Comprehensive studies of the sputtering effects on CO_2 atmospheres: Mars and Venus

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Abstract

The atmospheric loss rates related to the solar wind interactions with the weakly magnetized planets in the inner solar system are important for understanding their evolution histories. Besides photochemical mechanisms, sputtering by the re-impact of the heavy pick-up ions may play a key role, provided that their planetary fields were weak throughout much of their past. We use a 3D Monte Carlo model coupled to a molecular dynamic calculation to simulate the atmospheric sputtering effects due to pick-up O^+ on CO_2 atmospheres of Venus and Mars. The pick-up O^+ precipitation distributions are obtained from a 3D Monte Carlo Pickup Ion Transport model, which includes the electromagnetic backgrounds from the 3D multi-species MHD simulations. The influences on the sputtering efficiencies due to different atmosphere and exosphere structures, the existence of the crustal fields at Mars, and the variation with the solar wind conditions at their heliocentric distances are examined for the two planets. The escape rates and the formation of hot coronae due to sputtering are compared in order to provide a comprehensive point of view on the sputtering efficiencies of these two terrestrial planets with CO_2 atmospheres.

1. Introduction

- The re-impact of the pick-up O^+ could have played a role in earlier epochs and at solar maximum in the present epoch [J.G. Luhmann et al., *GRL 19, 2151-2154*, 1992].

2.1 Atmospheric sputtering model

- A Monte Carlo model of the upper atmosphere coupled to a molecular dynamic calculation [F. Leblanc and R.E. Johnson, *JGR 107, 5010*, 2002] is used to simulate the pick-up O^+ sputtering.
- The background atmospheres are shown in Figure 1 [Y. Ma et al., *JGR 109, A07211*, 2004; A.E. Hedin et al., *JGR 88(A1), 73-83*, 1983].

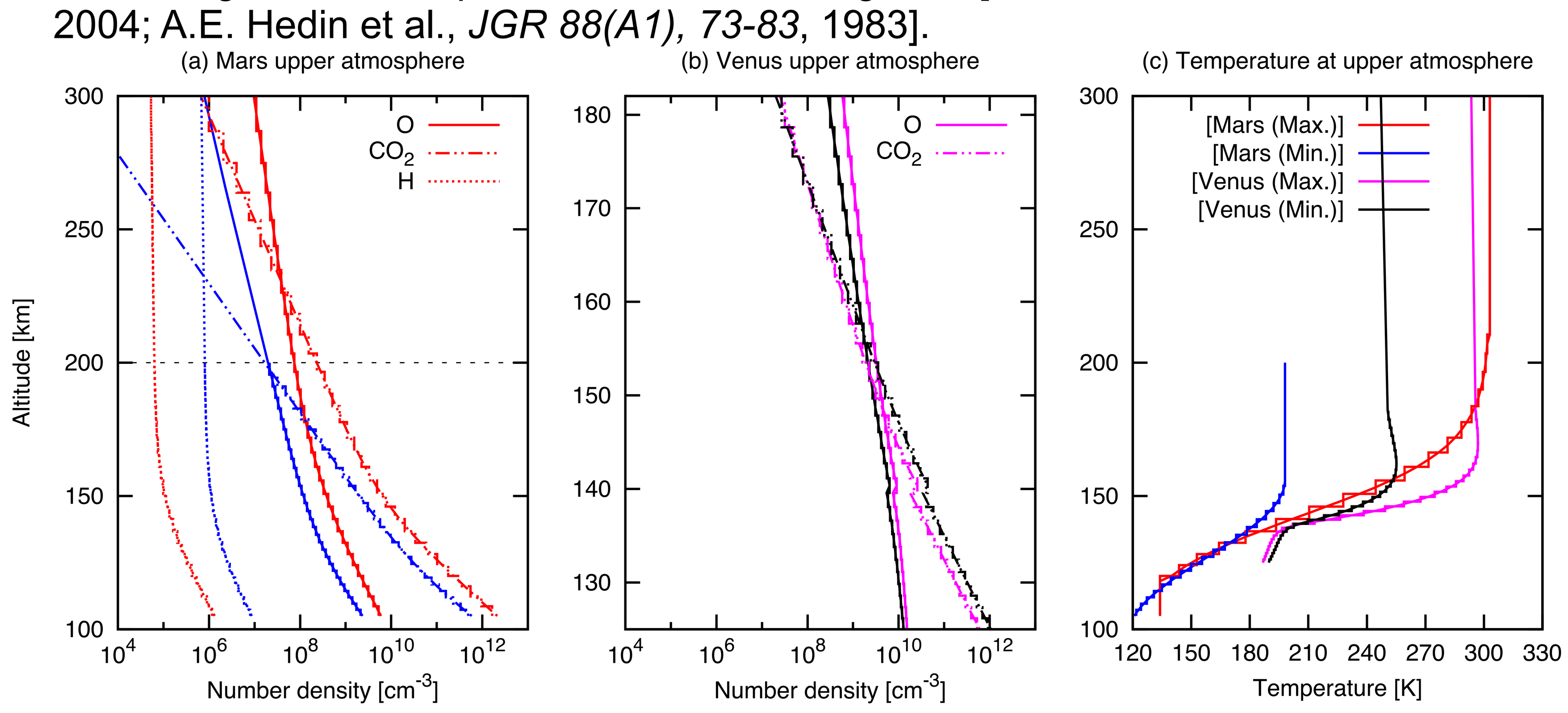


Figure 1. Upper atmosphere densities and temperature distribution in model.

2.2 Pick-up O^+ precipitation simulation results

- The electromagnetic fields from six Mars and two Venus cases are simulated with multi-species MHD model [Y. Ma et al., *JGR 109, A07211*, 2004; Y. Ma and A. F. Nagy, *GRL 34, L08201*, 2007; Y. Ma et al., *JGR 118, 321-330*, 2013]. See Table 1.
- The resultant pick-up O+ precipitations are calculated with Monte Carlo method based on the MHD results [X. Fang et al., *JGR 113, A02210*, 2008; X. Fang et al., *GRL 20, 1-6*, 2013; S.M. Curry et al., *JGR 118, 554-569*, 2013]. See Table 2 and Figure 2.

Table 1. Parameters of the simulated cases.

Cases		n_{sw} [cm^{-3}]	V_{sw} [km/s]	IMF [nT]	Crustal field	Solar cycle
Mars	Quiet	4	400	3 nT Parker spiral (56°) toward Mars	noon	Max.
	Active	4	1200	3 nT (+B_y)	noon	Max.
	Extreme	20	1000	20 nT (+B_y)	noon	Max.
	noonC	4	400	3 nT Parker spiral (56°) toward Mars	noon	Min.
	dawnC	4	400	3 nT Parker spiral (56°) toward Mars	dawn	Min.
	NoC	4	400	3 nT Parker spiral (56°) toward Mars	Not included	Min.
Venus	Vmax	17	400	15 nT Parker spiral (36°) away	No	Max.
	Vmin	22	420	9.6 nT Parker spiral (36°) away	No	Min.

NOTE (1): The solar wind electric fields are pointing northward for all Mars cases and southward for all Venus cases.
NOTE (2): Mars cases include hot O corona in the MHD model whereas Venus cases include only cold components.

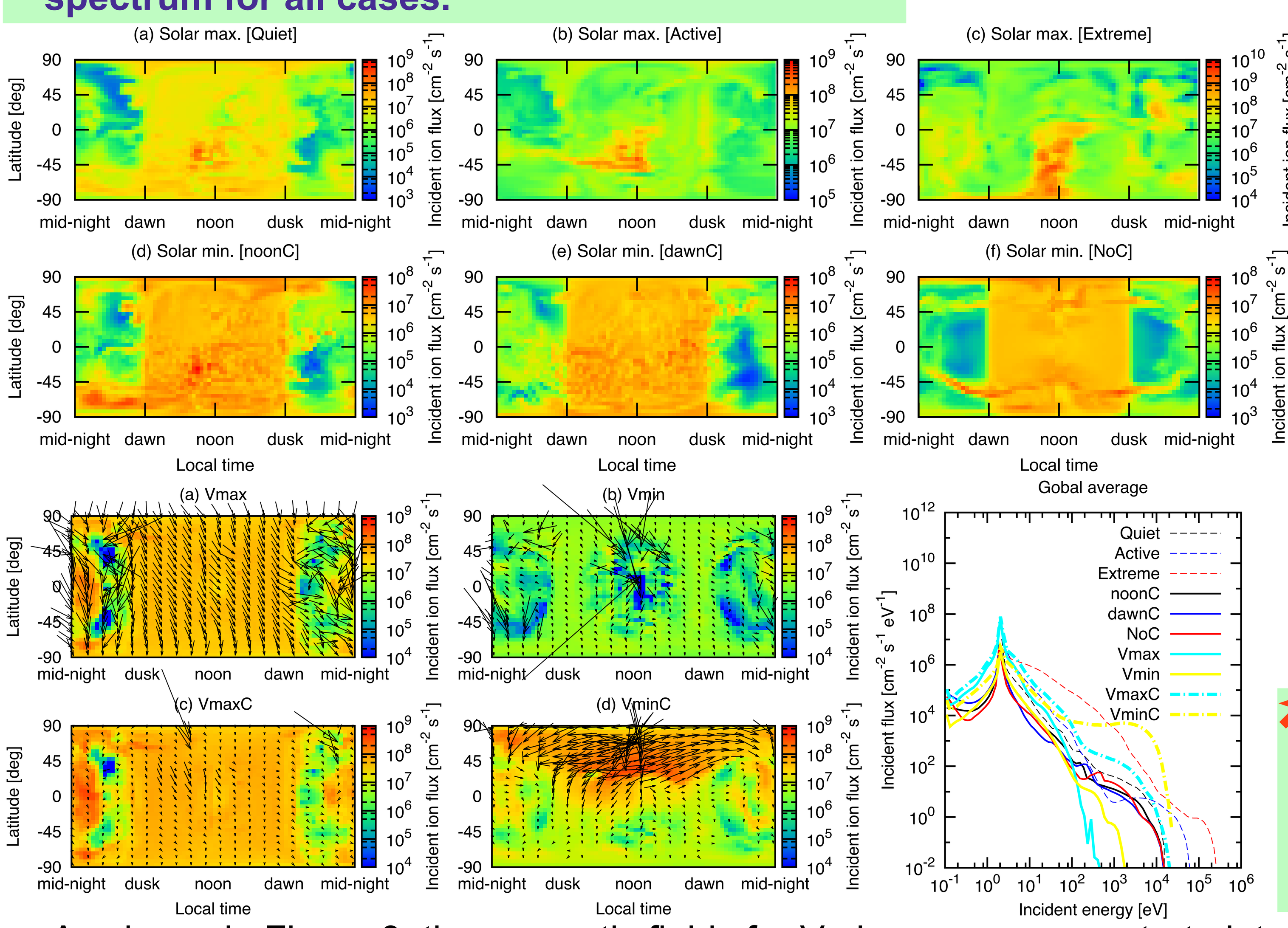
Table 2. Simulated pick-up O^+ precipitation rates.

Cases		Precipitation rate	Avg. energy flux	Avg. energy Day/night	Avg. incident angle
Mars	Quiet	1×10^{25} s^{-1}	4×10^{8} eV cm^{-2} s^{-1}	60 eV 42/160 eV	47 deg
	Active	3×10^{25} s^{-1}	1×10^{9} eV cm^{-2} s^{-1}	83 eV 81/88 eV	50 deg
	Extreme	9×10^{25} s^{-1}	3×10^{10} eV cm^{-2} s^{-1}	486 eV 493/467 eV	50 deg
	noonC	6×10^{24} s^{-1}	7×10^{7} eV cm^{-2} s^{-1}	25 eV 17/72 eV	48 deg
	dawnC	7×10^{24} s^{-1}	1×10^{8} eV cm^{-2} s^{-1}	20 eV 15/69 eV	46 deg
	NoC	4×10^{24} s^{-1}	9×10^{7} eV cm^{-2} s^{-1}	35 eV 34/48 eV	53 deg
Venus	Vmax	2×10^{26} s^{-1}	9×10^{7} eV cm^{-2} s^{-1}	3 eV 2/4 eV	78 deg
	Vmin	1×10^{25} s^{-1}	1×10^{7} eV cm^{-2} s^{-1}	4 eV 3/6 eV	76 deg
	VmaxC*	3×10^{26} s^{-1}	1×10^{9} eV cm^{-2} s^{-1}	22 eV 33/8 eV	72 deg
	VminC*	2×10^{26} s^{-1}	1×10^{11} eV cm^{-2} s^{-1}	3125 eV 3.5/1.9 keV	78 deg

*Artificially add hot corona to pick-up O^+ sources in Venus pick-up ion model.

NOTE:
EUV (1026-15Å) at Mars = 5×10^{11} eV cm^{-2} s^{-1}
EUV (1026-15Å) at Venus = 2×10^{12} eV cm^{-2} s^{-1}

Figure 2. The pick-up O^+ precipitation distributions and the global average incident spectrum for all cases.



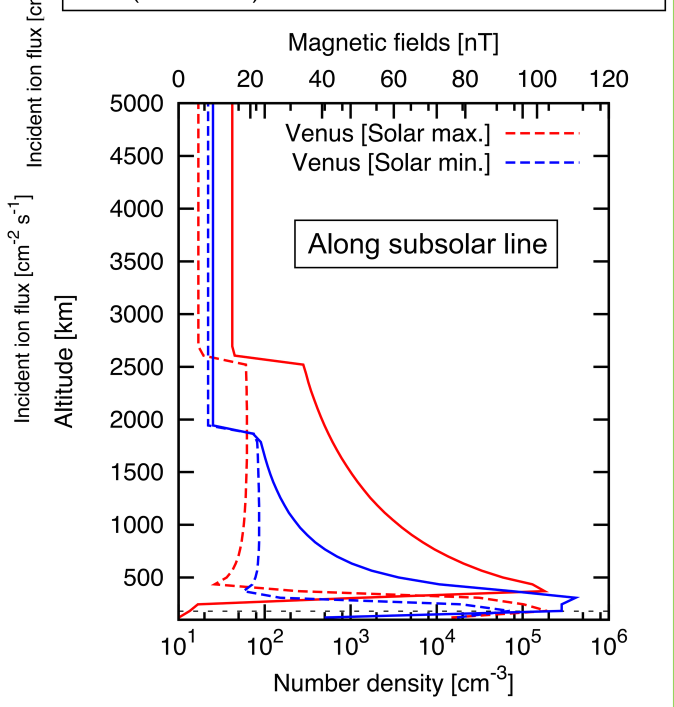


Figure 3. Ionosphere density (dashed lines) and magnetic field (solid lines) profiles from MHD results for Venus cases.

- As shown in Figure 3, the magnetic fields for Vmin case can penetrate into the ionosphere and reach the exobase (~175 km) at the subsolar region [Y. Ma et al., *JGR 118, 321-330*, 2013]. Pick-up O^+ will be temporally trapped in the magnetic pile-up region, which does not precipitate or escape in the simulation time period. Therefore, depletion of precipitation flux near subsolar region occurs for Vmin case.
- With higher ionopause altitude for Vmax case, larger portion of pick-up ions at lower altitudes can re-impact into atmosphere. On the contrary, pick-up ions at higher altitudes (c.f. VmaxC case) become more difficult to precipitate.

3. Pick-up O^+ sputtering simulation results

- Table 3 shows the gas mixing ratios near the exobase for different atmospheres. Since the major component is different for Mars and Venus cases, the primary collision species is different as well.
- Although the gravity is larger on Venus, the O escape yields shown in Figure 4 has similar energy dependence for both planets. This is because O+O collisions can produce more energetic O than O $+CO_2$ collisions [F. Leblanc and R.E. Johnson, *JGR 107, 5010*, 2002].
- On the other hand, in addition to the larger gravity, when CO_2 collisions are much less on Venus than on Mars, there is almost no escape CO_2 due to sputtering.
- Table 4 shows the global sputtering escape rates for different cases. Due to larger pick-up O^+ sources at lower altitude for Venus cases, the precipitation rates are also larger. However, when the re-impact pick-up ions are majorly from lower altitudes, the impact energy is smaller than Mars cases. Therefore, for Vmax and Vmin cases, the escape rates are small.

Table 3. Gas mixing ratios near the exobase for different atmospheres.

Mixing ratio		Altitude	O	CO2	H
Mars	Max.	200 km	0.244	0.756	0.0002
	Min.	150 km	0.055	0.944	0.0005
Venus	Max.	175 km	0.987	0.013	-
	Min.	175 km	0.744	0.256	-

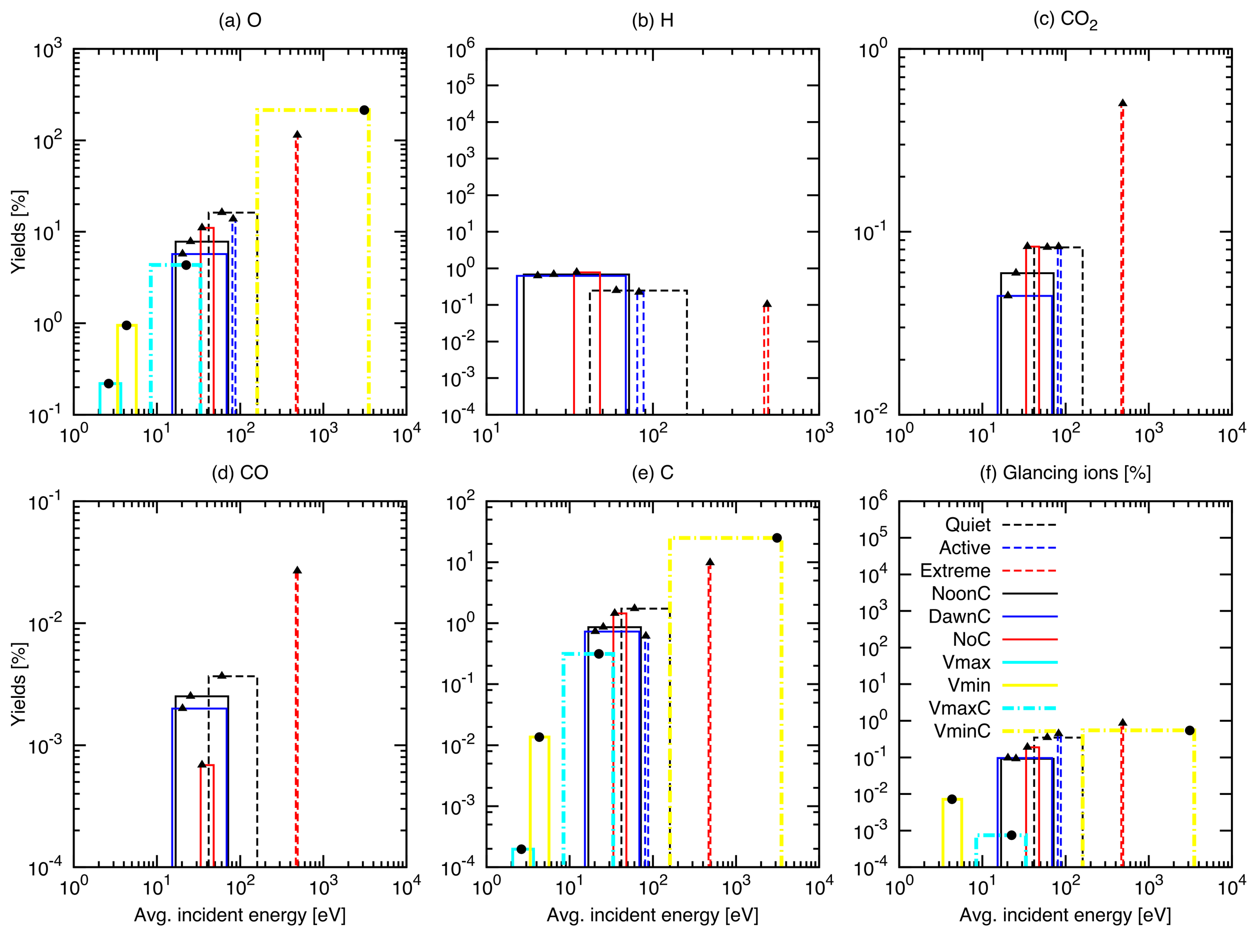


Figure 4. Simulated escape yields respect to 1 incident O^+ for different cases. The average energy for each case in x-axis are the global (black symbols), day and night (lines) side average shown in Table 2.

Table 4. Simulated sputtering escape rates.

Escape rate [s^{-1}]		O	CO2	CO	C	H
Mars	Quiet	2×10^{24}	9×10^{21}	4×10^{20}	2×10^{23}	3×10^{22}
	Active	4×10^{24}	2×10^{22}	0	2×10^{23}	6×10^{22}
	Extreme	1×10^{26}	4×10^{23}	2×10^{23}	8×10^{24}	9×10^{22}
	noonC	5×10^{23}	4×10^{21}	2×10^{20}	6×10^{22}	5×10^{22}
	dawnC	3×10^{23}	3×10^{21}	1×10^{20}	4×10^{22}	4×10^{22}
	NoC	5×10^{23}	4×10^{21}	3×10^{19}	6×10^{22}	3×10^{22}
Venus	Vmax	3×10^{23}	0	0	3×10^{20}	-
	Vmin	1×10^{23}	0	0	2×10^{20}	-
	VmaxC*	1×10^{25}	0	0	8×10^{23}	-
	VminC*	4×10^{26}	0	0	5×10^{25}	-

- If pick-up O^+ sources from hot corona are added into the model (VmaxC and VminC), the escape rates can significant increase due to both larger precipitation rates and larger incident energies.
- Figure 5 shows the sputtered hot O and CO_2 corona for different cases. It is notable that for VminC case, the sputtered hot O can be significant. MHD results with hot corona for Venus cases are needed to verify this result in future.

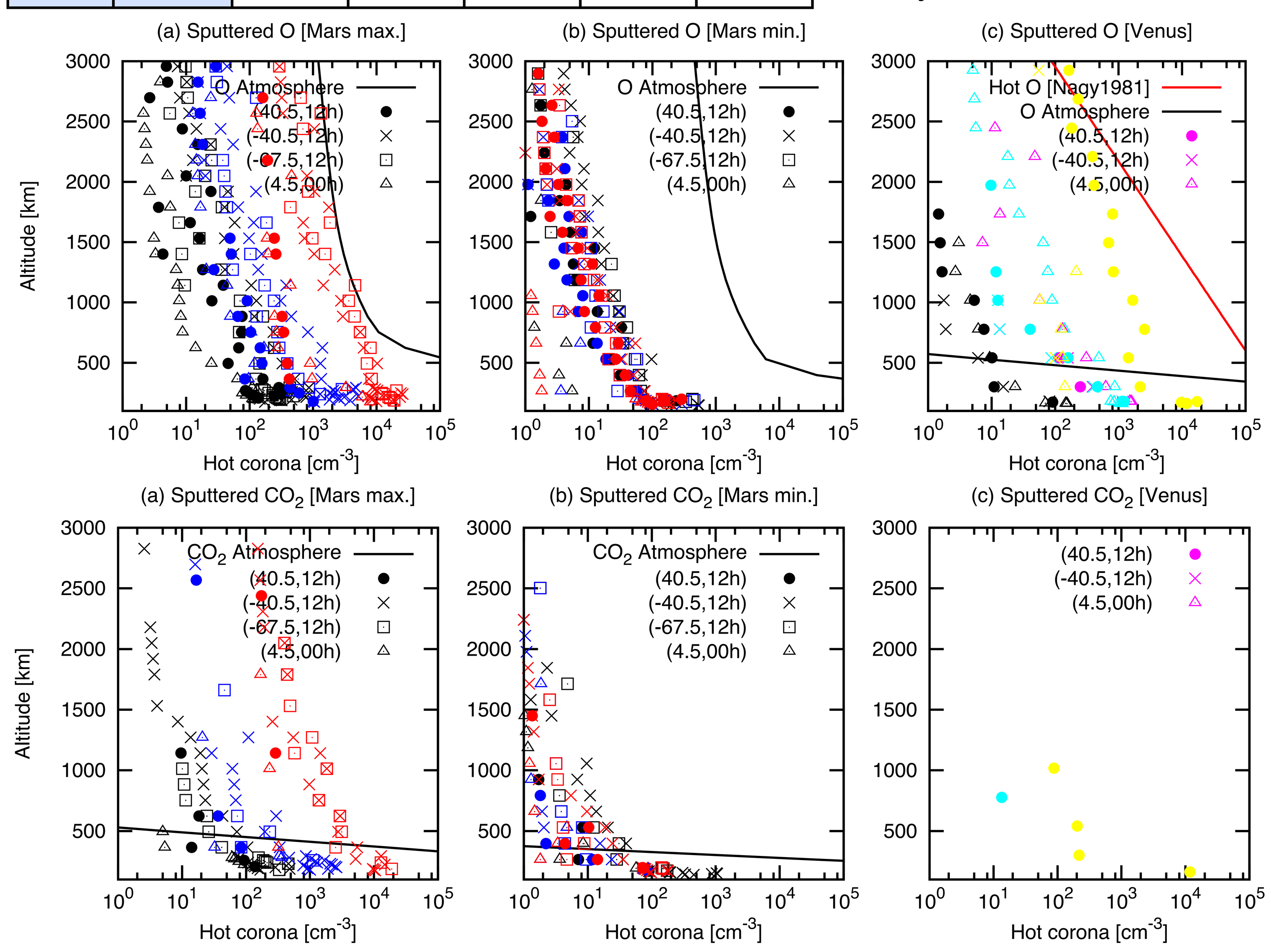


Figure 5. Sputtered hot O and CO_2 altitude distributions for different cases. Different colors represent different cases. In Mars max. subfigures, black, blue, and red represent Quiet, Active, and Extreme cases. In Mars min. subfigures, black, blue, and red represent noonC, dawnC, and NoC cases. In Venus subfigures, purple, black, cyan, and yellow represent Vmax, Vmin, VmaxC, and VminC cases respectively.

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