ANGULAR MOMENTUM TRANSFER EFFICIENCY IN COLLISIONS BETWEEN RUBBLE PILE OBJECTS. T. Takeda[1] and K. Ohtsuki[2], [1]National Astronomical Observatory of Japan, 2-21-1, Oosawa, Mitaka-shi, Tokyo, 181-8588, Japan. takedatk@cc.nao.ac.jp [2]University of Colorado, 392 UCB, Boulder, CO 80309-0392, USA. ohtsuki@lasp.colorado.edu

Introduction: Recent observations suggest that many of small asteroids (100m < R < 100km) may be gravitational aggregates [1]. Since collisions change the spin of these asteroids, their spin distribution would provide useful information about their origin and collisional evolution. There have been several attempts to model the collisional evolution of asteroids that include their spin evolution [2,3]. However, the spin of a gravitating asteroid caused by an impact is not well understood. Previous SPH simulations showed that the efficiency of angular momentum transfer in collisions between large asteroids appears to be significantly smaller [4] than observed in centimeter-scale laboratory impacts (from 0.01 to 0.1) [5, 6]. We used N-body method to simulate impact events between rubble pile objects [7, 8, 9] and investigated the angular momentum transfer efficiency from orbital motion to the spin of the target (or to the spin of the largest remnant if the impact is more disruptive).

Simulation Method: The target and the impactor are represented by a large number of self-gravitating spheres. We included the radial repulsive force and damping force between individual spheres. However, we do not include the spin of the individual spheres, so that the tangential friction is not included. Typical particle numbers are 4096 or 16384. We performed simulations with various values of parameters, such as the impactor-target mass ratio, impact parameter, impact speed, and the degree of energy dissipation at impact, and investigated the angular momentum transfer efficiency. Since the energy dissipation rate relevant for collisions of asteroids is unclear, we performed simulations with a wide range of parameters for energy dissipation.

Results: Figure 1 shows snapshots of typical oblique impact simulations. Panel (a) shows the snapshot of a relatively low speed impact. Panel (b), (c) and (d) show time sequence of a moderately catastrophic impact. At the impact, the target is pulverized (panel (b)), however, several aggregates are formed by selfgravity (panel (c)), and these aggregates coagulate to form the largest remnant (panel (d)). We evaluated the spin of the largest remnant at this stage, and investigated the angular momentum transfer efficiency.

In this work, we performed simulations from low energy impacts to moderately catastrophic impacts where the mass of the largest remnant is about the half of the total mass. If the impact speed is sufficiently low and the collision results in perfect accretion, all the orbital angular momentum is transferred to the spin angular momentum. In the case of relatively low-speed oblique impact, the impactor richocheted to the downward, and angular momentum is carried away by the fast moving fragments which mostly comes from the impactor. In the case of higer-speed oblique impacts, the target is pulverized and only the relatively slowly-moving fragments coagulate, and the fast moving fragments are lost with angular momentum. Thus, angular momentum transfer efficiency decreases with the increasing degree of mass loss.

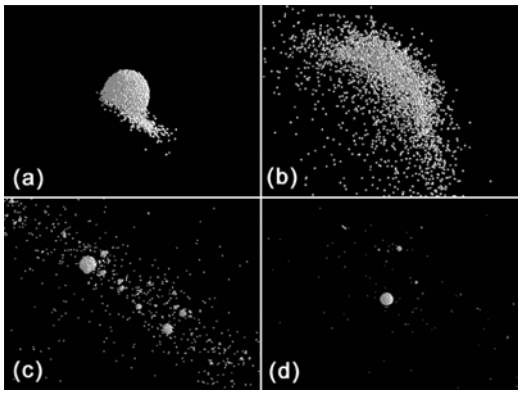

Figure 1: Snapshots of simulations. The scale and the location of the images are selected by hand for the largest remnants to be shown in the image.

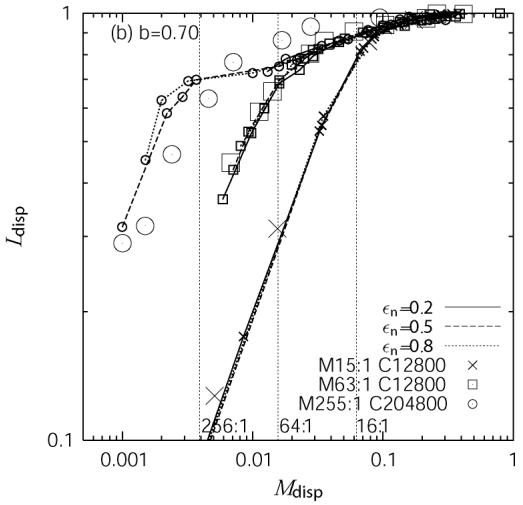

Figure2: Relations between the ratios of angular momentum dispersed and the mass dispersed. The impact parameter is 0.7 (R_{tgt}+R_{imp}), where R_{tgt} and R_{imp} are radii of the target and the impactor respectively.

Figure 2 shows the relation between the dispersed angular momentum (L_{disp}) and the dispersed mass (M_{disp}) in the oblique impact. The angular momentum transfer efficiency is 1-L_{disp}, which is the ratio of the spin angular momentum of the largest remnant to the initial orbital angular momentum. L_{disp} increases with an increasing M_{disp}, since the dispersed fragments carry away a significant amount of angular momentum. When M_{disp} is about the mass of the impactor, more than half of the angular momentum is carried away by the ricocheting fragments (which mostly come from the impactor). In the higher-speed impact case, L_{disp} continues to increase with increasing M_{disp}, but more slowly. At moderately disruptive collisions (M_{disp} ~ 0.5), the angular momentum transfer efficiency is very low. This low efficiency comes from the fact that fragments with low angular momentum is selectively coagulated to the largest remnant, which is similar to the angular momentum splash mechanism [11].

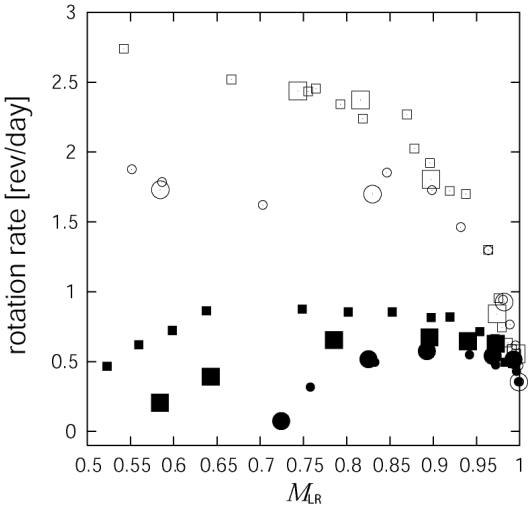

Figure3: Relations between the final rotation rate and the mass fraction of the largest remnant. The mass ratio of the impactor to the target is 1/63.

This tendency is rather independent of numerical parameters. However, the final rotation rate of the largest remnant depends on the degree of energy dissipation, because the amount of orbital angular momentum brought in by the impactor is much larger than the final spin angular momentum of the remnant, and the small difference in the angular momentum transfer efficiency can result in considerable difference in its rotation rate. Figure 3 shows the relation between the final rotation rate and the mass of the largest remnant. In the low dissipative impact case (filled symbols, restitution coefficient of constituent particles is about 0.8), a larger amount of angular momentum is carried away by the escaping fragments and the final rotation rate is quite low. In the more dissipative impact case, the final rotation rate is several times larger (open symbols, restitution coefficient is about 0.2), though the angular momentum transfer efficiency is still quite low.

We found that the angular momentum transfer efficiency and the degree of disruption have a relationship, and angular momentum transfer rate is very low at moderately catastrophic impact. This relationship does not depend on the dissipation parameter in the simulation, so that we consider this relationship is rather robust results.

Discussion: The above simulations focused on the case with initially-non-rotating targets. In order to discuss the effect of successive collisions on the rotation of asteroids, the effect of initial rotation must be included. Our numerical results demonstrate the importance of the selective reaccumulation, which implies that the angular momentum splash mechanism [11] may have played an important role in the collisional and rotational evolution of asteroids. We will also discuss numerical results for collisions onto initially rotating targets.

References: [1] Richardson, D.C. et al. (2002), *Asteroids III*, pp. 501-515. [2] Davis, D.R., et al. (1989), *Asteroids II*, pp. 806-825 [3] Farinella, P., et al. (1992), *Astron. Astrophys. 253*, 604-614. [4] Love, S.G. & Ahrens, T.H., (1997) *Nature*, *386*, 154-156. [5] Fujiwara, A., & Tsukamoto, A. (1981), *Icarus*, *48*, 329-334. [6] Yanagisawa, M., et al. (1991), *Icarus*, *94*, 272-282. [7] Leinhardt, Z.M., et al. (2000) *Icarus*, *146*, 133-151. [8] Leinhardt, Z.M., & Richardson, D.C., (2002) *Icarus*, *146*, 306-313. [9] Takeda, T., & Ohtsuki, K., (2007) *Icarus*, in press [10] Dobrovlskies, A.R., & Burns, J.A., (1984), *Icarus*, *57*, 464-476. [11] Cellino, A., et al. (1990), *Icarus*, *87*, 391-402.