9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Effects of a planetary magnetic field on ion escape from ancient Mars based on 3D global multifluid MHD simulations

Ryoya Sakata[1,2], Kanako Seki[1,2], Naoki Terada[3], Shotaro Sakai[4], Hiroyuki Shinagawa[5]
[1]Research Center for Advanced Science and Technology, The University of Tokyo, [2]Graduate School of Science, The University of Tokyo, [3]Graduate School of Science, Tohoku University, [4]Faculty of Environment and Information Studies, Keio University, [5]International Research Center for Space and Planetary Environmental Science, Kyushu University
e-mail (speaker): rsakata@g.ecc.u-tokyo.ac.jp

Mars experienced a significant loss of atmosphere, which is widely believed to have led to drastic climate change during its early period of history. The escape of ionized atmospheric particles to space, known as ion escape, is thought to have contributed to the atmospheric loss because ancient Mars was exposed to stronger solar XUV (X-ray and extreme ultraviolet) radiation and intense solar wind from the young Sun. However, the presence of a global intrinsic magnetic field on ancient Mars, suggested by the crustal remnant magnetic field on the surface, complicates the scenario. An intrinsic magnetic field alters the planetary magnetosphere configuration, substantially affecting the interactions between the solar wind and the upper atmosphere, and thereby ion escape.

Our previous studies[1, 2] investigated the effects of a dipole field on ion escape from ancient Mars based on global multispecies single-fluid magnetohydrodynamic (MHD) simulations. These studies revealed that the effects of a dipole field depend on its strength relative to the solar wind dynamic pressure. A dipole field suppresses ion escape if it is strong enough to sustain the solar wind dynamic pressure, but otherwise it enhances ion escape. However, the single fluid approximation of the model, which assumes the same velocity and temperature for all ion species, may underestimate ion outflows from the ionosphere.

In this study, we investigated the role of the intrinsic magnetic field on ion escape from ancient Mars using a newly developed global multifluid MHD model with the cubed sphere grid system, named MAESTRO. This model improves the representation of ion outflows by resolving species-dependent dynamics. We conducted a series of multifluid MHD simulations with varying dipole field strengths, while keeping other simulation inputs (neutral atmosphere, solar XUV flux, and solar wind) constant. For comparison, we also performed multispecies MHD simulations under the same conditions.

Figure 1 summarizes the escape rate of heavy ions (O^+, O_2^+, and CO_2^+) in the multifluid (red) and multispecies (black) simulation cases. The multifluid simulation cases show higher escape rates of molecular ions than the multispecies simulation cases, indicating that the single-fluid approximation underestimates ion outflows from the ionosphere. This enhancement is particularly notable in the strong dipole field cases, where cusp outflow is the dominant escape channel. In contrast, the multifluid representation slightly reduces the O^+ escape rates in the no or weak dipole field cases. This is due to the suppression of pickup-like escape in the –E hemisphere, where the convection electric field of the solar wind is directed toward the planet.

Overall, the presence of a strong dipole field reduces the total escape rate of heavy ions by a factor of six. Although the impacts on atmospheric escape are diminished compared to the previous studies, they remain significant. This study also highlights the need for using a multifluid modeling approach in evaluating ion escape from magnetized planets.

References
[1] Sakata *et al.*, JGR: Space Physics, **125** (2020)
[2] Sakata *et al.*, JGR: Space Physics, **127** (2022)
[3] Sakata *et al.*, JGR: Space Physics, **129** (2024)

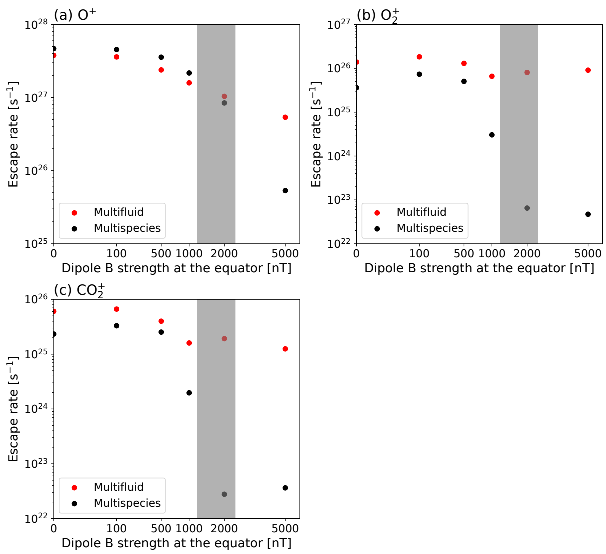

Figure 1.[3] Escape rates [s^{-1}] of O^+, O_2^+, and CO_2^+ ions in multifluid (red) and multispecies (black) simulation cases. The grey hatch region corresponds to the dipole field strength at the equatorial surface where the magnetic pressure of the dipole field is comparable to the solar wind dynamic pressure.