Reports

Accretionary Processes in the Early Solar System: An Experimental Approach

Abstract. *Micrometer-size silicate flakes do not accrete during impacts in the velocity range 1.5 to 9.5 kilometers per second. Conventional accretionary theories for silicate bodies are applicable only to particles whose orbits are similar. Metal-silicate fractionation in the solar system may have been affected by differences in the accretionary behavior of the metal and silicate particles.*

Most modern theories of the origin of the solar system involve a sequence of events in which solid grains are thought to have condensed from a gas and subsequently accreted to form larger bodies (planets, satellites, and asteroids) (*1, 2*). In its initial, nongravitational stages, the accretionary process may be regarded as a series of collisions between grains in intersecting orbits under conditions which result in a net transfer of mass to some of the grains. One important parameter for accretion theories is the range of impact velocities over which accretion occurs. The purpose of the experiment we report here was to determine this velocity range by studying the impact, at different velocities, of particles analogous to material thought to be present in the early solar system.

Impact processes for metallic materials have been studied over a wide range of velocities (*3, 4*). However, the compositions of present members of the solar system show that most accreting particles could not have been metallic but were probably silicates (*5*). Little is known about impact processes in silicates. Gault *et al.* (*6*) fired centimeter-size aluminum projectiles into basalt targets and determined the mass of ejecta. For velocities above 0.4 km/sec, the total mass ejected exceeded the total mass of the projectiles; that is, no accretion occurred. Similarly, for micrometer-size aluminum spheres impacting oligoclase and olivine (*7*), the mass of material dislodged exceeded the mass of projectile remnants in the crater in the velocity range studied (4 to 14 km/sec).

By contrast, Neukum (*4*) showed that, for micrometer-size iron projectiles impacted into a variety of metallic targets, virtually the entire projectile mass is transferred to the target for all velocities between 0.5 and 13 km/sec, the upper limit of velocity attained in his experiment. Because of uncertainties in the amount of target material excavated in each case, it is not possible to determine the velocity range over which *net* accretion occurred; however, microscopic examination of impact sites suggests that, up to at least 1.5 km/sec, effectively no mass was lost from the system. Below 0.5 km/sec, to an experimental lower limit of 0.2 km/sec, iron projectiles rebounded from all metallic targets.

We have applied the techniques that Neukum used, electrostatic particle acceleration and electron microprobe analysis of impact sites, to the case of silicate particles impacting silicate. The 1.5-Mv vertical linear accelerator, used

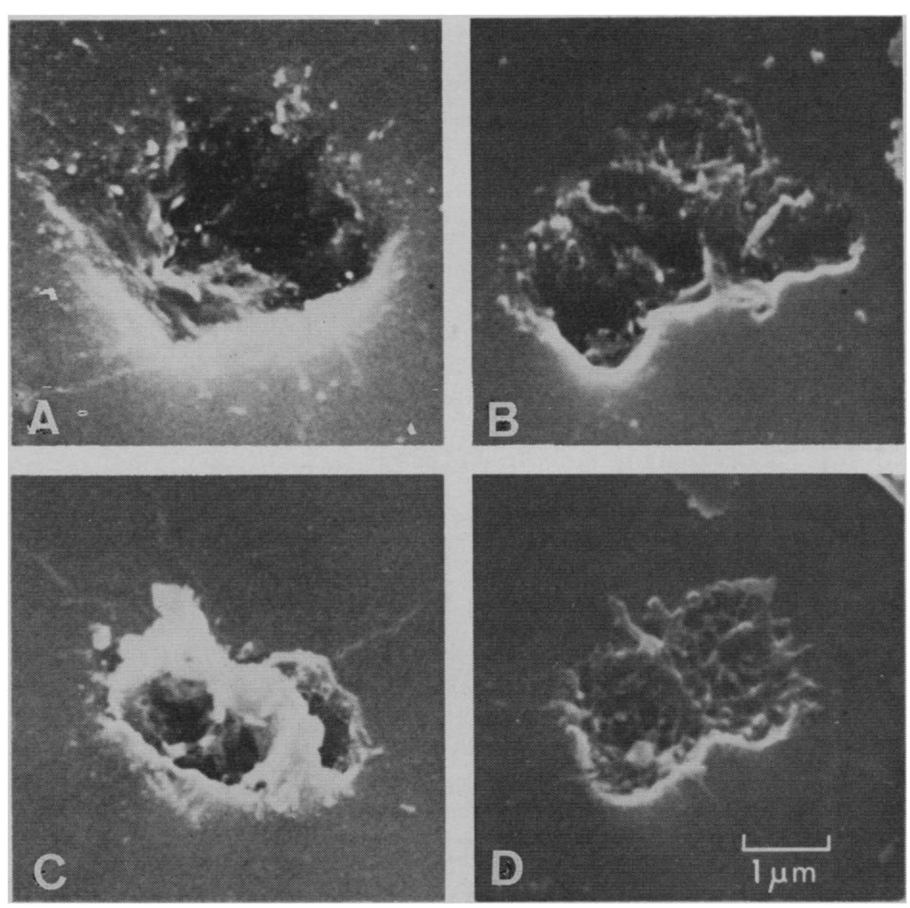

Fig. 1. Micrographs (SEM) of craters formed in clinochrysotile by the impact of kaolinite particles at normal incidence with the following velocities and masses: (A) 1.9 km/sec, 35 pg; (B) 3.9 km/sec, 4.3 pg; (C) 4.3 km/sec, 6.4 pg; and (D) 9.4 km/sec, 1.0 pg. The craters in (B) and (C), formed by projectiles with similar velocities, are quite different. The visual evidence of the projectile material in (C) was confirmed by the fact that the microprobe detected a significant aluminum response.

to impart the appropriate velocity to each particle, possesses a unique feature which makes possible the use of dielectric particles. Single particles are charged by an ion beam while being levitated in an electrodynamic suspension system (*8*). The charged particle, ejected from the source, is accelerated by the first of four drift tubes, each of which is held initially at a high negative voltage. If each tube is grounded sequentially, four stages of acceleration may be achieved, the timing sequence for the operation being controlled by the particle's charge-to-mass ratio, measured immediately prior to ejection. Induced-charge detectors (*9*) at both ends of the accelerator record the passage of the particle. The final detector, terminating 4 cm above the target, measures the velocity and charge of the particle and locates its impact site. The measured velocities have an accuracy of $\pm$ 5 percent, and the masses, computed from the charge and charge-to-mass ratio, have an uncertainty of $\pm$ 12 percent. Particles ranging in mass from 0.2 to 120 pg were accelerated to velocities in the range 1.5 to 9.5 km/sec. Since, in general, small particles attain a higher charge-to-mass ratio than large ones, the highest velocities correspond to the smallest particles.

The projectile material was kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) in the form of thin, laminated flakes with a density of 2.63 g/cm^3 (*10*). This material was chosen because it structurally resembles the major mineral component of the primitive type I carbonaceous meteorites (*11*). Similar grains were almost certainly involved in the accretion of at least one meteorite parent body and may well have been widespread in the early solar system. The requirements on the target material were (i) that it contain no aluminum, the element to be used as a tracer for projectile transfer; (ii) that it be similar in structure and density to the projectile material; and (iii) that it have a surface suitable for the identification of impact sites. Thick ($\sim$5 mm) sections of clinochrysotile ($3MgO \cdot 2SiO_2 \cdot 2H_2O$) with a density of 2.50 g/cm^3 were used (*12*). Although the detailed crystal structure of this mineral is very different from that of kaolinite, a fundamental structural unit (the silicon-oxygen sheet characteristic of phyllosilicates) is common to both. Electron probe microanalysis showed that the chrysotile contained 0.2 percent (by weight) Al_2O_3.

Clinochrysotile crystallizes as tubes approximately 500 Å in diameter and up to several centimeters long (*13*). Samples consisting of massive bundles of tubes were embedded in epoxy and sectioned perpendicular to the tube axis to produce targets with an area of about 1 cm^2. Target faces were petrographically polished with diamond paste (0.25-μm diamond was used in the final stage) and then cleaned by stripping several times with replicating tape. Before being inserted into the accelerator, each target was given a coating of gold (100 Å thick) which peels back from an impact leaving a well-marked site.

Up to 40 impacts were made at normal incidence into each target. The impact sites were located by means of an optical microscope, and the target was transferred, after carbon coating, into a scanning electron microscope (SEM) (JEOLCO). Each site was photographed in the SEM, and Fig. 1 shows examples of the impact morphology characteristic of different velocity regimes.

Using a microprobe (Applied Research Lab EMX 21100) operated at a voltage of 20 kv and a beam current of 0.1 μa, we carried out a quantitative analysis of projectile material in the impact sites. We monitored the aluminum Kα radiation using a potassium acid phthalate crystal and a flow proportional counter. The diameter of the electron beam was adjusted to exceed that of the largest impact site to be studied during each operation, and background measurements were made after every second site analysis. A "standard" impact site containing a substantial amount of aluminum was analyzed at least once during each operation. A value for the yield, Y, of projectile material within each impact site was calculated from the expression:

$$Y = \frac{I}{I_s} \frac{m_s}{m}$$

where the subscript s denotes the standard site, I and I_s are the aluminum Kα intensities after subtraction of background, and m and m_s are the masses of the projectiles prior to impact, computed from accelerator data. Figure 2 shows the values of Y obtained at different velocities after normalization to a maximum Y value of unity. These "yield" data are purely relative and do not reflect absolute values for the mass after impact at the crater site (*14*).

The following conclusions may be drawn from the data in Fig. 2. Even if the maximum "yield" value is assumed to correspond to 100 percent efficient accretion, it is clear that, in any velocity range, impacts in which a significant transfer of projectile material occurred are outnumbered by those in which little or no transfer took place. In addition, each impact, at least above 2 km/sec, was accompanied by the for-

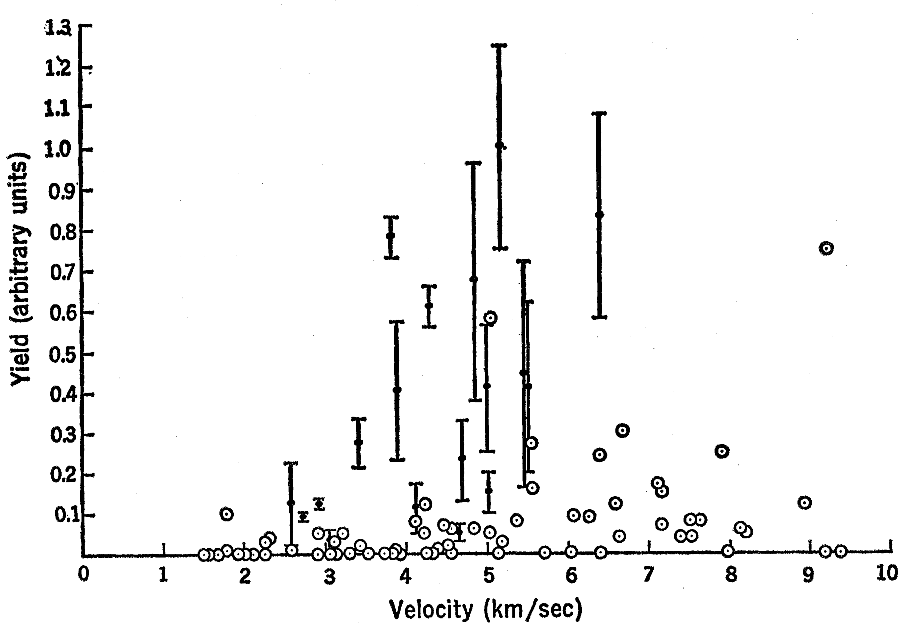

Fig. 2. Projectile yield, in relative units, for sites resulting from the impact of kaolinite flakes into clinochrysotile at different velocities in the range 1.5 to 9.5 km/sec. Uncertainty bars correspond to $\pm 2(b)^{1/2}$, where b represents background counts. This quantity is approximately equal to the observed statistical fluctuation. Open circles correspond to data that are statistically within the background.

mation of a crater with dimensions comparable to or greater than those of the projectile. Although a fraction of each crater volume undoubtedly represents inelastic compression of the target, examination of crater morphologies suggests that this fraction is small and that, throughout the velocity range studied, erosion was more effective than accretion. Thus, there is no disagreement between our results for hydrated silicates and those of Gault *et al.* (*6*) for basalt. However, there is a striking difference between the accretionary behavior of silicates and that of metals (*4*).

The silicate data pose no major problems for current accretionary theories (*1, 2*). Indeed, this conclusion has already been reached by Hartmann (*15*), on the basis of an analysis of the data of Gault *et al.* (*6*). Silicate accretion took place only between particles whose orbits were similar. However, over at least part of the velocity range in which silicate accretion was efficient, metal particles would have rebounded without accreting. This finding suggests that, if both metal and silicate were present during accretion, fractionation of one with respect to the other would have occurred. In particular, at the low velocities which must have prevailed during most of the accretionary process, silicates would have been preferentially accreted. Similarly, if some regions of the solar system were characterized by higher interparticle velocities, bodies enriched in metal may have been produced. In this respect it may be significant that among the terrestrial planets there is a rough tendency for density, and therefore assumed metal content, to increase with orbital velocity.

These conclusions clearly apply only within the framework of conventional accretionary theories. Alternative theories, such as that of Urey (*16*) in which planetary growth is thought to have occurred by gravitational collapse of local regions of gas and dust, are by no means excluded. In addition, the presence of volatile coatings on grains or the existence of an appreciable gaseous nebula during accretion would undoubtedly have had significant effects on the accretion efficiency.

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References and Notes

1. See, for example: G. P. Kuiper, in *Astrophysics*, J. A. Hynek, Ed. (McGraw-Hill, New York, 1951), p. 369; H. Alfvén and G. Arrhenius, *Astrophys. Space Sci.* **8**, 338 (1970).
2. W. K. Hartmann, *Astrophys. J.* **152**, 81 (1968).
3. S. Auer, E. Grün, P. Rauser, V. Rudolph, K. Sitte, in *Space Research*, A. P. Mitra, L. G. Jacchia, W. S. Newman, Eds. (North-Holland, Amsterdam, 1968), vol. 8, p. 606; V. Rudolph, *Z. Naturforsch. A* **24**, 326 (1969); H. Dietzel, G. Neukum, P. Rauser, *J. Geophys. Res.*, in press.
4. G. Neukum, thesis, University of Heidelberg (1968).
5. H. C. Urey, *The Planets, Their Origin and Development* (Yale Univ. Press, New Haven, 1952).
6. D. E. Gault, E. M. Shoemaker, H. J. Moore, *Nat. Aeronaut. Space Admin. Tech. Note D-1767* (1963).
7. J. F. Vedder, *Earth Planet. Sci. Lett.* **11**, 291 (1971).
8. ———, *Rev. Sci. Instrum.* **34**, 1175 (1963).
9. H. Shelton, C. D. Hendricks, Jr., R. F. Wuerker, *J. Appl. Phys.* **31**, 1243 (1960).
10. Kaolinite was obtained from the Particle Information Service, Los Altos, California. For an illustration of this material, see R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York, 1953), p. 111.
11. Type I carbonaceous meteorites are commonly considered primitive because they exhibit less elemental fractionation with respect to solar abundances than any other material [see H. C. Urey, in *Nuclear Processes in Geologic Settings* (National Academy of Sciences–National Research Council, Washington, D.C., 1953), p. 49; E. Anders, *Geochim. Cosmochim. Acta* **35**, 516 (1971)]. The primitive chemistry of the bulk meteorite is probably dominated by the ill-defined phyllosilicate which makes up approximately 60 to 70 percent of such a meteorite [see J. F. Kerridge, in *Mantles of the Earth and Terrestrial Planets*, S. K. Runcorn, Ed. (Wiley, London, 1967), p. 35; *Nature Phys. Sci.* **230**, 66 (1971)].
12. The sample, from Salt River Valley, Arizona, was supplied by J. Sinkankas.
13. W. A. Deer, R. A. Howie, J. Zussman, *Rock-Forming Minerals* (Wiley, New York, 1962), vol. 3.
14. The distribution of projectile material inside the impact crater was irregular and unknown. Consequently, it was not possible to use conventional methods of correcting x-ray intensities for absorption and other geometrical effects, nor was it possible to convert x-ray intensity values into absolute mass units.
15. Hartmann (*2*) has shown that, with a 100 percent sticking efficiency and a reasonable value for the spatial density of accretable material, the asteroids could have accreted within 10^8 years if interparticle velocities fell in the range 0.04 to 0.2 km/sec.
16. H. C. Urey, *Mon. Not. Roy. Astron. Soc.* **131**, 199 (1966).

17. We thank G. Arrhenius for suggesting the study of low-density silicates. We thank D. Avant, K. Bozeman, J. Erlichman, R. Garrard, H. Lem, L. Vedder, and W. Wallace for assistance. We thank D. C. Black, W. L. Quaide, and R. T. Reynolds for critical comments. One of us (J.F.K.) was supported by a National Aeronautics and Space Administration–National Research Council postdoctoral associateship.

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Telecommunications with Muon Beams

Abstract. *The properties of well-collimated beams of muons with energies in the range of 10^9 electron volts may be suited to some specialized needs in telecommunications. A demonstration of muon telecommunications has been carried out at Argonne National Laboratory.*

The unique penetrating power of high-energy muons compared to that of other particles results from their lack of strong (nuclear) interactions and from their large mass compared to the electron mass, which reduces their electromagnetic energy losses in matter. Thus, except for light and neutrinos, muons form the bulk of the cosmic radiation fluxes at the bottom of the atmosphere. Muons from cosmic rays have been used in "x-raying" pyramids (*1*). For the same reasons, terrestrial point-to-point communications could be carried out by sufficiently energetic collimated beams of muons, which can penetrate the thickness of the earth's atmosphere. I discuss, first, short-range (about 20 km) communication systems, then long-range (1000 km or more) systems.

Angular divergences of a few milliradians or less are easily obtained in presently available secondary beams from high-energy accelerators. This means that for a path length of 10 km, a square detector 10 m on a side can pick up a large fraction of the beam. Such large detectors could be either scintillator counter-telescopes or large, inexpensive Cerenkov counters with a medium of air.

Scattering in the air over such a path can be reduced to a few milliradians if the beam energy is above 3 Gev. These beams can penetrate metal or other dense or conducting substances, the thickness of penetration being roughly proportional to the beam energy. (For each 10^9 electron volts of energy, muons can pass through about 0.5 m of steel.) They provide, therefore, an alternative to microwave communications for point-to-point systems if physical barriers intervene.

The flux required would increase linearly with the information bandwidth and vary inversely with the cross section of the beam. Present-day accelerators are quite adequate for supplying the necessary muon fluxes, through pi-meson decays, from secondary beams.