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Mission operations in low-gravity regolith and dust

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1 Introduction

The method to be used for mitigating the impact of an asteroid on Earth depends on the nature of the asteroid. A compact rock would react very differently to almost any violent mechanical event than would an object that consisted of unconsolidated dust and fragments. A water-rich, comet-like object would react very differently to laser heating than a completely hydrated object. Thus, impact mitigation begins with scientific investigation.

We have been investigating physical processes likely to be occurring on asteroids in connection with our efforts to understand the origin and history of meteorites and their relationship to asteroids. In this connection, we have been developing proposals for a near-Earth asteroid sample return mission called Hera (Sears *et al.* 2002c) (Fig. 15.1). Hera will visit three near-Earth asteroids, spend 3 months to 1 year in reconnaissance, and then nudge itself gently down to the surface to collect three samples from each asteroid at geologically significant sites (Britt *et al.* 2001). By returning weakly consolidated surface samples, the Hera mission will clarify many issues relating to the asteroid–meteorite connection and the origin and evolution of the solar system (Sears *et al.* 2001). In addition, interstellar grains in the samples will shed light on the relationship between our Sun and other stars.

The major challenge of the Hera mission is the design of the collector and this depends on a knowledge of the nature of the surface. We now have many images of asteroid surfaces from the Galileo and NEAR missions, some of them at high resolution (Fig. 15.2), and it seems clear that a surface of unconsolidated material is to be expected on all asteroids greater than about 200 m in size (Whiteley *et al.* 2000). It is also clear that there are a variety of surface features to be expected and collecting samples from different geological contexts will help in the interpretation

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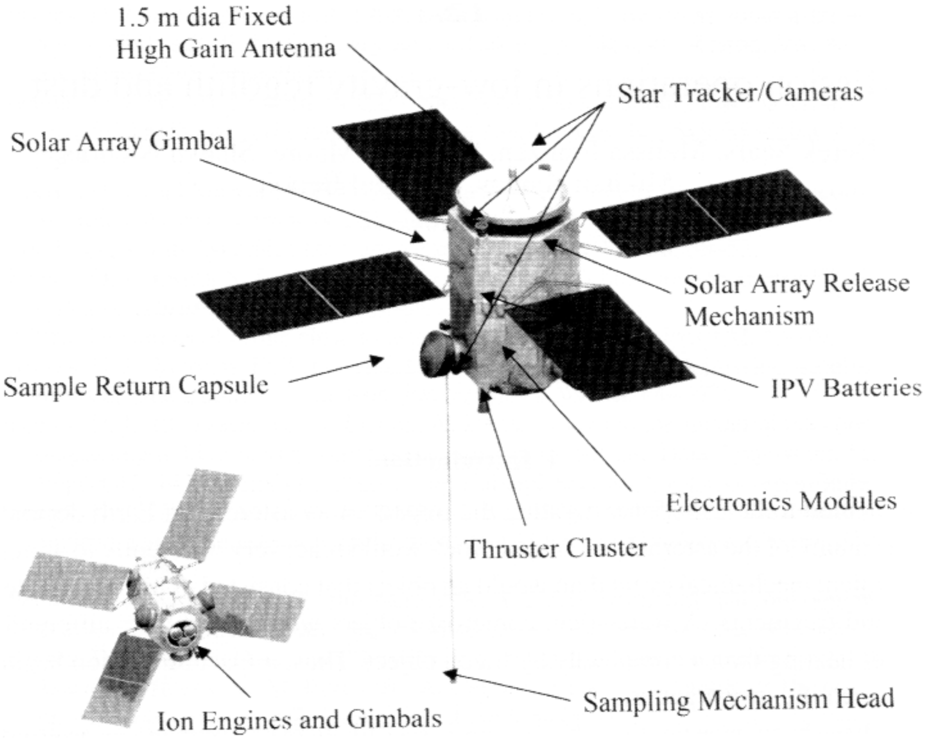

Figure 15.1 The Hera spacecraft according to concept drawings by SpaceWorks Inc. (courtesy of Jeffrey Prebble) and mission design by Leon Gefert (Glenn Research Center). The spacecraft has three sample return capsules, each with its own sample collection device, which is lowered to the surface without the spacecraft landing.

of the returned samples and meteorites already in our collections (Sears *et al.* 2002b). A great many collectors have flown on missions (Sears and Clark 2000), but all involve landers and are, therefore, impractical for our first low-cost sampling missions to asteroids. Three "touch-and-go" collectors have been described in the literature: the Lockheed-Martin auger attached to a large momentum wheel (Nygren 2000), the Honeybee counter-rotating cutters that are part of the present study (Sears *et al.* 2002a), and the MUSES-C percussion method (Yano *et al.* 2000) (Fig. 15.3).

We have performed experiments using simulated regoliths of sand, iron filings, gravel, and concrete (Akridge and Sears 1999; Bogdon *et al.* 2000). We have performed experiments in the laboratory under Earth's gravity and we have performed three sets of experiments (which we will refer to as campaigns I, II, and III) on NASA's KC-135 aircraft. The aircraft flies about 40 1-min "parabolas," rising steeply to 9750 m, tipping over and descending to 7300 m to create about 25 s of microgravity comparable to that on the surface of an asteroid. Each parabola

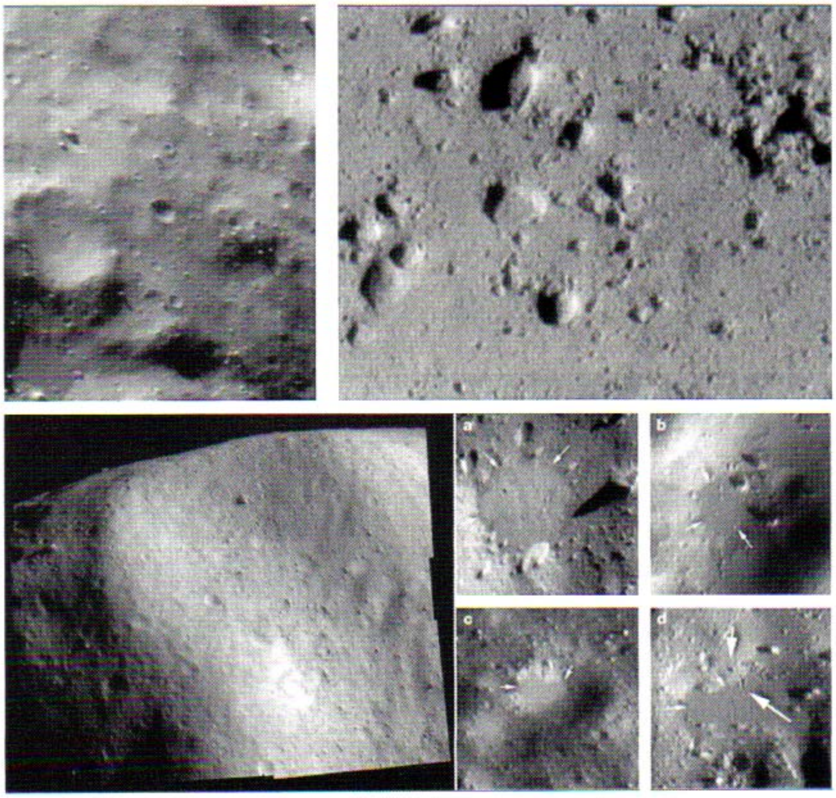

Figure 15.2 The surface of Eros as imaged by the *NEAR–Shoemaker* spacecraft. Top left and right, the regolith from orbit and on close approach during landing. Bottom left, a boulder-rich region on Eros viewed. Bottom right, four craters containing fine-grained deposits sometimes referred to as "ponds" (see Robinson *et al.* 2002, for details).

can be considered as having four phases, positive gravity (during climb), microgravity (as plane turns over the top of the parabola), transitioning from microgravity to negative gravity, and recovery (as the plane comes out of descent). We flew twice during each campaign, for a total of ~240 parabolas. It is particularly helpful to compare the test results in microgravity with the results in the laboratory. Our experiments have enabled us to gain some insights into the behavior of surface materials on asteroids and into mission operations in the presence of microgravity regolith and dust.

2 Ground-based experiments

For several years we have been investigating the behavior of mineral mixtures in fluidized beds (bed mobilized by the upward flow of gas) on the centimeter scale. This produced a realization that experiments relating to the behavior of materials

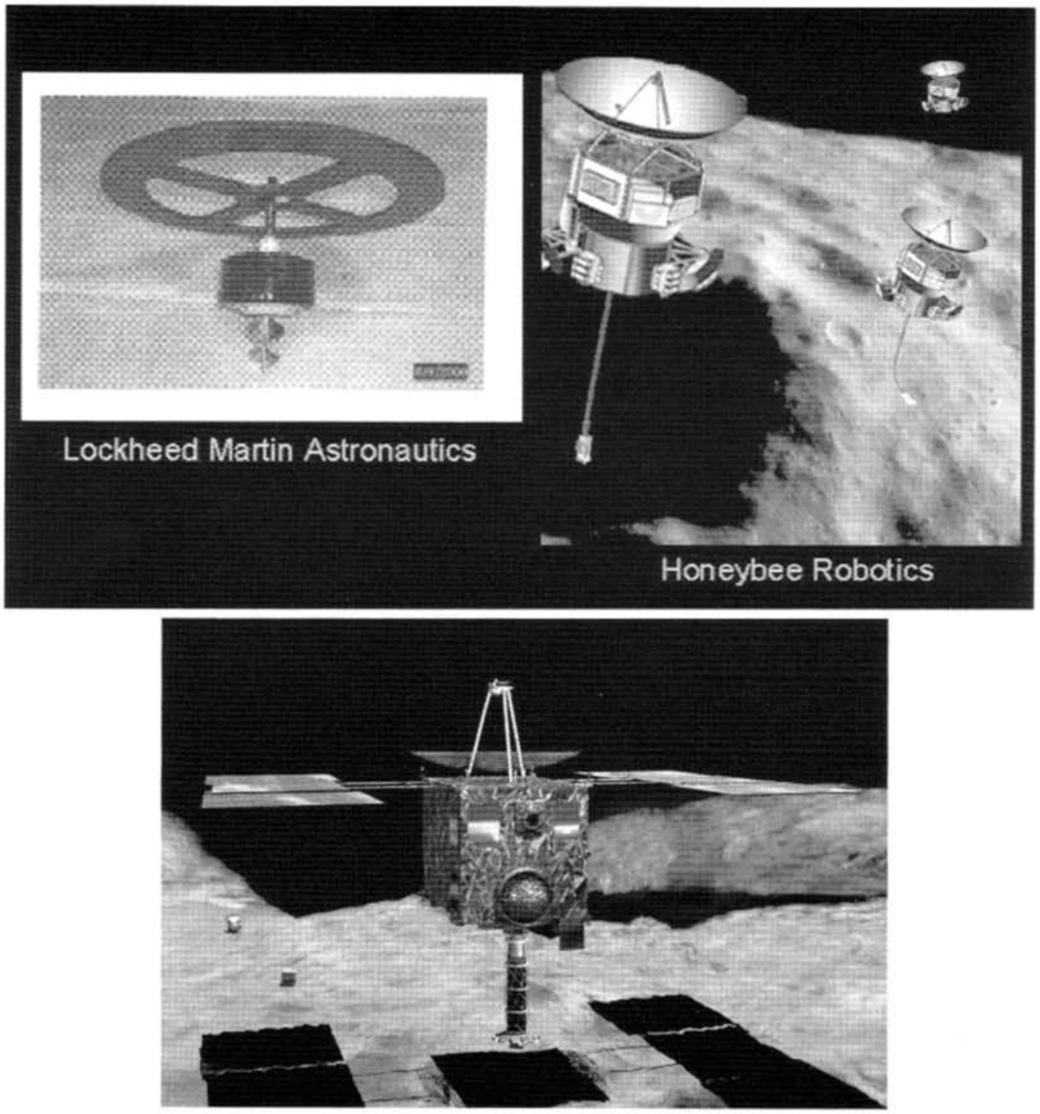

Figure 15.3 Sample collectors that have been proposed for use on asteroids that do not require the spacecraft to land. Lockheed-Martin has proposed a large auger attached to a momentum wheel, Honeybee Robotics has proposed a device with two counter-rotating cutters, while MUSES-C fires projectiles into the surface and collects the ejecta. SpaceWorks have also proposed sticky footpads on the end of articulated arms.

on the surface of asteroids needed to be performed analogous to the large volume of work performed simulating the surface conditions of comets (Sears *et al.* 1999). We have, therefore, constructed the Andromeda planetary environmental chamber. The chamber has been described elsewhere (Sears *et al.* 2002b) but essentially consists of a stainless steel cylinder 70 cm in diameter and 2 m long which is wrapped in heating elements and three sets of cooling coils, which may contain liquid nitrogen, methanol-CO_2 slurry, or chilled water. A stainless steel container

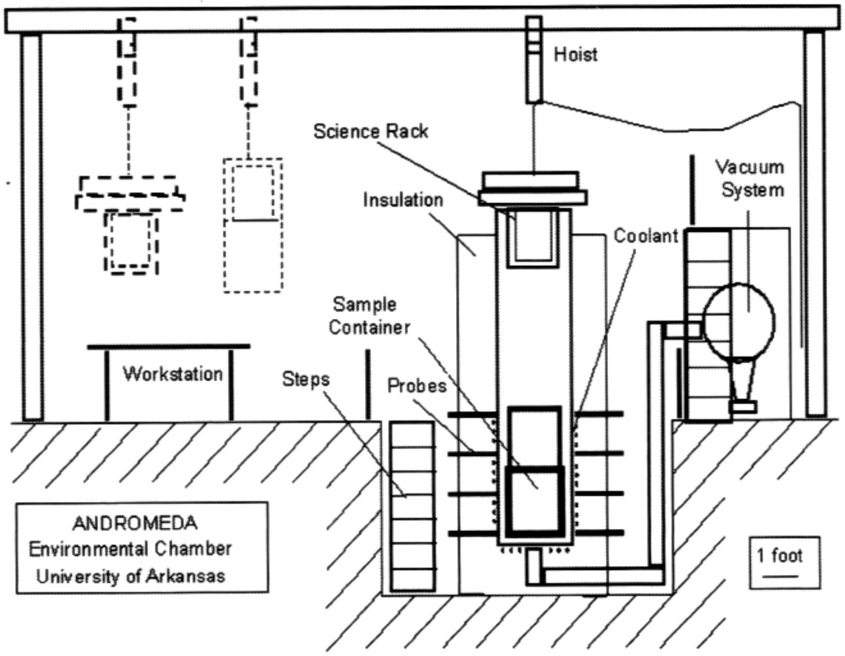

Figure 15.4 The Andromeda planetary environmental chamber at the University of Arkansas. This apparatus is being used to simulate conditions on the surface of asteroids except for gravity. Three sets of coolant coils are wrapped around the chamber, one for liquid nitrogen, one for methanol-CO_2 slurry, and one for chilled water. In addition, the chamber is wrapped with heater cable.

that can hold 1 m^3 of soil simulant can be lowered into the chamber and a lid holding a number of environmental simulators (solar lamps, power laser) and measuring instruments seals the chamber. A visible spectrometer, mass spectrometers, gas chromatograph, and closed circuit digital television cameras are also installed in the chamber (Fig. 15.4).

As an example of the sort of observations that can be made in the chamber Fig. 15.5 shows a small crater containing a "pool" of fine-grained material. The whole structure resembles the ponds on Eros. These features were made when frozen cultures were buried in the chamber as part of an experiment to investigate the survivability of anaerobic microorganisms on Mars. Upon exposure to vacuum, the water evaporated and the flow of gases upward produced the crater and size-sorted the grains to produce the fine-grained pools. Previously it had been suggested that the Eros ponds are the result of electrostatic levitation of grains and flow into small craters, or that they are the result of seismic shaking of regolith on the asteroid. Our results suggest an additional possibility which is that the ponds are due to the mobilization of dust in the surface by escaping fluids. Some meteorites are up to

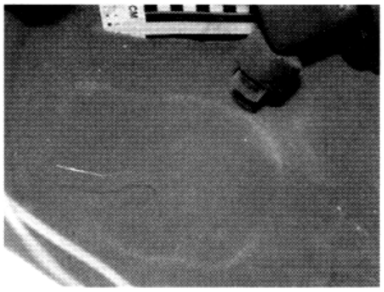

Figure 15.5 Inside a bucket in the chamber of the Andromeda planetary environmental chamber. After escape of subsurface volatiles, craters containing ponds of fine-grained material were produced.

20 volume percent water and the low density of asteroids suggests that some of them might be ice-rich.

Laboratory studies have also been made on the Honeybee sample collector. The results are shown in Table 15.1. The collector worked well at picking up gravel with only two attempts out of twelve failing to pick up a sample. Typically two pieces of gravel were collected. Only one attempt out of six failed to pick up a sample of gravel and sand, but the reproducibility in picking up sand and gravel in the original proportions was poor. The efficiency of picking up sand and iron filings was also very high and the reproducibility of picking up iron and sand in the original proportions was excellent.

3 Campaign I

During the first campaign, 310 Plexiglas tubes 2.5 cm in diameter and 10 cm long were filled with various sand and iron mixtures and flown (Fig. 15.6). The sand grains had mesh sizes of 149–250, 250–300, 300–425, and 425–600 and the iron filings had mesh sizes of 74–105, 105–149, and 149–250. The sand to iron volume ratio was 19 : 1. These values of grain size and sand–metal proportions are guided by the values observed in chondritic meteorites. Air was passed through the beds at a predetermined rate during the period of microgravity to simulate the release of volatiles or mechanical disturbance and a plunger was depressed to freeze the columns before the plane pulled out of free fall. About 25% of the tubes that acted as controls were released and sealed without any air flowing through the tubes. Separation of iron and sand was determined from image analysis of photographs of the tubes after flight and from the measurements of removed samples.

An example of the results from campaign I is shown in Fig. 15.7. Many of the tubes showed a tendency for the sand to iron ratio to be smaller in the lower half of the 10-cm bed than in the upper part of the bed. Experiments in the

Table 15.1 *Collection details for sand and gravel in the laboratory tests of the sampler*

Sample	Number of chips	Gravel g	Sand g	Iron g	w/w
Gravel	1	0.219	–	–	–
Gravel	0	–	–	–	–
Gravel	4	2.978	–	–	–
Gravel	0	–	–	–	–
Gravel	5	5.05	–	–	–
Gravel	1	1.313	–	–	–
Gravel	2	2.912	–	–	–
Gravel	5	7.756	–	–	–
Gravel	2	2.812	–	–	–
Gravel	2	4.047	–	–	–
Gravel	2	2.633	–	–	–
Gravel	3	2.975	–	–	–
Sand+Gravel	2	1.203	1.387	–	0.87
Sand+Gravel	1	0.638	0.519	–	1.23
Sand+Gravel	0	–	0.12	–	–
Sand+Gravel	2	1.397	0.058	–	24.1
Sand+Gravel	3	2.886	2.092	–	1.38
Sand+Gravel	1	0.114	0.536	–	0.21
Sand+Gravel[a]	–	–	–	–	0.72
Sand	–	–	8.319	–	–
Sand	–	–	9.719	–	–
Sand	–	–	7.382	–	–
Sand	–	–	9.354	–	–
Sand	–	–	7.782	–	–
Sand	–	–	5.118	–	–
Sand+iron	–	–	5.836	2.929	1.99
Sand+iron	–	–	3.249	1.433	2.27
Sand+iron	–	–	0.689	0.382	1.80
Sand+iron	–	–	1.792	0.806	2.22
Sand+iron	–	–	2.468	1.174	2.10
Sand+iron	–	–	2.211	1.055	2.10
Sand+iron[a]	–	–	16.479	8.335	1.98

[a] Control sample.

laboratory also showed that under certain circumstances metal rises to the surface due to its smaller grain size and greater tendency to be lifted in the gas flow (Akridge and Sears 1999). Ground tests also showed that this tendency for metal to rise increased with increasing size of the larger grain (in this case sand). We tested this by plotting the sand-to-metal ratio at 6–10 cm divided by the sand-to-metal ratio at 1–5 cm against sand particle size. Figure 15.7 shows that the tendency for metal and sand to segregate is related to the relative size of the grains.

Figure 15.6 Undergraduate students Ryan Godsey and Katrina Bogdon with the apparatus for campaign I. The apparatus consists of 310 2.5-cm Plexiglas tubes containing sand and iron files of chondritic grain sizes and in various proportions. The white "pistons" were depressed while the beds were under microgravity conditions in order to "freeze-in" any segregation that may have occurred during flight.

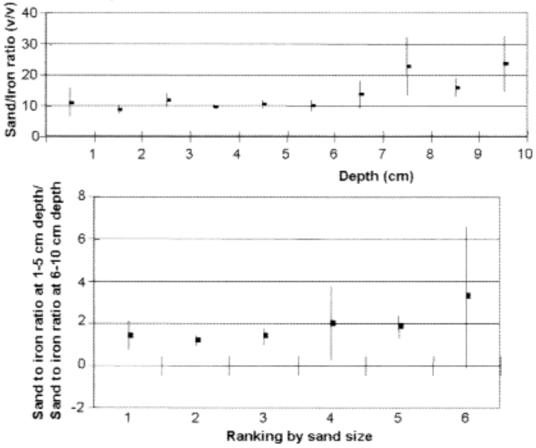

Figure 15.7 Examples of results from campaign I. In the upper graph, the sand-to-iron volume ratio was plotted against depth. The lower graph shows how the increase in sand-to-iron ratio with depth depends on the sand grain size. Tubes in which the sand-to-iron ratio is largest show the greatest tendency for segregation to occur.

Figure 15.8 Undergraduate students Amber Holley and Mike Meyer operating the apparatus for campaign II. The apparatus consists of two 15-cm Plexiglas cylinders containing sand and iron filings with similar grain sizes and in similar proportions to those of chondritic meteorites. The experimenters recorded the behavior of the beds using digital cameras as the KC-135 went through nearly 80 parabolas of positive gravity, microgravity, and negative gravity and then positive gravity again.

Further details of these experiments can be found in Franzen *et al*. (2003).

4 Campaign II

For the second campaign, the alternative approach of observing a limited number of tubes very closely was taken. Two 15-cm diameter Plexiglas cylinders containing sand–iron mixtures in approximately chondrite grain sizes and proportions (300–425 mesh sand and 74–105 mesh iron) were mixed in 20 : 1 proportions (by volume) and observed with digital cameras (Fig. 15.8). The behavior of the mixture, in particular the separation of iron and sand was noted and any surface structures were recorded digitally. An experimenter then viewed the data filling out a questionnaire.

Some sample results appear in Table 15.2 and Fig. 15.9. The behavior of the beds as the plane went through the gravity cycles was very reproducible. A few anomalies were associated with unusual accelerometer data and therefore with unusual parabolas. Nothing would happen during positive gravity, but as gravity lessened air flowing through the bed would cause the bed to rise and metal to migrate fairly quickly to the surface. Then negative gravity would cause the surface of the bed to rise in a swirl but the metal–sand stratigraphy would prove very resilient

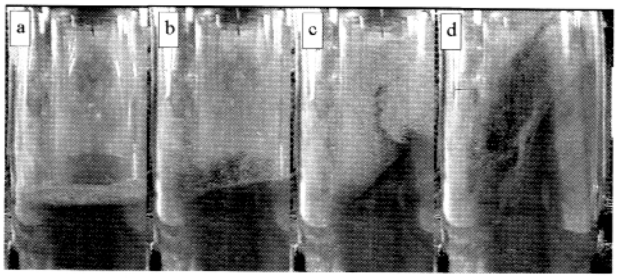

Figure 15.9 One of the experimental beds in campaign II as the KC-135 goes through a cycle of (a) positive gravity, (b) microgravity, (c) transitioning from microgravity to negative gravity, and (d) negative gravity while air flows vertically through the beds from below. As soon as the bed became mobilized, metal and sand separated with the metal moving to the top. This segregation survived considerable subsequent movement of the beds.

only to be lost when complete chaos set in (Fig. 15.9). In beds in which no air was flowing, no segregation was observed. Table 15.2 is a small fragment of our observations, but it illustrates the behavior of the beds and the contrast between cases in which air flowed and did not.

Further details of these experiments can be found in Moore *et al.* (2002).

5 Campaign III

The third campaign was essentially a test of the Honeybee Robotics touch-and-go surface sampler being considered as a possible sample collector for the Hera mission (Rafeek and Gorovan 2000). This device consists of two counter-rotating cutters that eject material into a cylindrical container with front doors, to allow collection, and a trap door below to allow ejection into the spacecraft container (Fig. 15.10). The collector was mounted on a vertical rail inside a double-walled enclosure and attempts were made to sample four surface stimulants: sand, sand and iron mixtures, sand and gravel mixtures, and concrete.

The samples consisted of 500 μm sand, 500 μm sand and 200 μm iron filings mixture (sometimes with 10% by volume 1–2-cm sized gravel pieces representing "clasts"), gravel, and concrete. The tests were designed to address several specific questions. Did the collector work under microgravity conditions? How much mass can be transferred by a 1–2-s touchdown? Did the collector change the metal–silicate ratio? Did the collector change the size distribution of the surface materials? What is the largest particle the collector could collect?

The results are shown in Table 15.3. Attempts to collect gravel and concrete were very successful, and although the concrete mass recovered was small it would still be enough for several laboratory measurements. The difficulties were with sand and iron filings, where a large number of attempts failed to collect material and where

Table 15.2 *Sample of data*[a] *obtained from campaign II*

Parabola	Gas flow	Description of bed at reduced gravity	MSF[b]	Flotsam
1	Yes	Fluid, turbulent (wave-like), spouting	Yes	Metal
2	Yes	Fluid, turbulent (wave-like), spouting (went to the side)	Yes	Metal
3	Yes	Was well mixed but data was inconclusive	Yes	Metal
4	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
5	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
6	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
7	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
8	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Mixture
9	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
10	Yes	Fluid, turbulent (wave-like), spouting in middle, right twist	Yes	Metal
17	No	Hard to see trends, top layer rises	No	Mixture
18	No	Hard to see trends, top layer rises	No	Metal
19	No	All fell to the left of the cylinder	No	Unclear
20	No	Hard to see trends, top layer rises, metal spouts in middle	No	Unclear
21	No	Hard to see trends, top layer rises, metal spouts in middle	No	Unclear
22	No	Inconclusive	No	Metal
23	No	Inconclusive	?	?

[a] The full data set consists of about 80 parabolas (see Moore *et al.* 2002).
[b] Metal silicate fractionation, i.e., did the metal separate from the silicates?

the collector repeatedly jammed. After the second day of the flight tests, when the collector was stripped down for shipping, an iron-filing/sand mixture was found in the collector space with exactly the proportions of the original sample.

6 Summary of major findings as they concern mission operations

The major results of the three campaigns, in terms of implications for mission operations on the surfaces of asteroids and comets were several.

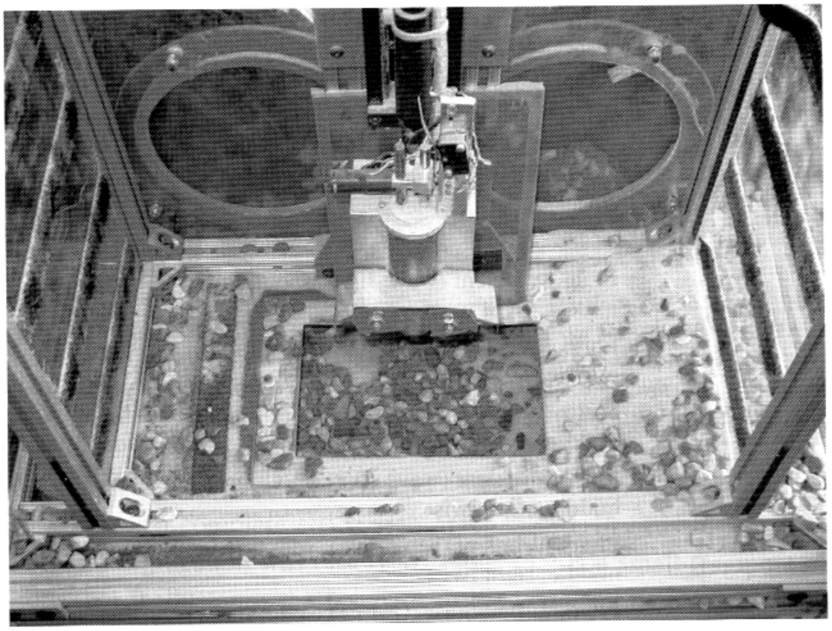

Figure 15.10 A sample collector developed by Honeybee Robotics, New York, in test apparatus designed by SpaceWorks aboard the KC-135 during campaign III. Regolith simulants consisting of sand, gravel, sand and gravel, sand and iron filings, and concrete were used for the tests.

Particle size sorting of the surface material occurs readily

While there are many details yet to be understood, it seems clear that segregation of minerals with different physical and chemical properties will occur readily on asteroid surfaces when the surface is disturbed. Aerodynamic sorting is an important process when the surface is degassing as a result of the disturbance, but mechanical sorting alone will also segregate grains with different physical properties like size and density. Furthermore, these segregations, once produced, are quite resistant to mixing by subsequent activities.

Segregations that occurred early in the process are retained during considerable amounts of subsequent activity

We were able to observe repeatedly that the stratigraphy introduced by the initial stages of microgravity, with a dark layer of metal at the surface of the beds, persisted as the bed was lifted by the negative gravity pulse and "faulted" as part of the process of swirling to the top of the chamber. While the surface grains are being subjected to considerable and fairly complex forces they are all suffering the same processes and tend to move together.

Table 15.3 *Collection details for gravel and concrete for the KC-135 tests of the sampler*

Sample	Number of chips	Mass (g)
Gravel	9	9.034
Gravel	2	3.356
Gravel	1	0.879
Gravel	4	~4
Gravel	1	~1
Gravel	1	0.422
Gravel	1	0.483
Concrete	–	0.041
Concrete	–	0.021
Concrete	–	0.053
Concrete	–	0.128
Gravel	1	1.595
Concrete	–	0.335
Concrete	–	0.026
Gravel[a]	19	25.4

[a] Control.

It was difficult to "see-through" the periods of negative g, which are an artifact of the KC-135 tests and would not be present during sample collection on an asteroid

However, perhaps the major lessons learned from the experiments are the problems posed by negative gravity on the present KC-135 tests. This negative gravity pulse would not occur during surface operations on an asteroid.

Laboratory versus flight tests

A most significant result is that though the collector worked well on the ground, it worked far less well under microgravity conditions. Under microgravity conditions there was movement of the disturbed surface in all directions but mostly away from the collector and this was a big problem. In addition, once material had been thrown into the collector by the component engaging the surface, it would tend to move out again. An important message here is that intuition and experience applies to the Earth-gravity environment and we take much for granted. Surfaces do not move away from us on Earth and material thrown into a container stays there. For this reason and others, clogging of moving parts in such a dusty environment was also a problem, especially since the dust was mobile in a fashion different from that in the terrestrial environment.

7 Implications

Implications for science

The tendency of the material to segregate easily has implications for both the science of performing surface operations on asteroids, and for the engineering. First, it means that the science value of the returned materials will be compromised if the sample collection procedure alters their surface proportions. For example, the ratio of silicates to metal is an important characteristic of the major chondrite classes and the cause of the metal–silicate fractionation is the subject of considerable discussion by cosmochemists. Similarly, an important and highly enigmatic component in primitive meteorites are the chondrules, ~200-μm crystallized glass beads whose origin has perplexed scientists for 200 years. Chondrules will readily segregate from other smaller components under microgravity conditions, especially since one of the smaller components is metal which also has a higher density that could enhance its tendency to segregate. Finally, but related to the previous two points, is that cosmochemists have developed a number of ideas and theories relating to even small (10–20%) deviations in bulk composition. All of these fundamental studies in cosmochemistry would be jeopardized if the material returned had suffered segregations during collection. The irony is that the predicted segregations concern the very components that are at the heart of understanding meteorite genesis.

Implications for engineering

For engineering there are two implications. First, chondritic metal is very ductile, and will readily clog moving parts. If segregation causes localized enrichments of metal on the surface of the asteroid then these would be a hazard to equipment that collects the samples with an instrument dependent on moving parts. More significantly, science calls for a collector design that does not cause segregations of the surface materials. Several options are possible. A collector might be designed that identifies an area and then picks up everything in that area regardles of physical properties. Alternatively, a collector might be designed that picks up coherent rocks, or soil clods, and not unconsolidated material. This also jeopardizes the value of the samples somewhat, since significant science related to space weathering and the interpretation of astronomical spectra, and the whole field of solar interactions, requires the fine-grained surface materials.

Implications for future work

It is clear that surface operations on asteroids require an apparatus that will disturb the surface as little as possible, and should collect rocks and clods as well as unconsolidated material. We do not yet have such a collector, but at least we have defined its chief characteristics. It also seems clear that we should be cautious in relying on experience and intuition, because they are not only of minimal relevance but may actually be misleading. Instead, we must rigorously test equipment in a reasonable microgravity environment. There are serious difficulties in using the KC-135 as a test bed for microgravity operations. Although we have not yet explored options for handling these problems, some improvements might include a test rig that "floats" rather than being anchored to the floor of the aircraft, or an apparatus that covers the simulated surface materials during negative gravity and reveals them only during microgravity. A more promising approach might be to use drop towers, the Shuttle, or the International Space Station. Simple collectors with a minimum of moving parts and with as much dust protection as possible are required. Collectors that cover or retain the surface materials as they are collected stand the best chance of success for recovering the most scientifically valuable samples.

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References

Akridge, D. G. and Sears, D. W. G. 1999. The gravitational and aerodynamic sorting of meteoritic chondrules and metal: experimental results with implications for chondritic meteorites. *J. Geophys. Res.* **104**, 11853–11864.

Bogdon, K., White, C., Godsey, *et al.* 2000. The origin of chondrites: metal–silicate separation experiments under microgravity conditions. *Meteorit. Planet. Sci.* **35** (supp.), A30.

Britt, D. T., Sears, D. W. G., and Cheng, A. F. 2001. Asteroid sample return: 433 Eros as an example of sample site selection. *Meteorit. Planet. Sci.* **36**, A30–31.

Franzen, M., Nichols, S., Bogdon, K., *et al.* 2003. The origin of chondrites: metal–silicate separation experiments under microgravity conditions – I. *Geophys. Res. Lett.* **30**, issue 14, SSC7–1.

Moore, S. R., Franzen, M., Benoit, P. H., *et al*. 2002. The origin of chondrites: Metal–silicate separation experiments under microgravity conditions – II. *Geophys. Res. Lett*. **30**, issue 10, 29–1.

Nygren, W. D. 2000. Rapid remote sample collection mechanism for near-Earth asteroid sample return. In *Near-Earth Asteroid Sample Return Workshop (abstracts)*, Lunar and Planetary Institute, Houston, TX, LPI Contribution no. 1073.

Rafeek, S. and Gorovan, S. 2000. NEA touch and go surface sampler. In *Near-Earth Asteroid Sample Return Workshop (abstracts)*, Lunar and Planetary Institute, Houston, TX, LPI Contribution no. 1073.

Robinson, M. S., Thomas, P. C., Veverka, J., *et al*. 2002. The geology of 433 Eros. *Meteor. and Planet. Sci*. **33**, 1651–1648.

Sears, D. W. G. and Clark, B. C. (2000) Sample collection devices for near-Earth asteroid sample return. In *Near-Earth Asteroid Sample Return Workshop (abstracts)*, Lunar and Planetary Institute, Houston, TX, LPI Contribution no. 1073.

Sears, D. W. G., Kochan, H. W., and Huebner, W. F. 1999. Laboratory simulation of the physical processes occurring on and near the surface of comet nuclei. *Meteor. and Planet. Sci*. **34**, 497–525.

Sears, D. W. G., Allen, C., Britt, *et al*. 2001. Near-Earth asteroid sample return missions. In *Space 2001 Conference and Exposition*, Albuquerque, NM, Paper no. 2001-4728.

2002a. Near-Earth asteroid sample return. In *The Future of Solar System Exploration, 2003-2013: Community Contributions to the NRC Solar System Exploration Decadal Survey, 2003-2013*, pp. 111–139.

Sears, D. W. G., Benoit, P. H., McKeever, S. W. S., *et al*. 2002b. Investigation of biological, chemical and physical processes on and in planetary surfaces by laboratory simulation. *Planet. Space Sci.* **50**, 821–828.

Sears, D. W. G., Franzen, M., Bartlett, P. W., *et al.* 2002c. The Hera mission: laboratory and microgravity tests of the Honeybee Robotics touch-and-go sampler. *Lunar Planet. Sci*. Conf. **33**, Abstract no. 1583.

Whiteley, R. J., Tholen, D. J., Bell, J. F., *et al*. 2000. Sample return from small asteroids: mission impossible? In *Near-Earth Asteroid Sample Return Workshop (abstracts)*, Lunar and Planetary Institute, Houston, TX, LPI Contribution no. 1073.

Yano, H., Fujiwara, A., Hasegawa, S., *et al*. 2000. MUSES-C's impact sampling device for small asteroid surfaces. In *Near-Earth Asteroid Sample Return Workshop (abstracts)*, Lunar and Planetary Institute, Houston, TX, LPI Contribution no. 1073.