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The Observational Feasibility of Escape of Water Vapor Atmosphere from Terrestrial Exoplanets by Ultraviolet Transit Spectroscopy

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In current terrestrial exoplanet explorations, the primary targets are planets orbiting low-mass stars. Although atmospheric observations are underway to estimate the habitability of such planets, our understanding of the atmospheres remains limited due to their small radius. On the other hand, low-mass stars emit strong XUV (X-ray and extreme ultraviolet) radiation over gigayear timescales. Therefore, atmospheric escape is expected to occur due to the strong heating of the upper atmosphere by XUV radiation, even near the habitable zone where the intensity of visible and infrared radiation is comparable to that of present-day Earth. If terrestrial planets with oceans receive stellar radiation beyond the radiation limit, a water vapor atmosphere would form because of the runaway greenhouse effect. In the upper atmosphere of such planets, the photodissociation of water vapor produces hydrogen and oxygen atoms, which eventually escape. As a result, it would form an optically thick atmosphere covering the stellar disk. This causes apparent dimming during planetary transits in the hydrogen Ly-α line (121.6 nm) and OI emission lines (130.2, 130.5, 130.6 nm) due to scattering by atmospheric hydrogen and oxygen atoms. The transit depth reflects the atomic number density of the exosphere, thus allowing us to estimate the atmospheric escape rate in high XUV conditions, which is not observable in the current Solar system. The atmospheric escape rate under such XUV conditions is an important parameter for understanding the atmospheric evolution of terrestrial planets in the early solar system. Hence, observations of the upper atmosphere are expected to advance our understanding of atmospheric evolution on terrestrial planets.

Future missions with ultraviolet detectors, such as LAPYUTA (JAXA) and HWO (NASA), are expected to detect atmospheres of terrestrial exoplanets by ultraviolet transit spectroscopy. Therefore, numerical models that can capture the strong radiation pressure and photoionization, such as in environments around low-mass stars, are necessary to examine and interpret observations.

In this study, we examined the feasibility of observing the upper atmosphere in a terrestrial planet with a water vapor atmosphere using a three-dimensional particle model. This model accounts for stellar and planetary gravity, radiation pressure of atomic emission lines, and photoionization. The simulation results showed that large exospheric clouds composed of hydrogen atoms form a comet-like tail structure, observed in some hydrogen-dominant gas exoplanets, due to the high radial velocity caused by a strong hydrogen Lyman-α radiation pressure and the rapid orbital motion of planets orbiting at short intervals of several days. We also confirmed that the absorption in the blue wing and the transit duration last over several hours, which sustains for a while in the post-transit phase due to the elongated tail structure. In contrast, oxygen clouds have a compact and spherical spatial distribution because of a higher photoionization rate and the negligible effect of radiation pressure compared to hydrogen. For this reason, the transit duration is shorter than for hydrogen atoms, and the transit depth is symmetric in time with respect to the transit center. In this presentation, we will demonstrate how XUV radiation intensity, atmospheric temperature, and the strength of radiation pressure from atomic emission lines influence the structure of the atmosphere and the transit features of the hydrogen Lyman-α and O Ⅰ lines. We will also discuss the feasibility of exospheric atmospheres in terrestrial exoplanets with future UV observatories.