EXPERIMENTS ON EARLY GROWTH OF MOON AND PLANETS, William K. Hartmann, Planetary Science Institute, 2030 E. Speedway, Tucson, AZ 85719.

BACKGROUND. Accretionary theories of planetary growth have always faced an obstacle in demonstrating that accretion could accompany collisions of small (sub-mm to km scale) planetesimals in the early solar system. Some theorists therefore postulated special sticking mechanisms, such as sticky organic coatings. Mass loss and cratering at asteroidal impact speeds around 5 km/sec were well known from the experiments of Gault and others (1). Kerridge and Vedder (2) sought accretion during collisions of planetesimal-like silicate particles at speeds of 1.5 to 9.5 km/sec; they found mass loss, not mass gain. Such investigators concluded that accretion must have occurred during collisions at much lower velocities, but it was still not clear how mass gain occurred. The problem was ameliorated somewhat, but not entirely, by Goldreich and Ward (hereafter GW) who showed that gravitational collapse of dust particle swarms could form planetesimals of radii up to 100 m, which then gravitationally cluster into planetesimals of radius approximately 5 km, based on a theoretical model of the solar nebula. Even if this process occurred, it has not been clear how further interactions produced growth, rather than mass loss by sandblasting effects or catastrophic fragmentation. Therefore, the present project was designed to study mechanics of low-velocity collisions in conditions simulating the early solar system.

EXPERIMENTS AND RESULTS. Mechanics of low-velocity impacts involve several phenomena of importance to planetary growth. First, at the lowest speeds, are phenomena of simple rebound. Second is locating the transition from simple rebound without fracture to shattering. To investigate these phenomena, I have carried out experiments at velocities in the range of 1 to 50 m/s, both in vacuum and in air, at NASA's Ames Research Center and in our PSI laboratory in Tucson. These velocities correspond to escape velocity on planetesimals with radii from 0.95 to 45 km. Many experiments have been filmed at speeds of 100 to 400 frames per second, allowing measurement of impact, rebounds, and fragment velocities.

Of special interest are rebounds of rocky projectiles off surfaces with varying amount of regolith powder (simulated in various experiments with basalt, pumice, and mortar powders resembling lunar regolith. Results (Figs. 1 and 2) show that for projectiles of diameter D, regolith of depth 0.03 D begins to retard the rebound speed, and regolith of depth 4D virtually stops the projectile, during impacts at a few meters per second, corresponding to free-fall impacts onto GW planetesimals.

APPLICATIONS. The results show that GW-type planetesimals would grow and would accumulate regolith. The reasoning is as follows. Safronov (3) has calculated impact velocities in swarms of particles of different sizes. These are controlled by the gravity of the largest particles. He finds that if the largest planetesimals are decameter size, their collisions occur at roughly 1.3 \( V_{\text{esc}} \) (0.4 cm/sec). If the largest are kilometer-scale planetesimals, collisions occur at about 1.7 \( V_{\text{esc}} \) (50 cm/sec). Now suppose the planetesimals start with no regolith. My experiments show that during collisions of small basaltic and other igneous projectiles into semi-infinite targets, the transition from rebound to shattering occurs around velocities of 37 m/sec; for icy particles,
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Figs. 1 and 2. Measurements of rebound of rocky particles off semi-infinite surfaces with different depths of regolith. Initial velocities = 1 to 8 m/sec. Smooth basalt spheres (Fig. 1) rebound off clean smooth surface at about 0.85 impact velocity, but regolith layers thinner than the particle diameter strongly inhibit rebound. When same experiment is done with natural, irregular rocks (Fig. 2), energy is lost in rotation, producing a scatter of rebound velocities including lower values than in Fig. 1.

around 9 m/sec; for dirt clods (silicate particles probably bonded by evaporites) around 2 m/sec (Fig. 3). Thus, interactions of GW planetesimals (and smaller ones) occur in the rebound regime, unless material is very loosely bonded, in which case the experiments show that shattering would occur and some debris would fall back on the target. If the planetesimals are stronger than dirt clods, the experiments show that rebound would frequently be at less than escape velocity, and again regolith would accumulate. Therefore, regolith forms on the largest planetesimals in any swarm, even if they start "clean". Regolith begets regolith.

Once the surface is granular, whether by initial conditions (such as GW gravitational collapse) or by regolith accumulation (as above), Figs. 1 and 2 show that the surfaces of the larger ones will be very effective in accreting more material. This is because, following Safronov's analysis, the objects collide at somewhat more than the escape velocity of the largest particles; but for particles of diameter D, rebound off a regolith of depth D will occur at only a few percent of impact velocity. Particles will fall back onto the planetesimal surface. The largest particles in any swarm grow fastest. (Smaller particles in the swarm may not grow at all, since rebound occurs at greater than escape velocity.)
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The same process of regolith-inhibited rebound promotes growth until the materials begin to fragment, whereupon the issue is then controlled by speeds of ejected fragments. For rocky material with fragmentation speed of $37 \text{ m/sec}$, and density $2 \text{ gm/cm}^3$, this would occur on planetesimals with radii about 20 to 35 km.

My experiments are continuing, in order to map out the consequences of collisions through a wide range of phase space with coordinates of velocity vs. planetesimal radius, as shown in Fig. 4. These results will allow better theoretical modelling of early processes of planetary growth, now under way in a separate project at PSI (4), as well as elsewhere.


Fig. 3. Fragmentation of three types of material striking flat targets (see cartoon, lower left). Transition from rebound to complete breakup is well defined.

Fig. 4. Events in phase space of impact velocity vs. target radius. Diagonal line gives impact velocity + $2 V_{\text{esc}}$. To right, rebounder falls back to surface; to left, it drifts off. Above horizontal line, rock shatters and cratering occurs. Accretion is determined by how much ejecta is blown off at $V = V_{\text{esc}}$. 