

Transformation from comet to asteroid by ice sublimation: Inward flow of water vapor and recondensation to ice

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The asteroid probe “Hayabusa2” has revealed that the asteroid Ryugu is a spinning-top shaped object with a rubble pile structure and its composition is rich in organic substance. Recently, it has been proposed that Ryugu was formed by the sublimation of only ice from the comet nucleus which is a mixture of ice and rock, and accumulation of remained rock (cometary origin scenario [1,2]). Miura et al. [3] proposed the theoretical model based on the cometary origin scenario and estimated the time required for the sublimation of ice and the increase rate of rotation velocity. As a result, assuming physical quantities of a typical comet nucleus as initial conditions, it was found that the ice sublimates in about tens of thousands of years, and the rotation velocity can increase to a sufficient value to acquire the spinning-top shape. However, their model has a problem of assuming that the temperature inside the comet nucleus is uniform and constant. If the comet nucleus is heated by sunlight as the authors supposed, it is reasonable to assume that the temperatures at the center and the surface of the comet nucleus are different. In this research, we consider the numerical model taking into account the time variation of the temperature distribution inside the comet nucleus, and investigate how the temperature evolution affects the evolution from a comet nucleus to an asteroid.

In our model, the parent body is supposed to be a spherical and porous comet nucleus composed of water ice and rocky debris. At the surface of the nucleus, the energy supply by the solar radiation and the energy loss by the thermal radiation are considered. Assuming that the interior temperature field is spherically symmetric, the time-dependent heat conduction equation is solved numerically with the energy balance at the nucleus surface as a boundary condition to obtain the time variation of the interior temperature field. Then, the vapor pressure distribution is derived assuming that the sublimation of water ice is balanced with the internal flow of water vapor at arbitrary position. The variation of the volume fraction of ice is calculated using the vapor pressure. If the volume fraction of ice decreases and the porosity exceeds from the initial value, we assumed that the entire nucleus shrinks until the porosity becomes equal to the initial value. On the other hand, if the volume fraction of ice increases and the porosity decreases, the nucleus size is assumed to be unchanged. Using this model, we calculated the evolution of a comet nucleus orbiting at 1.1 au from the Sun. The luminosity of the Sun was assumed to be the current value and the initial temperature of the comet nucleus was assumed to be uniform at 194.9 K.

As a result, we obtained the temperature distribution with a temperature increasing toward the surface. Near the surface, the water vapor flows out to the outside of the comet nucleus. Inside the surface, we confirmed the area where the water vapor pressure increases from the inside to the outside of the nucleus due to the temperature distribution. In this area, the water vapor flows inward and condenses to ice in the lower temperature part in the inside of the nucleus. Thus, the pores are filled up with the water ice and impermeable layer for the water vapor is formed (ice crust). We also found that a repeated structure with dense parts (bumps) and sparse parts of ice was observed inside the ice crust.

To find the origin of the repeated structure, we conducted a test calculation with a one-dimensional plane-parallel geometry in which only temperature distribution, ice sublimation, and vapor flow were considered, and found that the repeated structure was reproduced. From this test calculation, the origin of the repeated structure is considered that the suppression of vapor flow by a bump amplifies the change of the volume fraction of ice at the downstream side.

References: [1] E. Nakamura et al. In: Proc Jpn Acad Ser B Phys Biol Sci 95.4 (2019), pp. 165–177. [2] C. Potiszil et al. In: Astrobiology 20.7 (2020). PMID: 32543220, pp. 916–921. [3] H. Miura et al. In: The Astrophysical Journal Letters 925.2 (2022), p. L15.

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