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Planet Formation: Mechanism of Early Growth

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Experiments in vacuum (approx. 0.5 to 1 mbar) and in air quantify mechanics of collisions, rebound, and fragmentation at low velocities (1–50 m/sec), under the conditions usually postulated for the preplanetary environment in the primitive solar nebula. Such collisions have been little studied experimentally. Contrary to widespread assumptions, accretionary growth of the largest meteoroid- and asteroid-sized bodies in a given swarm results spontaneously from the simple mechanics of these collisions, without other ad hoc sticking mechanisms. The smaller bodies in the swarm are less likely to grow. Granular surfaces form, either by gravitational collapse of dust swarms or by rapid formation of regolith surfaces on solid planetesimals; these surfaces strongly promote further growth by retarding rebound. Growth of large bodies increases modal collision velocities, causing fragmentation of smaller bodies and eventual production of interstellar dust as a by-product of planetesimal interactions.

BACKGROUND: THE ACCRETIONARY HURDLE

In view of modern evidence that collisions dominated much of solar system evolution, various investigators have studied mechanics of these collisions. In spite of theoretical indications that the earliest collisions might have occurred at speeds less than a few meters per second, published planetary experimental data have been limited to the kilometer-per-second regime common in the solar system today. For example, Gault *et al.* (1963), Stoffler *et al.* (1975), and Fujiwara *et al.* (1977) have studied collisions of rocky and other particles at speeds of about 1–6 km/sec, primarily to illuminate lunar and asteroidal impacts. In the absence of other data, workers such as Marcus (1969) used ejection velocities and other data from those experiments to study the early solar system; Marcus recognized the importance of the low-velocity regime and attempted to extrapolate to it. Such studies generally led to recognition of a seeming hurdle that had to be crossed in the planet-growing process: if the rocky planetesimals of submeter size or even kilometer size were considered, their collisions appeared not to lead to mass gain. Researchers found that high-speed collisions lead to shattering and ejecta mass loss. Kerridge and Vedder (1972) specifically designed impact experiments with silicate particles striking silicate particles at speeds of 1.5 to 9.5 km/sec to test whether any sticking or welding occurred; they found none. Many researchers evidently assumed that very low speed impacts would merely produce rebound with no mass gain. Some investigators hypothesized coatings of sticky organic molecules, electrostatic sticking, or other ad hoc mechanisms that might lead to accretion upon low-speed contact.

Goldreich and Ward's (1972) study of gravitational instabilities in the dust com-

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ponent of the solar nebula was greeted as a needed explanation of how planetesimals could get past the hurdle by initially forming at sizes of a few kilometers. In particular, Goldreich and Ward concluded that planetesimals of radius about 5 km could form by gravitational collapse of dust. These could be visualized as loosely consolidated aggregates of silicates or other materials with escape velocities about 5 m/sec (as a rule of thumb, V_{esc} in m/sec $\simeq$ radius in km, assuming density 2 g/cm^3). Nonetheless, this work does not really settle the problem of accretion because (1) as Goldreich and Ward pointed out, further growth remains untreated (km/sec collisions of these bodies would still cause mass loss); and (2) the gravitational-collapse process and the calculated sizes are model-dependent; gravitational collapse might have been superceded by accretion processes with shorter timescales. It also has not been shown applicable to growth of satellite systems.

EXPERIMENTAL COLLISIONS

For these reasons, I undertook experiments on low-velocity impacts with the purpose of broadly mapping the consequences of collisions between bodies for a wide range of relative speeds and sizes. Although the experimental results are independent of any theoretical model, the reasons for experimental design may be clearer from the following brief review of conditions in the early solar system. It is assumed that a swarm of coorbiting dust particles has condensed from gas in the solar nebula. Because their orbits are not precisely circular, at any given stage in their evolution they will collide with some characteristic velocity. In general there will be some unspecified distribution of sizes and velocities.

Safronov (1972) showed that in a swarm of such particles, freshly condensed from the solar nebula, velocities would be much lower than the kilometer-per-second values hitherto studied experimentally. In any region (e.g., a toroidal volume) particles are stirred gravitationally primarily by the effects of the largest planetesimals interacting with the region. Safronov found that equilibrium encounter velocities were generally about 1.3 to 2 times escape velocity of the largest particles. More specifically, for decameter-sized particles Safronov found collisions at 0.4 cm/sec (1.3 V_{esc}). For kilometer-scale particles, he found collisions at about 50 cm/sec (1.7 V_{esc}). Goldreich and Ward (1973) indicate a similar result, with $V_{impact} \approx V_{esc}$. By considering gas drag in such a system Weidenschilling (1977) found that particles in certain intermediate size ranges (decameter in his models) may have higher radial velocity components (some m/sec relative to the swarm) than other particles. In general, however, for plausible size distributions and velocity distributions, the largest particles in given swarms would be struck by smaller particles with a wide range of masses, moving at impact speeds of the order 1.5 V_{esc}. [This statement would appear to be true whether the planetesimals have reached Goldreich–Ward size (radius $=5$ km, $V_{esc} = 5$ m/sec) or whether they are considerably smaller.]

How do such bodies interact during collisions? To investigate this, I have carried out experiments at velocities in the range of 1 to 50 m/sec both in vacuum (usually 0.5 to 1 mbar of pressure) and in air, at the Ames Research Center and in our laboratory in Tucson. Many of these experiments have been filmed at speeds of 100 to 400 frames per second, allowing measurements of impact, rebounds, and fragment velocities when fragmentation occurred. Impacts were made into clean rock targets and into rock and mortar powders simulating mechanical properties of lunar regolith.

The first step is to determine what speed separates the shattering regime from simple rebound. Figure 1 shows results of firing

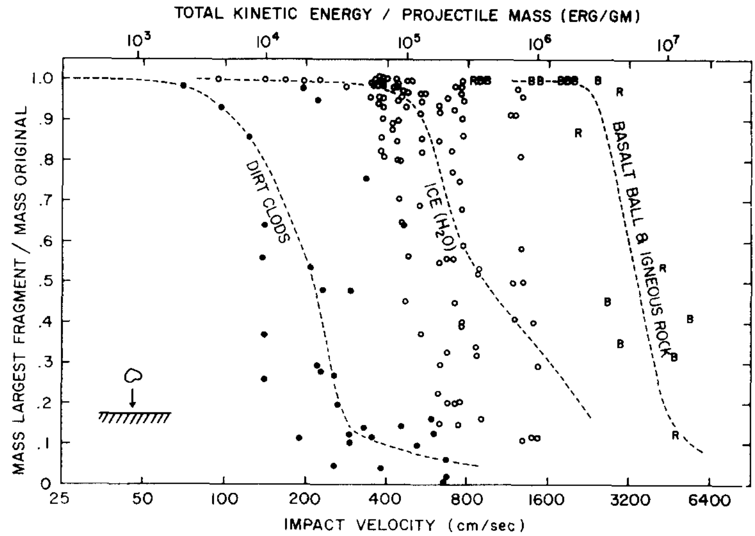

FIG. 1. Experimental determination of velocities and energy densities marking transition from rebound (left) to shattering (right) during impacts onto semi-infinite surfaces, as shown in cartoon, lower left. Transition from little chipping to catastrophic fragmentation is fairly well defined.

or dropping centimeter-scale projectiles of different materials into flat rock targets. Projectile materials relevant to the early solar system were basalt and other igneous rocks, H_2O ice, and dirt clods (dry silicate particles presumably welded by evaporites, plausibly resembling primitive carbonaceous–chondrite-like early aggregates, which are weaker than most igneous rocks). Figure 1 shows rapid transition in velocity–space from no fragmentation to complete fragmentation into many small particles. For the three materials, velocities of catastrophic disruption (defined by largest fragment equalling half original mass) were 37, 9, and 2 m/sec, respectively.

At velocities much below these, planetesimals of the indicated materials would rebound and not shatter. As Safronov showed, typical impact velocities are scaled to the size of the largest planetesimals. Thus, if the earliest coorbiting planetesimals initially condensed at sizes smaller than a few kilometers, they would have begun interacting in the rebound regime.

The second step, therefore, is to examine the mechanics of rebound interactions. The worst case, from the point of view of achieving accretion, is the most elastic case, which involves clean, smooth rock surfaces. This case is most likely to result in particles separating at $V_{\text{rebound}} > V_{\text{esc}}$, with no net mass gain or loss. Experiments with polished basalt spheres (kindly provided by Gault and his co-workers at Ames, and used in some of their earlier work) indicated rebound off smooth massive rock targets at $V_{\text{rebound}} \simeq 0.85\ V_{\text{impact}}$ independent of impact speed in the range up to the speed where shattering occurs. For the largest bodies in the swarm, this corresponds to $V_{\text{rebound}} \simeq 1.1\ V_{\text{esc}}$ to $1.4\ V_{\text{esc}}$ for Safronov's conditions quoted above. However, with a reasonable distribution of velocities, a low velocity tail would be expected to produce a few particles rebounding at slightly less than escape velocity, with resultant fallback into the surface. Thus, even the worst case of smooth igneous spheres interacting at low velocity would probably produce growth in the form of a surface layer of small particles on the largest bodies.

But the above worst case is unrealistic in several ways. The earliest, smallest

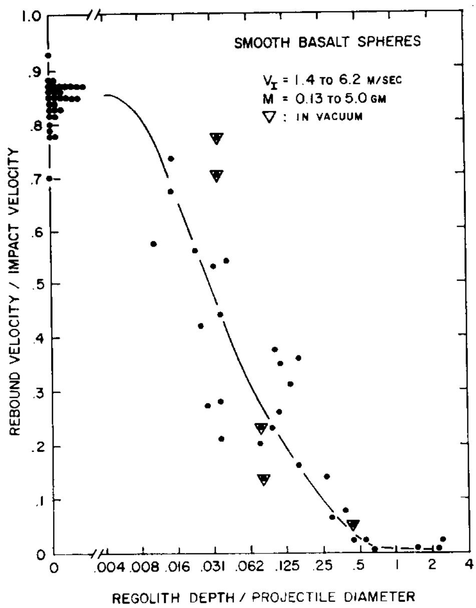

FIG. 2. Effects of regolith depth on rebound velocity in air and vacuum for impacts at a few meters per second, for smooth basalt spheres onto smooth rock target, covered with varying layers of rock powders having mechanical properties similar to lunar regolith. These regolith layers strongly inhibit rebound.

planetesimals would not likely be polished igneous spheres. By the very argument given above, any such early particles would eventually accumulate regolith-covered surfaces, or in fact consist entirely of loose aggregates of condensed crystals or other primitive materials. Condensation and aggregation processes would probably produce irregular shapes. Occasional fragmentations among the fastest particles (if a high-V tail were present in the early V distribution) would certainly produce irregular shapes.

To illustrate the effect of shape alone, the above experiments were repeated with natural igneous rocks. These results showed that, depending on the geometry of impact, rebound energy is often lost into rotation and probably internal vibration along interior inhomogeneities in natural materials. Slow rotating natural particles typically rebounded at a range of velocities of 0.25 to 0.6 V_{impact}. For the largest bodies in the swarm, this corresponds to rebounds at speeds commonly as low as 0.3 V_{esc}, so that efficient mass gain would occur on these bodies, building up a regolith layer. (If rotational equilibrium existed, some fast rotators would gain translational energy on impact. If surfaces were clean, these would simply rebound away and be irrelevant; but once surfaces were regolith-covered, even these collisions would lead to mass gain as will be shown in a moment.) In summary, in any swarm of natural coorbiting particles, with a wide range of initial elasticities, shapes, rotations, and other properties, orbiting in near-circular orbits as considered by Safronov, I conclude that the *largest bodies* would either start out as loosely consolidated granular material or accumulate surface debris—a thin regolith layer.

The third step, therefore, is to examine low speed impacts into thin regolith layers of varying depth. Figures 2 and 3 show the results of this study: *Regolith strongly favors accretion by inhibiting rebound.* Figures 2 and 3 include the results mentioned above, by showing (left ordinate) rebound velocities for zero depth of regolith. As the figures show, results in both vacuum and air indicate that a regolith depth of only about 0.04 projectile diameters will cut rebound to $V_{\text{rebound}} = 0.4$ V_{impact}, or about 0.6 V_{esc} on the largest bodies. Regolith of depth comparable to the projectile diameter virtually stops the projectile. These experiments were performed at velocities suitable to impacts on Phobos-sized Goldreich–Ward planetesimals. The conclusion is that among any planetesimals formed as loose aggregations, or with thin dust layers on their surfaces, the largest ones would grow by capturing smaller particles. A regolith of initial depth d would capture particles of diameter d, grow to depth D, collect larger particles of diameter D, and so on. Regolith begets regolith.

One might ask if regolith would be knocked off by the faster particles in the swarm, faster than it could accumulate. The early conditions described by Safronov do not indicate a likelihood of enough energy in a high-V tail of the V distribution to cause mass loss from the largest planetesimals, since Figs. 2 and 3 indicate very efficient capture. However, sufficiently *small planetesimals* in the swarm would be hit at many times their escape velocity and they would lose loose mass. Weidenschilling's gas-drag mechanism would produce some higher relative-velocity particles of certain sizes, but Weidenschilling (private communication) notes that the larger bodies, including the Goldreich–Ward bodies, should follow the Safronov velocity distribution fairly well. It appears (but has not been proved) unlikely that a sufficient fraction of mass could, by Weidenschilling's mechanism, pass through the swarm at high enough relative V to stop growth on the largest particles. Later, formation of a large planet elsewhere in the solar system could produce a destructive high-mass, high-V tail, as we will consider in a moment.

These experiments, incidentally, fit not only the early solar system, but also present-day collisions between Phobos and its circum-Martian debris (and Deimos and its debris belt) as described by Soter (1971). The experiments strongly support Soter's prediction that Phobos and Deimos should have a regolith layer built up from low velocity debris knocked into Martian dust belts from meteoritic impacts on these satellites, and gradually reaccreted onto the satellites after several collisions.

Figure 2 and 3 establish that such a surface would be extremely effective in promoting further growth of the largest primitive planetesimals through inhibiting rebound. Additional experiments in vacuum show that, contrary to everyday experience with powders in air, regolith powders are extremely effective in inhibiting throwout

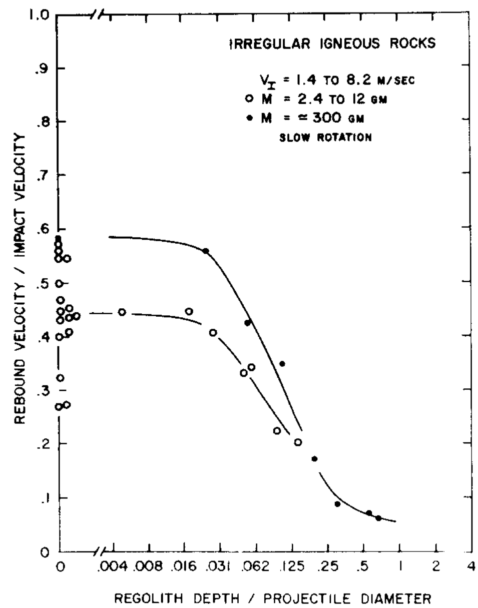

FIG. 3. Same as Fig. 2, but with natural rock-fragment projectiles. Due to absorption of energy in spin and internal vibration, a wider range of rebound velocities is found on bare rock targets, including some much lower than in Fig. 2. This encourages regolith formation.

of ejecta. Figure 4 shows 14.3 g of ejecta thrown out onto a black card during impact of a 14.2 g rock into powdered pumice at 5.6 m/sec *in air*; mass loss occurred in the target (assuming loss of this ejecta into space). The same experiment *in vacuum* ejected only 0.024 g onto the same card; mass gain occurred. Ejecta mass in vacuum was thus only 1.7 (10^{-3}) of the ejecta mass in air, because without air filling the powder pore spaces, the powder loses its fluidlike splash quality.

Weidenschilling (private communication) notes that because the "vacuum" conditions reported here actually correspond to slight gas pressure of 0.5 to 1 mbar, they may actually be more applicable to the true nebula than experiments in a pure vacuum. One experimental impact into powders at 10 mbar did not detectably differ from other experiments at 0.5 to 1 mbar, and I thus suspect that the results reported here

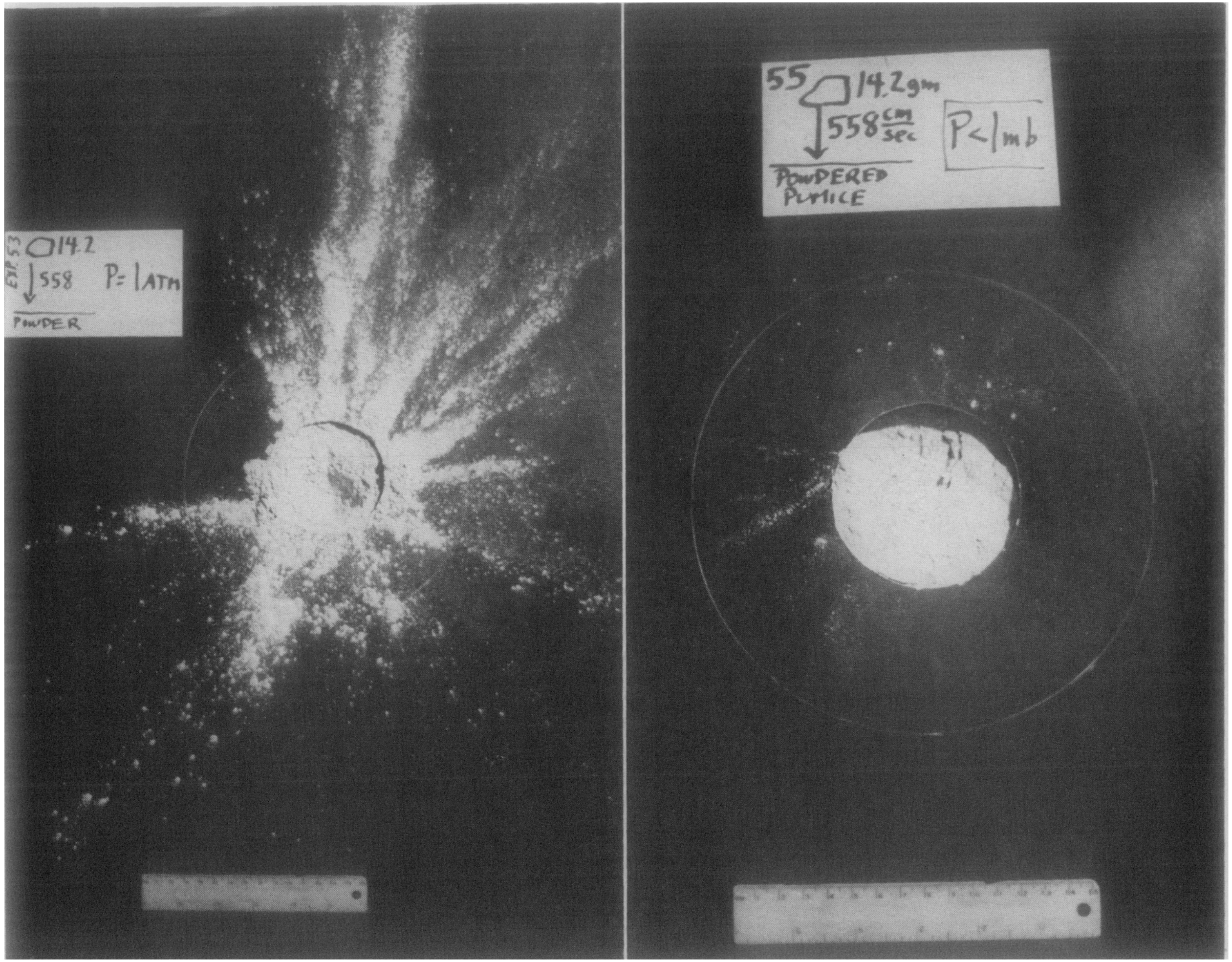

FIG. 4. Photographs of ejecta from two identical impacts into regolith-simulating power. The photographs are printed at different scale. Ejecta went from crater onto same black card in each case. From 14.2-g projectile impact, in air, 14.3 g was ejected onto the card; in vacuum, only 0.0236 g. In conclusion, 606 times less ejecta were released in space conditions, indicating that regoliths in vacuum favor accretion, contrary to familiar experience with powders in air.

would apply to all nebular environments below 10 mbar. (Vacuum welding between regolith grains at very low pressures might occur. It would presumably be overcome by modest-speed impacts, but remains to be investigated.)

As the *largest bodies* grow by this mechanism, encounter velocities increase. What happens when velocities get high enough for shattering to begin? A final step in the analysis is to consider ejecta mechanics in the shattering regime. Again, the worst case from the point of view of accretion would be shattering on a clean, coherent rock target, where minimal ejecta energy would be lost in a regolith. Preliminary studies of igneous rocks shattering under these conditions at 30 to 50 m/sec indicate a spread of fragment velocities usually 0.1 to 0.7 V_{impact}. The median ejecta velocity was about 0.3 V_{impact}. These speeds are again less than V_{esc} if the target is one of the largest bodies in the swarm, so that the largest bodies would continue to grow. Regolith or weak surface materials, formed during earlier growth, would further ensure additional energy-loss and efficient accretion of mass. (Experimental note: in the experiments conducted near catastrophic fragmentation speeds, little correlation was observed between fragment size and fragment speed; some equipartition of energy among fragments may occur during more complete fragmentation at higher impact speeds.)

STABILITY OF REGOLITHS

According to the preceding results regoliths or regolith-like textures of loose materials near the surface of the largest planetesimals will strongly aid their growth. Noting this, Joseph Burns (private communication) has made an interesting criticism. He reasoned that if equipartition of kinetic energy applied between rotation and and relative translation energies, then equatorial rotation velocities might frequently exceed escape velocity, throwing off regolith and thus destroying the growth-promoting surface property.

Is the stable equatorial rotational velocity, V_{rot} actually likely to exceed escape velocity, V_{esc}? If translational kinetic energy $\frac{1}{2}mV^2_{\text{approach}}$ on the average equaled rotational kinetic energy, $\frac{1}{2}I\omega^2$ (where $I = \frac{2}{5}mR^2$ for homogenous spheres), then $V_{\text{rot}} \simeq 1.6 V_{\text{approach}}$. Assuming the Safronov rule of thumb that the impact occurs at about 1.5 V_{esc} on the largest bodies, then on the largest bodies, we would have $V_{\text{rot}} \simeq 1.8\ V_{\text{esc}}$, and regolith would indeed be unstable.

But this condition is unlikely, on both theoretical and observational grounds. First, as Safronov (1972) points out, there are other sources of energy dissipation besides rotation, so that linear kinetic energy is not partitioned solely with rotation. One loss is heat generated by impacts. Safronov gives a theoretical discussion of predicted rotation rates but stops short of a complete analytic theory. However, he notes that "if the thermal losses increase (i.e., the mechanical energy decreases) . . . the velocity of rotation will decrease." Another interesting loss would occur if a planetesimal spun up toward the instability limit. While regolith would not collect at the equator, it would collect at the poles, aiding polar growth. Poleward growth would change the moments of inertia, causing constant reorientation and consequent radiation of internal friction-generated heat—representing more energy loss to the swarm in general.

Harris (1977, and in press) has applied earlier rotational calculations of Giuli to create an analytic theory of rotation, and concludes (private communication and in press) that the largest bodies in a swarm will accumulate regolith. He also finds that coaccreting bodies growing in a swarm of particles would not spin up to the instability rate, but reach an equilibrium rotation at a rate equal to some fraction of the instability rate.

This is actually the observed case: asteroids and several of the planetary systems obey an angular momentum law with rotation rates close to 0.2 times the instability rate (Fish, 1967; Hartmann and Larson, 1967). Burns (1975) reanalyzed these results with new asteroid data and found a good fit of 67 asteroids and several planets to a rotation law with angular momentum corresponding to homogeneous bodies (density = 3.0 g/cm^3) spinning with a period of 8.8 hr, compared to the instability period for comparable bodies of 1.9 hr. This relation is empirically valid across 9 orders of magnitude in asteroid mass, and 14 orders as applied to planets including Jupiter. It suggests that the collisionally dominated system spun its bodies up to, but not beyond, some equilibrium point probably defined by competition between collisional spin-up and growth. Bodies rotating too near the instability rate would tend to lose mass instead of gain mass during collisions.

In conclusion, regoliths will accumulate on the largest bodies in the swarm, and these bodies will grow by accreting smaller bodies.

SUMMARY: A GROWTH SCENARIO

Figure 5–7 show the intended result of the series of experiments, an attempt to map the consequences of collisions in a phase space defined by target particle size and collision velocity. For a collision of a small body striking any given target at any given velocity, the map attempts to show the result. Figure 5 shows the results for solid targets without regolith. Above a certain critical velocity (horizontal band) there is shattering (causing craters) and below, only rebound. If the target is too small, with too small a surface gravity (left of diagonal line), the rebounding projectile (or fragments) fly off too fast to be captured. Mass gain can occur only in the narrow diagonal band where impact velocity is just greater than escape velocity. But for the largest bodies in the swarm, this is exactly the velocity regime where Safronov predicts collisions, as shown schematically by the small $\times$'s. The initially smaller bodies of the swarm will not grow. If collisions on the largest body were entered on the diagram by $\times$'s in appropriate positions, one would predict the $\times$-swarm to migrate up the diagonal band as the largest particle grew.

Figure 6 is a somewhat more preliminary diagram based on the experiments with regoliths. It shows that the effect of regolith, or granular texture, is to greatly widen the width of the diagonal mass-gain band, since rebounders or ejecta depart with much lower velocity than in Fig. 5 with its bare surfaces. Because planetesimals will acquire regolith surfaces or granular structure throughout as a result of processes described here, Fig. 6 is expected to be a more accurate depiction of planet-forming conditions than Fig. 5, although the details of Fig. 6 need to be clarified by more experiments with impacts at different velocities and regoliths of different depths. Figure 7 schematically summarizes the regions of the diagram with respect to mass gain and loss.

A scenario for planet growth can be sketched by means of these diagrams. Following the condensation of silicate and icy grains from the solar nebula, the grains aggregated by an uncertain process, indicated in the microscopic structure of matrices of primitive meteorites. This may have occurred by gravitational aggregation as sketched by Goldreich and Ward, who predict initial nuclei of 5-km radius; or it may have occurred by grain–grain collision processes similar to those sketched here. In any event, by the time bodies of multimeter dimension formed, they should have had regolith surfaces or granular structure throughout. As shown here, these would have grown very efficiently by collisions with neighboring bodies due to inhibition of rebound. Collisions on the largest body at any given time would be represented by

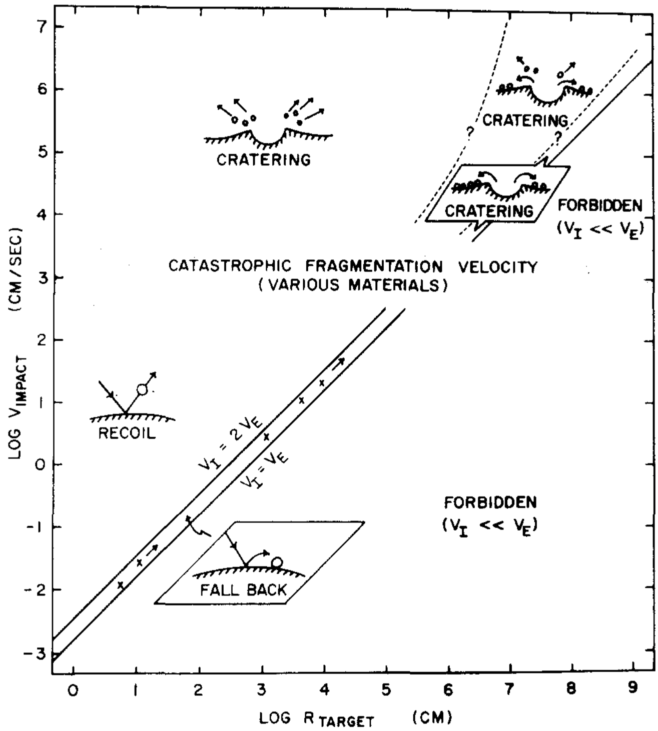

FIG. 5. Map of experimental results for impacts between clean solid projectiles and targets. Axes are impact velocity and target size. Horizontal band shows transition between rebound (below) and shattering/cratering (above) for different materials ranging from weak carbonaceous-chondrite-like aggregates to igneous rocks, based on results in Fig. 1. Cartoons show result of impact, including cratering results based on work of Gault and other at 1–6 km/sec. Diagonal band where impact speed is between V_{esc} and $2V_{esc}$ is region where fallback of projectile or debris is expected, yielding mass gain. According to Safronov and others, earliest impacts on largest planetesimals would occur in this band at lower left; as planetesimals grow and speeds increase they would migrate up band to upper right, as shown schematically by X's and arrows.

the X's in Figs. 5 and 6, and as largest sizes increased, X's would evolve up the diagonal band. Collisions among the smaller bodies would result in no mass change.

By the time the largest objects reached radii of about 2 to 5 km, impact velocities in the swarm would enter the regime 2 to 50 m/sec where shattering occurs. The smaller bodies would now be shattering each other during their collisions, grinding themselves into smaller fragments, probably extending in power-law size distribution down to microscopic coherent crystals (Hartmann, 1969). Some of these fragments would be swept up by the large, growing bodies. Other particles of metallic, icy, or silicate composition in the size range roughly 0.05 to 1 μm would experience strong radiation pressure (Soter *et al.*, 1977); many of the latter would be driven out of the solar system and would account for a significant fraction of the interstellar dust (Herbig, 1970; Hartmann, 1970). The largest planetesimals, meanwhile, would keep on growing toward planetary dimensions, since collisions in the velocity regime considered, slightly exceeding their escape velocities, do not accelerate appreciable regolith mass to more than escape velocity. Growth of the largest body may have been further accelerated if its gravitational cross section ever began to dominate over its

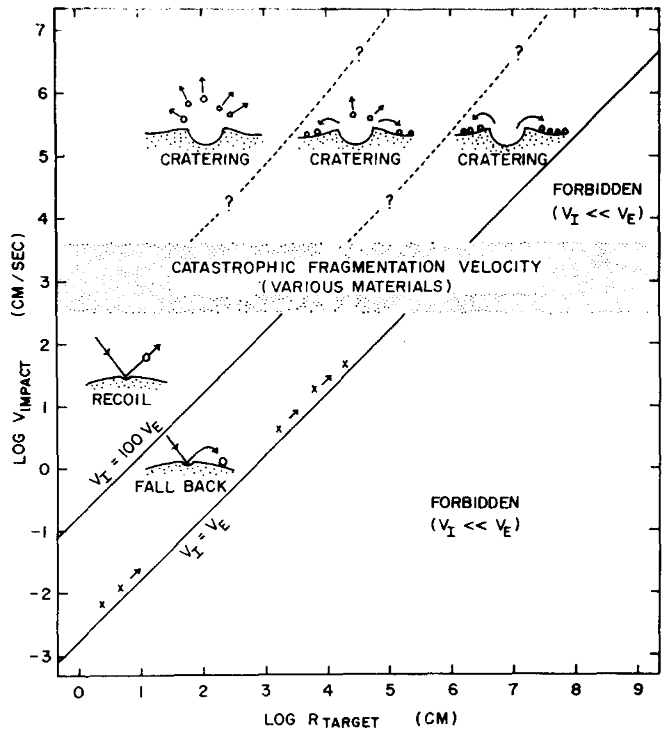

FIG. 6. Same as Fig. 5, but for planetesimals in vacuum and covered with a regolith layer comparable in depth to the diameter of the projectiles considered. Same regions appear, but diagonal band representing fallback of projectile or debris is about 50 times wider, resulting in much more efficient mass gain. Impact events, designated schematically by ×'s, still occur at impact speeds about 1.5 V_{esc}, according to Safronov and others. Details of crater ejecta speeds are less certain for regoliths than for solids shown in Fig. 5.

geometric cross section (either by random statistical fluctuation in the ratio of largest-body size to modal velocity, or a direct physical cause); this would cause onset of rapid growth because the former continues increasing as R^4 instead of R^2 for a fixed modal velocity in the particle swarm (Hartmann, 1968). In this way, the largest bodies would tend to run away from the other bodies in size, being struck at velocities only slightly exceeding their own escape velocities, minimizing mass loss, maximizing their own accretion, and leading to a few large objects interacting with a swarm of small ones. This could explain some observed peculiarities of the solar system such as the Mars-crossing population of asteroids (Wetherill, 1977) and anomalous satellites (Hartmann and Davis, 1975).

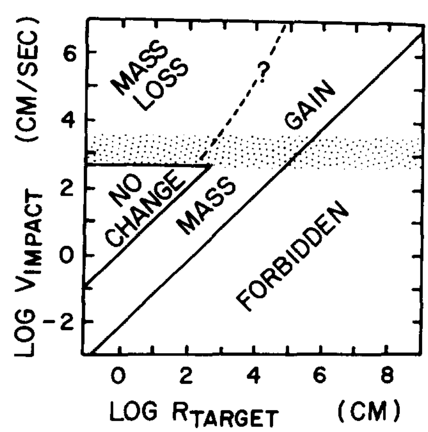

FIG. 7. Schematic synthesis of regions on impact-speed/target-size diagrams of Figs. 5 and 6, plotting results of impacts with respect to net mass gain or mass loss. The largest of the initial planetesimals grew because most impacts on them occurred in the mass-gain regime.

Appearance of these larger bodies would broaden the velocity range expected at a given time, since a large planet in one region could accelerate particles at high speed into other regions.

Finally, growth could have been terminated either by consumption of all accretable material or by appearance of a high-velocity tail in the V distribution. A sufficient mass in the high-V tail could blow mass off surfaces faster that it could accumulate (one gram hitting a clean body of $R = 400$ km at 1.1 V_{esc} could cause mass gain of 1 g; but incoming at, say, 10 V_{esc} $=4$ km/sec, it could cause mass loss of 500 g, according to results of Gault and others). Kaula and Bigeleisen (1975), Wetherill (1976), and Weidenschilling (1976) have all discussed scenarios in which one planet (Jupiter?) reaches large size first by runaway growth, scatters planetesimals at high V, and contributes to termination of other planets' growth in this way. In particular, a high-V tail of planetesimals passing through the asteroid belt could have stopped growth of Ceres, which may have already started its runaway growth, being twice the size of the next largest asteroid. Growth of Ceres obviously was not terminated by lack of accretable material, though some planets may simply have consumed all available mass, or have run out of small material when the small grains were depleted by solar wind or Poynting–Robertson effects.

FUTURE WORK

This work suggests a number of further studies that would increase our understanding of planet formation both in the solar system and elsewhere. Perhaps most important is a more complete mapping of collision results as a function of velocity, target mass, projectile mass, and ambient gas density. It is especially important to fill the velocity gap from 50 to 1000 m/sec, where few (no?) experiments have been reported. This velocity regime would illuminate not only ancient planet-forming conditions, but also present-day conditions that may apply in the rings of Saturn and Uranus (Greenberg *et al.*, 1977a), Trojan asteroid swarms, dust belts in satellite orbits (Soter, 1971), and environments with low-speed secondary cratering.

A second area of urgently needed study involves theoretical modelling of the velocities that actually apply in coorbiting swarms of particles in different environments. Some specific problems are: (a) What are the exact consequences of gravitational stirring of the small particles by larger particles in the swarm? Is Safronov's treatment (a basic part of the conclusions in this paper) sufficiently accurate? (b) Goldreich and Ward (1973) picture initial nucleation with a group of similar-sized particles formed by gravitational collapse, but once velocities are high enough to cause fragmentation, a power-law size spectrum with few big particles and numerous small particles will evolve (Hartmann, 1969). How are the Safronovian mutual scattering velocities affected during this change in mass spectrum? Are equilibrium velocities achieved, or does the swarm's size spectrum evolve too fast? (c) How are velocities in different mass-spectra swarms affected by Weidenschilling's gas drag process? When does this gas disperse? Is it possible for planetesimals in certain size ranges to achieve high enough velocities with respect to the rest of the swarm to inhibit the growth process described here for the largest bodies? (d) Velocities cannot be adequately modelled by considering only a toroidal volume around the central star, because of possible planet-forming events elsewhere. Can the growth process be inhibited or eventually stopped by a high-velocity tail of fragments entering the swarm after gravitational scattering by a large planet already formed elsewhere, as pictured by Kaula and Bigeleisen (1975)?

The experimental results reported here, along with preliminary considerations of some of the above questions, are being applied to a computer simulation of the growth of planets (Greenberg *et al.*, 1977b). Further reports of the results are in preparation.

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