EXPERIMENTAL STUDIES OF ANGULAR MOMENTUM TRANSFER IN LOW VELOCITY OBLIQUE IMPACTS: IMPLICATIONS FOR ASTEROIDS Masahisa Yanagisawa*, Janusz Eluszkiewicz and Thomas J. Ahrens, Caltech, Pasadena, CA 91125, USA
*Present address: Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229, Japan.

INTRODUCTION Collisions affect asteroid rotation through the cumulative effect of non-destructive impacts from smaller asteroids and the partitioning of angular momentum in catastrophic impacts. The histogram of the observed rotation rates for 375 asteroids resembles a three dimensional Maxwellian [1], which suggests that the cumulative mechanism may be dominant, especially for the largest asteroids. Harris [2] considered the change of an asteroid's spin rate due to non-disruptive collisions and arrived at the conclusion that asymptotically the spin rate of the asteroid should be proportional to ζ, the efficiency of angular momentum transfer between the impactor and the target asteroid. The parameter ζ, which is the primary subject of the present investigation, was first introduced by Burns and Safronov [3]

$$\zeta = \frac{\Delta K}{m\ell v}$$

where ΔK is the change of the angular momentum of the target due to a collision with a projectile of mass m, travelling at velocity v (~ 5 km s^{-1} in the present asteroid belt) and impact parameter ℓ. ζ is thus the fraction of the angular momentum of the projectile transferred to the rotational motion of the target. Burns and Safronov argued that the equilibrium nutation angle of an asteroid should be proportional to ζ. Assuming $\zeta = 1$, they came to the conclusion that nutation (free precession) could only be observed for objects smaller than ~ 10 km and identified the most likely asteroids to exhibit precession. To date, no unambiguous case of free precession has been demonstrated [1]. This could become more understandable if $\zeta << 1$.

The foregoing arguments serve as an illustration for the relevance to the asteroid studies of experimentally determined values of ζ. Unfortunately, only a single measurement for ζ has been reported in the literature [4]: $\zeta < 0.1$ for an impact of a polycarbonate projectile into a basalt target at impact velocity 2.7 km s^{-1}. Obviously, there is a great need for an experimental determination of ζ for different target materials, impact velocities, incidence angles, and other parameters which may affect ζ. The present study was devoted to an investigation of a small subset of the multidimensional space of parameters on which ζ depends. Despite the limitations of low impact velocity and small targets, our experiments provide a better understanding of factors affecting ζ.

EXPERIMENTS A description of our experiments was presented at the XXI LPSC [5]. The experimental setup is shown in Fig. 1. Targets are spheres or cylinders made of plaster, mortar, and cement. One experiment was conducted on a spherical granite target. Lead and aluminum projectiles were accelerated by commercial rifles (with velocities 310-390 and 610-1190 m s^{-1}, respectively). The impacts were recorded by means of a high speed camera. The angular velocity and the velocity component of the impacted target parallel to the projectile motion were obtained from an analysis of the images. An electronic signal was generated when the wire placed at the bottom of the impact chamber was cut by the ricochetted projectile or the fragments. The velocity of some ricochetted projectiles was then obtained from the travel time between the impact point and the wire. All experiments were conducted under atmospheric conditions. Since in our experiments targets were not spinning initially, $\zeta = I\Omega/m\ell v$ where I and Ω are the moment of inertia and the post-impact angular velocity of the target, respectively (the target mass loss was usually less than 2%, except for plaster where it was less than 5%). ζ is plotted vs. projectile incidence angle ϕ (measured relative to surface normal at the impact site) in Fig. 2.

SUMMARY OF RESULTS

1. For the same incidence angle ϕ, the efficiency ζ of angular momentum transfer decreases as the indentation hardness H of the target increases. At $\phi \sim 35°$, $\zeta = 0.07$ for granite (H = 850 kg mm^{-2}) and $\zeta = 0.7$ for plaster (H = 7.5 kg mm^{-2}). Mortar and cement (H = 76 kg mm^{-2}) yielded intermediate values of ζ (but the values for cement were consistently lower than for mortar).

2. The dependence of ζ on ϕ for the same target material can be expressed in the form $\zeta = A(\cos\phi)^{\beta}$. For cylindrical mortar targets A = 0.9, β = 1.7 and β decreases from 1.9 to 1.4 as the specific impact energy ε (= kinetic energy of the projectile/mass of target) increases from 0.7 to 2.5 x 10^6 erg g^{-1}. More energetic impacts transfer angular momentum more efficiently.

3. For constant ε, ϕ, and target material, ζ is weakly dependent on the mass of the projectile.

4. ζ increases from 0.2 to 0.8 as the crater depth normalized by projectile size increases from 0.2 to 1.6.

5. The fraction of projectile angular momentum carried away by ejecta is less than 30% and decreases with decreasing impact energy.

TENTATIVE CONCLUSIONS

A. The equilibrium nutation angles may be smaller than those calculated with $\zeta = 1$, especially for strong objects for which ζ may be significantly less than 1. This would make nutation even harder to observe and would help explain the absence of such an observation to date.

B. Taxonomic classes are probably representative of asteroid bulk properties: C asteroids are weaker than S asteroids which in turn are weaker than M asteroids (this appears to be reflected in observed mean rotation rates of 2, 2.4 and 3.6 rev day^{-1}, respectively). If asteroid spin rates are the result of non-catastrophic collisions, than the differences in the mean spin rate between the three classes should be less than those calculated from a consideration of relative strengths and densities only. This follows from our finding that hard targets are harder to spin up (exhibit smaller values of ζ).

C. The size of the largest crater on an asteroid should be correlated with the asteroid spin rate.

ACKOWLEDGEMENTS We thank Dr. W. Knauss for the use the framing camera, M. Long for his assistance in the experiments and W. Yang for conducting the hardness measurements. This work was supported by NASA and the Japanese Ministry of Education.

REFERENCES

[1] Binzel, R. P., P. Farinella, V. Zapalla, and A. Celino, in Asteroids II , pp. 416-441, 1989.
[2] Harris, A. W. Icarus, 40, 145-153, 1979.
[3] Burns, J. A. and V. S. Safronov, Mon. Not. R. Astron. Soc., 165, 403-411, 1973.
[4] Fujiwara, A. and A. Tsukamoto, Icarus, 48, 329-334, 1981.
[5] Yanagisawa, M., J. Eluszkiewicz, and T. J. Ahrens, LPSC, XXI, 1364-1364, 1990.

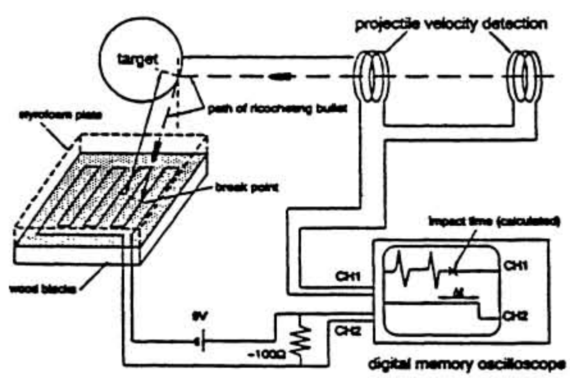

Fig. 1 Experimental setup for oblique impact experiments. The styrofoam plate covers an array of wires used to measure the velocity of the ricochetted projectile.

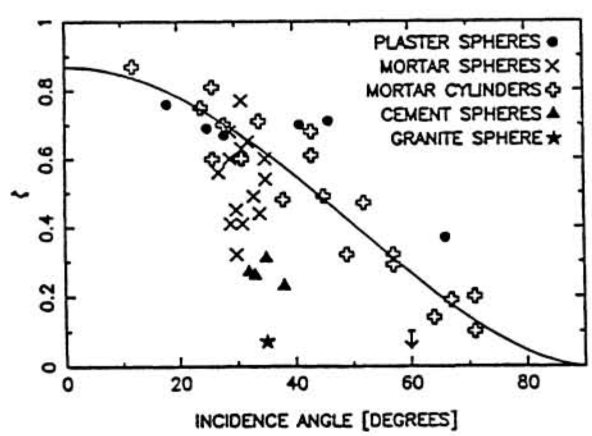

Fig. 2 Efficiency of angular momentum transfer ζ as a function of projectile incidence angle ϕ. The solid line is the least-squares fit $\zeta = 0.9(\cos\phi)^{1.7}$ for mortar cylinders. The arrow corresponds to the upper limit obtained by Fujiwara and Tsukamoto [4] for a basalt target.