PROPERTIES OF MARS APHELION VOLCANO CLOUDS FROM COMBINED MARS GLOBAL SURVEYOR MOC AND TES MEASUREMENTS. J. L. Benson 1, D. A. Glenar2, P. B. James3 and M. J. Wolff3,

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Introduction: The climatological importance of water ice clouds in the Martian atmosphere and general circulation has been established [1, 2]. HST observations in 1995 at Ls = 68º identified an aphelion-season cloud belt, extending from approximately -10º to +30º latitude [1, 3]. Orographic clouds such as those over Tharsis, Olympus, and Elysium Mons were observed to be a particularly bright component in this season and latitude region. HST observations in 1997 indicated that the belt was again present between Ls = 60º and 140º [4]. Subsequently, it was found to have also been present during the Viking years [5] and is clearly evident in both MGS MOC and TES data [6, 7]. This cloud belt therefore is a regular seasonal feature on Mars near aphelion. Clancy et al. [1] suggested that the tropical cloud belt results from cooling and low altitude saturation of water vapor trapped in the upward branch of the solstice Hadley cell. Aphelion-season cloud behavior was subsequently reproduced in a global circulation model by [2].

Cloud formation over the volcanoes is fostered by the same factors that lead to the formation of the aphelion cloud belt, namely the seasonal maximum in northern hemisphere water vapor, combined with cold aphelion temperatures and low saturation altitude. Mesoscale model simulations [8] show that the primary cause of afternoon cloud formation over volcanoes during this season is thermally-induced slope flow which drives water vapor up the flanks, adiabatically cooling and condensing it.

Orographic cloud extinction optical depth has been measured using both telescopic and spacecraft observations at multiple wavelengths. Christensen and Zurek [9] observed water ice clouds on the flanks of Olympus Mons at Ls ~ 29º with visual optical depth near unity. James et al. [3] found the optical depth of the Alba Patera cloud to be 0.46 in 1995 (Ls = 63.7º) and that of the Olympus Mons cloud to be 0.48 in 1993 (Ls = 20.2º), both values determined from HST F410M images. Akabane et al. [10], using telescopic multi-filter imaging between 400-440 nm, estimated the optical depths of Olympus Mons clouds in 1995 and 1997 during northern summer (Ls = 68º to 110º), and found values of 0.4 – 0.8 at Martian local time near 1400 LST. At Arsia Mons, Pearl et al. [11] found values of 825 cm⁻¹ (12.1 µm) absorption optical depth as high as ~0.6 during northern fall (Ls = 196º and Ls = 210º), derived from periapsis passes over the volcano by MGS/TES. A subsequent study of Arsia Mons clouds by [12] showed that clouds with 825 cm⁻¹ optical depth between 0.3 and 0.7 persist throughout the Martian year. Benson et al. [13] measured cloud optical depths from MOC WA blue (425 nm) images at the locations of several volcanoes and spanning a full annual cycle. Optical depth values retrieved in this study spanned 0.11-1.0 at Olympus Mons, 0.10-1.4 at Ascreaus Mons, 0.16-1.3 at Pavonis Mons, 0.08-0.82 at Arsia Mons, and 0.16-0.75 at Alba Patera.

In previous analyses [e.g., 4, 11, 14, 15, 16, 17], properties of orographic clouds have been quoted as mean values or coarsely binned averages over large spatial scales, as a consequence of either low spatial resolution, restricted time sampling, signal to noise limitations or some combination of all of these. A quantitative study of topographically related cloud properties at spatial scales of a few kilometers has thus been lacking. In this study, we produce and analyze high spatial resolution maps of 425 nm optical depth derived from MOC WA blue images of aphelion clouds near Olympus Mons, Ascreaus Mons.

Observations and Modeling Approach: We chose six aphelion-season MOC WAB image strips, two each for Olympus, Ascreaus, and Elysium Mons, which exhibit well-defined clouds and which include TES dust and cloud optical depth measurements within the MOC field of view. These images were selected by first surveying the TES measurement database and applying location (longitude-latitude) and season (Ls) filters in order to find those orbits that lie within our aphelion season search window and also show pronounced cloud structure near the volcanoes.

Figure 1 shows the selected MOC WA blue images displayed in a latitude – west longitude grid with Mars Orbiter Laser Altimeter (MOLA) topographical contours at 1/8º resolution superimposed on the images. Olympus Mons is shown in Fig. 1a and b, Ascreaus Mons in 1c and d, and Elysium Mons in 1e and f. White boxes outline the cloud regions for which optical depth calculations were made, and red lines in three of the images show where the TES orbital track traverses well-defined clouds or (in the case of Elysium) a westward extended cloud plume.
Cloud Modeling and Optical Depth Measurement:
Optical depth retrievals were performed for each cloud image by equating the measured reflectance at each MOC WAB pixel with I/F values computed for a surface-plus-atmosphere model consisting of surface, cloud, and dust aerosol. Clouds were confined to 10 to 25 km above the surface, and dust was uniformly mixed through the atmosphere [18].

Reflectance calculations are carried out using a discrete-ordinate radiative transfer code (DISORT) [19], and by adjusting cloud optical depth so that the computed values of I/F agree with measured reflectances, expressed in the same units. (Here, I/F is defined as the reflected intensity in the observing direction, with solar irradiance equal to pi in the illumination direction). In addition to the known observing geometry at each pixel, the code requires: RT properties (single scattering albedo and phase function shape) for the dust and water ice aerosol layers; the optical depth of the dust aerosol; and the surface reflectance at each pixel position. Though small, the Rayleigh scattering component \( \tau \approx \lambda^{-4} \) is also included. For the purpose of deriving cloud optical depths, we adopt:

1. The TES solar-band (0.3 – 3 µm) normalized single scattering phase function shape for “Type 2” aphelion ice cloud particles, derived from TES EPF (emission phase function) measurements [19].
2. A value of unity for the ice aerosol single scattering albedo, due to the fact that water ice is essentially non-absorbing at visible wavelengths. Lower values for this quantity are considered in the context of retrieval uncertainties since ice grains are known to be seeded by dust particles, effectively lowering their albedo.
3. An isotropically scattering surface reflectance function.

Optical Depth Maps: Figures 2a-7a show the retrieved 425 nm ice extinction optical depth maps, within the regions defined by the white outlines in Fig. 1. For convenience we include with each map the corresponding portions of the original cloud images at the same scale (Figs. 2b-7b). The intensity scale for these images is in units of I/F. MOLA topographical contours at 1/8° resolution, which show altitude in meters, are superimposed on both the maps and images.

Olympus Mons:

![Figure 2](https://example.com/figure2.png)

Figure 2: (a) Extinction optical depth map of Olympus Mons cloud (e22-411, \( L_s = 92.37^\circ \)) within the bounding box in Fig.1a. The largest optical depth (exceeding 1.0) lies along the slope to the north of the summit. (b) MOC WA blue image of Olympus Mons cloud region used to measure optical depths in Fig. 2a. A bright cloud core is observed to the north of the volcano summit, corresponding to the largest optical depth seen in Fig. 2a while the rest of the cloud is more diffuse. The intensity bar scale is in units of I/F.
Olympus Mons shows the largest optical depth of the volcano clouds observed in this study. Maximum optical depth for the Olympus Mons observation at \( L_S = 92.37^\circ \) exceeds 1.0 (Fig. 2a), and at \( L_S = 122.09^\circ \) it is \( \sim 1.4 \) (Fig 3a). In both early and late-season examples, the spatial distribution of opacity is similar, with the largest optical depths lying to the north of the summit following lines of constant elevation. In the late-season cloud (e22-411), the region of significant optical depth (\( \sim 1.0 \)) extends to at least 15 km altitude, as can be observed in Fig. 3a. Cloud optical depth is smaller but still significant at the volcano summit (i.e., \( \sim 0.40 – 0.50 \) at \( L_S = 92.37^\circ \) and \( \sim 0.50 – 0.60 \) at \( L_S = 122.09^\circ \)).

Ascraeus Mons: In both of the Ascraeus examples, maximum cloud optical depth is \( 0.8 – 0.9 \) (Figs 4a and 5a). These clouds are formed to the west of the summit and significant optical depth (\( \sim 0.70 \)) extends to at least 15 km. As is true for Olympus Mons, the spatial cloud distribution for Ascraeus has a distinct character which persists from early to late aphelion season, suggesting that it is strongly controlled by the underlying topography. In the case of Ascraeus, the cloudy region forms an arc stretching from north of the summit to the west following constant elevation lines.

Elysium and Elysium Mons: Cloud structures at this location show clear differences at \( L_S = 104.22^\circ \) and \( L_S = 123.84^\circ \), which may indicate a strong seasonal dependence. Clouds observed at \( L_S = 104.22^\circ \)
(Fig. 6a) occur in two well-separated regions. One region is an arc that extends clockwise from north of the Elysium Mons summit around to the east following constant elevation lines. This cloud also includes a radial filament that extends nearly to the summit. The other cloudy area is centered to the west of the summit in Elysium, on an area of flat topography and at lower elevation (~ 1 km). Both of the cloudy areas have optical depths as high as 0.75, and considerable water ice aerosol ($\tau_{\text{ice}} > 0.50$) also fills in the intervening area.

Later in aphelion season ($L_S = 123.84^\circ$, Fig. 7a) the Elysium cloud has disappeared, and the cloud on the flanks of Elysium Mons now shrouds the southwest portion of the volcano, extending counterclockwise from northwest of the summit around to the southeast. A region of large optical depth (~ 0.55 – 0.60) also extends to the summit.

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**References:**