A NEW MODEL OF SEISMICITY ON ASTEROIDS IMPLIED BY THE SCI EXPERIMENT OF THE HAYABUSA2 MISSION: INSIGHTS FROM THE EXISTENCE OF BOULDERS PERCHED ON OTHER BOULDERS.

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Introduction: Recently, multiple space exploration missions have revealed that asteroids have complex geomorphological features that may indicate downslope motion of loose regolith. For example, Eros and Itokawa have flat-floored sediments ponds in craters, and large blocks surrounded by debris aprons [1, 2]. A deficit of small craters has also been observed on Ryugu by Hayabusa2 [3], indicating mass movements on the asteroid's surface. However, processes behind transportation of asteroid regolith in both lateral and vertical directions remains ambiguous.

Although many renewal processes have been proposed, impact-induced seismic shaking [2] is regarded as the most efficient process for the mass transport of asteroid regolith. When a meteoroid hits an asteroid, a small fraction of the kinetic energy of the impactor is converted into seismic waves. The ground acceleration of seismic waves on the surface can overcome the microgravity of asteroids, causing global surface renewal. Numerical simulations and laboratory experiments support this hypothesis. Seismic shaking on a rubble-pile asteroids was tested by a Small Carry-on Impactor (SCI) experiment [4] on the Hayabusa2 mission, which explored the near-earth asteroid Ryugu from June 2018 to November 2019. The seismic energy induced by the SCI experiment was expected to be large enough to cause large boulder movements.

By analyzing the images from pre- and post- the SCI experiment, however, the movement distances of boulders around the artificial crater appeared to be smaller than 1 m [5], which indicates the induced seismic energy is much smaller than expected. This discrepancy is possibly due to the behavior of loose powdery regolith under microgravity. For seismic waves to propagate, the material needs to be elastic, and seismic pressure is limited by the yield strength. Under microgravity conditions, the yield strength of powdery material could be so low as to make the seismic energy of the SCI impact small.

In addition, some boulders perched upon other boulders have been found on Ryugu. Based on the study of paleoseismology on Earth, the top boulder will fall when it is destabilized by seismic acceleration larger than the net gravity on the asteroid. Thus, their existence may indicate the low seismicity on asteroid Ryugu, contrary to the previous models.

In order to explain unstable boulders on Ryugu, we propose a new seismic shaking model using the SCI result. Below, we first formulate seismic shaking by Rayleigh and coda waves induced by a single impact, which is compatible with the SCI observation. Next, the area affected by seismic shaking induced by each impact is integrated with the size-frequency of impactors. Thus, we estimate the cumulative modified area ratio. Finally, by comparing the cumulative modified area ratio with the production rate of boulders landing on other boulders, we constrain the seismic energy diffusivity of asteroid regolith.

Formulations: First, we relate the ground acceleration using the seismic stress. Using empirical scaling of the source time duration for an impactor, and the analytical solution for a Rayleigh wave in semi-infinite space, the seismic acceleration at the crater rim, a_0, is

$$a_0 = 1.1 \times \rho^{-\frac{2}{3}}\, m_p^{-\frac{1}{3}}\, \epsilon^{\frac{1}{3}}\, \sigma_Y \qquad (1)$$

where ρ is asteroid density, m_p is impactor mass, ϵ is seismic efficiency, and σ_Y is yield strength. Seismic efficiency is the ratio of the seismic energy to the impactor's kinetic energy [6].

Then, we formulate ground acceleration by Rayleigh wave, a_R, and coda wave, a_C, as

$$a_R(\theta) = a_0 \left(\frac{r_0}{R\sin\theta}\right)^{\frac{1}{2}} \exp\left(-1.2\frac{\rho^{\frac{1}{3}}\epsilon^{\frac{1}{3}}(R\theta - r_0)}{{}^{E}Q m_p^{\frac{1}{3}}}\right) \qquad (2)$$

$$a_C(\theta) = \frac{a_0}{4}\left(\frac{r_0}{R\sin\frac{\theta}{2}}\right)^2 \exp\left(-\frac{2f\left(4R^2\sin^2\frac{\theta}{2} - r_0^2\right)}{\xi\pi\ {}^{I}Q}\right) \qquad (3)$$

where r_0 is crater radius in gravity regime, R is asteroid radius, θ is colatitude from the crater center, ${}^{E}Q$ is effective quality factor, ${}^{I}Q$ is intrinsic quality factor, f is frequency of seismic wave, ξ is seismic diffusivity [6]. ξ is the parameter of scattering intensity and depends on the wavelength and size distribution of scatters. Using the lunar regolith model [7] and boulder size distribution[8], we model ξ as

$$\xi = \xi_0 \left(\frac{f}{4}\right)^{-1.65} \qquad (4)$$

where ξ_0 is diffusivity at 4 Hz. ${}^{E}Q$ includes ${}^{I}Q$ and scattering quality factor. We incorporate the relationship between scattering quality factor and ξ to model the attenuation of Rayleigh wave.

Finally, we integrate the area where seismic acceleration exceeds gravity across all sizes of impactor. Changing ξ_0, we estimate the cumulative modified area ratio per year.

Results: Figure 1 shows the cumulative ratio of area modified by seismic shaking and cratering for Ryugu, Bennu, and Itokawa as a function of ξ_0. Here we use lunar-like ${}^{I}Q$ of 2000 and σ_Y of 500 Pa as the cohesion strength of Ryugu subsurface [4]. For example, if ξ_0 of Ryugu is the same as that of lunar soil of 0.03 km^2/s, the cumulative area ratio is 0.03 per year, in other words, it takes about 30 years for the whole asteroid surface to experience seismic acceleration larger than gravity.

To sustain unstable boulders, the production rate of boulders upon boulders has to be higher than the cumulative modified area ratio. On Ryugu, sub-metre sized boulders are found on other boulders. The most plausible process of such boulder formation is ejecta landing on lower boulders during large crater formation. For example, assuming boulders will be ejected from a crater of 3 m, ξ_0 has to be lower than 0.0003 km^2/s. Thus, the ξ_0 of asteroid regolith needs to be smaller than that of lunar soil.

Discussions: The ξ_0 of asteroid regolith is lower by two orders of magnitude than that of lunar soil. This difference can be attributed to the grain size difference because the intensity of scattering is dependent on the heterogeneity size. The scattered power from a single heterogeneity is proportional to the fourth power of its size [9]. Considering that the regolith size of Ryugu is larger by some orders of magnitude than that on the Moon, the intensity of scattering may differ drastically between Ryugu and lunar soil. Thus, intensive scattering on Ryugu may reduce the efficiency of seismic energy propagation across the whole surface, resulting in surface modification rate by seismic shaking being lower than in previous models.

Boulders on boulders are found on Bennu, too [10]. On the other hand, no gravel isolated on top of boulders has been observed on Itokawa [2]. If the elastic properties of Itokawa are the same as Ryugu, the frequency of surface modification would be almost the same (Figure 1). This discrepancy may indicate two possibilities: the presence of an inner core and recent global shaking on Itokawa.

The existence of bedrock on Itokawa has been already considered from the gravitational potential analysis [11] and slope distribution [12]. If Itokawa has an inner core with a high quality factor, seismic waves can propagate in a wider area than if Itokawa were homogeneous, resulting in higher bulk diffusivity. Furthermore, the index of the power law between the number of impactors and radius of the local seismic shaking circles is around -2. Based on the analogy to crater equilibrium, such an index may indicate that the seismic shaking is a stochastic process. Thus, if a projectile large enough to cause global seismic shaking hit Itokawa recently, all boulders on boulders may have fallen off before the Hayabusa spacecraft's arrival. This hypothesis is also consistent with a strong deficit of craters smaller than 10 m [13].

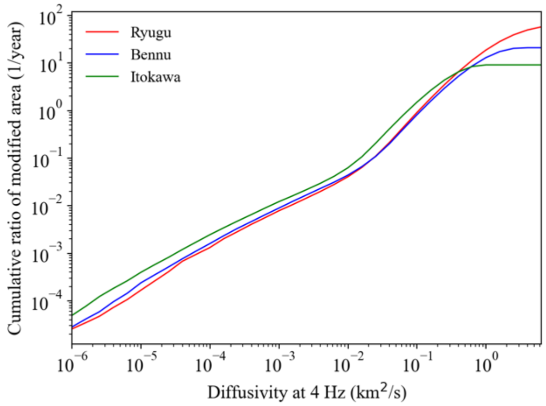

Figure 1: Cumulative ratio of area modified by seismic shaking on Ryugu (red), Bennu (blue), and Itokawa (green) as a function of diffusivity at 4 Hz.

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References: [1] Veverka J. et al. (2001) Science, 292, 484-488. [2] Miyamoto H. et al. (2007) Science, 316, 1011-1014. [3] Sugita S. et al. (2019) Science, 364, eaaw0422. [4] Arakawa M. et al. (2020) Science, 368, 67-71. [5] Honda R. et al. submitted to Icarus. [6] Nishiyama G. et al. (2020) Journal of Geophysical Research: Planets, 121, e2020JE006594. [7] Nakamura Y. (1976) Bulletin of Seis. Soc. Ame. 66(2), 593-606. [8] Michikami T. et al. (2019) Icarus, 331, 179-191. [9] Papadakis, E.P. (1968) Physical Acoustics, 4, 269-328. [10] Jawin E. et al. (2020) Journal of Geophysical Research: Planets, 125, e2020JE006475. [11] Kanamaru M. et al. (2019) Planetary and Space Science, 174, 32-42. [12] Barnouin-Jha O. S. (2008) Icarus, 198(1), 108-124. [13] Michel P. (2009) Icarus, 200(2), 503-513.

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