 1897; Holden et al., 1890; 1894)* however, the analysis was failed to distinguish between mountain and cloud due to the topographic model of Mars. The current topographic model allows the scientific community to analyses that most of these observations of bright features are either water ice, CO2 ice, or dust. (*Zurek, 2017; Clancy et al., 2017*). In this present work, we study twilight clouds (Figure 1) captured by Mars Colour Camera (MCC) onboard India's first Mars Orbiter Mission. For more information on MCC see *Mishra et al., 2016*. MCC is probably the best suited among available instruments for this kind of study, as it has a wide field of view, very high resolution (nearly 20m/pixel), used to take full disk images showing the terminator of Mars, and its archive covers 8 Martian Years. We also used Mars Climate Sounder (MCS) data to understand the atmospheric changes during the reported cloud events and figure out the plausible reason. Through the zonal opacity analysis, we tried to confirm our findings regarding altitude, coordinate and temperature estimation.

Figure 1. The figure illustrates the morning terminator cloud patches that appear in Martian atmosphere captured by MCC. This mid-latitude cloud shows a distinguishable brightness and from the colour channel we confirm that the cloud is water ice cloud.

2. Theoretical Background and Methodology:
2.1 MCC image processing:

The MCC images have been processed through MATLAB and GIMP to enhance the contrast of the cloud and geometry projection. We also project the incidence angle to visualize the satellite view of the planet. Further from the spectral analysis, we concluded the nature of the cloud.

2.2 Cloud Height Calculation:

For the calculation of the height of the cloud we adopted simple trigonometry as follows (*Bernal et al., 2020*),

$$\text{Height}_{projeted} = R_{planet} \tan \alpha \tan \frac{\alpha}{2} \qquad (1)$$

Here α represents the 90 degree -incident angle. We use this formula to calculate the height of the upper tropospheric water ice clouds.

2.3 MCS Data Analysis:

Deposition of aerosol (dust and hexagonal water ice crystal) put an impact on the variation of convective boundary layer (CBL) height. Further, we reported CBL height based on the MCS data. We computed the approximate height of the CBL based on the MCS temperature data. MCS data helped us to predict the intensity and height of the observed dust storm. The present work also focused on the dust and water ice opacity for the MCC observed events and the temperature profile derived from MCS. For that, we need to estimate the dust extinction value. We estimated density-scaled opacity by scaling the opacity ($d_z\tau$ in km^{-1}; i.e., extinction per unit height due to dust or water ice) by atmospheric density ($\boldsymbol{\rho}$), i.e., $d_z\tau$ / $\boldsymbol{\rho}$ in m^2 kg^{-1}. We used DDR-version 5 data to estimate the required parameters through simulation. We followed the Mie theory to calculate the effective radius of the particle. First, we calculate the density scaled opacity derived from MCS dust extinction and water ice extinction data. We used the data to estimate the mixing ratio of dust particle, then using the Mie theory; we calculated the effective radius of the particle as

$$mixing\ ratio(q_d) = \frac{4\rho_d(\ d_z\tau\ )\ r_{eff}}{3Q_{ext}\rho} \qquad (2)$$

Also, the effective radius of water ice particles as,

$$mixing\ ratio(q_I) = \frac{4\rho_I(\ d_z\tau\ )\ r_{eff}}{3Q_{ext}\rho} \qquad (3)$$

The value of 'Qext' is 0.78 for water ice particles, and 0.350 in the case of a dust particle can be obtained from the Mie theory described by (*Kleinböhl et al., 2009*), where 'r_{eff}' is the effective radius of particles. Density ρ is obtained from MCS data using the ideal gas equation. ρ_I and ρ_d are the retrieved densities that have the value of 900 kg m^{-3} and 3000 kg m^{-3} respectively. The calculated effective radius of the particles varies from 1.40 to 3.2 μm.

3. Result and Discussion:

Here we have illustrated an evening terminator cloud observed on 5 August 2017 over the midlatitude or specifically over Cimera region.

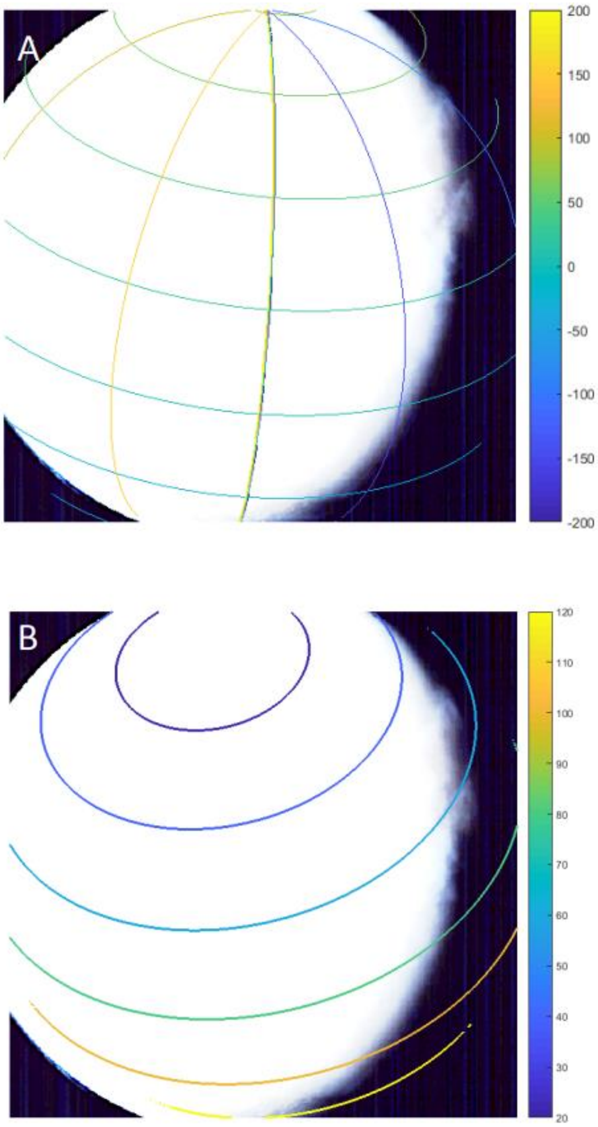

Figure 2. (A) illustrate the geometry projection of MCC images. From the image we can easily estimate that the cloud coordinate as 25N to 35 N, and 60 to 65 W. (B) further, figure B illustrate the incident angle projection on the MCC images from where we may see the angle is varying from 75 to 85 degree.

In figure 2 we have shown the twilight cloud with a central coordinate 30^0 N and 62.5^0 W. Since the incidence angle is 8 degree so the estimated height is around 25±2 km. We have studied other events and found the height may reach up to 45±3 km (Table 1). Here our main focus is on the upper tropospheric water ice cloud hence we consulted the MCS observations to verify whether at the same coordinate water ice cloud is present or not for the observed event. We found a latitudinal expansion of the cloud with negligible longitudinal expansion, thus, we may conclude it as a localized water ice cloud. Figure 2 (C, D, E) shows the vertical profiles of dust extinction, water ice extinction, and temperature during the observed event.

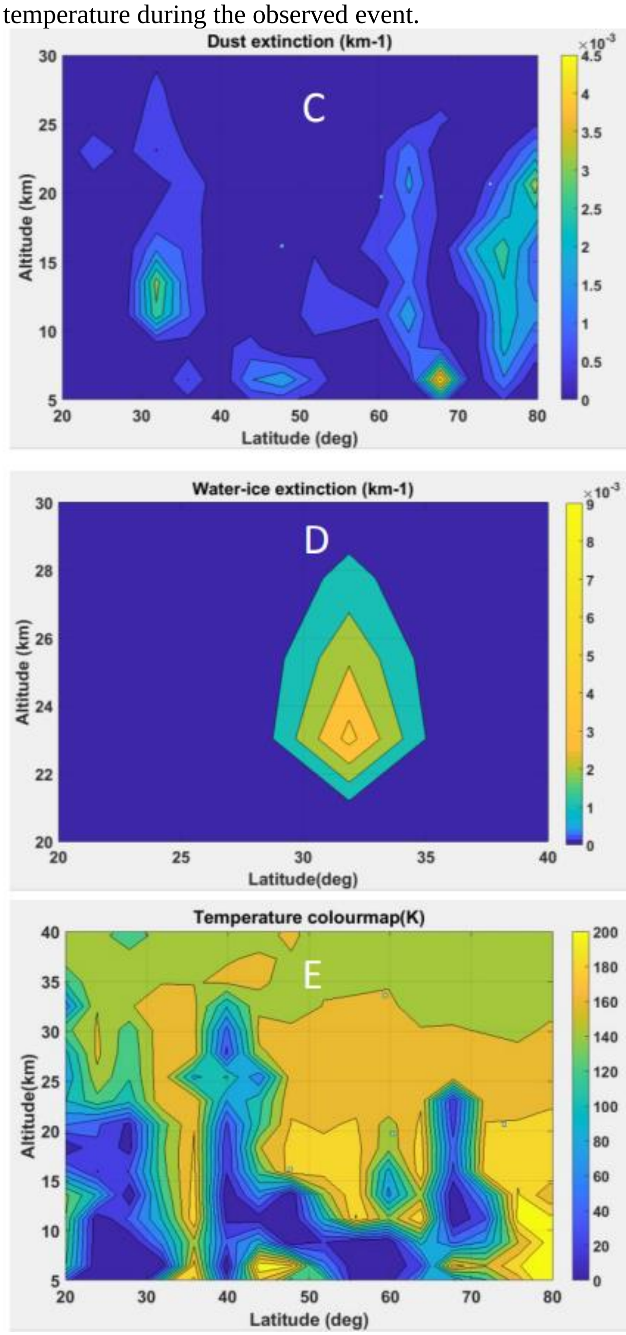

Figure 2 (continued). The figure shows the analyzed MCS data for the reported event. Plot (C) illustrate the dust opacity during the event, (D) illustrate the water ice opacity as a function of altitude and (E) shows the temperature variation during the event.

From the figure 2(D), we may easily see that the cloud form between 28^0 N to 35^0 N at a height of 24 to 29 km. The cloud top height is around 29 km confirms the upper tropospheric estimation with the help of image processing. A very high dust opacity from 10 to 25 km confirms that the detached layer of the cloud is accompanied by a dust aerosol from the ground (Figure 2(C) and (D)). Spectral analysis of the images shows only the presence of a water ice cloud which is further verified by the MCS data. Further, we consulted Mars Climate Database (MCD) based on the Global Circulation Model and estimated the effective radius using extinction value. The estimated effective radius of the dust particles varies from 1.40 to 2.2 μm whereas, the effective radius of the water ice particles varies from 0.80 to 3.2 μm. This shows that the particles are of coarse mode nature. Analysis of other 4 similar events is shown in table 1, where from it is clear that the clouds may reach up to mesospheric level.

Table 1: Illustrate the terminator cloud event for 4 different days during 2017.

Ls	Height of the cloud (Km)	Evening /morning	Nature of the cloud
65.3	44±3	Evening	Water ice
71.5	27±2	Evening	Water ice
72.3	29±2	Evening	Dust and water ice
80.1	33±3	Morning	Dust and water ice

From the above table, it is clear that the cloud may reach up to the lower mesosphere also. These detached layers of water ice cloud are accompanied by a continuous haze from the surface. Temperature variation leads to the condensation of the cloud over the observed location. In the image, we may see discontinuity in the cloud patches. If we observe the temperature plot we may easily find that at the height of nearly 28 km temperature changes layer by layer. In the low-temperature region due to condensation water ice, a cloud is formed and the mechanism is driven by the incoming solar radiation and dust radiative heating.

Concluding Remarks:

1. Height of the cloud is varying from 25 to 45 km.
2. Temperature inversion due to dust radiative heating helps the formation of these water ice clouds.
3. All clouds used to form over the western midlatitude and follow the low solar longitude trend.
4. Twilight cloud also may reach up to Mesosphere.
5. All clouds are accompanied by a continuous dust haze from the surface.
6. Most of the clouds are water ice clouds.
7. Effective radius is varying from 0.8 to 3.2 micrometer for the detected Martian aerosol.
8. Most of the clouds are observed at the upper troposphere, few are observed in lower mesosphere.
9. The observation of the twilight can provide valuable information about water vapor distribution

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