EFFECTS OF ION-ION AND ELECTRON-NEUTRAL COLLISION ON VERTICAL DISTRIBUTION OF CO_2^+ IN MARTIAN IONOSPHERE BASED ON MULTI-FLUID MHD SIMULATIONS. Kyohei KOYAMA[1], Kanako SEKI[1], Naoki TERADA[2], Kaori TERADA[2], [1]Nagoya University, Japan, (Furo-cho, Chikusa-ku, Nagoya, JAPAN 464-8601, Mail: kkoyama@stelab.nagoya-u.ac.jp), [2]Tohoku University, Japan (Aramaki Aza Aoba 6-3, Aoba, Sendai, Miyagi, 980-8578).

Introduction: Comparison of the mass fraction of CO_2 and N_2 with regard to the total mass of each terrestrial planet suggests importance of the atmospheric escape to space in Martian atmospheric evolution [1]. It has been considered that heavy CO_2^+ ions are difficult to escape based on known atmospheric escape processes. Observations of a large amount of CO_2^+ ion escape by the Mars Express thus challenged the existing escape processes. Vertical distribution of CO_2^+ density in the ionosphere is one of important factors that determine the escape rate of CO_2^+. Chemical reactions in the ionosphere have been implemented in previous studies using multi-species MHD simulations [e.g., [2];[3]]. The velocity difference between ion fluid cannot be reproduced by the multi-species MHD approximation. On one hand, the importance of vertical transport in the upper ionosphere (>300km altitude) was pointed out by some ionospheric models [4]. Multi-fluid MHD code [5] can solve such ion-species dependent velocity. In this study, we investigate the effects of ion-ion collisions as well as electron-neutral collisions on vertical CO_2^+ distrubution in the Martian ionosphere based on multi-fluid MHD simulations.

Simulation code: In order to reproduce velocity difference for each ion species, our multi-fluid MHD code solves the continuity and momentum equations for each ion species. Neutral densities and temperature as well as ion temperatures are fixed in time. Basic equations used in the simulation code are as follows:

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{m_e \rho_s q_s}{m_s \rho_e e}\frac{\partial \boldsymbol{F}'}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} + \frac{m_e \rho_s q_s}{m_s \rho_e e}\frac{\partial \boldsymbol{G}'}{\partial y} + \frac{\partial \boldsymbol{H}}{\partial z} + \frac{m_e \rho_s q_s}{m_s \rho_e e}\frac{\partial \boldsymbol{H}'}{\partial z} = \boldsymbol{S}$$

where the state vector **Q** and the flux vector compornents[***F***,***G***,***H***] and [***F'***,***G'***,***H'***] are defined as

$$\boldsymbol{Q} = \begin{bmatrix} \rho_s \\ \rho_s u_{sx} \\ \rho_s u_{sy} \\ \rho_s u_{sz} \\ B_x \\ B_y \\ B_z \end{bmatrix}, \boldsymbol{F} = \begin{bmatrix} \rho_s u_{sx} \\ \rho_s u_{sx}^2 + p_s \\ \rho_s u_{sy} u_{sx} \\ \rho_s u_{sz} u_{sx} \\ 0 \\ v_x B_y - v_y B_x \\ -(v_z B_x - v_x B_z) \end{bmatrix}, \boldsymbol{F}' = \begin{bmatrix} 0 \\ p_e + \frac{B^2}{8\pi} - \frac{B_x^2}{4\pi} \\ -\frac{B_y B_x}{4\pi} \\ -\frac{B_z B_x}{4\pi} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

[***G***,***H***]are symmetric vector of ***F***. [***G'***,***H'***] are symmetric vector of ***F'***. The source term in equation (1) is

$$S = \begin{bmatrix} S_s - L_s \\ n_s q_s\{(u_{sy} - v_y)B_z - (u_{sz} - v_z)B_y\} + \rho_s g_x + \rho_s \sum_\alpha \nu_{st}(u_\alpha - u_s)_x + S_s u_{nx} - L_s u_{sx} \\ n_s q_s\{(u_{sz} - v_z)B_x - (u_{sx} - v_x)B_z\} + \rho_s g_y + \rho_s \sum_\alpha \nu_{st}(u_\alpha - u_s)_y + S_s u_{ny} - L_s u_{sy} \\ n_s q_s\{(u_{sx} - v_x)B_y - (u_{sy} - v_y)B_x\} + \rho_s g_z + \rho_s \sum_\alpha \nu_{st}(u_\alpha - u_s)_z + S_s u_{nz} - L_s u_{sz} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

In the above equations, ρ is the mass density, ***u***, the velocity of each plasma fluid; ***v*,** velocity of center of gravity of plasma; ***g***, gravitational acceleration ***B***, the magnetic field; p, gas pressure; γ, the ratio of specific heats; ν, effective momentum transfer collision frequencies. The subscripts i, e, and n correspond to ion species, electron, major neutral species. Subscript α is target ions, electrons, and neutrals. Subscript s represents ions and electrons. S_s and L_s are ion production and loss rates by chemical reactions including photoionization.

Simulation settings: In this study, we used four ion species (H^+, O^+, O_2^+, and CO_2^+) and three neutrals (H, O, CO_2). Vertical density distribution of neutrals and temperature of ion, electron, and neutral is given in static value table[6]. We conducted one dimentional simulations in vertical direction with number of grids of 96 and spatial resolution of 4.0km in the altitude range of 100-480 km. Upper and lower boundary conditions are set as ***u*** = 0 and ***v*** =0. Initial conditions of v = 0, B = 0, ρ_s = 0, and ρ_e = 0 are set in common for all runs. Our code includes ion-ion collisions and electron-neutral collisions in order to investigate their effects on the vertical distribution of CO_2^+ density in the Martian ionosphere. Five cases of the simulation runs (Runs 1-5) are carried out with different settings as summarized in Table 1.

Table 1: Simulation settings for Runs 1-5.

RUN	Velocity- difference	ion-ion collison	electron-neutral collision
1	✓	✓	✓
2	✓	✓	
3	✓		✓
4	✓		
5			✓
		✓:include	

Result: We compared the results of 5 simulation runs in Table 1, after each simulation run reached to a quasi-steady state. Result of ion density distributions in Martian ionosphere is shown in Figure 1. The CO_2^+ density at altitude 400 km in Runs 1-5 were 39.1, 84.8, 42.1, 198.0, and 0.72 [cm^{-3}], respectively. CO_2^+ density at 400km of Run5 is small than other results. Since Run 5 does not contain velocity difference of each ion fluid, vertical CO_2^+ transportation is limited. The result of Run 5 suggests the importance of the velocity difference for transportation from low altitude to upper ionosphere. In Run 4, vertical transportation of CO_2^+ is significantly increased by different velocities for each ion species. However, the density of CO_2^+ and O^+ at altitude 220 km is not reversed. In Runs 1-3, CO_2^+ at altitude 400 km and density reverse of CO_2^+ and O^+ around 220 km are resemble with a previous Martian ionosphere model [4]. CO_2^+ density at altitude 400 km in Run 2 is slightly different from Run 1. Density is two times of Run 1.

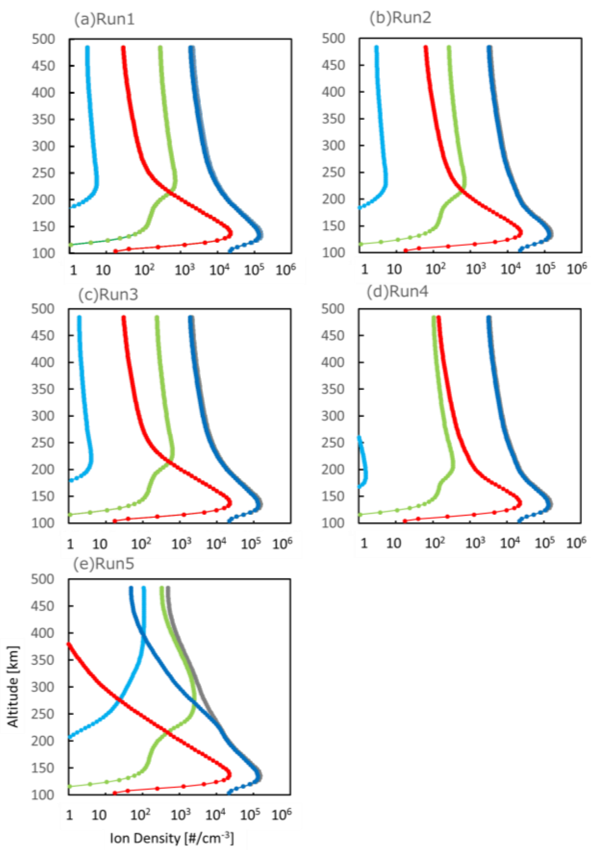

Figure 1: Vertical distributions of ion densities in Martian ionosphere. Panels a-e correspond to the Runs 1-5 explained in the text and Table 1. Black, light blue, green, dark blue, and red colors in each panel represent electrons, H^+, O^+, O_2^+, and CO_2^+ ions, respectively.

Discussion and Conclusion: Difference in results of Runs 2 and 3 is due to difference of altitude dependence between ion-ion and electron-neutral collisions. Martian ionospheric CO_2^+ is mainly produced in low-altitude ionosphere about altitude of 150 km. Generated CO_2^+ in the low altitudes are transported to upper ionosphere. In this transport process, collisions limit the transport of CO_2^+. Ion-neutral collision is most strong limiter of transportation below altitude of 200 km. Below altitude of 200 km, convection with ion velocity differences does not occur by ion-neutral collisions. Above altitude 200 km, ion fluxes takes individual velocities. The effect of CO_2^+ transport limitation of electron-neutral collisons are larger than ion-ion collisions for CO_2^+ at altitude between 200 and 460 km. These results show that the ion-ion and electron-neutral collisions limit the vertical transportation of CO_2^+ from low to high altitudes in Martian ionosphere. Thus inclusion of these collisions are important to reproduce the realistic ion density distributions in the Martian ionosphere.

References: [1] Chassefiere. et al. (2007) *Planetary and Space Science, 55,* 343-357. [2] Ma. et al .(2004) *JGR, 109,* A07211. [3] Terada. et al. (2009) *JGR, 114,* A09208. [4] Fox . (2009) *JGR, 114,* E12005. [5] Najib. et al. (2011) *JGR, 116,* A05204. [6] Shinagawa and Cravens. (1989) *JGR, 94,* 6506-6516.