The origin of chondrites: Metal-silicate separation experiments under microgravity conditions - II

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[1] In order to understand mechanical processes likely to be occurring on the surfaces of asteroids, we have performed experiments with mineral mixtures on NASA's KC-135 microgravity facility. The behavior of sand and iron filing mixtures, the sand and metal being in the proportions and with grain sizes of ordinary chondrite meteorites, was observed with digital cameras as gas was flowed upward through the mixtures and the plane went through cycles of positive, zero, negative and normal gravity. Partial separation of gas and sand occurred readily under gas flow and microgravity conditions and sometimes survived subsequent turbulence. This behavior is consistent with predictions of the Ergun equation derived from terrestrial experiments. The data have implications for understanding chondrite genesis, for understanding the spectra of asteroid surfaces, and for the design of equipment to function on asteroid surfaces. *INDEX TERMS:* 3672 Mineralogy, Petrology and Mineral Physics: Planetary mineralogy and petrology (5410); 3662 Mineralogy, Petrology and Mineral Physics: Meteorites; 6205 Planetology: Solar System Objects: Asteroids and meteoroids; 6055 Planetology: Comets and Small Bodies: Surfaces and interiors. **Citation:** Moore, S. R., M. Franzen, P. H. Benoit, D. W. G. Sears, A. Holley, M. Meyer, R. Godsey, and J. Czlapinski, The origin of chondrites: Metal-silicate separation experiments under microgravity conditions - II, *Geophys. Res. Lett.*, *30*(10), 1522, doi:10.1029/2002GL016860, 2003.

1. Introduction

[2] One of the chief characteristics of the primitive meteorites, the chondrites, is the metal-to-silicate ratio, which in large part determines class membership [*Urey and Craig*, 1953; *Sears and Dodd*, 1988]. The origin of differences in the metal-to-silicate ratio is completely unknown and a great many theories exist. Most of the theories involve processes occurring in the primordial solar nebula and utilize the different physical properties of the metal and silicates, including magnetism, ductility, crystal growth mechanisms, aerodynamic processes, and thermodynamic properties [*Donn and Sears*, 1963; *Orowan*, 1969; *Larimer and Anders*, 1970; *Larimer and Wasson*, 1988; *Whipple*, 1971, 1972; *Dodd*, 1976; *Liffman and Brown*, 1995, 1996]. We have suggested that metal and silicates may have become separated from each on or near the surface of the meteorite parent bodies, the asteroids, perhaps as a result of gas flow through the unconsolidated regolith [*Huang et al.*, 1996; *Akridge and Sears*, 1999]. The separation of metal from silicates on asteroid surfaces has also been much discussed in connection with space weathering [*Pieters et al.*, 2000] and the interpretation of astronomical spectra [*Chapman*, 1996; *Gaffey et al.*, 1993].

[3] In view of an interest in possible surface processes on asteroids that could cause chemical separations, and their possible relevance to major problems in meteorite and asteroid science, we have been conducting a number of investigations of the behavior of metal-silicate mixtures subjected to fluidization by gas flow. We have previously reported the results of experiments in the laboratory [*Akridge and Sears*, 1998]. We now report experiments performed under microgravity conditions during parabolic flights on NASA's KC-135 aircraft (Figure 1) during the summer of 2001. In a companion paper, we reported on experiments on the effects of microgravity sorting on 310 sand and metal mixtures, measured in the summer of 2000. In the present case, just a single mixture was flown, but the effects were observed in great detail using digital cameras.

2. Experimental Methods

[4] Two Plexiglass cylinders, 14 cm in diameter and 35 cm long, were about one-quarter-filled with 90 vol % sand (~450 μm grain size) and 10 vol % iron filings (~100 μm grain size). The behavior of the beds under microgravity conditions was recorded with fixed and hand-held digital cameras. Air could be passed through the bed from a diffuser in the base of the bed from a gas cylinder connected via a flow meter and valve. A one-way valve in the top of the cylinder prevented a build-up of pressure in the cylinder. The whole apparatus was enclosed in a Plexiglass dust cabinet. An accelerometer attached to a scientific calculator recorded the effective gravity throughout the flight. The apparatus was flown on two flights.

3. Results

[5] Accelerometer data were obtained for 34 parabolas on the first flight and 30 on the second. The accelerometer data showed that despite a few problems, the parabolas were reproducible (Figure 1).

[6] Useful images of the beds were obtained for 42 parabolas; instrumental difficulties prevented data being

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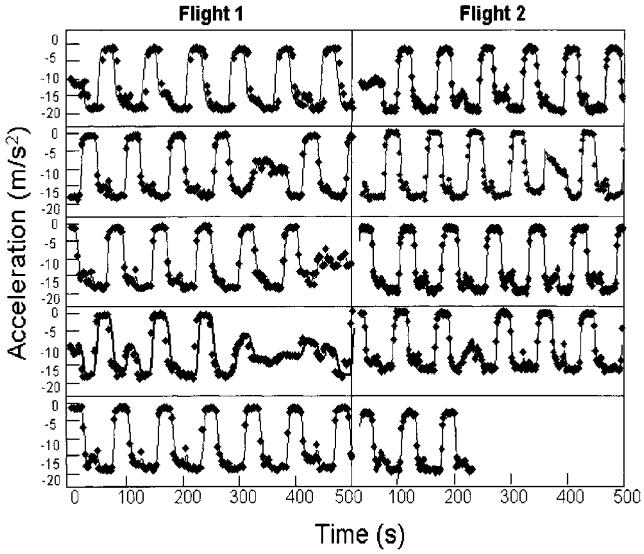

Figure 1. Accelerometer data for the KC-135 flights demonstrating the actual trajectories achieved. The parabolas were remarkably reproducible; periods of level flight (1 g) are plateaus at -9.8 m/s^2.

obtained for the others. The behavior of the beds is summarized in Figure 2 and given in Table 1. While there is some variation between experiments (Table 1), the results are generally in good agreement over the entire series. While not discussed extensively here, some of the variation observed probably reflects minor differences in flight turbulence and orientation, an intrinsic factor in any aircraft-borne experiment of this type. Based on our observations, we define four stages of bed behavior, delineated by gravity regime.

[7] *Phase 1.* (Figure 2a) Under positive gravity, no changes occurred in the bed. The gas flow was insufficient to cause any motion in the sand-iron mixture.

[8] *Phase 2.* There was considerable activity in the bed under microgravity conditions. In cases where air was allowed to flow upwards through the bed, the bed would double in volume, and the surface would bubble as if boiling. During this process, metal would segregate from the mixture, rising to the surface (Figure 2b). The surface is said to be "turbulent" and the overall condition is described as "fluidized" in Table 1. The turbulence often had a wavelike motion and there was a central "spouting" of metal-rich material and the mixture tended to exhibit a vortex motion (Figure 2c). In cases where there was no flow of air through the beds, there was no increase in bed volume, no fluidization effects, and no segregation of metal and silicate.

[9] *Phase 3.* (Figure 2d) During the period of negative gravity, material was violently thrown to the top of the cylinder. Some mixing of silicates and metal occurred.

[10] *Phase 4.* At the end of the period of negative gravity, the bed fell to the bottom of the container. In a significant number of instances the segregation produced in phase 2 survived the mixing of negative gravity (Phase 3) and metal was enriched on the surface.

4. Discussion

[11] The movement of particles in a gravity field under the influence of an upward flow of gas is given by the Ergun equation, a semi-empirical equation derived from terrestrial data and so far only tested in Earth's gravity [*Kunii and Levenspiel*, 1991]. The equation essentially balances downward gravity with upward aerodynamic drag:

$$\frac{1.75\,R_e^2}{\varepsilon^3\phi} + \frac{150(1-\varepsilon)R_e}{\varepsilon^3\phi^2} = \frac{d^3\rho_g\left(\rho_s-\rho_g\right)g}{\mu^2} \tag{1}$$

where ε is the void fraction under minimum flow conditions, ϕ the sphericity and d the diameter of the particles, ρ_g and ρ_s the densities of the gas (calculated assuming an ideal H_20 gas) and solids, μ the viscosity of the gas, and g the acceleration due to gravity. The Reynold's number, R_e, depends on flow rate of the gases:

$$R_e = dv_{mf}\,\rho_g/\mu \tag{2}$$

where v_{mf} is the minimum flow rate required for fluidization. The results of solving these equations are shown in Figure 3. Although not discussed extensively here, we note that it is possible to produce pore gas densities sufficiently high for this process using heating from either impacts or decay of short-lived radionuclides for hydrous materials [*Akridge*, 1998]. We assume a 100 km asteroid, which has the gravitation field reproduced - at least nominally - on the KC-135, and we have used other physical parameters described in *Akridge and Sears* [1999]. We express the results as minimum flow velocity as a function of particle size for metal and silicate grains.

[12] The minimum flow velocity needed to fluidize a bed of iron filings with the present dimensions is ~0.01 cm/s, while for the sand it is ~0.1 cm/s (Figure 3). Thus a flow rate of 0.01 cm/s would be enough to suspend iron filings but not sand, while a flow rate of 0.1 cm/s would suspend sand and metal. In the first case, metal grains would be carried through the intergranular space of the sand to the surface while the sand remained at the bottom of the bed. The degree of metal and silicate segregation would be determined by the ease of passage of metal through intergranular space, reflecting at least partially the porosity of the bed. In the second case, the gas flow would suspend the sand grains but is an order of magnitude

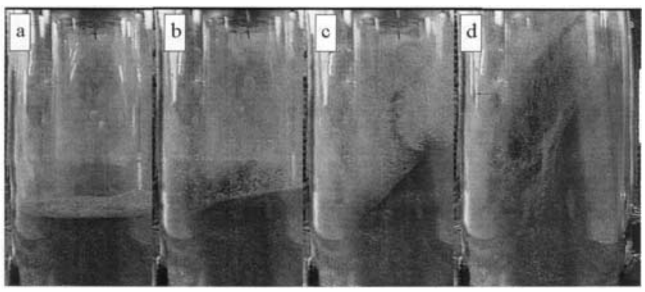

Figure 2. One of the experimental beds through a cycle of (a) positive gravity, (b) microgravity, (c) transitioning from microgravity to negative gravity and (d) negative gravity while air flows vertically through the beds from below. As soon as the bed becomes mobilized, metal and sand segregated and metal moved to the top. This segregation survived considerable subsequent movement of the beds.

Table 1. Description of the Behavior of the Sand-iron Filing Mixtures of Chondritic Sizes and Proportions Under Parabolic Flight on NASA's KC-135 Aircraft

Parabola number	Gasflow	Phase 2 Description of metal/sand distribution in microgravity	Phase 2 Disturb	Phase 2 MSF	Phase 2 Flotsam	Phase 3 Retain	Phase 4 Stratif	Phase 4 Flotsam
1,2,4,9,14	yes	fluid., metal to top, turb (wavelike), sptg	yes	yes	metal	yes	yes	metal
3	yes	Was well mixed but data was inconclusive	yes	yes	metal	yes	yes	metal
5	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	yes	uncl	uncl
6	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	yes	no	metal
7	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	yes	no	mixture
8	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	mixture	mostly	yes	mixture
10	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	yes	uncl	metal
11	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	mixture	yes	uncl	mixture
15	yes	no fluid, no metal to the top, weak trends, top layer rises	no	uncl	uncl	uncl	uncl	metal
16	yes	no fluid, no metal to the top, weak trends, top layer rises	no	yes	metal	yes	yes	uncl
17	no	no fluid, no metal to the top, weak trends, top layer rises	no	no	mixture	uncl	uncl	metal
18	no	no fluid, no metal to the top, weak trends, top layer rises	no	no	metal	yes	yes	uncl
19	no	All fell to the left of the cylinder	no	no	uncl	uncl	uncl	uncl
22	no	incon	no	no	metal	uncl	yes	metal
23	no	incon	no	Incon	incon	incon		
24	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	no	metal	uncl	yes	metal
27	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	no	mixture	uncl	uncl	uncl
28	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	no	nothing	no	uncl	uncl
29	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	no	nothing	no	no	uncl
30	no	Did not lift off the ground						
31	no	Did not lift off the ground						
12,13	yes	fluid, metal to top, turb (wavelike), sptg in mid,right twist,	yes	yes	metal	yes	yes	uncl
20,21	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	no	uncl	uncl	uncl	uncl
25,26	no	no fluid, no metal to top, weak trends, top layer rises, metal spouts in mid	no	yes	metal	uncl	yes	sand
27,28	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	uncl	yes	mixture
29,31	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	uncl	yes	sand
30	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	uncl	uncl	uncl
32	yes	incon	yes	Incon	incon	uncl		
33	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist		yes	uncl	uncl	uncl	uncl
34	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	uncl	yes	metal	uncl	yes	metal
35,36,37	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	uncl	yes	metal
38,39,40,41	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	metal	uncl	yes	uncl
42	yes	fluid, metal to top, turb (wavelike), sptg in mid, right twist	yes	yes	uncl	uncl	yes	uncl

Explanations: sptg, spouting; fluid, fluidized; mid, middle; inconcl, inconclusive; uncl, unclear; turb, turbulence; MSF, metal-silicate fractionation; retain; structures retained; stratif; stratified.

greater than the velocity needed to suspend the metal grains so that drag forces would greatly exceed gravitational forces and the grains would be lifted through the sand to the surface. In either case, the metal would be separated from the sand to some degree and carried to the surface.

[13] The observations of the present experiments are consistent with the behavior predicted by the Ergun equation. That separation of sand and metal does not occur in the absence of a gas flow also suggests that our results reflect both density and aerodynamic separation as described by the Ergun equation. The separation of silicates and metal is thus not simply the result of mechanical agitation acting alone, in contradiction to suggestions for mechanism for grain size sorting on the asteroid Eros [*Cheng et al.*, 2002; *Robinson et al.*, 2002].

[14] Significant about the present results is (1) the facility with which separations occur, (2) that separation is not an all-or-nothing process and (3) the resilience of the segregations once created. Gas flow rates required to mobilize the surface grains on an asteroid are extremely small, on the

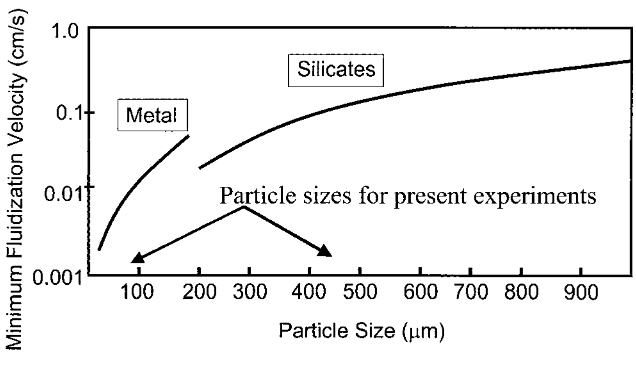

Figure 3. Plot of minimum gas flow velocity needed to suspend silicate and iron particles as a function of diameter calculated from the Ergun equation that balances upward drag due to a flowing gas with downward gravity. The diagram shows results of calculations for the surface of a 100 km diameter asteroid, with other properties described by *Akridge and Sears* [1999].

order of millimeters per second. Such gas release would be hardy perceptible to observers on the surface. While the low densities of asteroids are often thought to indicate considerable porosity, there are many instances where these seem inadequate. The most primitive meteorites are the CI chondrites, which contain 10–20 vol % water, so it is arguable that at least some and perhaps many asteroids have volatile-rich interiors. Given the short duration of our experiments and our focus on physical rather than chemical effects of gas-solid interaction, the use of pressurized air in our experiments rather than water vapor (or CO_2), more likely to occur on and in asteroids, should not materially change our conclusions.

[15] That even metal-rich and silicate-rich layers are still mixtures is significant because ordinary chondrites are mixtures. One problem in understanding ordinary chondrites is understanding how the metal-silicate fractions are relatively subtle; most theories would result in all-or-nothing separations of metal and silicates. The differences in fluidization behavior of metal and silicate grains, due to their different densities and sizes, allows mixtures to partially segregate during periods of waning gas flow.

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