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Article

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The asteroid 162173 Ryugu: a cometary origin

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The Japanese Hayabusa2 mission has revealed in detail the physical characteristics of the C-type asteroid 162173 Ryugu, in particular, its spinning top-shaped rubble pile structure [1] and the potentially extremely high organic content [2, 3]. A widely-accepted formation scenario for Ryugu is catastrophic collision between larger asteroids and the subsequent slow gravitational accumulation of collisional debris [4, 5]. However, the collisional re-accumulation scenario does not explain the origin of the abundant organic matter. An alternative scenario is that Ryugu is an extinct comet, which lost its icy components [2, 6, 3]. Here, the sublimation of water ice from a uniform porous cometary nucleus was numerically simulated until the refractory components, such as silicate rocks and organic matter were left behind as evapora-

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tive residues. Such a process represents the transformation from a comet to an asteroid. The spin-up related to the shrinking nucleus, associated with the water ice sublimation, was also calculated. The result of the calculation indicates that the cometary origin scenario can quantitatively account for all the features of Ryugu discussed above. We conclude that organic-rich spinning top-shaped rubble pile asteroids, such as Ryugu, are comet-asteroid transition objects or extinct comets.

Sample return missions represent great opportunities to study materials from known locations on the objects other than the earth. The Hayabusa mission returned material to Earth from the asteroid Itokawa in 2010 [7] and revealed through geochemistry that the asteroid was genetically related to ordinary chondrites [8, e.g.,]. The following Hayabusa2 mission returned material from Ryugu to Earth on 6th of December, 2020 [1] and the OSIRIS-REx mission is expected to return samples from another asteroid Bennu in 2023 [9]. Both Ryugu and Bennu are C-type asteroids and are considered to be genetically related to carbonaceous chondrites. The aforementioned sample return missions are expected to dramatically advance our understanding of the processes affecting the formation of and evolution of bodies within the Solar system along with the origin of the prebiotic organic matter performing a detailed comprehensive geochemical analysis of the returned samples with state-of-the-art analytical equipment on the earth.

The Hayabusa2 mission has revealed three major features of the asteroid Ryugu based on the proximity remote sensing observations. The first feature is the rubble pile structure. Because of the high porosity and the large boulders on the surface of Ryugu, the interior was considered to consist of a rubble pile structure of large rocks weakly agglomerated gravitationally [1], similar to Itokawa as investigated by the predecessor Hayabusa mission [7]. It has been proposed that the rubble pile structure was formed by the re-accumulation of collisional debris after catastrophic collision between larger asteroids [4, 5]. The second feature is the spinning top-shape, which suggests a rotation-induced deformation. The spin period required for the deformation is estimated to be about 3.5 hr, below which the centrifugal force exceeds the gravitational force at the equatorial plane of the object [1]. In the scenario with accretion of collisional debris, numerical simulations supported that the spinning top-shape is the consequence of the angular momentum gained during re-accumulation [10]. The third feature is the extremely high organic matter content compared to those in carbonaceous chondrites. Mass balance calculations based on the difference in albedo between the surface and the underground materials recognized after the touchdown of Hayabusa2 spacecraft inferred that the surface layer of Ryugu would contain about 60% organic matter by area, if the coexisting silicate components have optical properties similar to those of the CM chondrites [2]. This estimate is much larger than the typical organic content in carbonaceous chondrites (likely < 10 wt.% [11]). It has also been pointed out that the low thermal inertia and bulk density of Ryugu may be due to its high organic content [12]. The re-accumulation scenario explains the first and second features but not the third one.

An alternative scenario, which can satisfy the three different major features of the asteroid Ryugu simultaneously, is a cometary origin [2, 6, 3].

Comets are small bodies formed at the outer cold region of the Solar system and contain significant amounts of water ice. If they enter the inner Solar system due to some dynamical effect, such as gravitational perturbation associated with the migration of giant planets [13], they will capture the rocky debris scattered within the region, which probably formed as a result of the formation of planets and collision-induced fragmentation in the asteroid belt [14]. In fact, some textures that are presumed to have formed when the rocky debris was captured by a comet nucleus were observed in the Chelyabinsk meteorite [6]. Subsequently, the water ice almost completely sublimates, leaving the captured rocky debris behind and finally transforms into a compact rubble pile asteroid. The ice sublimation also causes the spin-up of the comet due to the shrinkage of the nucleus and the consequent decrease in the moment of inertia [15]. As the result of the spin-up, the comet nucleus may have acquired the fast rotation required for the formation of the spinning top-shape. In addition, comets are expected to contain a fraction of organic matter that formed in the interstellar medium [16, 17]. The refractory organic matter will be deposited filling the space between the rocky debris as an organic residue layer after the water ice sublimates. However, it is unknown how long it takes for the ice to sublimate completely, and how much the body will eventually spin-up by.

In order to quantitatively verify the cometary origin scenario of Ryugu, a numerical simulation was undertaken, in which the ice is sublimated from a cometary nucleus until it transforms to a rubble pile asteroid. Figure 1 shows the outline of our model. Let us consider a uniform, spherically symmetric, highly porous cometary nucleus composed of water ice particles and rocky debris. As the water ice sublimates from the outer layer of the nucleus, the remaining rocky debris piles up on the surface to form a dust mantle. The dust mantle is also highly porous and therefore permeable, allowing the sublimation of water ice from inside. As the water ice continues to sublimate, the cometary nucleus shrinks and eventually becomes a compact rubble pile asteroid consisting only of rocky debris. We derived an analytical solution of the pressure distribution of water vapor in the interior of the cometary nucleus with a two-layered structure of the inner primitive region and the outer dust mantle, and used it to determine the contraction rate of the nucleus. In order to obtain the time until the water ice sublimates completely (sublimation time), the time evolution equation for the radius of the cometary nucleus was numerically integrated until the radius of the primitive region became zero. We also calculated the change in the spin rate of the cometary nucleus as it contracts, and determined how much the angular velocity can be amplified by relative to the pre-sublimation state. Watanabe [15] formulated the spin-up associated with the contraction of a cometary nucleus, but it was based on the assumption that the contraction is sufficiently small relative to the initial radius. We have extended the Watanabe's formulation to apply to the drastic transformation from comet to asteroid. Details of our formulation are described in the Supplementary Information.

Figure 2 shows the time evolution of the radius of the cometary nucleus over time with the initial radius being 3 km. The initial composition of the cometary nucleus is assumed to be 99 wt.% water ice, with the remaining 1 wt.% being captured rocky debris. The icy particles and the rocky debris

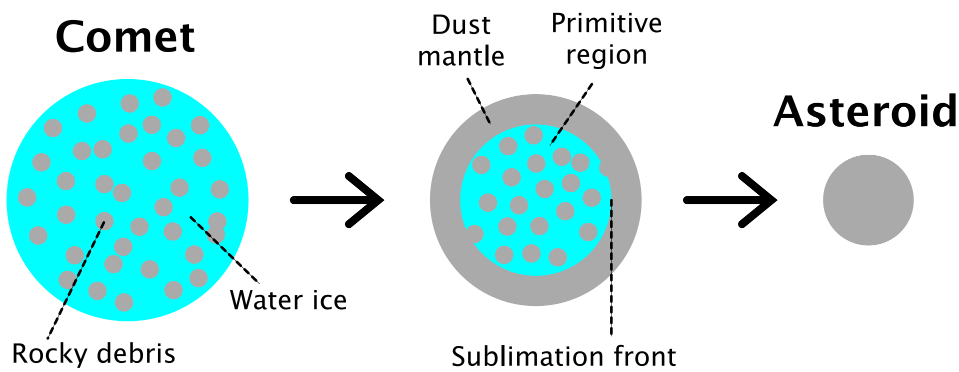

Figure 1: **A model of water ice sublimation from a porous cometary nucleus.** The cometary nucleus is initially assumed to consist mainly of water ice particles with a small amount of rocky debris uniformly contained within. As the water ice sublimates from the surface of nucleus, the primitive region shrinks, and the remaining rocky debris accumulate on its surface to form a dust mantle. Since the inner primitive region and the dust mantle are highly porous and therefore permeable, the water vapor generated inside leaks out through the dust mantle. The water ice sublimation occurs at the very surface of the primitive region, so here we refer to the boundary between the primitive region and dust mantle as the sublimation front. Finally, the cometary nucleus transforms to a rocky asteroid after almost complete sublimation of water ice. In addition, if the cometary nucleus is initially spinning, the rotation would be accelerated because of the decrease in the moment of inertia.

are assumed to be spheres with radii of 1 μm and 1 cm, respectively, and both are randomly packed in the primitive region, while the dust mantle is occupied by rocky debris only. As the water ice sublimates, the rocky debris left behind accumulate on the surface of the nucleus to keep the macroporocity at a constant value, assumed to be 0.6 in this study. The temperature inside the nucleus is assumed to be homogeneous at 200 K. The rationale for the values given above is described in Methods. Figure 2 demonstrates the rapid shrinkage of the primitive region and simultaneously the increase in the thickness of the dust mantle as the water ice sublimates. It took about 230 years for the dust mantle to reach a thickness of 1 m, and about 9 kyr to reach 10 m. The sublimation rate decayed as the dust mantle grew, and it took about 150 kyr for the water ice to sublimate completely. The thickness of the final dust mantle, i.e., the radius of the rubble pile asteroid, is 449 m, which is approximately equal to the radius of present-day Ryugu (about 420 m).

Figure 3 shows the change in the angular velocity associated with the contraction of the cometary nucleus. The radius of the primitive region halves in about 11 kyr, but the angular velocity remains almost unchanged during this period. As the water ice sublimation progresses and the dust mantle growth becomes more pronounced, the angular velocity increases rapidly. The spin acceleration is due to the fact that the decrease in the moment of inertia of the cometary nucleus is more remarkable than the angular momentum loss by the release of water vapor. The angular velocity eventually increases to about 3.2 times the initial value.

A major question concerning the current study is whether the cometary

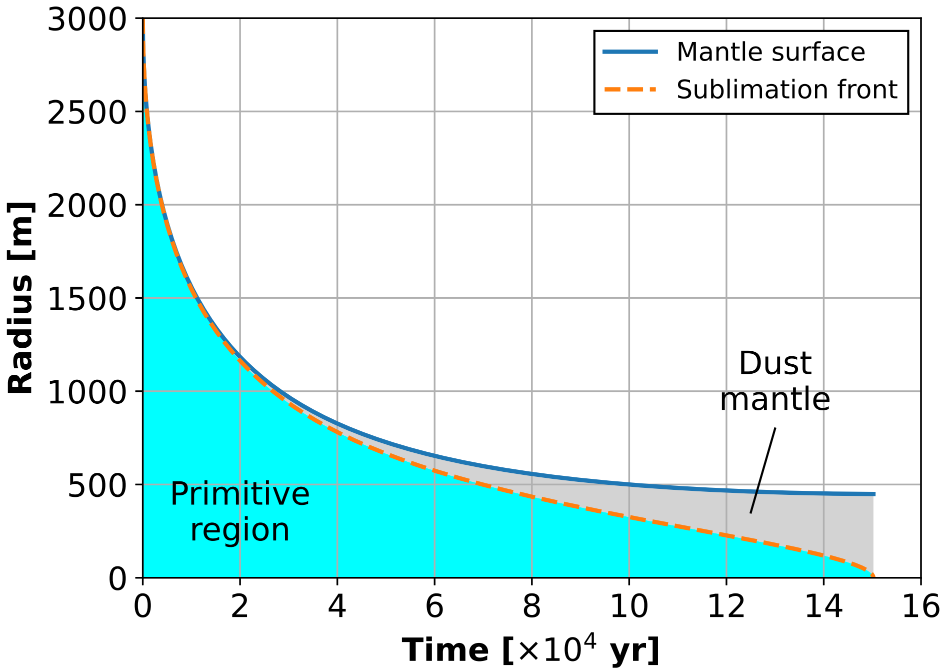

Figure 2: **The numerical result of the shrinkage of the cometary nucleus due to water ice sublimation.** The time variations of the radii of the primitive region and the dust mantle are shown by dashed and solid curves, respectively.

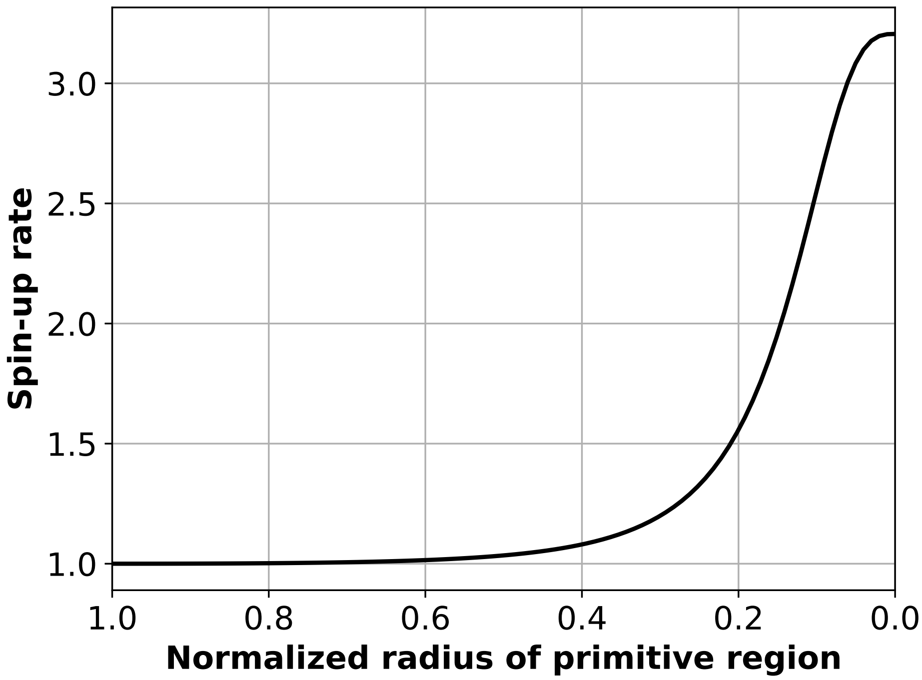

Figure 3: **The change in angular velocity of the cometary nucleus associated with the shrinkage due to water ice sublimation.** The spin-up rate in the vertical axis is the angular velocity when the radius of the primitive region contracts to the value given by the horizontal axis as the ratio with respect to the initial angular velocity.

nucleus is able to achieve the angular velocity necessary to reproduce Ryugu's spinning top-shape. The model outlined so far, contains only a mechanism to amplify the initial rotation of the cometary nucleus. In other words, we need information on the initial angular velocity of the cometary nucleus, which was the parent body of Ryugu. Figure 4 shows the distribution of spin periods of 28 cometary nuclei that have been observed. The spin period is widely distributed up to 3.5-78.4 hr, with a median of about 12 hr. If the Ryugu's parent comet had a spin period corresponding to the median, it would be necessary to amplify the initial angular velocity by a factor of 3.4 to bring the spin period to 3.5 hr due to the water ice sublimation. The required spin-up rate is in good agreement with the rate calculated when almost all of the water ice sublimates in Figure 3. In this mechanism, the rotation is slowly accelerated as the water ice sublimates. Such quasi-static rotational acceleration is thought to be desirable for the formation of a spherically-symmetric spinning top-shape like Ryugu [1].

The spin period of asteroids can be modified to be longer and shorter by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect—a radiation recoil torque affecting the rotation state of a small asteroid [5]. The time for a km-sized body to halve or double its spin rate by this effect is on the order of ~ 1 Myr [20]. In contrast to the YORP effect, the timescale of the spin-up due to the water ice sublimation is an order of magnitude faster, about 0.1 Myr (see Figure 2). Therefore, Ryugu's spinning top-shape can be formed in a shorter period of time compared to the case assuming the YORP effect. However, the sublimation time strongly depends on the temperature of the cometary nucleus (see Eq. S29). If we change only the temperature from 200

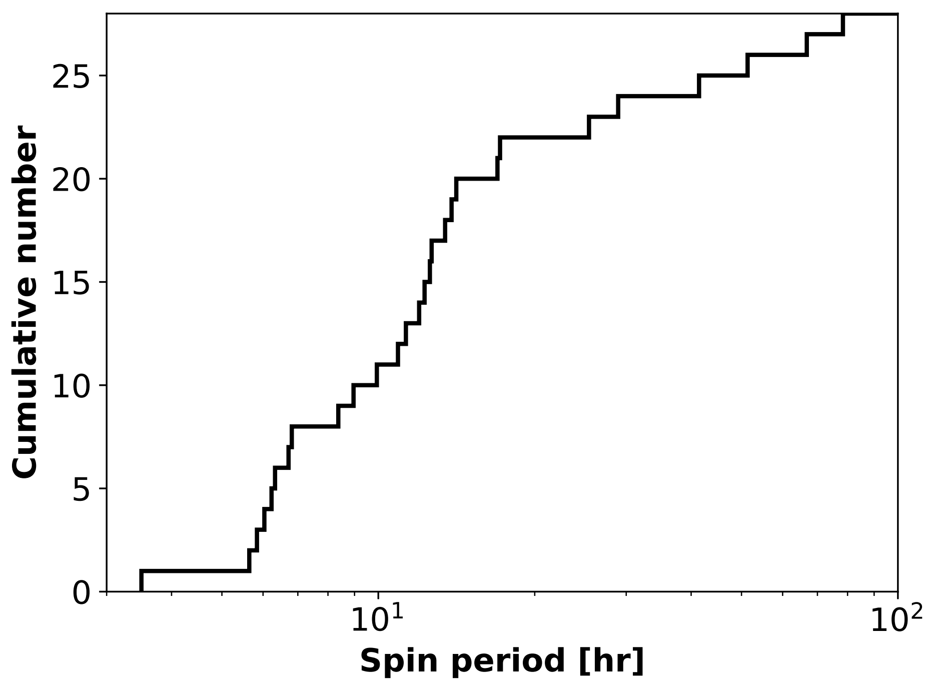

Figure 4: **The distribution of spin periods of 28 cometary nuclei measured so far.** The data is compiled from observational results in the literature [18, 19]. The vertical axis represents the cumulative number of cometary nuclei with the spin period shorter than the value given by the horizontal axis.

K to 188 K under the same condition as in Figure 2, the sublimation time will exceed one million years. The sublimation time also depends on other parameters such as initial radius of cometary nucleus, macroporosity, size of the rocky debris, and so forth. The parameter dependence may provide constraints on the orbital evolution of Ryugu, the size of the constituent particles, and the internal macroporosity.

Cometary nuclei are thought to contain organic molecules that were formed in interstellar space as well as in the outer Solar system as confirmed by infrared observations [16]. The organic molecules detected include CO, CO_2, CH_3OH, OCS, H_2CO, $HCOOH$, CH_4, and OCN^-, which account for several % with respect to H_2O [17]. When the water ice sublimates, the organic residue concentrates and is left behind with the rocky debris. The mass ratio of the rocky debris and the refractory organics left behind is equal to that of both in the initial cometary nucleus. If the cometary nucleus is mainly composed of water ice that contains 1 wt.% refractory organic matters, and captures 1 wt.% rocky debris as assumed in Figures 2 and 3, the masses of organic matters and rocky debris left behind become comparable. The mass ratio is consistent with the estimate of the organic content of Ryugu's surface layer from its albedo [2]. The organic-rich surface of comet 67P/Churyumov-Gerasimenko [21] may also be explained by the sublimation-induced concentration of organic matter.

Conventional models for sublimation of volatiles from a porous cometary nucleus, though they did not consider the shrinkage of the nucleus, took into account not only the gas flow in the porous medium but also the internal thermal evolution [22, 23, 24]. In contrast to these conventional models, our model, which assumes a uniform and constant internal temperature, may not be able to avoid criticism for being oversimplified. However, by setting the uniform and constant temperature beforehand, it is possible to answer the more general question, "What will happen if a comet experiences a given temperature and for how long?" Our approach will provide fundamental insights for examining the long-term evolution of cometary nuclei when heated.

Our calculation suggests that Ryugu was once a comet and active for the first several 10 kyr and spent the rest of its dynamic lifetime as a rubble-pile asteroid. This scenario is consistent with the dynamical evolution of modern comets in the Solar system [25]. In addition, the scenario presented in this paper may be applicable to another asteroid Bennu, which is also a spinning top-shaped rubble pile. In fact, there is some evidence which suggests that Bennu is a transitional object on its way from a comet to an asteroid [26, 25]. This is also consistent with the fact that the current spin period of Bennu ($\sim$ 4.30 hr [27]) is shorter than that of Ryugu ($\sim$ 7.63 hr [1]). Such facts suggest that Bennu is in an earlier evolutional stage of Ryugu and the spin rate of Ryugu was reduced by some mechanism such as meteorite impacts [28] and the YORP effect [29].

Comet-asteroid transition objects (CATs) are small objects that were once active like comets, but have become dormant and apparently indistinguishable from asteroids [30]. CATs are thought to provide a new insight into the Solar system, because of their similarities to both comets and asteroids [31]. Our results suggest that organic-rich spinning top-shaped rubble pile objects such as Ryugu and Bennu are members of the CATs population. As demonstrated for the Chelyabinsk meteorite [6], analysis of collected samples of Ryugu and Bennu in the terrestrial laboratory in a comprehensive way will further evaluate the interlink between rubble-pile asteroids and comets.

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Methods

Calculation for shrinkage of cometary nucleus

We have developed an original method to calculate the contraction of a porous cometary nucleus due to the water ice sublimation. The interior of the cometary nucleus is filled with water vapor generated by the ice sublimation. Most of the interior is in solid-vapor equilibrium, but in the top of the primitive region and in the dust mantle, the water vapor pressure is lower than the equilibrium value because of the leakage of the vapor to the outside. In order to obtain the contraction rate of the cometary nucleus, it is necessary to determine the water vapor pressure distribution inside the nucleus and the water vapor flux flowing out from the surface of the cometary nucleus. We derived an analytical solution for the pressure distribution inside the cometary nucleus, which has a two-layered structure of primitive region and the dust mantle, based on the equation for the water vapor flux in porous bodies [22]. Using this analytical solution, the water vapor flux outflowing from the surface of the cometary nucleus was determined, and then the contraction rate was also determined. Details of the formulation is described in Supplementary Information.

Calculation for spin-up

Since assuming the spherical symmetry, the water vapor does not exert any reaction torque on the cometary nucleus when ejected. Therefore, the nucleus never starts spinning if not rotating initially. However, if the nucleus is initially rotating, the moment of inertia will change as it contracts, and its spin rate may also change. Watanabe [15] formulated the spin-up by taking into account the angular momentum loss due to the ice sublimation and the decrease in the moment of inertia due to the contraction of the cometary nucleus. However, he assumed the case where the cometary nucleus shrinks only slightly, so his model cannot be directly applied to the drastic change where the cometary nucleus loses almost all of water ice. Here, we modified the Watanabe's formulation to apply to the case where the radius of the cometary nucleus changes significantly. Details of the formulation is described in Supplementary Information.

Input parameters

We set the parameters used in our calculations as follows. The diameter of water ice particles is the typical size of interstellar dust particles. The diameter of the rocky debris is the typical size of regolith on the surface of Ryugu estimated from the thermal inertia [32] and of particles ejected from an artificial impact crater on Ryugu [33]. Ryugu is believed to have passed through the $\nu6$ resonance to its current near-Earth orbit [34]. For the temperature T, we used the radiative equilibrium temperature near ~ 2 au, where the $\nu6$ resonance exists. The initial radius of the cometary nucleus was chosen based on the typical size of cometary nuclei, so as to become a comparable size to Ryugu after the water ice sublimation. The cometary nucleus was assumed to capture rocky debris equivalent to about 1 wt.% of its own mass. The macroporosity is based on the typical value of cometary nuclei [35]. These input parameters are tabulated in Supplementary Table 1.

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Author contributions

Physical modeling and numerical simulation: H.M. Proposal of cometary origin of asteroid Ryugu: E.N. and T.K. Writing: H.M. All authors discussed the results and commented on the manuscript. E.N. conceived the project.

Competing interests

The authors declare no competing interests.

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