論文の内容の要旨

Hydrodynamic escape of mineral atmosphere on hot rocky exoplanet: impacts on the evolution of planetary mass and atmospheric composition

(主星近傍をまわる岩石系外惑星のミネラル大気の流体力学的散逸：
惑星質量及び大気組成の進化への影響)

氏名：伊藤祐一

Exoplanet surveys over the past two decades have revealed that there are a variety of planets beyond the Solar system (called exoplanets) and detected a growing number of small-size exoplanets of 1 to 2 Earth radii (often called super-Earths). Many of those small-size exoplanets are expected to be rocky planets. In contrast to the terrestrial planets in the Solar system, some of them are in environments hot enough that their surface temperatures are higher than the melting/vaporization temperature of rock. Such exoplanets are called hot rocky exoplanets in this study. Thus, hot rocky exoplanets likely have global magma oceans and also atmospheres that are composed of gases vaporized from the magmas. These atmospheres are called mineral atmospheres in this study. At present, we are expected to move into a new era of characterizing the atmosphere of hot rocky exoplanets, thanks to near-future space telescopes such as James Webb Space Telescope (JWST). Such characterization is crucially important to know not only what they are like but also how they were formed. Also, recent observations reported on the detection of close-in exoplanets with dusty tails and hot rocky exoplanets with extended sodium atmospheres, suggesting that there are rocky planets currently evaporating and losing parts of their masses. However, if this is the case, it is puzzling why many hot rocky super-Earths currently detected could have survived such evaporative mass loss.

Towards linking the current state of hot rocky exoplanets to their formation, it is necessary to understand their evolution. In particular, the escape of planetary atmospheres is one of the most important processes that change the mass and bulk composition of close-in planets extremely irradiated by stellar UV. The purpose of this study is to investigate the hydrodynamic escape of the mineral atmosphere, for which there are no theoretical studies, considering the details of the elementary processes involved, and derive the mass loss rate via that hydrodynamic escape.

I have developed my own hydrodynamic code for simulating the one-dimensional (along the line connecting the planetary and stellar centers), steady hydrodynamic motion of the highly XUV-irradiated atmosphere that is in the chemical equilibrium with the magma ocean at its bottom. Also, for considering the energy budget in the atmosphere in detail, I have taken into account photo- and thermo-chemistry, non-LTE radiative/chemical processes for heating and cooling, thermal conduction, and multi-component ambipolar diffusion of Na, O, Si, Mg, their multiple-charged ions and electrons, which are the major components in the mineral atmosphere. The magma ocean is assumed to be free of volatile and its composition is that of the bulk-silicate Earth (BSE). Also, the planet is assumed to be orbiting at 0.02 AU around a young Sun-like star. I have investigated the dependence of the hydrodynamic escape on planetary gravity and on stellar XUV flux through the simulations for three different planetary masses, namely 10, 1, and 0.1 $M_\oplus$ and two different stellar ages, namely 0.1 and 1 Gyr.

I have found the two regimes of the hydrodynamic escape of the mineral atmosphere. One is the regime that I call the global-cooling-limited escape. This occurs on hot rocky exoplanets with high gravity such as the super-Earth-mass (10 $M_\oplus$) and Earth-mass (1 $M_\oplus$) cases. As the dominant process in this escape regime, almost all of the incident XUV energy from the host-star is converted into the radiative emission due to electronic transition in Na, Mg^+, Si^{2+}, Na^{3+} and Si^{3+}. The mass loss rates that I have derived in the 10 $M_\oplus$ and 1 $M_\oplus$ cases are relatively low, but massive enough for the atmosphere to remove completely the major species Na. For instance, the mass loss rate is on the order of 10^{-2} $M_\oplus$/Gyr for the 10 $M_\oplus$ case at the stellar age of 0.1 Gyr. And the mass loss rate increases linearly with incident stellar XUV flux. The other is the regime that I call the FUV-and-visible-energy-limited escape. In this escape regime, I have found that the mass loss rate is massive enough to lose all the planetary mass. This is because not only the FUV energy but also the visible light energy from the host star is used to efficiently drive the atmospheric motion. This occurs on hot rocky exoplanets with low gravity such as the 0.1 $M_\oplus$ case. The estimated mass loss rates are as high as 4.9×10^2 $M_\oplus$/Gyr and 5.1×10^2 $M_\oplus$/Gyr for the stellar ages of 0.1 and 1 Gyr, respectively; the mass loss rate is found to be independent of stellar XUV flux. Thus, in the present study, I have demonstrated that hot rocky exoplanets of 0.1 $M_\oplus$ selectively evaporate through the hydrodynamic escape of the mineral atmospheres, but ones of ≥ 1 $M_\oplus$ survive. It has been demonstrated that consideration of atmospheric escape is crucial for understanding the current state and origin of close-in rocky exoplanets.