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# Geophysical Research Letters

## RESEARCH LETTER

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### Key Points:

- We report the first detections of two high-altitude nighttime CO<sub>2</sub> clouds on Mars during southern summer
- The altitude profile of extinction indicates that the cloud layers are confined horizontally to sizes less than ~500–700 km
- Examination of the CO<sub>2</sub> density and temperature profiles reveals that tides are important in the formation of Martian CO<sub>2</sub> clouds

### Supporting Information:

- Supporting Information S1
- Table S1

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## Detection of Mesospheric CO<sub>2</sub> Ice Clouds on Mars in Southern Summer

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**Abstract** This paper reports the first detections of two high-altitude nighttime CO<sub>2</sub> clouds on Mars during southern summer ( $L_s = 264^\circ$  and  $L_s = 330^\circ$ ) with stellar occultation measurements by the Imaging Ultraviolet Spectrograph on board the Mars Atmosphere and Volatile Evolution spacecraft. Interpretation of the transmission spectra with Mie theory indicates particle radii of ~90–110 nm assuming a monodisperse distribution. The altitude profile of extinction indicates that the cloud layers are confined horizontally to sizes less than ~500–700 km. Examination of the CO<sub>2</sub> density and temperature profiles reveals strong wave-like perturbations. Supersaturated temperatures occur at the maximum negative extent of these wave-like perturbations, which are organized in longitude with a dominant  $m = 3$  zonal harmonic. This suggests that tides are important in the formation of CO<sub>2</sub> clouds.

### 1. Introduction

The existence of mesospheric CO<sub>2</sub> ice clouds on Mars was first suggested by Clancy and Sandor (1998) based on temperature profiles with a minimum that falls below the CO<sub>2</sub> saturation conditions (hereafter referred to as cold pocket) detected by Pathfinder (Schofield et al., 1997) and later observationally confirmed by Mars Reconnaissance Orbiter (Clancy et al., 2019; Vincendon et al., 2011), Mars Odyssey Thermal Emission Imaging System (McConnochie et al., 2010), and various instruments on board Mars Express (MEX): SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM; Montmessin et al., 2006), Planetary Fourier Spectrometer (Aoki et al., 2018), Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA; Määttänen et al., 2010; Montmessin et al., 2007; Scholten et al., 2010), and High Resolution Stereo Camera (Määttänen et al., 2010; Scholten et al., 2010).

Four main types of Martian CO<sub>2</sub> ice clouds have been reported, one forming in the troposphere during the polar night with particle sizes of several tens or hundreds of micrometers (Colaprete & Toon, 2002; Hayne et al., 2012, 2014; Ivanov & Muhleman, 2001; Pettengill & Ford, 2000; Tobie et al., 2003), one appearing between 60 and 85 km during equatorial daytime with particle sizes of 0.5–3  $\mu\text{m}$  (Määttänen et al., 2010; Montmessin et al., 2007), one occurring at night between 80 and 100 km in equatorial regions with particle sizes around 100 nm (Montmessin et al., 2006) and one emerging in the midlatitude mesosphere with particle sizes of 0.5–3  $\mu\text{m}$  (Määttänen et al., 2010; McConnochie et al., 2010). The presence of temperatures below the CO<sub>2</sub> saturation point is a prerequisite for the formation of CO<sub>2</sub> ice clouds (Forget et al., 2009; Listowski et al., 2014; Montmessin et al., 2006; Schofield et al., 1997). Forget et al. (2009) investigated 616 temperature profiles measured by stellar occultations with Mars Express SPICAM and found that 45 profiles exhibited temperatures below the CO<sub>2</sub> saturation point. Montmessin et al. (2006) identified four low-latitude CO<sub>2</sub> ice clouds in the supersaturated nighttime atmosphere during the southern winters out of 412 SPICAM stellar occultation measurements. The cloud particle effective radius derived from Mie theory ranged from 80 to 130 nm when assuming a pure CO<sub>2</sub> ice composition and spherical particles. More recently, Stevens et al. (2017) reported numerous clouds in the 60- to 80-km region from Mars Atmosphere and Volatile Evolution (MAVEN)/Imaging Ultraviolet Spectrograph (IUVS) limb measurements of solar scattered radiation. Nearby measurements by Mars Reconnaissance Orbiter/Mars Climate Sounder (MCS) did not show super-

saturated temperatures near the IUVS clouds, but the IUVS and MCS observations were not colocated or simultaneous and there might be undetected cold regions on small spatial or temporal scales that cause CO<sub>2</sub> condensation. Thermal tides (González-Galindo et al., 2011) and mesoscale gravity waves (Spiga et al., 2012; Yigit et al., 2015) have been suggested to be responsible for the generation of supersaturated cold pockets. In addition, the presence of nuclei is necessary for the heterogeneous nucleation of CO<sub>2</sub> ice clouds (Listowski et al., 2014; Määttänen et al., 2010; Plane et al., 2018).

The IUVS (Gröller et al., 2015, 2018; McClintock et al., 2015) on board the MAVEN (Jakosky et al., 2015) is designed to utilize stellar occultations to characterize the mesosphere of Mars with high sensitivity and spectral resolution of which the midultraviolet (MUV) channels from 180 to 340 nm are sensitive to CO<sub>2</sub>, O<sub>2</sub>, O<sub>3</sub>, and clouds and aerosols. In this study, we report the detection of aerosol layers with stellar occultation profiles obtained by the IUVS. The aerosol layers occur at altitudes of 90–100 km and are coincident with cold temperature regions yielding supersaturated CO<sub>2</sub> densities. We therefore interpret the aerosol layers as CO<sub>2</sub> ice clouds. We provide estimates of the horizontal extent and mass of the CO<sub>2</sub> clouds and investigate the role of atmospheric waves in the formation of clouds.

## 2. Observations

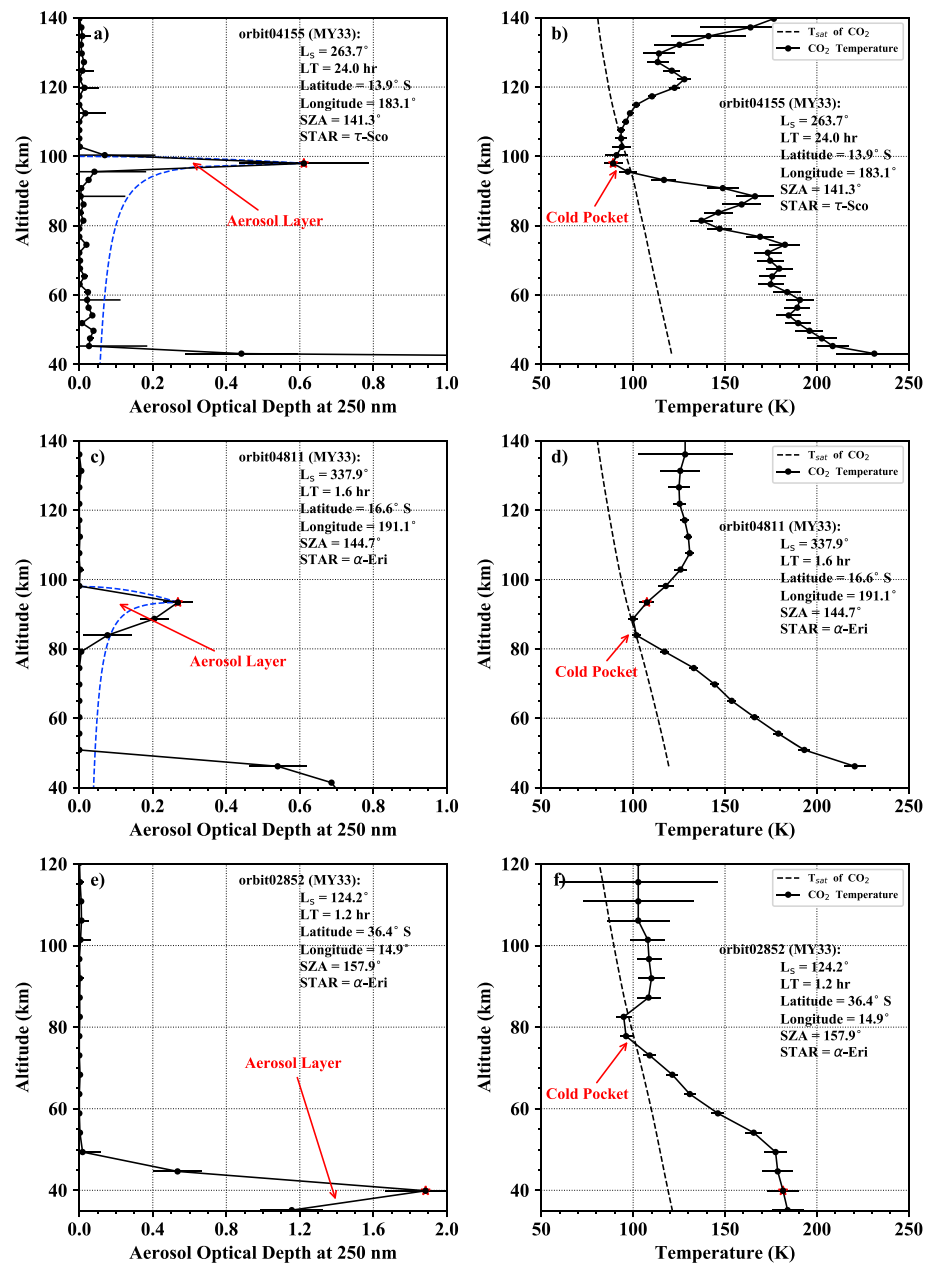
Ultraviolet stellar occultation is a well-established technique probing the Martian mesosphere (Bertaux et al., 2006; McClintock et al., 2015). By monitoring the ratio of the attenuated spectra through the atmosphere to the unattenuated spectrum outside the atmosphere as a star rises or sets behind the horizon, the transmission spectrum of the atmosphere is measured. Analysis of these spectra reveals the molecular species and their density profiles according to their distinct absorption signatures. The retrieval procedure of MAVEN/IUVS stellar occultation data was described in Gröller et al. (2018), from which the CO<sub>2</sub>, O<sub>2</sub>, and O<sub>3</sub> densities as well as the temperature profiles are retrieved, in addition to the aerosol extinction. The transmission spectra are available in the IUVS processed “occultation” profiles (Level 1c), while the derived profiles (Level 2) contain the derived physical quantities, such as the local CO<sub>2</sub> number density, temperature, and aerosol optical depth. We use the v13 release in this study.

Twenty stellar occultation campaigns have been performed from March 2015 to April 2018 (Martian Year, MY32–MY34), during which 309 MUV occultation profiles were acquired, sampling latitudes from 79°S to 68°N, the full range of longitude, and local times  $\leq 4.8$  and  $\geq 18.7$  hr. Among these 309 MUV occultation profiles, we find 166 profiles with detached aerosol layers and 32 with cold pockets where the inferred atmospheric temperature drops below the CO<sub>2</sub> saturation temperature. Most of the aerosol layers occur at lower altitudes (<50 km) and likely consist of dust raised from the surface by Martian winds (Kahre et al., 2017) with a fraction of them being water ice clouds (Montmessin et al., 2017). There are two special cases exhibiting distinct layers at altitudes greater than 90 km, similar to the altitudes of CO<sub>2</sub> ice clouds detected with SPICAM occultations by Montmessin et al. (2006). We suggest that they are CO<sub>2</sub> ice clouds and present a further analysis in the following section.

## 3. Results and Interpretations

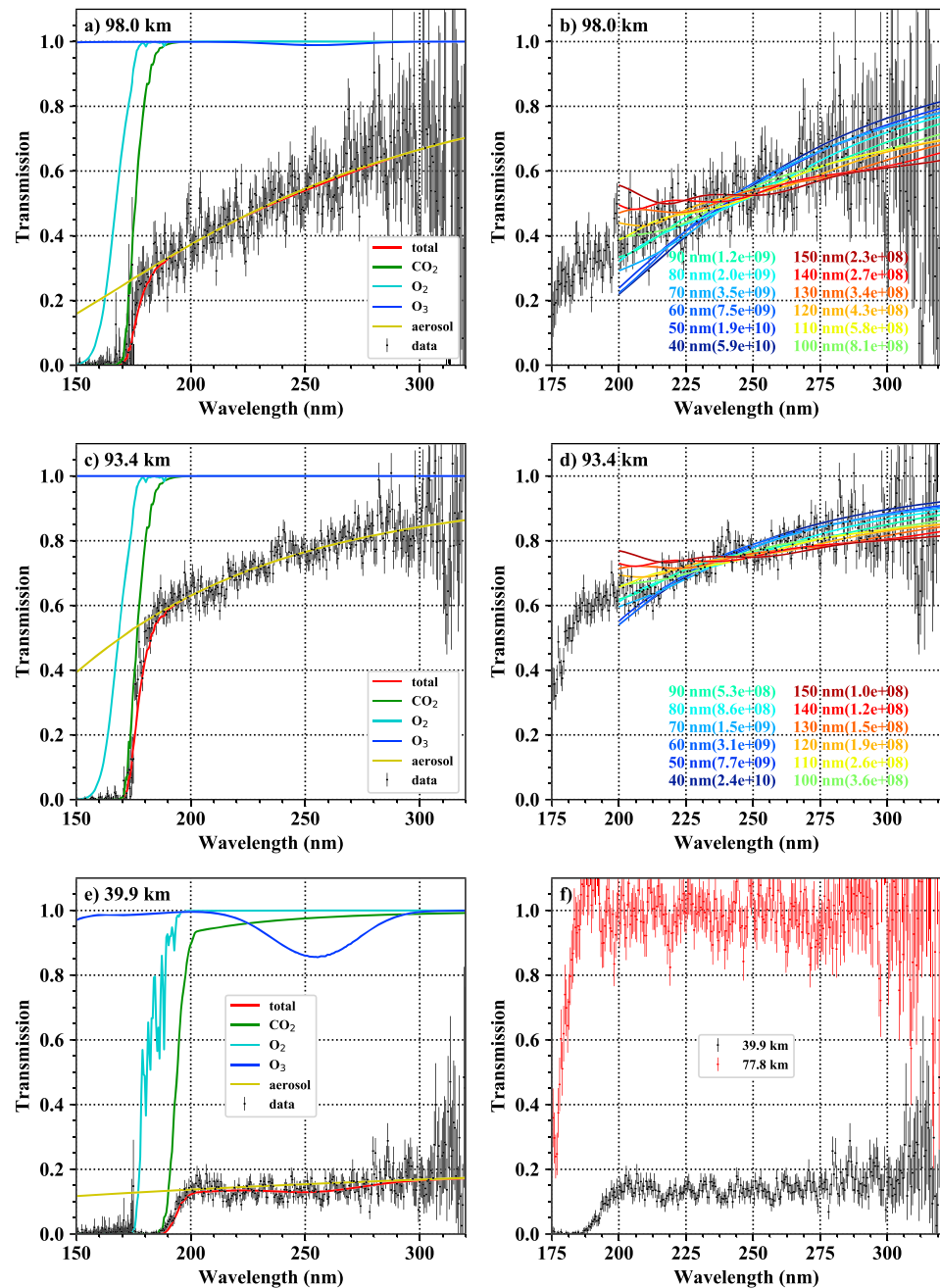
The top two rows in Figure 1 show the vertical aerosol optical depths at 250 nm (a and c) and the corresponding temperature profiles (b and d). Distinct layers can be easily identified in the aerosol profiles, as indicated by red arrows. The extinction maxima appear at altitudes of 98.0 km (a) and 93.4 km (c), respectively. Both layers appeared in the nighttime atmosphere (LT = 24.0 and 1.6 hr) of the Martian southern tropics (13.9°S and 16.6°S). One cloud occurred near the southern summer solstice ( $L_s = 264^\circ$ ), while the other appeared in late summer ( $L_s = 338^\circ$ ). Equatorial mesospheric CO<sub>2</sub> clouds on Mars were usually observed between  $L_s = 0$ –180° (Clancy et al., 2019; Montmessin et al., 2006, Montmessin et al., 2007; 2010; Stevens et al., 2017), although Määttänen et al. (2010) have reported one daytime equatorial CO<sub>2</sub> cloud at  $L_s = 330^\circ$  in MY29 with MEx/OMEGA observations. Thus, the clouds reported here are the first tropical high-altitude nighttime clouds to be observed during southern summer.

The vertical extent of the discrete layers is roughly 10 and 20 km for orbits 4155 and 4811, respectively. These values are similar to the cloud thickness of ~5–20 km inferred by Montmessin et al. (2006). The temperature profiles derived from the CO<sub>2</sub> absorption signatures in these two occultations have deep minima near the locations of layers where the value falls below the CO<sub>2</sub> condensation temperature. However, the profile in orbit 4155 shows a temperature decrease of ~8 K below the CO<sub>2</sub> condensation temperature, while the cold



**Figure 1.** Vertical profiles of aerosol optical depth at 250 nm (left column) and CO<sub>2</sub> temperature (right column) for three occultation measurements targeting  $\tau$ -Sco (a and b),  $\alpha$ -Eri (c and d), and  $\alpha$ -Eri (e and f), respectively. The Imaging UltraViolet Spectrograph data are plotted with black solid lines. The blue dashed lines in panels (a) and (c) indicate the model results by assuming horizontally infinite clouds (see text). The detached aerosol layers and cold pockets are labeled with red arrows, while the red star symbols mark the altitude of the maximum extinction within the aerosol layers. The dashed lines in the right panels indicate the CO<sub>2</sub> saturation temperatures. The top two rows illustrate the two occultation profiles detecting CO<sub>2</sub> ice clouds at the altitudes around 98 and 93 km, respectively, while the bottom row shows the profiles with a layer at an altitude of 40 km.

pocket presented in orbit 4811 is only a fraction of a Kelvin below the condensation temperature. In addition, the former temperature profile shows a wave-like structure, which is not as obvious in the latter profile. The altitudes of the two aerosol layers presented here > are similar to that of the mesospheric CO<sub>2</sub> ice clouds found by Montmessin et al. (2006) with SPICAM occultation measurements. However, unlike the situation shown in Montmessin et al. (2006) that the observed clouds formed below the supersaturated portions, the aerosol layer in orbit 4155 is directly formed within the cold pocket, while the layer in orbit 4811 appears slightly above the cold pocket.



**Figure 2.** Corresponding transmission spectra (black) at the altitudes with maximum extinctions (marked with red stars) within the aerosol layers in Figure 1. (a, c, e) Contributions of CO<sub>2</sub> (green), O<sub>2</sub> (cyan), O<sub>3</sub> (blue), and aerosol (yellow) to the fitted transmission spectra (red) at the altitudes indicated with the red stars in Figure 1. (b, d) Fitted results to the same transmission spectra as in (a) and (c) with Mie theory, assuming particle sizes ranging from 40 to 150 nm. The numbers in parentheses are the relevant fitted column densities per square centimeter. (f) Transmission spectra within the aerosol layer (black) and the cold pocket (red), at the altitudes indicated by the red star in Figure 1e and the red arrow in Figure 1f, respectively.

We estimate the size of the clouds with some simple models. Assuming that the clouds are spherically symmetric (horizontally homogeneous over the region sensed in the occultation), of limited vertical extent, and with uniform density within that vertical range, we calculate the optical depth, which is proportional to the path length along the line of sight intersecting the cloud. The results are shown with blue dashed lines in Figures 1a and 1c for the two CO<sub>2</sub> clouds. The model results can reproduce the IUVS occultation measurements above the altitude of the peak column density; however, at lower altitudes, the model results are

significantly larger than the measured optical depth. This suggests that the clouds must be of limited horizontal extent. If we require that the line of sight completely misses the cloud for a tangent altitude of  $\sim 90$  km (for the cloud in orbit 4155) or  $\sim 80$  km (for the cloud in orbit 4811), we can estimate the horizontal extent of  $\sim 500$  km for the cloud in orbit 4155 and the horizontal extent of  $\sim 700$  km for the cloud in orbit 4811, respectively. For both observations the line of sight is within  $30^\circ$  of the east-west direction and these estimates therefore pertain to the longitudinal extent of the cloud. The observations provide no strong constraints on the latitudinal extent of the cloud. Obviously, these simple models are unlikely to accurately represent the distribution of cloud opacity and the values presented above should be interpreted as rough estimates for the size of the cloud.

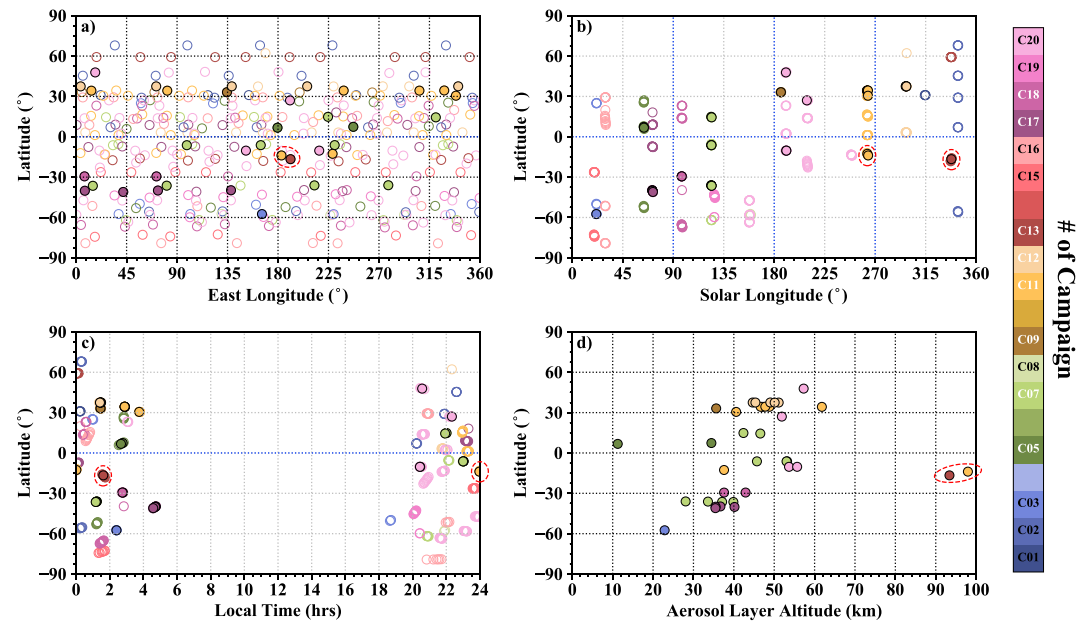
For comparison, another profile with an aerosol layer at the altitude of 40 km is shown in Figures 1e and 1f, which is also a low-latitude nightside profile but in the southern winter season ( $L_s = 124^\circ$ ). A cold pocket is present in the temperature profile as well but at the altitude of 80 km well above the aerosol layer. No layer is found around the altitude of the cold pocket, which is probably because the layer had an optical depth below the detection limit of 0.01 (Gröller et al., 2018).

The corresponding transmission spectra at the altitudes with maximum extinctions (marked with red stars) within the aerosol layers are shown with black points with error bars in Figure 2. The left column of Figure 2 illustrates the separate contribution of  $\text{CO}_2$  (green),  $\text{O}_2$  (cyan),  $\text{O}_3$  (blue), and aerosols (yellow) to the atmospheric absorption (red). The absorption cross sections are adopted from Table 2 of Gröller et al. (2018, and references therein). As revealed in the figure, aerosols dominate the atmospheric extinction at wavelengths longer than 200 nm. There is no detectable  $\text{O}_3$  in these occultations.

As shown in Figure 2, the transmission spectra for the high-altitude aerosol layers (panels a and c) increase strongly with wavelength, whereas the transmission spectrum for the low-altitude layer (panel e) is roughly flat. This indicates that the aerosols in the high-altitude layers are smaller than the ultraviolet wavelengths measured here, while in the low-altitude layer the aerosols are larger than ultraviolet wavelengths (Montmessin et al., 2006). By assuming  $\text{CO}_2$  spherical ice particles, we fit the transmission spectra for the two high-altitude clouds with Mie theory using refractive indices adopted from Warren (1986). We assume a range of ice particle sizes from 40 to 150 nm and fit the transmission spectra with the column densities as free parameters. The best fit results are shown with colored solid lines in Figures 2b and 2d. As revealed by the figure, the column densities, as well as the slopes of fitted spectra, decrease as the particle sizes increase. For the case shown in Figure 2b, the best fit monodispersed particle radius is  $105 \pm 5$  nm, with a column density of  $(6.9 \pm 1.2) \times 10^8 \text{ cm}^{-2}$ , while for the other, the best fit parameters are  $95 \pm 1$  nm and  $(4.3 \pm 0.1) \times 10^8 \text{ cm}^{-2}$ , respectively. A Monte Carlo technique is used to derive the uncertainties of fit parameters. Assuming a log-normal size distribution with an effective variance  $v_{\text{eff}} = 0.15$  (adopted from Montmessin et al., 2007) yields a best fit effective radius of  $\sim 87$  and  $\sim 78$  nm and number densities of  $1.1 \times 10^9$  and  $1.0 \times 10^9 \text{ cm}^{-2}$ , respectively. The uncertainties quoted here are formal results from the fit and do not include the likely larger systematic uncertainty related to the assumption of Mie scattering. The results are in agreement with the  $\text{CO}_2$  ice particle sizes of 80–130 nm obtained by Montmessin et al. (2006). With the particle size derived here, we calculate the sedimentation velocity by multiplying the Stokes fall velocity by the Cunningham factor (Listowski et al., 2014) and find that the sedimentation velocity exceeds 10 m/s at the altitude of higher than 90 km. The cloud particles would fall out of the clouds in less than 2,000 s accordingly.

Considering a typical  $\text{CO}_2$  cloud with a vertical width of 10 km and a uniform column density of  $5 \times 10^8 \text{ cm}^{-2}$ , we estimate the particle number density of  $9.5 \times 10^6 \text{ m}^{-3}$  for a horizontally infinite cloud and the number density of  $1.6 \times 10^7 \text{ m}^{-3}$  for a cloud with a finite horizontal extent, which are in agreement with the model estimation of  $10^6$ – $10^8 \text{ m}^{-3}$  by Listowski et al. (2014). Assuming that the 100-nm cloud particles are spherical and using a  $\text{CO}_2$  ice density at 100 K of  $1.7 \text{ g/cm}^3$  (Mangan et al., 2017), we estimate a total mass density of  $\sim 10^{-13} \text{ g/cm}^3$  for a typical  $\text{CO}_2$  ice cloud detected by the IUVS, which is far below the ambient  $\text{CO}_2$  gas density of  $\sim 10^{-10} \text{ g/cm}^3$  at the altitude of 90–100 km. The mass mixing ratio of  $\text{CO}_2$  ice is much larger than  $\text{H}_2\text{O}$  available at these altitudes (Fedorova et al., 2018; Maltagliati et al., 2013).





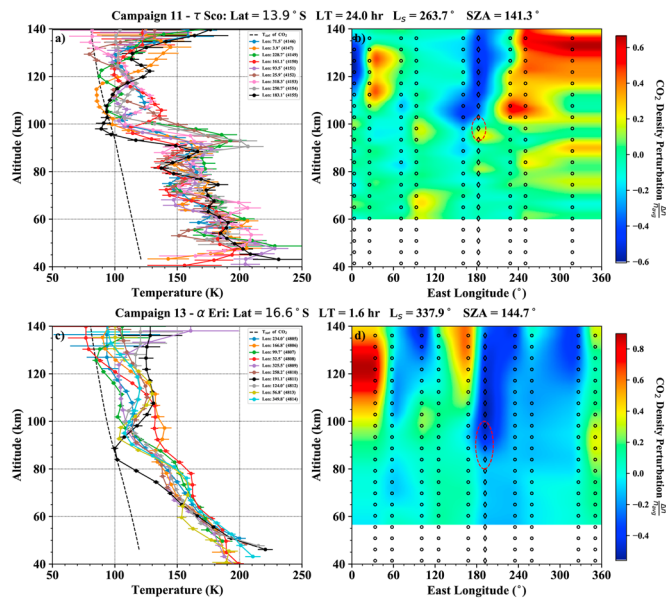
**Figure 3.** Geographic distribution of the midultraviolet occultations executed by Imaging UltraViolet Spectrograph from March 2015 to April 2018 with latitude versus east longitude (a), solar longitude (b), local time (c), and aerosol layer altitude (d). The empty circles indicate the occultation profiles without cold pockets, while the solid circles denote the profiles with cold pockets. Campaigns C1–C20 are indicated with different colors, as shown in the color bar, with those with cold pockets indicated with white labels. There are no midultraviolet occultation data available in Campaigns C4, C6, C10, and C14. For those profiles with more than one layer, only the altitudes of the highest layers are shown in panel (d). The two CO<sub>2</sub> ice clouds are marked with the dashed ellipses. A table of the geophysical information for these occultations is provided in the Supporting Information.

Water clouds are unlikely candidates, for the reason that extraordinarily high mass mixing ratios would be required to match both particle size and the measured cloud opacity. The water mass mixing ratios can be calculated with (Heavens et al., 2010)

$$q_{ice} = \frac{4}{3} \frac{\rho_{ice}}{Q_{ext}} \frac{d_z \tau}{\rho} r_{eff} \quad (1)$$

where  $\rho_{ice}$  is the density of water ice,  $Q_{ext}$  is the extinction coefficient,  $d_z \tau$  is the water ice opacity per unit height,  $\rho$  is the atmospheric density, and  $r_{eff}$  is the particle radius. Following Heavens et al. (2010), we assume that  $\rho_{ice} = 900 \text{ kg/m}^3$  and  $Q_{ext} = 0.773$ . The atmospheric density and  $d_z \tau$  measured by IUVS occultations at the altitude of CO<sub>2</sub> clouds are  $\sim 10^{-7} \text{ kg/m}^3$  and  $\sim 10^{-4} - 10^{-5} \text{ m}^{-1}$ , respectively. The water particle size can be derived with Mie theory by fitting the transmission spectra with revised water ice refractive indices adopted from Warren and Brandt (2008), which gives particle radii,  $r_{eff} \sim 100 \text{ nm}$ . The predicted water ice mass mixing ratios are up to  $10^{-2} - 10^{-1}$ , which is larger than the value of tens or hundreds of parts-per-million in the Martian mesosphere presented by previous studies (Fedorova et al., 2018; Maltagliati et al., 2013).

Figure 3 shows the geographic distribution of latitude versus east longitude (a), solar longitude (b), local time (c), and aerosol layer altitude (d) for all the occultation campaigns with MUV observations in this study. All the MUV occultations are sampled in the nightside to avoid stray light contamination. As revealed in the figure, there is no obvious dependence of cold pocket occurrence on longitude. The occurrence of cold pockets is confined in the latitude range of 40°S to 40°N, with 16 in the northern hemisphere and 16 in the southern hemisphere. Among the 32 profiles with cold pockets, 10 appeared in the latitude of 20°S to 20°N, while 20 occurred in the 30°S to 40°S and 30°N to 40°N, and the remaining two were at the latitude of 29°S. Except for two cold pockets near the equinox ( $L_s = 186^\circ$  and  $L_s = 338^\circ$ ), the remaining 30 cold pockets occurred around the solstice, with 17 at  $L_s = 60 - 125^\circ$  and 13 at  $L_s = 260 - 300^\circ$ : this may indicate a seasonal variability of the cold pockets. Forget et al. (2009) found that supersaturation temperatures were rare in southern summer with detection of only one case between  $L_s = 240^\circ$  and  $300^\circ$ . In contrast, we find that 13 out of 66 MUV occultation profiles in this solar longitude range have supersaturated temperatures. This suggests that the occurrence rate of supersaturated temperatures varies with MY, a hypothesis that can



**Figure 4.** (a, b) Longitudinal perturbations of temperatures and CO<sub>2</sub> densities using occultations from consecutive orbits targeting  $\tau$ -Sco during Campaign 11 at a latitude of 8.7°S, a local time of 23.9 hr, and a solar longitude of 263.7°. The CO<sub>2</sub> cloud profile is plotted with the black solid line in (a). The black dashed line in (a) indicates the CO<sub>2</sub> saturation temperature. The CO<sub>2</sub> density perturbations shown in (b) are defined as the difference between the local number density and the longitudinal mean of densities at that altitude divided by the longitudinal density mean. The image is created by linear interpolation between the data points. Vertical markers represent the longitudes of the measurements, with the cloud profile indicated with the diamonds. The altitude of the cloud is marked with the red dashed ellipse. (c, d) Same as (a) and (b) but from consecutive orbits targeting  $\alpha$ -Eri during Campaign 13 at a latitude of 17.7°S, a local time of 1.7 hr, and a solar longitude of 337.9°.

be tested with future MAVEN occultations. Forget et al. (2009) also showed that supersaturation temperature inferred from SPICAM occultation measurements presented no apparent correlation with longitude, consistent with our results.

It is interesting that the two clouds detected in this study occur at similar longitudes (183°, 191°) and latitudes (14°S, 17°S). The clouds detected by Montmessin et al. (2006) also occurred in the southern equatorial regions (latitudes of 15°S, 15°S, 32°S, and 38°S) but over a range of longitudes (15°, 134°, 182°, and 277°). Moreover, all four clouds detected by Montmessin et al. (2006) occurred in the winter hemisphere ( $L_s = 134\text{--}137^\circ$ ), while the clouds detected here were found in the summer hemisphere ( $L_s = 264^\circ, 338^\circ$ ). The dust opacity in the atmosphere at the location and time of our detections were significant with vertical optical depths in the infrared of 0.6 and 0.7 (Montabone et al., 2015). In summary, all detections to date occurred in southern equatorial regions and the observations presented here show that mesospheric CO<sub>2</sub> clouds occur in southern summer during significant dust activity. Mesospheric CO<sub>2</sub> clouds have been detected at a variety of longitudes, but three of the six detections are close to a longitude of 180°. Generalizations are difficult given the small number of observations, but the cloud detections to date are clustered in a small region of parameter space.

Since their discovery, it has been suggested that the mesospheric clouds on Mars are created when the temperature perturbations associated with tides and gravity waves become large enough for the temperature to dip below the CO<sub>2</sub> saturation temperature (Clancy & Sandor, 1998; Montmessin et al., 2006). Our observations provide strong support for this hypothesis. Figure 4a shows that the condensation cloud seen in campaign 11 is associated with a temperature profile containing wave-like perturbations that grow with increasing altitude. The wave signature is less strong in the temperature profile association with the cloud seen in campaign 13 but still appears present. The importance of tides is seen more directly in the longitudinal variations of density shown in Figures 4b and 4d. During an occultation campaign, IUVS executes several consecutive occultations of a particular star every  $\sim 4.5$  hr, thereby sampling nearly the same latitudes and local times but different longitudes. For these consecutive orbits targeting the same star in one campaign, the differences in latitude and local time are less than 2.5° and 0.2 hr, respectively. The drift of latitude and



longitude during a single stellar occultation is less than  $1^\circ$ . We present the longitudinal perturbations of  $\text{CO}_2$  densities for the two campaigns with detected  $\text{CO}_2$  ice clouds in Figure 4. The interpolation method of temperature profiles has been described and discussed in Gröller et al. (2018), which showed that, for one example from campaign 11 with particularly strong tides, the density perturbations from the interpolated occultation profiles had similar amplitudes and were roughly in phase with the perturbations calculated from the Mars Climate Database (Forget et al., 1998, 1999; González-Galindo et al., 2015; Madeleine et al., 2011; Millour et al., 2018). For the two cases considered here, large perturbations are seen in the  $\text{CO}_2$  number densities, especially at higher altitudes. As indicated by the vertical diamond markers in Figures 4b and 4d, the  $\text{CO}_2$  number densities dropped dramatically at and above the altitude of  $\text{CO}_2$  ice clouds, consistent with the cold temperatures and hydrostatic equilibrium. For the  $\tau$ -Sco occultations there is significant variability at altitudes below 90 km but no clear periodicities. This changes above 90 km where the perturbations show a periodic structure in longitude. The  $\alpha$ -Eri occultations show far less variability at altitudes below 90 km but, similar to  $\tau$ -Sco, exhibit strong periodicity at higher altitudes.

As discussed in Gröller et al. (2018), the occultation observing strategy is especially sensitive to nonmigrating tides. Other tidal modes or gravity waves could also contribute but have signatures that are less easy to discern. The correlation with these strong, low-harmonic longitude perturbations suggests that nonmigrating tides play a role in formation of the clouds. The measured perturbations appear to be dominated by an  $m = 3$  wave, a common situation on Mars (Forbes et al., 2002; Gröller et al., 2018; Lo et al., 2015; Stevens et al., 2017; Wilson, 2002). Fourier analysis indicates that the longitudinal wave for the  $\tau$ -Sco occultations gives amplitudes of 27% and 53% for the  $m = 2$  and  $m = 3$  waves, with lesser contributions from other waves (see Gröller et al., 2018, for a description of the Fourier analysis). A similar analysis for the  $\alpha$ -Eri occultation finds that the longitudinal wave at 93 km (the location of the cold pocket and cloud) finds amplitudes of 37% and 41% for the  $m = 2$  and  $m = 3$  waves. The supersaturated cold pockets occur where the  $m = 2$  and  $m = 3$  waves are in phase. We note that Stevens et al. (2017) observed  $m = 3$  periodicity in the occurrence rate of mesospheric clouds.

A puzzling aspect of the observations is that aerosol opacity is detected in only one occultation in the set of  $\tau$ -Sco occultations, while supersaturated conditions exist in several occultations. As pointed out earlier, subcondensation temperatures are detected quite often but aerosol layers coincident with the cold temperatures are detected only rarely (Forget et al., 2009; Montmessin et al., 2006), less than 10% of the time. The low detection rate may be due to the short cloud lifetime. The model results of Listowski et al. (2014) show that clouds should become observable in 1–3 hr after temperatures drop below the  $\text{CO}_2$  condensation point and should persist 10–30 min after the supersaturated regions disappear (see their Figures 8–19 and related text). The possible correlations with tides found here suggest that supersaturated conditions are formed when the main tidal modes are in phase. Because the IUVS occultation campaigns repeatedly measure the atmosphere at the same local time, it is not possible to determine the separate zonal ( $s$ ) and diurnal ( $n$ ) wave numbers for the tidal modes but only  $m = s - n$ . If these have the same diurnal wave number, then they would remain in phase at all times, but if the main tidal modes have different diurnal wave numbers, then they would be in phase for a period of roughly several hours, comparable to the time estimated by Listowski et al. (2014). Further investigations into this hypothesis require coupling a microphysical model for cloud evolution to a realistic atmospheric model including tides and gravity waves.

#### 4. Concluding Remarks

From March 2015 to April 2018, the IUVS on board the MAVEN spacecraft has obtained 309 stellar occultation profiles in the MUV spectral band from which 166 profiles with aerosol layers and 32 profiles with supersaturated  $\text{CO}_2$  conditions. In two cases the aerosol layers are coincident with  $\text{CO}_2$  saturation and both of these occur above 90 km, much higher than the other aerosol layers detected in the occultations. These are the first detections of high-altitude nighttime  $\text{CO}_2$  clouds during southern summer ( $L_s = 264^\circ$  and  $L_s = 330^\circ$ ). The measured aerosol extinction increases strongly with decreasing wavelength for the high-altitude layers indicating much smaller particle sizes than for the low-altitude aerosol layers. Interpretation of the transmission spectra with a Mie scattering model indicates particles sizes of  $\sim 90$ – $110$  nm. Aerosols of this size would sediment out of the cloud layer in a time less than 2,000 s. The altitude profile of extinction indicates that the layers are confined horizontally to sizes less than 500 and 700 km. We estimate that the mass density within the cloud is roughly 0.1% of the local atmospheric mass density. The mass required to form these clouds is so much larger than the available water vapor that  $\text{H}_2\text{O}$  composition of these clouds

can be ruled out. Examination of the CO<sub>2</sub> density and temperature profiles retrieved simultaneously with the aerosol extinction reveals strong wave-like perturbations. The supersaturated temperatures occur at the maximum negative extent of these wave-like perturbations. This supports earlier arguments that the CO<sub>2</sub> clouds are produced by atmospheric waves. The perturbations are also organized in longitude with a dominant  $m = 3$  zonal harmonic. This suggests that tides are important in the formation of the clouds. The CO<sub>2</sub> clouds only appear in a small percentage of the supersaturated CO<sub>2</sub> profiles (two out of 32). We speculate that the relative lifetimes of the temperature perturbations and clouds may play a role in their detectability, but much remains to be learned about their formation and evolution.

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