Theoretical Prediction of Climates of Ocean Terrestrial Exoplanets in the Habitable Zone and Its Verifiability via UV Transit Observation of Planetary Oxygen Coronae

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Constraining the partial pressure of carbon dioxide (CO_2) in terrestrial exoplanet atmospheres observationally is of crucial importance, because CO_2 is a major greenhouse gas and its pressure is regulated by the geochemical carbon cycle for planets in the habitable zone. Our recent climate models (Nakayama et al. 2019) demonstrate that such a thermostat effect by the geochemical carbon cycle strongly depends on ocean mass, which must be diverse outside the solar system, given diverse water-supply processes and their stochastic nature. Thus, the CO_2 pressure and climate of terrestrial exoplanets in the habitable zone are predicted to be also diverse.
Carbon dioxide greatly affects the temperature structure of the upper atmosphere. A previous study suggested that transit depths of atomic oxygen lines (OI lines) in the UV wavelength range can be a clue to constraining the CO_2 pressure because the major coolant CO_2 determines the expansivity of terrestrial upper atmospheres. Such observations will be possible in near future by the Russian space telescope, World Space Observatory-Ultra-violet (WSO-UV), to be launched in 2025, which plans to observe exoplanets transiting in front of relatively low temperature stars (or M-type stars) with the OI lines. Here, we develop new upper atmospheric models and transmission models for highly UV-irradiated planets orbiting an M-type star and estimate the absorption by the planets with expanded atmospheres during a transit at the OI lines. Our upper atmosphere simulation self-consistently includes the effects of variations in atmospheric composition and stellar spectrum, by considering thermo-chemical and photo-chemical reactions, chemical and thermal diffusions, absorption of stellar infrared irradiation, and radiative cooling. Then, we quantify the feasibility of constraining the CO_2 pressure and planetary climate through the UV transit observation.
We find that for the Earth-sized planets with low or moderate CO_2 pressures around quiet M-type stars, the atmospheres are in the blow-off state and as large in radius as the central star. Thus, such expanded atmospheres occult the central star greatly and results in significant absorption of the OI lines. On the other hand, CO_2-dominated atmospheres absorb only a small portion of stellar light. In contrast, there is no dependence of the absorption depth on CO_2 pressure for low-mass planets of about Mars mass because hydrodynamic escape occurs regardless of the amount of CO_2, even around quiet M-type stars. Those results suggest that the difference of CO_2 pressure and planetary climate of terrestrial exoplanets will be constrained by next-generation space telescopes such as WSO-UV. The predicted observable climatic features of terrestrial exoplanets would help us verify theories of planetary climates and clarify whether the planet has a geochemical carbon cycle, Earth-like plate tectonics, and oceans. This will mark a significant milestone in exoplanetary science.

Keywords: Habitable planet, Upper atmosphere , UV transit, Carbon cycle