

# Effect of the 2018 Martian global dust storm on the CO<sub>2</sub> density in the lower nightside thermosphere observed from MAVEN/IUVS Lyman-alpha absorption

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1       **Effect of the 2018 Martian global dust storm on the CO<sub>2</sub> density in the lower nightside**  
2       **thermosphere observed from MAVEN/IUVS Lyman-alpha absorption**

3  
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8  
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10       **Abstract**

11       The MAVEN/IUVS instrument measures Lyman- $\alpha$  emissions from interplanetary and martian  
12       hydrogen at the limb and through the extended corona of Mars. In June 2018, a Global Dust  
13       Storm (GDS) surrounded Mars for a few months, heating the lower atmosphere and leading to an  
14       expansion of the Martian atmosphere. Nightside IUVS observations before and throughout this  
15       GDS showed the altitude of CO<sub>2</sub> absorption of Lyman- $\alpha$  photons in the thermosphere to increase  
16       by  $4.5\pm 1.0$  km on 8 June 2018. This shift is attributed to an increase of the CO<sub>2</sub> density by a  
17       factor  $1.9\pm 0.2$  at 110 km due to the heating of the lower atmosphere. These nightside  
18       observations, not previously used to study dust storms, in an altitude range not sampled by other  
19       instruments, are consistent with dayside MAVEN observations and allow for more  
20       comprehensive determination of the global changes produced by the GDS on the Martian  
21       thermosphere.

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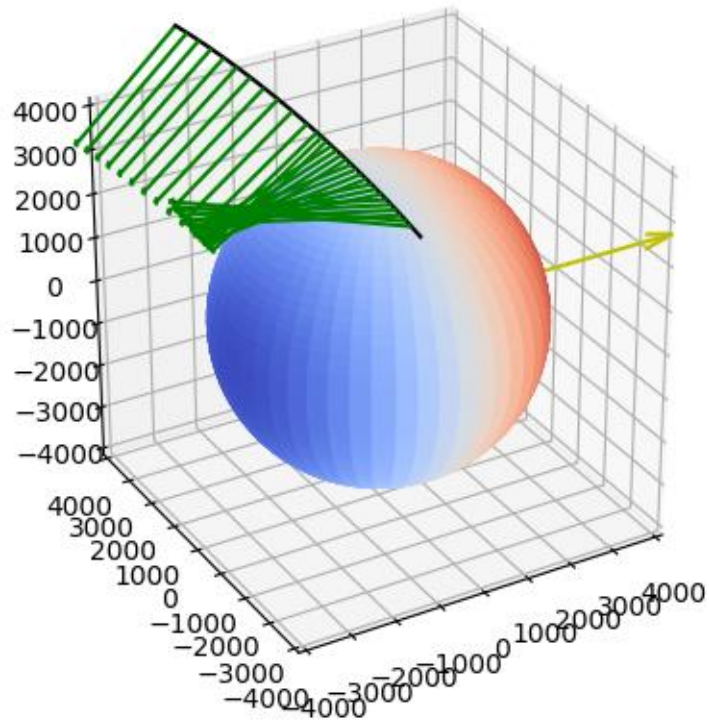
## 26        **1) Introduction**

27        Absorption of UV photons in the Martian upper atmosphere is the main source of thermospheric  
28        heating as well as of ionization, dissociation and excitation of CO<sub>2</sub> molecules (e.g. Fox et al.  
29        2008). The partial absorption of the UV solar or stellar photons can also be used by remote  
30        sensing instrument to derive the density, temperature or composition of the Martian thermosphere  
31        as done by Mars Express/SPICAM (e.g. Forget et al. 2009) and more recently by MAVEN/IUVS  
32        (Gröller et al. 2015, 2018). Another method used to derive the CO<sub>2</sub> density in the Martian  
33        nightside thermosphere near 110 km utilizes the absorption by CO<sub>2</sub> of Lyman- $\alpha$  photons emitted  
34        in the interplanetary medium and Martian exosphere (Bertaux et al. 2005, Chaufray et al. 2011).  
35        Chaufray et al. (2011) used this method to derive seasonal variations of lower thermospheric  
36        nightside CO<sub>2</sub> density that were in good agreement with variations deduced from stellar  
37        occultations. This method was shown to be less accurate than the stellar/solar occultation method  
38        because it is based on only one wavelength instead of the full UV spectral range for occultations,  
39        yet it has the advantage of simplicity due to requiring fewer constraints on pointing, and  
40        portability to any latitudes, longitudes, and local time at nightside compared with terminator-  
41        limited solar occultations. In June 2018, an intense Global Dust Storm (GDS) surrounded Mars  
42        lasting a few months, heating the lower atmosphere (Kass et al. 2018) and led to an expansion of  
43        the Martian atmosphere by few kilometers at thermospheric altitudes (Bougher et al., 2019, see  
44        also Jain et al. this issue, and Elrod et al this issue). Since Lyman- $\alpha$  absorption occurs in the  
45        lower thermosphere, an increase of CO<sub>2</sub> density at a given altitude during the GDS would be  
46        expected to increase the altitude of Lyman- $\alpha$  absorption by CO<sub>2</sub>. In this paper, MAVEN/IUVS  
47        nightside “limb scans” are used to estimate the increase of the CO<sub>2</sub> density at 110 km produced  
48        by this GDS. Section 2 describes the dataset and assumptions used to derive the CO<sub>2</sub> density. In

49 section 3 the variations of CO<sub>2</sub> density at 110 km during the dust storm are shown. The results are  
50 compared to dayside variations observed by other instruments in section 4.

## 51 **2) Data analysis**

52 At the beginning of the global dust storm, the MAVEN spacecraft periapsis was on the dayside,  
53 and its apoapsis on the nightside. The IUVS “coronal scans” occur on the inbound and outbound  
54 segments of the orbit from periapsis (McClintock et al. 2015). During these parts of MAVEN’s  
55 orbit, the Lyman- $\alpha$  emission of atomic hydrogen is observed scanning the limb with tangent  
56 altitudes ranging from below the planet’s surface up to the exosphere  $\sim 3400$  km. During the  
57 outbound leg, the spacecraft was partly in the dayside on 8 June 2018 and in the nightside during  
58 the inbound leg. In this paper, the nightside inbound observations from MAVEN/IUVS where the  
59 solar zenith angle of the tangent point is larger than  $\sim 90^\circ$  and the solar zenith angle of the  
60 spacecraft is larger than  $90^\circ$  are used. The geometry of one observation is displayed on Fig. 1



61

62 *Figure.1 Geometry of the observation during orbit 7178 in the Mars Sun Orbit (MSO) frame. All*  
 63 *axis are in km. The Martian surface is red at the dayside and blue at the nightside. MAVEN is*  
 64 *moving toward is pericenter and its position during the observation is represented by the black*  
 65 *solid line. The lines of sight of IUVS during the different inlimb scans are represented in green.*  
 66 *The sun direction is shown by the yellow arrow (X axis).*

67

68 Atmospheric hydrogen is not directly illuminated by the Sun in the shadow, and the brightness  
 69 dispersion at a given tangent altitudes is smaller on the nightside than on the dayside, making the  
 70 CO<sub>2</sub> density retrieval easier. In this study, we only use observations with a tangent altitude  
 71 spanning the surface to 250 km (files tagged “inlimb” in the Planetary Data System archives).  
 72 The resulting observations include 33 non-consecutive orbits spanning orbit # 7106 (25 May

73 2018) to orbit # 7256 (22 June 2018). Six inbound limb scans are done in each orbit with a  
74 sampling of approximately 10 km. 7 spatial bins are transmitted per limb scan, leading to 42  
75 individual limb profiles per orbit. The latitude, longitude, SZA and local time ranges at the  
76 tangent point covered for each orbit are given in Table 1

# Orbit	Day	Ls	SZA	Latitude	E Longitude	Local Time
7106	25 May	181.5	117-138	27-55	49-74	20.8-22.7
7112	26 May	182.2	117-138	29-55	17-42	20.8-22.6
7116	27 May	182.6	117-137	30-54	115-140	20.6-22.5
7120	27 May	183.0	118-137	26-54	215-239	20.5-22.4
7124	28 May	183.5	118-137	26-53	313-338	20.4-22.3
7128	29 May	183.9	118-136	25-53	52-76	20.4-22.2
7132	30 May	184.3	118-136	24-52	151-174	20.3-22.1
7136	30 May	184.7	118-135	23-52	250-273	20.2-22.1
7140	31 May	185.1	118-135	22-51	349-12	20.2-22.0
7144	01 Jun	185.6	117-134	22-51	88-111	20.1-21.9
7150	02 Jun	186.2	117-133	22-50	56-79	20.0-21.8
7154	03 Jun	186.6	117-132	21-49	155-177	20.0-21.7
7158	04 Jun	187.1	117-131	21-49	254-276	19.9-21.6
7162	04 Jun	187.5	116-131	20-48	353-15	19.8-21.5
7166	05 Jun	188.0	115-130	19-48	91-113	19.7-21.4
7170	06 Jun	188.3	115-129	19-47	190-211	19.7-21.3
7174	06 Jun	188.8	113-128	18-46	290-310	19.6-21.2
7178	07 Jun	189.2	112-127	18-45	28-49	19.5-21.2
7182	08 Jun	189.6	112-127	17-45	126-148	19.5-21.2
7198	11 Jun	191.4	108-124	15-43	162-182	19.2-20.7
7202	12 Jun	191.8	107-124	15-43	261-281	19.1-20.7
7208	13 Jun	192.4	106-123	14-42	230-250	19.0-20.6
7212	14 Jun	192.9	105-123	13-41	329-348	19.0-20.5
7216	14 Jun	193.3	104-122	13-41	67-87	18.9-20.4
7222	15 Jun	194.0	103-121	12-40	36-55	18.8-20.3
7226	16 Jun	194.4	102-120	11-39	135-154	18.7-20.2
7230	17 Jun	194.8	101-120	11-39	235-253	18.6-20.1
7234	18 Jun	195.3	99-119	10-38	333-352	18.6-20.1
7238	18 Jun	195.7	98-118	10-37	72-91	18.5-20.0
7244	19 Jun	196.4	97-117	10-37	41-59	18.4-19.9
7248	20 Jun	196.8	96-116	8-36	139-158	18.3-19.8
7252	21 Jun	197.2	95-115	8-36	239-257	18.2-19.7
7256	22 Jun	197.7	93-115	7-35	338-357	18.2-19.6

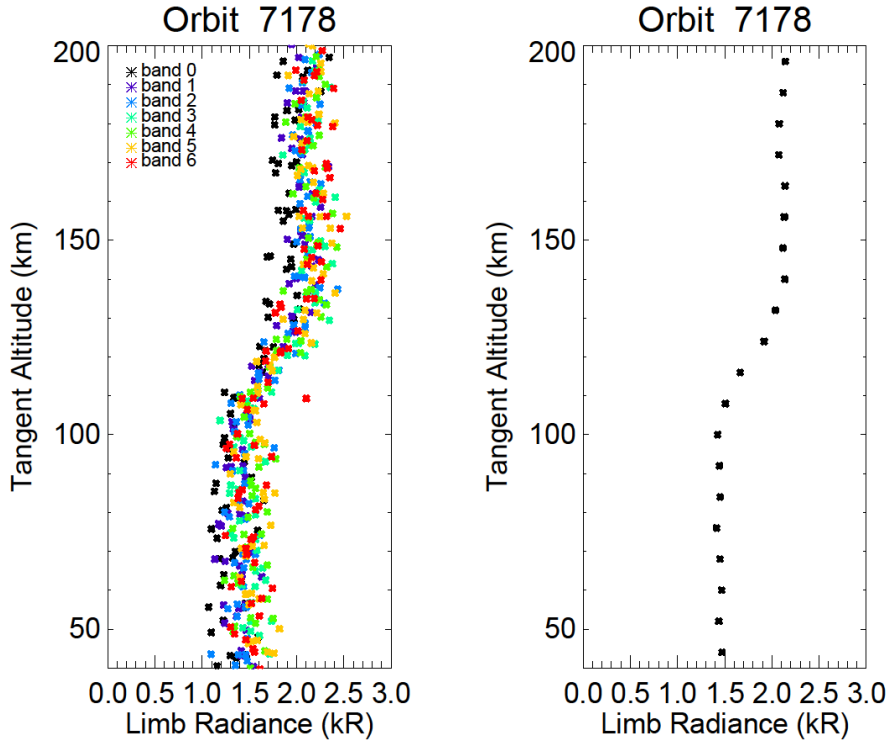
77 *Table 1 : MAVEN orbits used for this study (column 1). The spatial/temporal information for*  
78 *each orbits are also given. Solar Zenith Angla (SZA), latitude, East longitude and local time*

79 *range refers to the tangent point of the different lines of sight. The MAVEN orbits drift in*  
80 *longitude by  $\sim 115^\circ/\text{orbit}$  due to the Martian rotation.*

81

82 The spacecraft altitude varies between 2100 to 3400 km during these 6 inbound limb  
83 observations. During these observations, the approximate distance between the spacecraft and the  
84 tangent point is  $\sim 5000$  km. The IUVS slit projection is normal to the orbit of MAVEN  
85 (perpendicular to the vertical direction). The IUVS spatial bins (corresponding to a binning of  
86 115 physical pixels along the slit) projection at the tangent point is  $\sim 20$  km.

87 The 42 individual limb profiles for orbit #7178 are displayed in Figure 2. For all the orbits, the  
88 variations of the brightness between the different limb scans ( $\sim 0.14\text{kR}$ ) is close to the error bar  
89 of the individual measurement ( $\sim 0.13$  kR). There are small variations of sensitivity between the  
90 different spatial bins along the slit, but we do not apply any flatfield corrections in this study,  
91 because our results are not sensitive to the absolute sensitivity of the spatial bins. We average the  
92 profiles to increase the signal to noise. Profiles are averaged every 8 km. The average profile is  
93 shown in Figure. 2.



94

95 *Figure. 2 : Left : Vertical profiles of the H Lyman- $\alpha$  brightness measured at limb between 40 and*  
 96 *200 km for each of 7 spatial bins (labeled as “bands” and shown with different colors) during*  
 97 *orbit 7178 for all six inbound limb scans, observed on 7 June 2018. The error bar for each*  
 98 *individual value is  $\sim 0.13$  kR. Right : Average profile derived with a vertical resolution of 8 km.*  
 99 *The uncertainty on the mean is  $\sim 0.03$  kR, lower than the thickness of the points.*

100

101 The brightness between 160 and 200 km is approximately constant in the profiles shown in  
 102 Figure 2. The brightness between 40 and 80 km is also constant. The vertical variation of the  
 103 brightness is well described by the formulation in Equation 1 (see Chaufray et al., 2011):

$$104 \quad I(z) = I_0 + (I_1 - I_0) \exp(-\tau_{CO_2}(z)) \quad (1)$$

105 where  $\tau_{CO_2}(z)$  is the slant path integrated atmospheric transmittance by CO<sub>2</sub> at tangent altitude  $z$ ,  
 106  $I_0$  is the average brightness between 40 and 80 km,  $I_1$  is the average brightness between 160 and  
 107 200 km.  $I_0$  corresponds to Lyman- $\alpha$  photons emitted between the spacecraft and the absorption  
 108 layer, i.e. the region below 100 km,  $I_1 - I_0$  corresponds to the contribution of photons mostly  
 109 emitted above the absorption layer, in the solar illuminated side of the line of sight . These

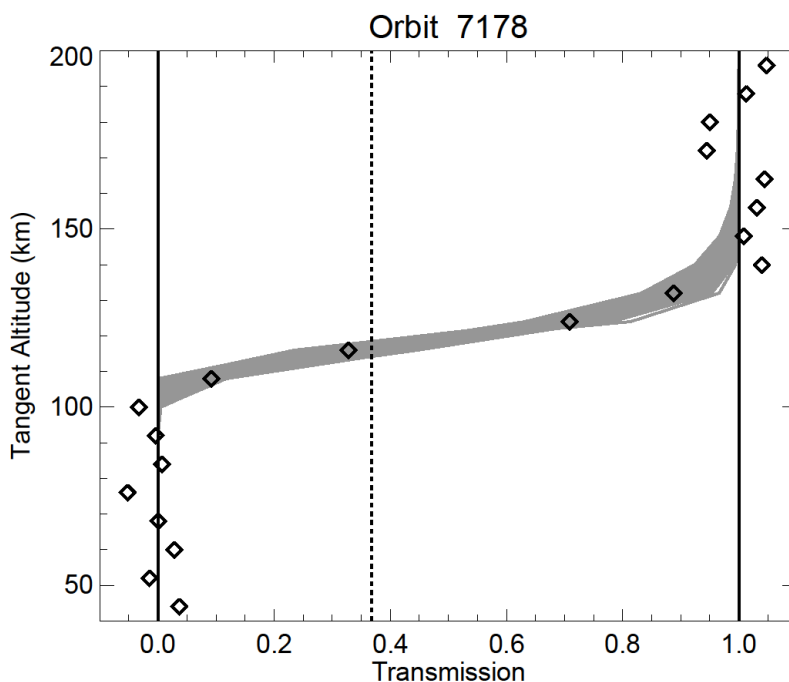


110 photons are absorbed or “occulted” by the atmospheric CO<sub>2</sub> for  $z$  lower than 100 km (where  $\tau_{\text{CO}_2}$   
 111  $\gg 1$ ), not absorbed for  $z > 160$  km (where  $\tau_{\text{CO}_2} \ll 1$ ), and partly absorbed in between.

112 For each observation, a normalized brightness or transmission function (Equation 2) can be  
 113 deduced. As the transmission function computed from stellar occultation (e.g. Quémerais et al.  
 114 2006), this function is independent of the absolute calibration of the instrument as long as the  
 115 sensitivity doesn’t drift over time of the observation.

$$116 \quad T(z) = \frac{I(z) - I_0}{I_1 - I_0} = e^{-\tau_{\text{CO}_2}} \quad (2)$$

117 An example of transmission function is displayed in Figure 3 for orbit #7178



118  
 119 *Fig. 3 Transmission function for orbit 7178 (diamonds) and the best fit derived using a function*  
 120 *given by Eq. 3 (solid line). The two vertical solid lines indicate Transmission= 0 and*  
 121 *Transmission =1. The vertical dotted line indicate Transmission =  $e^{-1}$ . Because  $I_0$  and  $I_1$  are*  
 122 *average values between 40-80 km and 160-200 km respectively, the computed individual*  
 123 *transmission values can be  $< 0$  (when  $I(z) < I_0$ ) near 100 km and  $> 1$  (when  $I(z) > I_1$ ) near 160*  
 124 *km respectively. The best fits obtained from a Monte Carlo error analysis are also displayed by*  
 125 *the grey area.*

126

127 A theoretical expression of the CO<sub>2</sub> absorption optical thickness can be derived assuming an  
 128 isothermal absorption layer between 100 and 160 km (Equation 3).

$$129 \quad \tau_{CO_2}(z) = n(z)H\sqrt{\frac{2\pi R}{H}}\sigma = n(z_0)H\sqrt{\frac{2\pi R}{H}}\sigma \exp\left[-\frac{(z-z_0)}{H}\right] \quad (3)$$

130 The isothermal assumption is justified at the nightside, given the limited accuracy of the method.  
 131 In Equation 3,  $n(z)$  is the CO<sub>2</sub> density at the tangent point altitude  $z$ ,  $H$  the scale height of the CO<sub>2</sub>  
 132 density,  $\sigma$  is the CO<sub>2</sub> absorption cross section at 121.6 nm (equal to  $6.2 \times 10^{-20}$  cm<sup>2</sup>), the product  
 133  $n(z)H$  is the column density above  $z$  and the factor  $(2\pi R/H)^{1/2}$  is the approximate ratio of the limb  
 134 length and the vertical length for a spherically symmetric atmosphere around the tangent point,  
 135 where  $R$  is the Martian radius.  $n(z_0)$  is the density at an arbitrary reference altitude  $z_0$ .

136 We assume the absorption cross section is independent on the temperature. The CO<sub>2</sub> cross section  
 137 at Lyman-alpha for  $T=195$  K and  $T=295$  K can be found in Qu  merais et al. 2006 (Fig. 17). At  
 138 121.6 nm, the relative difference is small  $\sim 0.2\%$ , so we could expect a small effect on our results  
 139 compared to other source of uncertainties.

140 This relation shows that the expected transmission function can be fitted by a function given by

$$141 \quad f(z) = \exp\left\{-A\sqrt{H} \exp\left[-\frac{(z-z_0)}{H}\right]\right\} \quad (4)$$

142  $A$  and  $z_0$  are not independent, and therefore  $z_0$  can be fixed arbitrarily (here to 110 km) without  
 143 losing generality. Changing  $z_0$  will provide exactly the same fit, since  $A$  would be adjusted to  
 144 produce the same transmission function.

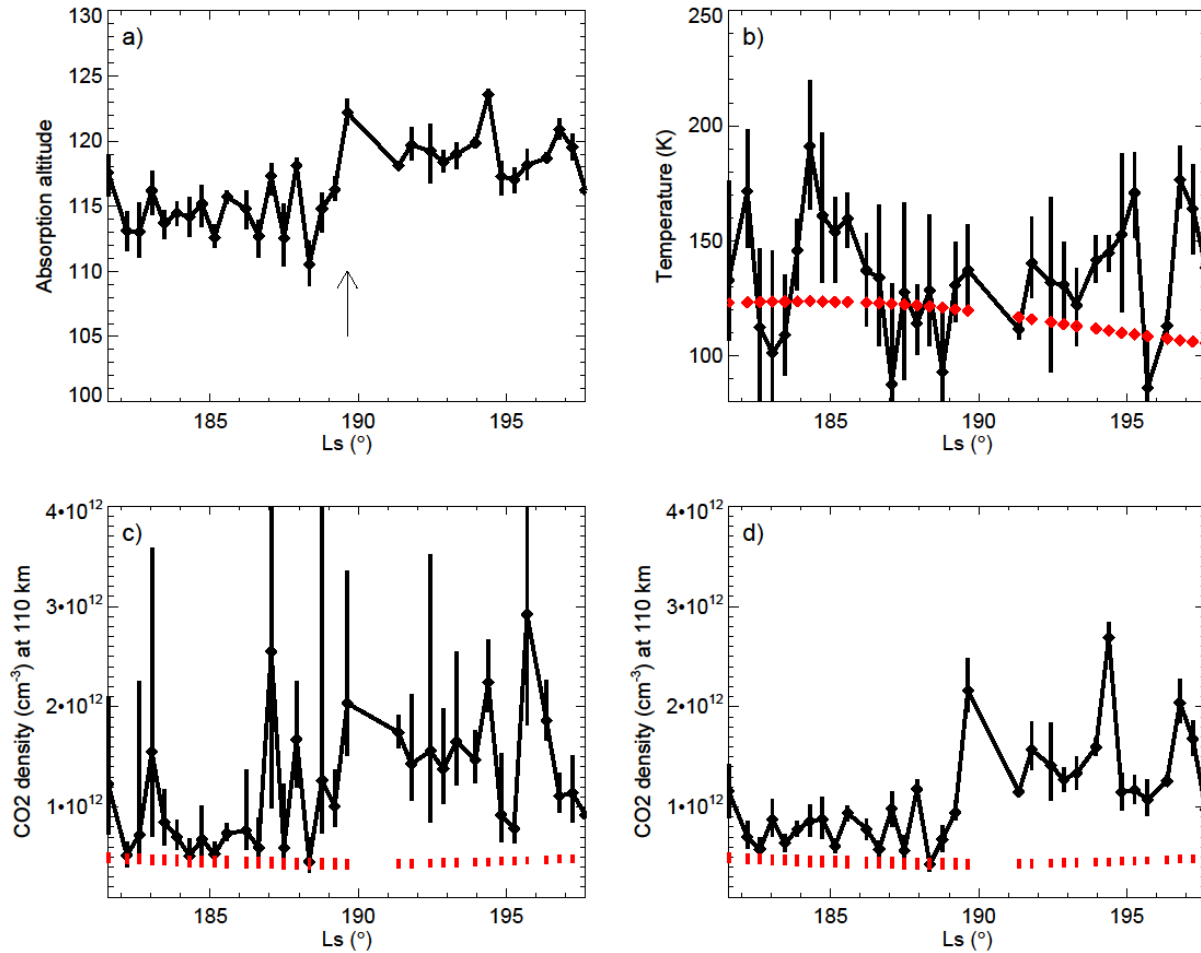
145 From  $A$  we can derive the CO<sub>2</sub> density at  $z_0$ , and from  $H$  we can derive the average temperature  
 146 of the 100 – 160 km layer and above.

147 We use a Levenberg-Marquardt fit, using the IDL fit package from Markwardt (2009) to derive  
148 the best fit of the observed transmission functions for each of the 33 orbits. For each orbit, we  
149 perform a Monte Carlo error analysis by adding a random noise to the observed transmission,  
150 following a gaussian law  $\exp(-\delta T^2/2\sigma^2)$  where  $\sigma$  is the standard deviation on the transmission  
151 between 40 – 80 km ( $\sim 0.05$ ). From 1000 random profiles, we derive the values of the two free  
152 parameters with the fit procedure described above. The 1000 best fits of the transmission  
153 obtained for orbit 7178 are shown in Fig. 3. From this sample, the median, first and last deciles of  
154 the free parameters are considered as the best fit values, and the uncertainties on the parameters.  
155 For each orbit, the altitude  $z$  where  $\tau_{CO_2} = 1$  (corresponding to a slant  $CO_2$  density of  $1.6 \times 10^{19} \text{ cm}^{-2}$ )  
156 can therefore be calculated.

157 To estimate the uncertainty associated to the non\_isothermal assumption, we have numerically  
158 computed the transmission function for non isothermal cases using the temperature profiles from  
159 the Mars Climate Database (MCD) or from Groller et al. (2018). We then applied the same  
160 retrieval method to the computed transmission function. The uncertainty on the altitude where  $\tau =$   
161 1 due to the non-isothermal assumption is estimated to be lower than 2 km.

### 162 **3) Results**

163 The altitude where  $CO_2$  optical thickness is equal to 1 and the temperature of the absorption layer  
164 are displayed in Figure 4. The  $CO_2$  density at 110 km derived from the best fit temperature as  
165 well as from an assumed constant temperature of 135 K for all observations are also shown.



166  
 167 *Fig. 4 a) Variations of the CO<sub>2</sub> absorption altitude (km), defined as the altitude where the slant*  
 168 *CO<sub>2</sub> absorption optical thickness at Lyman- $\alpha$  is equal to 1 with the solar longitude Ls. b) derived*  
 169 *temperature for each orbit from the CO<sub>2</sub> scale height. c) variations of the CO<sub>2</sub> density with Ls*  
 170 *considering the temperature derived from the fit. d) Same as c) but using a same temperature of*  
 171 *135 K for the full period. The range of temperature and CO<sub>2</sub> density at 110 km extracted from the*  
 172 *Mars Climate Database at the same position are shown by red lines for panels 3b, 3c and 3d. The*  
 173 *arrow on panel 3a indicate the time of orbit #7182.*

174 The altitude where the CO<sub>2</sub> optical thickness is equal to 1 is almost constant before orbit #7182  
 175 (114.5 km with a standard deviation of 2 km) and increases to 119.0 km (standard deviation of 2  
 176 km) for the period starting with orbit 7182. The uncertainty on the mean value is 0.5 km for both  
 177 periods. Orbit 7182 occurred on 8 of June 2018 corresponding to the time where the increase of  
 178 the dayside CO<sub>2</sub> density at 150 km was observed from the navigation camera (NAVCAM) of

179 MAVEN (Bougher et al., 2019) and IUVS dayglow emissions (Jain et al., this issue). This  
180 increase is associated with the heating of the lower atmosphere by the global dust storm.

181 The derived temperature is within the range expected for the deep nightside thermosphere (e.g.  
182 Forget et al. 2009, Gröller et al. 2018). The derived uncertainties are  $\sim 30\text{K}$  and are consistent  
183 with the range of temperature variations derived from stellar occultations (Forget et al. 2009,  
184 Groller et al 2018). The average temperature derived from the full set of observations is  $135\text{ K}$   
185 with a standard deviation of  $25\text{ K}$  similar to the uncertainty derived from the fits. The average  
186 temperature before orbit 7182 is  $133\text{K}$  with a standard deviation of  $28\text{K}$  and for the period  
187 starting with orbit 7182, the average value is  $136\text{K}$  with a standard deviation of  $23\text{ K}$ . This  
188 variation seems different from the temperature decrease predicted by the MCD. Given the large  
189 uncertainty on the derived temperature it is not possible to attribute this difference to the global  
190 dust storm. It is not possible from our observations to conclude if the orbit to orbit variations of  
191 the temperature is real because the temporal variation of the derived temperature is not different  
192 from the derived error bar. We also fit the transmission function for each observation using the  
193 value of the average temperature to derive the  $\text{CO}_2$  density variations at  $110\text{ km}$  (Fig. 4d). In this  
194 case, the  $\text{CO}_2$  density variations show an increase by a factor  $\sim 1.9\pm 0.2$  after orbit #7178. The  
195 average density calculated from all orbits before orbit 7182 is  $7.8\times 10^{11}\text{ cm}^{-3}$  and the standard  
196 deviation is  $2.0\times 10^{11}\text{ cm}^{-3}$  ( $5.8\pm 1.5\times 10^{-8}\text{ kg/m}^3$ , assuming a  $\text{CO}_2$  mixing ratio of 0.96). It increases  
197 to  $14.7\pm 4.8\times 10^{11}\text{ cm}^{-3}$  ( $11.2\pm 3.6\times 10^{-8}\text{ kg/m}^3$ ) after orbit 7182, as expected from the increase of  
198 the  $\text{CO}_2$  absorption layer altitude.  $\text{CO}_2$  densities derived before and after 8 of June are in the  
199 range of the  $\text{CO}_2$  density derived by Forget et al. (2009) near  $L_s = 180^\circ$ . Using another  
200 temperature changes the derived  $\text{CO}_2$  density, but the increase factor is only slightly modified.  
201 For example, using a temperature of  $120\text{ K}$  – close to the derived nightside temperature at  $110$

202 km obtained from stellar occultations by SPICAM in 2004, 2005 and 2006 (Forget et al. 2009) –  
203 we obtain a CO<sub>2</sub> density increase from  $9.0 \pm 2.4 \times 10^{11} \text{ cm}^{-3}$  to  $18.3 \pm 6.0 \times 10^{11} \text{ cm}^{-3}$ .

#### 204 **4) Discussion**

205 A large-scale dust storm was detected in early June by Mars Reconnaissance Orbiter (MRO) Mars  
206 Color Imager (MARCI) and Mars Climate Sounder (MCS) instruments. These instruments  
207 associated the dust storm with an increase in lower atmospheric temperature (Zurek et al. 2018,  
208 Kass et al. 2018). The first sign of this global dust storm was detected by MAVEN on 8 June  
209 (orbit #7184) in the dayside thermosphere. MAVEN accelerometers detected an enhancement in  
210 dayside CO<sub>2</sub> density at 150 km by a factor  $\sim 2$  (Zurek et al. 2018) in agreement with the density  
211 variations observed by the NAVCAM and NGIMS instruments (Elrod et al. this issue, Bougher et  
212 al. 2019). From dayglow observations, IUVS observed an increase in the altitude of peak  
213 brightness of 5 to 8 km (Jain et al. this issue). This variability is in agreement with the derived  
214 variability measured at the nightside for the observations presented in this study.

215 The atmospheric mass density measured by the NAVCAM was  $\sim 0.25\text{-}0.3 \text{ kg/km}^3$  at 150 km  
216 before the 8 of June and  $\sim 0.4\text{-}0.55 \text{ kg/km}^3$  after MAVEN orbit 7184 (Bougher et al., 2019). At  
217 such altitudes, assuming a CO<sub>2</sub> mass mixing ratio between 0.7 and 0.9, we convert the  
218 atmospheric mass density to CO<sub>2</sub> number density between  $2.3 - 3.7 \times 10^9 \text{ cm}^{-3}$  and between  $3.8$  and  
219  $6.8 \times 10^9 \text{ cm}^{-3}$  before and during the dust storm, respectively. To compare these values to the  
220 derived values in this study requires extrapolating the density derived at 110 km to 150 km.  
221 Assuming an isothermal layer between 110 and 150 km and a temperature of 135 K results in a  
222 nightside CO<sub>2</sub> density of  $3.2 \times 10^9 \text{ cm}^{-3}$  and  $6.1 \times 10^9 \text{ cm}^{-3}$  at 150 km, close to the dayside CO<sub>2</sub>  
223 density. Considering a temperature of 120 K gives respective CO<sub>2</sub> densities of  $2.0 \times 10^9 \text{ cm}^{-3}$  and  
224  $4.0 \times 10^9 \text{ cm}^{-3}$ , lower than the dayside derived density. However, NAVCAM shows a decrease of

225 the density at 150 km when MAVEN periapsis is moving from the dayside to the nightside  
226 (Bougher et al. 2019), and therefore a temperature of 120 K at the nightside between 110 and 150  
227 km would provide better agreement between the two sets of observations. A possible bias on our  
228 retrieved density is the uncertainty in the tangent altitude due to the uncertainty in the real  
229 pointing (Chaufray et al. 2011). During the observations presented above, the typical distance  
230 between the spacecraft and the tangent point is  $\sim 5000$  km. The IUVS spatial bins (corresponding  
231 to a binning of 115 physical pixels along the slit) projection at the tangent point is large  $\sim 20$  km.  
232 A systematic change of  $\pm 10$  km on the altitude of the tangent point would increase/decrease all  
233 the derived CO<sub>2</sub> densities at 110 km by a factor  $\sim 4$ . But in both cases, the ratio of the density  
234 during and before the dust storm would not be modified if these effects are systematic.

## 235 **5) Summary and conclusion**

236 IUVS observations of the Lyman- $\alpha$  hydrogen line in the Martian lower thermosphere show an  
237 increase in the altitude of absorption layer of the Lyman- $\alpha$  emission by CO<sub>2</sub> on 8 June 2018,  
238 coincident with the expansion of the dayside thermosphere observed by several MAVEN  
239 instruments. This increase is most likely associated with the large-scale dust storm observed by  
240 MRO few days before that heated the lower atmosphere. This altitude variation is attributed to an  
241 increase of the CO<sub>2</sub> density by a factor  $\sim 1.9 \pm 0.2$  assuming an isothermal atmosphere between  
242 100 and 160 km. While the absolute derived density is sensitive to the accuracy of the pointing  
243 and the assumed temperature, the relative variation in density is not. We can estimate the global  
244 heating of the lower atmosphere needed to produce such an increase of the density. Assuming a  
245 moderately deep region ( $\Delta Z = 50$  km) of uniform heating and a constant surface pressure. The  
246 increase of the CO<sub>2</sub> density at 110 km is related to the increase of the vertically average scale  
247 height  $\langle H \rangle$  by

248 
$$\beta = \frac{\langle H \rangle_2}{\langle H \rangle_1} = \frac{1}{1 - \frac{\langle H \rangle_1}{\Delta Z} \ln\left(\frac{n_2}{n_1}\right)}$$
 (5)

249 
$$\frac{1}{\langle H \rangle_i} = \frac{1}{\Delta Z} \int_0^{\Delta Z} \frac{dz}{H_i(z)},$$
 (6)

250 where,  $H_1(z)$  is the atmospheric scale height at  $z < 50$  km before 8 June 2018,  $H_2(z)$  the scale  
 251 height at  $z < 50$  km after 8 June 2018 and  $n_2/n_1$  the observed  $\text{CO}_2$  density increase at 110 km,  
 252 Assuming  $\langle H \rangle_1$  between 8 - 12 km, it leads to an average increase of the temperature between  
 253 ~10 - 20% (~25 – 50 K) in the lower atmosphere of Mars. This is just an estimate of the heating.  
 254 Simulations from Global Circulation Models, including the dynamics of the atmosphere are  
 255 needed to capture the links between the lower atmosphere and the upper atmosphere more  
 256 accurately. This analysis confirms the global effect of the GDS on the nightside thermosphere of  
 257 Mars at altitudes not sampled by other instruments and will provide additional constraints to  
 258 better understand the dynamics and heating distribution associated with such events.

259  
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 262 Program. All IUVS inbound limb (“inlimb”) data used in this paper with revision/version tag  
 263 v13\_r01 are archived in NASA’s Planetary Data System :

264 [http://atmos.nmsu.edu/data\\_and\\_services/atmospheres\\_data/MAVEN/maven\\_iuvs.html](http://atmos.nmsu.edu/data_and_services/atmospheres_data/MAVEN/maven_iuvs.html). The  
 265 parameters extracted from the MCD v5.3 can be found at [http://www-](http://www-mars.lmd.jussieu.fr/mcd_python/index5.html)  
 266 [mars.lmd.jussieu.fr/mcd\\_python/index5.html](http://www-mars.lmd.jussieu.fr/mcd_python/index5.html).



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269  
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Figure 1.

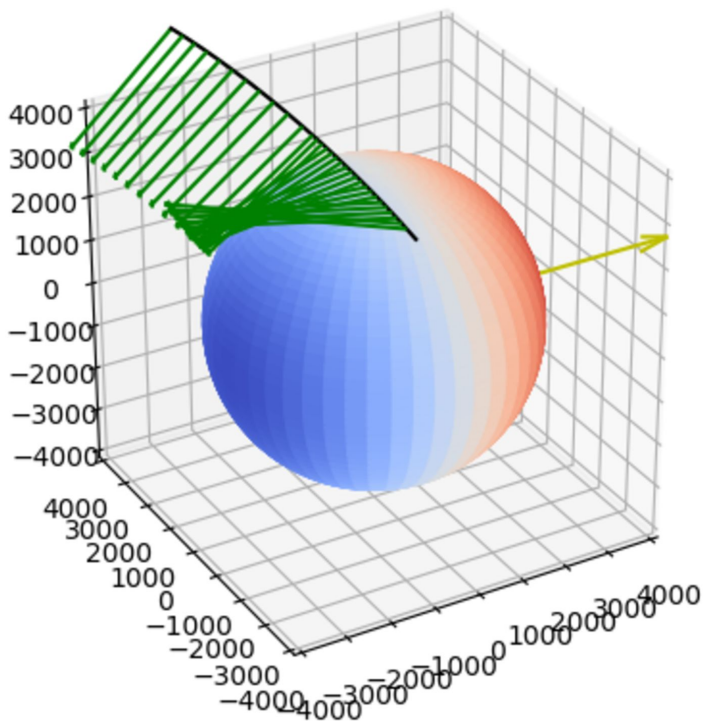
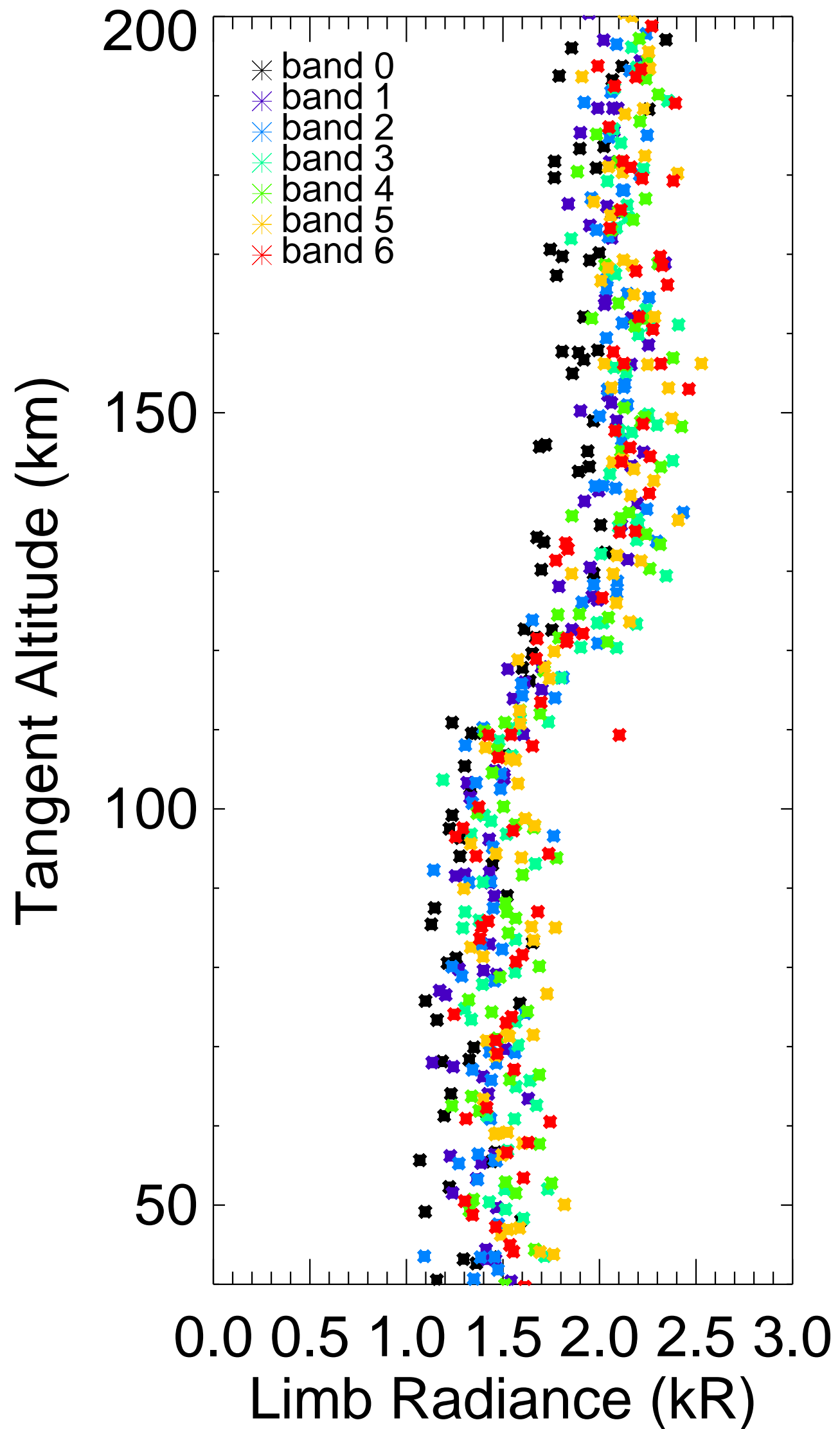


Figure 2.

# Orbit 7178



# Orbit 7178

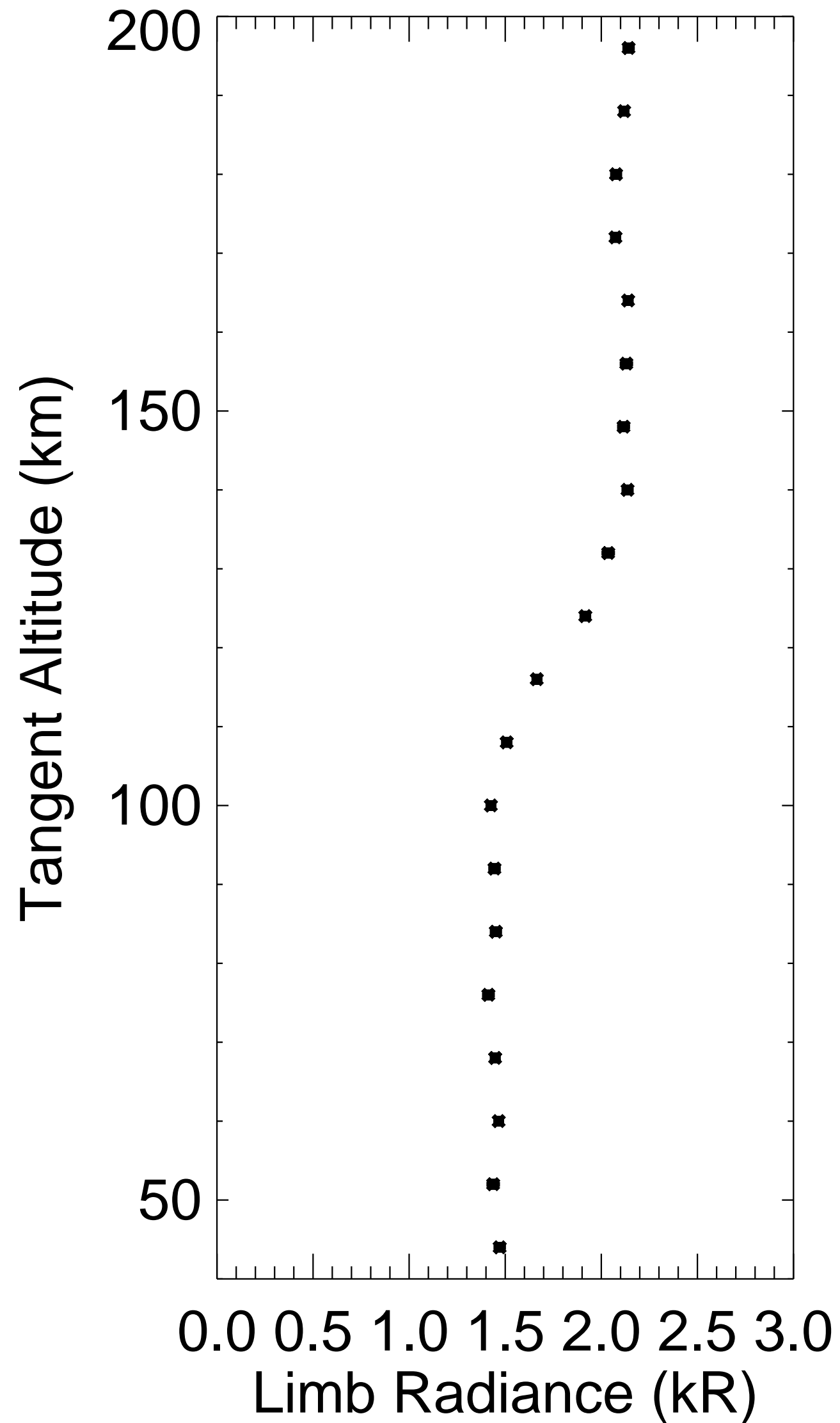
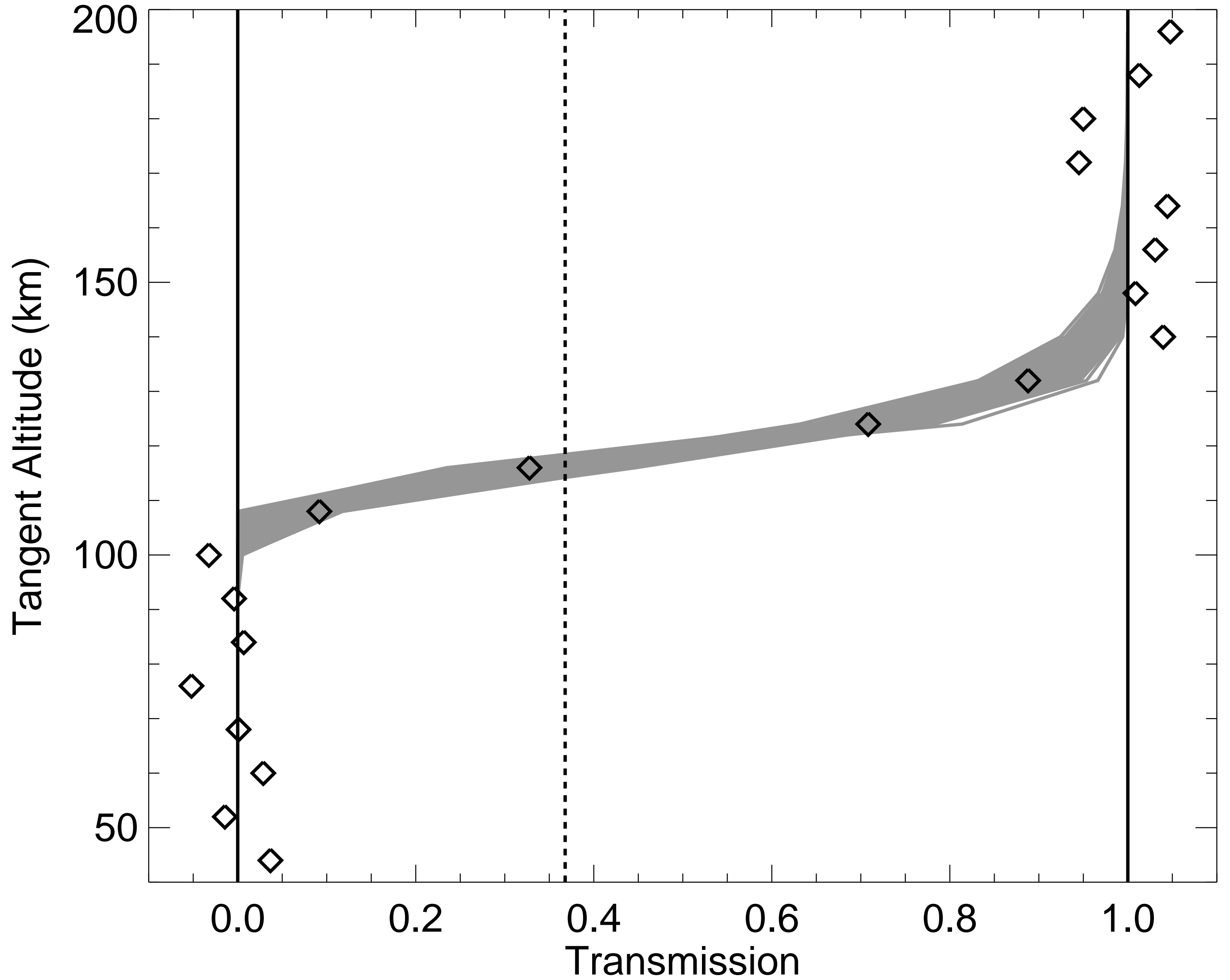


Figure 3.

# Orbit 7178





**Figure 4.**

