Size and density sorting of metal and silicate grains under microgravity conditions and the origin of chondrites

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[1] We report here experiments on NASA's KC-135 microgravity facility aimed at investigating metal-silicate fractionation in chondrites. Metal and sand particle mixtures, with sizes and relative proportions approximating chondritic values, were allowed to undergo density and aerodynamic sorting as air was passed through 310, ten-centimeter long 2.54 cm diameter columns under microgravity conditions. Metal and silicate fractionation was found to occur when gases passed through the mixtures and when the particle diameter ratio was large (~3.0), with sand being enriched near the surface of the beds. This is contrary to experiments performed under terrestrial gravity and the semi-empirical Ergun equation. While the reason for this discrepancy is not well understood, the present results do suggest that separation of metal and silicates will readily occur under microgravity conditions on the surface of asteroids. *INDEX TERMS:* 3662 Mineralogy and Petrology: Meteorites; 6040 Planetology: Comets and Small Bodies: Origin and evolution; 6045 Planetology: Comets and Small Bodies: Physics and chemistry of materials; 6019 Planetology: Comets and Small Bodies: Gravitational fields; 6205 Planetology: Solar System Objects: Asteroids and meteoroids. **Citation:** Franzen, M. A., S. Nichols, K. Bogdon, C. White, R. Godsey, N. Napieralski, P. H. Benoit, and D. W. G. Sears, Size and density sorting of metal and silicate grains under microgravity conditions and the origin of chondrites, *Geophys. Res. Lett.*, *30*(14), 1780, doi:10.1029/2003GL017659, 2003.

1. Introduction

[2] We have been investigating the extent to which the metal-silicate fractionation observed among the ordinary chondrites could be the result of density and size sorting under microgravity conditions. The chondrites are primitive meteorites and, arguably, the characteristic that best distinguishes the chondrite classes is their lithophile-siderophile element ratios or, more precisely, their metal-silicate ratio [*Urey and Craig*, 1953]. The major silicate phase is the chondrules, silicate beads typically 0.2–1.0 mm in diameter, while metal grains are generally irregular grains with dimensions of 0.02–0.22 mm. Many theories exist to explain the origin of the metal-silicate patterns in chondrites. Most involve processes that may have occurred in the primordial solar nebula prior to aggregation. Many physical properties of the metal and silicate particles have been invoked by various authors, including: magnetism, ductility, crystal growth processes, aerodynamic processes, thermodynamic processes, and others [*Donn and Sears*, 1963; *Orowan*, 1969; *Dodd*; *Larimer and Anders*, 1970; *Larimer and Wasson*, 1988; *Whipple*, 1971, 1972; *Dodd*, 1976; *Liffman and Brown*, 1995, 1996]. However, we propose that instead of occurring in the nebula, metal and silicate fractionation occurred in the regolith or megaregolith on the meteorite parent body, usually assumed to be an asteroid [*Huang et al.*, 1996; *Akridge and Sears*, 1999]. Many processes occur on the surface of a degassing body [*Sear et al.*, 1999], especially in the presence of ice. However, degassing always transpired and the gas drag causes particles to be lifted.

[3] The fractionation of metal and silicates on the surface of asteroids has been discussed in connection with the astronomical spectra of asteroids. It has been accepted that space weathering causes excess nanophase iron to be present on the surface of asteroids, thus reddening their spectra. Arguably, space weathering may be the explanation of the deficiency of asteroids with spectra similar to ordinary chondrites, the most abundant class of meteorites [*Chapman*, 1996; *Pieters et al.*, 2000].

[4] In order for us to better understand the physical processes that occur on the regoliths of small asteroids, we have preformed several sets of experiments using model regoliths mobilized in various ways on NASA's KC-135 reduced gravity facility. We have previously reported preliminary data for this flight [*Bogdon et al.*, 2000] and here we report a more complete summary of the results. Elsewhere we describe the results of our second [*Moore et al.*, 2003] and third campaigns [*Sears et al.*, 2002]. Although each campaign had unique objectives and apparatus, collectively they are producing a consistent image of how asteroid regoliths might behave as they are disturbed, either by natural events or by mission operations.

2. Experimental Methods

[5] The experiments were performed on NASA's KC-135 microgravity facility in March 2000. By soaring and plunging, this flying laboratory provided ~60 periods of ~25 seconds of microgravity during two flights. The apparatus used for this experiment consisted of 310 Plexiglas tubes 2.54 cm in diameter containing a 10-cm column of sand and iron filings. The sand and iron mixtures were blended at the airfield before flight. Various proportions and grain sizes of sand and iron filings were used (Table 1), approximating chondritic values. According to the Geldart classification

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Table 1. Experimental Conditions for the Particle Beds

		Component 1		Component 2	
Set	Metal: Silicate*	Phase	Size (μm)	Phase	Size (μm)
1	1:1	sand	149–250	sand	250–300
2	1:1	sand	149–250	sand	425–600
3	1:1	sand	300–425	sand	425–600
4	1:19	sand	250–300	iron	74–105
5	1:19	sand	149–250	iron	105–149
6	1:19	sand	250–300	iron	105–149
7	1:19	sand	250–300	iron	149–250
8	1:19	sand	300–425	iron	149–250
9	1:19	sand	149–250	iron	149–250
10	1:1	sand	149–250	iron	149–250
11	1:1	sand	350–425	iron	74–105
12	1:19	sand	300–425	iron	105–149

*Volume ratio.

[*Geldart*, 1973; *Akridge*, 1998], particles behave in one of four classes according to their density and mean particle size. The present mixtures, and most of the chondritic meteorite mixtures, fall into the Geldart B class, which are mixtures that are easily fluidized. Each of the sand and iron filing mixtures were run in triplicate. While under microgravity conditions, the particle beds were allowed to move freely through the entire 20 cm length of the tubes while air was passed at a predetermined rate through the columns. Then pistons were pressed down onto the beds and clamped to preserve the metal-silicate distribution in the column. After the flights, ten evenly spaced holes were drilled along the length of the columns and samples were collected through the holes using a specially-made scoop. The metal and sand were separated with a hand magnet and the fractions weighed.

3. Results

[6] A sample of the data we obtained is shown in Figure 1, which plots the weight ratio of sand to metal as a function of height in the tube for three of our sand iron filing mixtures. Most of the tubes showed little or no variation in the sand/iron weight ratio with depth, but some showed a factor of ~2 increase in this weight ratio in the upper few centimeters of the column. In the data in Figure 1, the mixtures with sand to metal diameter (size) ratios of ~1 and ~1.7 show little change throughout the bed, while it is the mixture with a sand to metal size ratio of ~3.1 that shows a factor of ~2 increase near the surface.

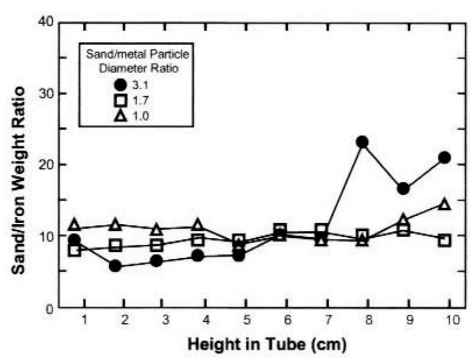

Figure 1. The separation of sand and metal in mixtures under microgravity conditions. The volume ratio of metal and sand is 1:19. Representative data for three mixtures are shown (sets 4, 8 and 9 in Table 1) where the ratios of the diameters of the sand to metal particles are ~3.1, ~1.7, and ~1.

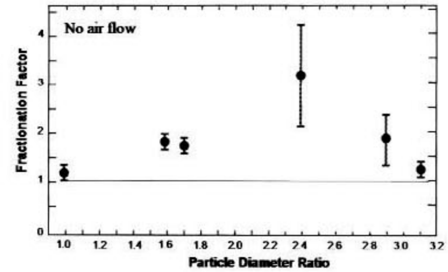

Figure 2. The "fractionation factor" as a function of sand to metal particle diameter ratios for tubes in which there was no flow of air during microgravity. Fractionation factor is defined as the weight ratio sand to metal averaged for the 1–6 cm samples divided by the sand to metal ratio at 7–10 cm.

[7] To more closely examine the trends, we defined a "fractionation factor" intended to describe the extent to which metal and sand separated during the experiment. The fractionation factor is the weight ratio of sand to metal averaged over the 7–10 cm (upper portion of tube) samples, divided by the same ratio averaged over the 1–6 cm samples (lower portion of tube). This division of samples (7–10 cm versus 1–6 cm) was chosen because when separation occurred it seemed to involve mostly the 7–10 cm fractions, thus the sensitivity of the fractionation factor is maximized. A high factor indicates that sand has moved towards the top of the column and that metal has moved towards the bottom of the column. Since it seemed from Figure 1 that the relative size of the sand and metal particles was important in determining metal-silicate behavior in the experiments, we plotted fractionation factor against sand to metal diameter ratio in Figures 2 and 3.

[8] Figure 2 shows such a plot for control tubes through which gas was not passed during the experiments. There is a slight upward trend in the plot and then a downward trend at high metal to sand size ratios; however, the uncertainty in the 2.4 particle size diameter experiment is particularly large, so it seems probable to us that there was no systematic trend in fractionation factor with sand to metal diameter ratio. On the other hand, as Figure 3 shows, there was such a trend in experimental tubes in which air was flowing during the experiment. The two mixtures with sand to metal diameter ratios of ~3 showed a fractionation factor of about two, while the mixtures with smaller sand to metal diameter ratios show no experimentally significant deviations from one.

4. Discussion

[9] As far as we are aware, these are the first experiments to investigate metal-silicate partitioning under microgravity conditions. We have shown that separation of metal and silicates by a flowing gas stream under microgravity conditions is possible, and that separation requires the gas stream. It is a subtle effect in the sense that sometimes there is little or no separation, and sometimes it involves factors of ~2 change in the metal to sand weight ratio, but it

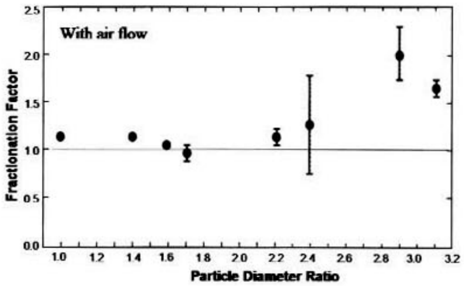

Figure 3. The "fractionation factor" (see Figure 2) as a function of sand to metal particle diameter ratio for tubes in which air was flowing during microgravity.

is not an all-or-nothing process, as might be expected. We can compare these results with similar measurements performed on the ground and we can compare them with predictions based on the Ergun equation [*Kunii and Levenspiel*, 1991].

[10] Figure 4 is a plot based on ground-based laboratory measurements similar to those performed under microgravity [*Akridge and Sears*, 1999]. A plot of sand to metal diameter ratio against volume fraction of metal has three regions. With small sand/metal diameter ratios, metal sinks to the bottom of the column. With large diameter ratios, and relatively small amounts of metal, metal grains are carried to the surface by aerodynamic drag through the larger sand grains. In the intermediate region, of sand to metal diameter ratios of ~3, complete mixing of the sand and metal occurs. The sand to metal ratios for mixtures used in the present study are plotted on Figure 4. Our mixtures are five volume percent metal and with sand to metal diameter ratios of 1–3.1 and, therefore, plot in the region in which metal sinks (sand to metal diameter ratios of 1–1.7) and the region in which there is mixing (sand to metal diameter ratios 2.4–3.1).

[11] Our mixtures with sand to metal diameter ratios of 2.2 to 2.4 are consistent with Figure 4 in that they showed no fractionations in sand and metal in the present microgravity experiments. However, the other mixtures are not behaving in a way consistent with Figure 4. The mixtures with smaller diameter ratios in the present experiments are showing complete mixing instead of metal sinking to the bottom of the column, while the mixtures with diameter ratios of ~3 are showing a depletion of metal near the surface instead of an enrichment. It would not be difficult to imagine an expansion of the central region on Figure 4 to encompass all our samples, but it is difficult to understand why, contrary to Figure 4, the mixtures with the largest sand to metal diameter ratios are showing a depletion in metal near the surfaces.

[12] The Ergun equation is a semi-empirical equation that describes the movement of particles in a gravity field under the influence of an upward flow of gas that was 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:

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

where ε is the void fraction under minimum flow conditions, ϕ the sphericity, d the diameter of the particles, ρ_g and ρ_s the densities of the gas (calculated assuming an ideal H_2O gas [*Akridge and Sears*, 1999]) and solids, μ the viscosity of the gas, and g the acceleration due to gravity. These values of H_2O gas were used because water is the most abundant volatile in asteroids and comets [*Sears et al.*, 1999]. The Reynold's number, R_e, depends on flow rate of the gases:

$$R_e = dv_{mf}\rho_g/\mu \qquad (2)$$

where v_{mf} is the minimum flow rate required for fluidization.

[13] If the Ergun equation is solved for mean sized metal grains and sand particles for a gravity field equivalent to that on a 100 km asteroid which, in turn, closely resembles the "microgravity" of the KC-135 experiments, it is possible to predict what, if any, separation of sand and metal could be produced by fluidization under microgravity conditions. In this way it is possible to predict from Figure 4, that sand would float for mixtures with sand to metal diameter ratios of 1.0 and 1.4, there would be mixing for sand to metal diameter ratios of 1.6 and 1.7, while metal would float for sand to metal diameter ratios of 2.2–3.1. These are in qualitative agreement with Figure 4 but suggests that the boundary curves in Figure 4 should be moved downwards by about one increment on the vertical scale. However, these results do not seem to be consistent with the present microgravity data.

[14] A plausible explanation for these results is that the experiment failed to achieve fluidization or that grain separation produced by fluidization was not preserved. The small diameter of the tubes (tube/grain diameter ratio of ~10 in some cases) may have resulted in the bed behaving as a plug rather than as a bed of free moving grains. A series of experiments conducted in larger tubes [*Moore et al.*, 2003] showed that particle separation did occur with the onset of microgravity, but also showed that

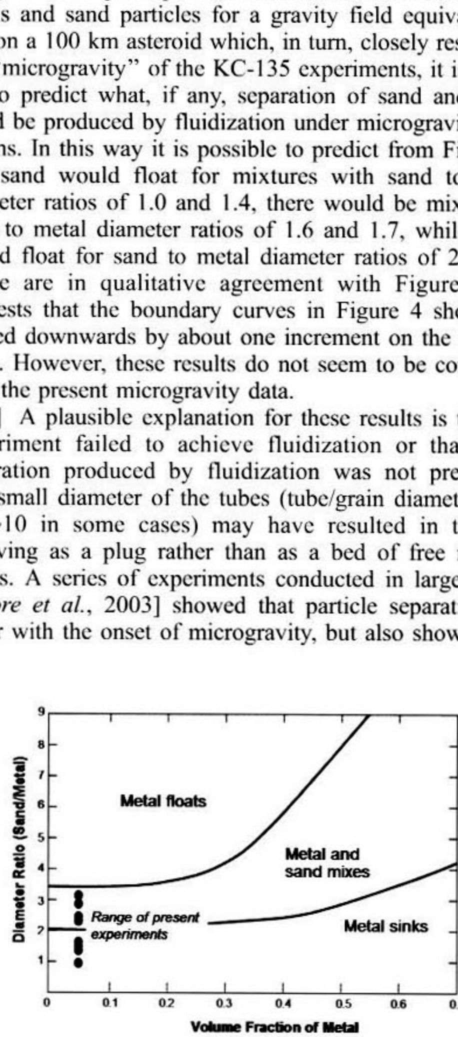

Figure 4. Sand to metal particle diameter ratio as a function of the amount of metal from laboratory experiments at normal gravity from the experiments of *Akridge and Sears* [1999]. When particle ratios are large, metal rises to the surface of the bed, whereas when sand to metal ratios are small, metal falls to the base of the bed. At intermediate ratios, the metal and the sand mix. The range of values used for the present experiments are also indicated.

the entire bed was disturbed and thrown to the top of the tube during periods of negative gravity. In the current experiment, the metal and sand separation would only be preserved if the plunger was lowered prior to negative gravity incursions.

[15] While our experiment may thus not reflect fluidization, it may reflect a different process also relevant to asteroid surfaces, namely vibration or seismic processing. In seismic separation, grain size sorting is typically more important than density of grains, with large grains moving to the top of the bed [*Benoit et al.*, 2003]. This is in accord with the present observations. The samples with a large difference in grain size exhibit a concentration of sand (the larger grains) at the surface, while those with less difference in sand and metal grain sizes show no apparent separation. On asteroids, a similar effect could occur due to meteroid impacts. Electrostatics [*Robinson et al.*, 2001] may have some affect on the results on our microgravity experiment. The grains sticking together or even to the walls of the Plexiglas tubes would most certainly affect the fluidization and the results of the Ergun equation. However, in our experiment the beds, quantitatively, behaved as grain beds and not as coherent units. Thus, electrostatics did not appear to be the major source of particle separation in our experiments.

[16] We suggest that our results show that grain sorting produced by fluidization on asteroids, if it occurs, can be modified by seismic processes. However, we also suggest that the relative importance of seismic processing and fluidization depends on a variety of factors, including the prevalence of meteoroid impacts, the thickness of fluidization-produced layers, grain size, and density properties.

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