Study of atmospheric ion escape from exoplanet TOI-700 d

*Tomoaki Nishioka[1], Kanako Seki[1], Ryoya Sakata[1], Kazuhiro Yamamoto[1], Naoki Terada[2], Hiroyuki Shinagawa[3]

1. Graduate School of Science, University of Tokyo , 2. Graduate School of Science, Tohoku University , 3. NICT

An important purpose of detecting and characterizing exoplanets is to find habitable planets like Earth. Liquid water is essential for planetary habitability, and it is necessary to retain the atmosphere in strong stellar wind to maintain liquid water. By the Transiting Exoplanet Survey Satellite (TESS), exoplanet TOI-700 d was discovered in January 2020 (Gilbert et al., AJ, 2020; Rodriguez et al., AJ, 2020). This is the first Earth-sized planet in the habitable zone (HZ) discovered by TESS. The host star is a M dwarf star, which has lower surface temperature, thus closer HZ to the host star, and stronger X-ray and EUV (XUV) radiation in HZ than the solar system around a G-type star. Another important difference is that direction of the interplanetary magnetic field (IMF) around the planet may be dominated by the radial component because of the proximity to the host star and planet. The IMF orientation can change the atmospheric escape rate from the exoplanet. In this study, we investigated effects of the XUV radiation and IMF orientation on the atmospheric ion escape.

In order to simulate the atmospheric ion escape from TOI-700 d, we used multi-species MHD simulations (e.g., Terada et al., JGR, 2009; Sakata et al., JGR, 2020). Our model solved three-dimensional multispecies MHD equations including continuity equations for 10 ion species (O^+, O_2^+, CO_2^+, NO^+, CO^+, N_2^+, N^+, C^+, He^+, H^+) the bottom of the ionosphere to the inter-planetary space where a constant stellar wind is assumed. The model includes photoionization, electron impact ionization, charge exchange, ion-neutral reactions, dissociative recombination, collisions (ion-electron, ion-neutral, electron-neutral). As stellar wind conditions, number density, velocity, and temperature were set to 450 cm^{-3}, 470 km s^{-1}, and 1.3×10^6 K, respectively, by referring to previous studies (Cohen et al., ApJ, 2020; Dong et al., ApJL, 2020). IMF was assumed to be a Parker spiral with an angle of 4° or 45° degrees and a magnitude of 12 nT. Also, the stellar XUV flux was set either as 30 or 50 times larger than the current value of the Earth (referred as XUV30 and XUV50 hereafter). We assumed a Venus-like atmospheric composition that depends on the stellar XUV flux as the input neutral atmosphere based on Kulikov et al. (Space Sci. Rev., 2007).

The results show that the IMF Parker spiral angle affects the structure of the induced magnetosphere. Therefore, the path of atmospheric ion escape differs greatly depending on whether IMF Parker spiral angle is 4° or 45°. In the case of 45°, the escape flux is confined to the current sheet similar to Mars and Venus in the solar system. This is because a typical induced magnetosphere is formed and the magnetic tension force of the drape magnetic field in the polar region accelerates the local ionospheric plasma. In the case of 4°, the escape from around SZA = 65° in the ionosphere becomes a ring-shaped escape flux in the induced magnetotail. The stellar XUV flux has a stronger effect on the escape rate of atmospheric ions than the IMF orientation. The larger the stellar XUV flux, the more atmospheric ions escape. This is because the scale height of atmospheric ions increases due to the increase in the stellar XUV flux. In the case of XUV50 and IMF angle 45°, the atmospheric ion escape rate obtained in this study is $\sim2.3\times10^{27}$ s^{-1} , which is about an order of magnitude larger than the value to be able to retain the 1-atm CO_2 atmosphere for about 10 billion years (Dong et al., ApJL, 2020). This result suggests that even if the atmosphere of TOI-700 d is Venus-like, it will be difficult to maintain it for a long time under strong XUV condition. This study also reveals that the escape rate of atmospheric ions, especially molecular ions, can be suppressed by small IMF Parker spiral angle which can become typical as the planet and the host star get closer.

Keywords: exoplanet, atmospheric escape, MHD Simulation