Oblique impact experiments of ice spheres simulating icy planetesimals

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Collisional disruption and re-accumulation processes among planetesimals and proto-planets have played important roles for the formation and the evolution of the bodies in the solar system. Particularly, "impact strength" and "ejection velocity of impact fragments" are key parameters to control the collisional outcome among the bodies. Some researchers carried out impact experiments to examine the impact strength and the ejection velocity of impact fragments depending on the target and projectile materials, size, impact velocity, etc. In this study, we focus on the effect of oblique impact on these parameters. Planetesimals and proto-planets could collide with each other at various impact angles. Fujiwara and Tsukamoto [1980] and Yasui et al. [2016] conducted oblique impact experiments of basalt, porous gypsum, and glass spheres simulating rocky bodies. In this study, we carried out oblique impact experiments for H_2O ice spheres simulating icy bodies and examined the effect of impact angle on the impact strength and the ejection velocity of impact fragments.
We carried out impact experiments by using two-stage H_2 gas gun at Kobe University. We prepared spherical targets with the diameter of 60 to 80 mm by pouring a tap water into the mold and freezing them in the refrigerator at the temperature of -25 °C. The porosity was ~0%. We used two types of projectiles, a polycarbonate spherical projectile with the diameter of 4.7 mm and a glass spherical projectile with the diameter of 2 mm (for only a head-on impact), and they were accelerated at 0.8 to 4 km/s. The impact angle, θ, was changed from 15° to 90° (a head-on impact). The ice target was set in a vacuum chamber installed in a cold room at the temperature of -15 °C. The vacuum chamber was evacuated below 200 Pa. The collisional phenomena were observed by a high-speed digital video camera at the frame rate of 10^5 fps and the shutter speed of 380 ns.
First, we measured the mass of all recovered fragments to examine the effect of impact angle on the size frequency distribution of impact fragments and the impact strength. The cumulative number distributions of all recovered fragments also matched very well at the θ larger than 30°, while the number of small fragments decreased as the θ became smaller. Next, we examined the relationship between the largest fragment mass normalized by the original target mass, m_l/M_t, and the impact angle, θ. As a result, the m_l/M_t was almost consistent with each other and it was about 0.05 at the θ from 30° to 90º. In the case of θ smaller than 30°, the m_l/M_t increased abruptly as the θ decreased: the m_l/M_t was about 0.25 at θ=20° and it was about 0.8 at θ=15°.
The impact strength, Q^*, is defined as an energy density, Q, when the largest fragment mass is half of the original target mass. The energy density, Q, is defined as $Q=m_p V_i^2/2M_t$, where m_p is the projectile mass and V_i is the impact velocity, that is, the kinetic energy of projectile per unit mass of original target. At a head-on impact, the impact strength for ice sphere was 17.0 J/kg, much smaller than those of porous gypsum sphere and glass sphere obtained by Yasui et al. [2016], about 1000 J/kg. As the impact angle decreased, the impact strength became larger.
Next, we measured the fragment velocity ejected from the antipodal point of impact point, V_a, as a representative of the ejection velocity of impact fragments (We call this velocity as an antipodal velocity). As a result, the V_a was proportional to the impact angle. At θ=20°, the V_a was almost consistent, about 1 m/s, irrespective of energy density, and at θ=50°, the V_a for 280 J/kg was about 6 m/s, twice as large as that for 135 J/kg.
Finally, we introduced the effective energy density, Q_{eff}, to represent the relationship between the impact

strength, Q^*, or the antipodal velocity, V_a, and the impact angle, θ, quantitatively. The effective energy density, Q_{eff}, is defined as $Q_{eff}=Q\sin^2\theta$. As a result, we obtained two empirical equations about the normalized largest fragment mass and the antipodal velocity, $m_l/M_t=7.54Q_{eff}^{-1.06}$ and $V_a=0.05Q_{eff}^{0.94}$, and furthermore, the effective impact strength, Q_{eff}^*, which is defined as Q^* when the largest fragment mass is half of the original target mass, was obtained to be 12.8 J/kg.

[References] Fujiwara and Tsukamoto [1980], Icarus 44, 142-153; Yasui et al. [2016], DPS meeting abstract #48, id. 318.12.

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