論文の内容の要旨

論文題目　Non-equilibrium tidal heating of Enceladus and compositional diapirism of Ceres, their roles in exoplanets

(エンセラダスの非平衡状態の潮汐加熱とケレスの組成プルーム、および系外惑星におけるそれらの役割について)

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Endogenic activities on the Earth such as plate tectonics and volcanic eruptions largely affect our environment. In our solar system, except for the Earth, Io and Enceladus have been recognized to have endogenic activity. In addition, some bodies such as Triton and Ceres exhibit vaporization, which may be induced by their endogenic process. Out of our solar system, there should be many active planets. Although analysis of their activity is important in planetary science and understanding our environment, detailed activity mechanism in each body is not known well. In this work, I focus such activities on Enceladus, Ceres and extrasolar rocky planets.

From the surface of Enceladus, plumes mainly composed of water vapor and ice grain emanate into the space, which implies a subsurface ocean in Enceladus. However, the mechanism that maintains liquid water in Enceladus remains unsolved enigma because conventional radiogenic and tidal heating processes cannot maintain the ocean for a long time if Enceladus has equilibrium orbital state. From the surface state, Enceladus has large probability that heating is not in steady state. I considered the interaction of tidal heating with interior structure and orbital evolutions. Although depending on the rheological parameters, the interior ocean can be maintained by the oscillatory variation of ice thickness and eccentricity if melting temperature decreases and core radius is less than 161 km. Our calculation results show that ocean thickness is no more than a few kilometers and that interior temperature has to be lower than 175 K, which is smaller than the estimated values by gravity and thermal measurements. Heat generated by chemical process may be an additional heat sources in order to keep Enceladus warm, which can be a future study to be considered.

At the dwarf planet in asteroid belt Ceres, it has been observed that water vapor emanated from the surface. Although vaporization of Ceres is not continuous emission, which is different from the plume of Enceladus, endogenic activity is suspected for the origin of the vaporization in Ceres. While Enceladus has tidal heating, Ceres does not have strong tide due to the large distance from the

Sun. As for the origin of Ceres' vaporization, I suggest the compositional diapirism in which less dense pure ice goes up to the surface by the buoyancy through dense rock-ice crust. If the curst density is around 2700 kg m^{-3} and temperature is less than 180 K, the crust is maintained for a few billion years. Surface temperature is estimated for 180 K at the equatorial region, and thus all the crust should have sunk to the interior. However, at the mid-latitude and the polar areas, surface temperature is less than 180 K. Thus, the crust may be maintained, and diapirism can be induced. By the numerical calculations, I found that induced diapir could appear at the surface within the solar system age if the surface temperature is around 170 K. On the other hand, if the surface temperature is 150 K, diapir cannot reach the surface because of high viscosity near the surface regioin. Observation showed that vaporization of Ceres came from mid-latitude of Ceres. The localization of vaporization results from the moderate temperature enough to induce diapir and transfer the pure ice to the surface.

Enceladus and Ceres are the celestial bodies in our solar system. In the following section, extrasolar terrestrial planets are considered. One important topic for exoplanets is searching for habitable planets out of the solar system. Recently, special attentions have been paid for exoplanets around M type stars as observational targets because a lot of M stars exist. Due to low temperature, habitable zone of M star is near the central star, which results in the large effect of tide. In this work, applying the Enceladus research, I conduct numerical calculations for tidal evolution of Martian-sized planets around M stars. By thermal-orbital coupled calculations, planets which orbit in the habitable zone of M stars can stay their habitable zone even though eccentricity is large. This is because the mantle melts by tidal heating and the magnitude of dissipation decreases, which results in the small orbital change. If the initial eccentricity is more than 0.2 and central star mass is less than 0.2 times of the solar mass, heat flux by tidal heating is suitable for habitability.

Although the distance from the central star is an important factor for the habitability of the planets, endogenic activity also plays an important role in habitability because interior activity largely affects the surface environment. As a next step, I consider the delamination process in super-Earths. Extrapolating the Earth model, magnitude of delamination is estimated at heavy rocky planets. In the model used in this work, Rayleigh number decreases with increasing the mass of the planets due to high pressure. Thus, the magnitude of the delamination process decreases at large planets even though it occurs. Delamination process depends on the local convection in asthenosphere, which is affected by the modeling condition. In addition, interior structure of terrestrial planet is not always the same to the structure of the Earth. More work is needed for more detailed study of delamination process in super-Earth.