

Near-Earth Asteroid Sample Return

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Abstract. The NEA Sample Return Community Panel for the NRC Decadal Study was assembled from selected participants of the Near-Earth Asteroid Sample Return Workshop held at the Lunar and Planetary Institute in December 2000 and summarized in presentations at the 33rd Lunar and Planetary Science Conference and the American Institute of Aeronautics and Astronautics' Space 2001 meeting in Albuquerque. Detailed views on the scientific value of NEA sample return of the many of the individual panel members prior to panel discussions can be obtained in the abstract volume for the workshop. This paper represents efforts

of the panel between June and November 2001 and was presented to the NRC Primitive Bodies Discipline Panel on 25th October 2001.

EXECUTIVE SUMMARY

A unique source of information about the early solar system, the formation of the planets, and the connection between stars and our Sun, are the meteorites and asteroids, yet studies of both are hindered by a lack of unequivocal and detailed information linking the meteorites and asteroids. Meteorites are rock samples of unknown provenance. We have no information about the geological context of the source of meteorites. They are also highly non-representative sampling of primitive solar system material because the terrestrial meteorite population is dominated by the ejecta of stochastic impacts and because the atmosphere filters out all but the toughest rocks. Without sample return, asteroids are not amenable to the depth and breadth of techniques available in the laboratory, yet the NEAR images indicate that there are many processes occurring on asteroids - or that could have occurred in the past - that we must understand if the meteorite data are ever to yield a clear image of early solar system processes. Technical developments of the last few years - the success of the NEAR-Shoemaker and Deep Space 1 missions, the progress of the technology development mission MUSES C, and the availability of sample collection and containment apparatus and the discovery of large numbers of NEA - mean that sample return from multiple asteroids is now within small mission capability. NEA sample return missions lend themselves well to Education and Public Outreach efforts, present few and well understood planetary protection issues, have a well established research and management infrastructure already in place, are excellent opportunities for international cooperation and pooling resources, integrate well into existing mission plans, have a part to play in the human exploration and development of space effort, and, most importantly, have the highest scientific priority.

REPORT

1. Current State of Knowledge

1.1. Primitive meteorites and the objects from which they come (asteroids and comets) offer unique insights into a wide variety of early solar system processes.

Primitive solar system bodies (comets and asteroids) have the potential to provide unique information about the early solar system and the material it contained. Meteorites and cosmic dust are samples of these bodies that are falling naturally to Earth. They have been intensely studied (Kerridge and Matthews 1988, Hewins et al. 1996). While much can be learned from cosmic dust, considerably more has been learned from meteorites, which can be studied on the macroscopic scale by a wide variety of very sophisticated techniques. Primitive meteorites have ages comparable to the age of the solar system, they have bulk compositions very similar to that of the Sun, and they have unique textures, sometimes being referred to as "cosmic sediments". The major components are

chondrules and refractory inclusions, metal and sulfide grains, and a fine-grained matrix. It has been argued that trace components in primitive chondrites, such as graphite, diamond, silicon carbide, and alumina, probably have an interstellar origin.

Detailed chemical and physical studies of primitive chondrites enables subdivision into a number of discrete classes, the largest of which are the ordinary chondrites, the H, L and LL chondrites, but especially significant scientifically are the rare carbonaceous chondrites, some of which can be up to 20% water by volume (Sears and Dodd 1988). The classes show subtle but significant deviations in composition from those of solar abundances. The existence of these classes and the physical and chemical trends they represent are important clues to processes occurring in the early solar system. One such process is the separation of silicates and metal. Another is volatile loss. Yet another is associated with the formation of the chondrules, glassy silicate droplets containing conspicuous crystal structures. Early solar system processes also resulted in variations in elemental abundance and isotopic proportions of oxygen. It is not clear what caused these variations in property or how they relate, but it is clear that they represent fundamental processes in the early solar system.

A variety of dating techniques have not only shown the antiquity of primitive meteorites, but have made it possible to resolve a great many events, some of them involving small time intervals for events occurring many years ago, such as the time interval between the end of nucleosynthesis and meteorite formation. Other dating techniques have identified the times of major and lesser breakup events. We return to this below. Near-Earth Asteroids (a few of which might be extinct comets) are the immediate parent bodies of primitive meteorites and returned samples will provide new insights into processes witnessed by the meteorites.

It seems clear that the asteroids are material that was prevented from accreting into planet by gravitational interaction with Jupiter and Saturn and that they are thus primitive solar system material (Binzel et al. 1989, SSB 1998). Size distributions and families of asteroid sharing similar orbits suggest that, except for the largest few, they are fragments resulting from multiple collisional break-ups. A few have satellites and many appear bifurcated, consisting of two lobes. The spectra of sunlight reflected from the asteroids indicates that they are compositionally very diverse, ranging from carbonaceous material not unlike the carbonaceous chondrites through silicate rich material superficially resembling the ordinary chondrites to metallic asteroids resembling iron meteorites (Binzel et al. 1989). In a few cases, it is possible to link meteorite classes with asteroid types by a convincing match of their spectra, especially if allowance is made for alteration of the surface by possible space weathering effects.

It is thought that nearly 1600 asteroids are in orbits that bring them close to the Earth (i.e., perihelia < 1.3 AU), and nearly 350 pass close enough to the Earth to be considered as potentially hazardous (< 1.3 AU, diameter > 200 m or $H < 22$). The NEA are in intrinsically unstable orbits with lifetimes on the order of 108 years and the population must be continually replenished from the main belt or from sources deeper in the solar system. In terms of their spectral classification, the population of NEA is very similar to that of the main belt.

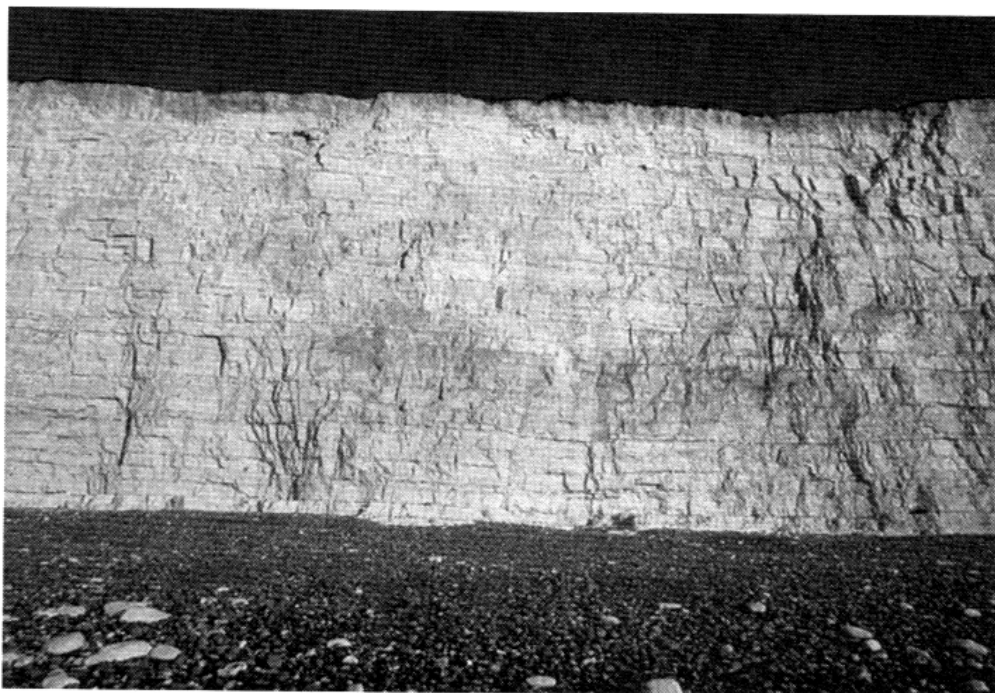


Figure 1. A pebble beach at the foot of the White Cliffs of Dover on the southeast coast of England (Corbis.com, with permission). Meteorites have the potential to tell us much about the origin and history of the early solar system, but they are cosmic jetsam, brought to Earth after a number of selection and alteration effects. Attempts to learn about the early solar system from them are somewhat analogous to learning about the geology of southern England from the pebbles on the beach instead of visiting the chalk cliffs themselves.

Many new insights have been obtained over the last one hundred years or so of primitive body research, but many questions have arisen and unequivocal answers to some fundamental questions - like the origins of the meteorite and asteroid classes and their characteristic properties - are still lacking. Our panel suggests that missions to return samples from near-Earth asteroids will provide major opportunities to for advancement in both meteorite and asteroid research and therefore in our understanding of some of the most fundamental questions in planetary science, the origin and early evolution of the solar system and the processes by which interstellar material becomes new planetary life-bearing systems.

1.2. Returned samples I - New kinds of primitive material, or “Why bring back asteroid samples when we have meteorites?”

Meteorites are, in effect, cosmic jetsam. The meteorite samples reaching the Earth are biased towards the fragments of bodies that recently broke up and towards materials strong enough to survive the rigors of reaching Earth. We are, in effect, trying to determine the formation of a mountain from stream

wash deposits rather than visiting the outcrop. A terrestrial analogy might be the chalk cliffs of southern England (Figure 1). At the base of every cliff is a pebble beach of flint nodules that have weathered out of the chalk. How difficult it would be to determine the geological history of the cliffs, and the large regions of England they represent, by looking only at the pebbles and knowing nothing about the chalk.

The Yarkovsky effect - uneven radiation pressure on a spinning object in space - ensures that small (~ 10 cm) samples of most material in the inner part of main belt reaches the vicinity of the Earth. In addition, the largest and most famous meteorite classes come from a few bodies that were broken up by impact relatively recently. They may have been located near dynamically favorable locations in the solar system, such as near resonances with Jupiter and Saturn. The existence of this event is demonstrated, and its age apparent, from preferred values in their cosmic ray exposure ages, in the case of the H chondrites (Figure 2), and their Ar-Ar ages (Figure 3), in the case of the L chondrites. We do not see similar preferred ages, or even sensible cosmic ray ages for the more primitive carbonaceous meteorites. Such fragile material is does not survive impacts but is continually abraded in space so that a single meaningful exposure age is not apparent.

Probably the major process removing the most primitive meteorites from the Earth's meteorite collection is passage through the Earth's atmosphere. Only tough material reaches the surface of the Earth while the fragile water-rich and particularly primitive materials are destroyed during atmospheric passage (Figure 4). Quantitative modeling by aerospace engineers interested in spacecraft reentry show that primitive carbonaceous meteorites suffer 1000-fold greater mass attrition during atmospheric passage compared with the tough ordinary chondrites that are the dominant meteorite classes on Earth (Figure 5). It seems almost certain that many kinds of currently unknown primitive materials exist in the asteroid belt. Perhaps relevant to this are the measured densities of asteroids that are lower than those of ordinary chondrites and only the largest of which are comparable with carbonaceous chondrites. Whether this reflects abundant volatiles or an unusual internal texture is unclear, but it does indicate that meteorites are giving an incomplete story about the nature of primitive solar system material.

Tantalizing evidence that there is primitive material not surviving atmospheric passage are a few spectacular falls, like Revelstoke and Tagish Lake. These are meteorites that produced large amounts of dust in the atmosphere, and huge visual and audible effects, but deposited very little in the way of macroscopic meteorites on the surface of the Earth. If reports had not been widely disseminated and search teams quickly on the spot, it is doubtful that any material would have been recovered. The small samples that were recovered were found to be very friable, carbon and water-rich meteorites. Every year there are thousands of bright fireballs that deposit no material on the Earth. Are these samples of new kinds of primitive material, full of undreamed of information about the solar system's formation and early history?

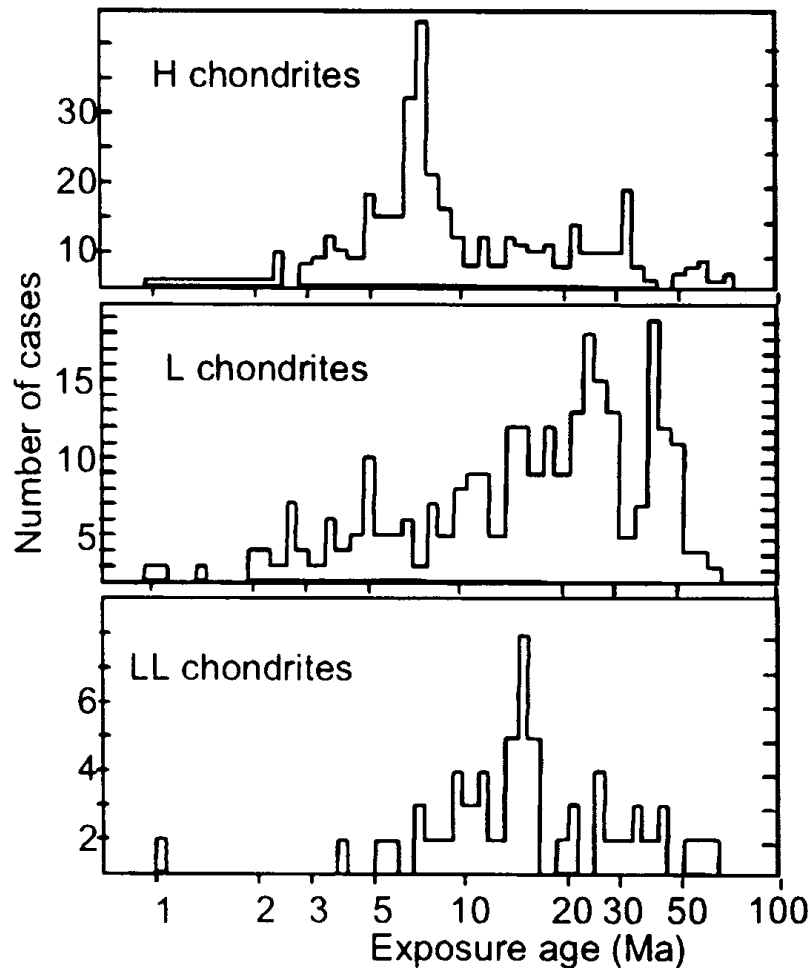


Figure 2. Cosmic ray exposure ages for the ordinary (H, L and LL) chondrites (Marti and Graf 1992). The peak in the distribution of cosmic ray ages for H chondrites at 8 Ma suggests that large numbers of these meteorites became exposed to cosmic radiation at this time by fragmentation into meter-sized chunks. The LL chondrites show a similar peak at 17 Ma. Some authors have argued that the L chondrites show evidence for a number of such major fragmentation events. Apparently, a large fraction of the meteorites in these classes shared a common parent body until very recently in solar system history. The carbonaceous chondrites do not show preferred values in their cosmic ray exposure ages which is commonly interpreted to mean that these friable rock continually break up during their passage through space. They also contain large amounts of inert gases trapped in their primary textures, so it is difficult to detect the cosmic ray produced gases over this large background.

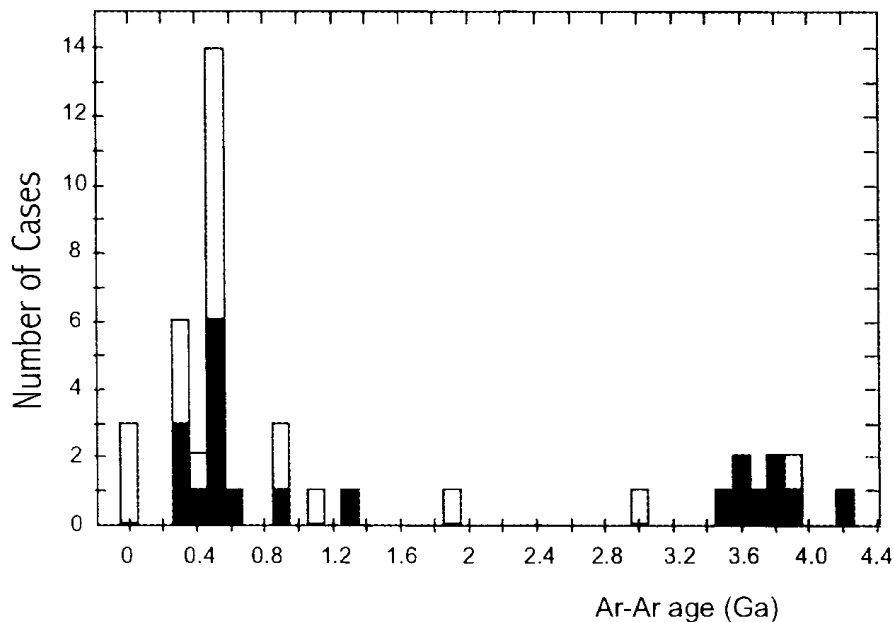


Figure 3. Argon-argon ages for L chondrites (Bogard 1995). The peak in the distribution of these ages at 500 Ma indicates that a major disruption of a common parent body (asteroid) at this time that heated the meteorites and caused the loss of accumulated Ar and thus a resetting of the chronometer. Meteorites plotting in the 500 Ma peak show a number of petrographic symptoms of shock heating.

1.3. Returned samples II - The value of context, or “Why bring back asteroid samples when we have meteorites?”

To return to our chalk cliffs of England, aside from knowing that there was chalk in the cliff, in addition to the pebbles of the beach, a terrestrial geologist would need to know whether the cliff made mainly of pebbles, or whether the pebbles are rare nodules that preferentially survive weathering, albeit somewhat altered. If we suspected the chalk existed, without ever seeing it, would we have any way of knowing whether the flint is spread uniformly through the chalk, or in narrow time horizons? Studying cosmic jetsam also means that not only do we not know what type of asteroid the meteorites are from, but we do not know the geological context from which the samples came. We do not know whether the samples are from inside a crater, from the crater rim, from the ejecta blanket of a crater, from bedrock, from the surface, from depth, from rare veins of particularly tough material, or from some other undreamed-of geological feature. No terrestrial geologist would think of discussing the origin and history of a rock without knowing its geological context. The NEAR-Shoemaker spacecraft presented a whole new world of structures and features and a number of scenarios in which meteorites could have formed (Figure 6). There were craters and ejecta blankets, linear structures and grooves, boulder strewn fields, regions of uninterrupted regolith (Veveřka et al. 2001) and curious flat regions of apparently fine-grained



Figure 4. A painting of the fall of the Sikhote Alin meteorite in eastern Siberia in 1947. Sikhote Alin is an iron meteorite, yet it produced enormous amounts of dust in its trail. Carbonaceous meteorites that are weakly agglomerated and contain ~20% water are almost entirely destroyed by atmospheric passage and produce large amounts of dust in the atmosphere and very little survives to reach the surface of the Earth. It is to be expected that anything more friable and more water-rich like primitive material is expected to be will not survive at all.

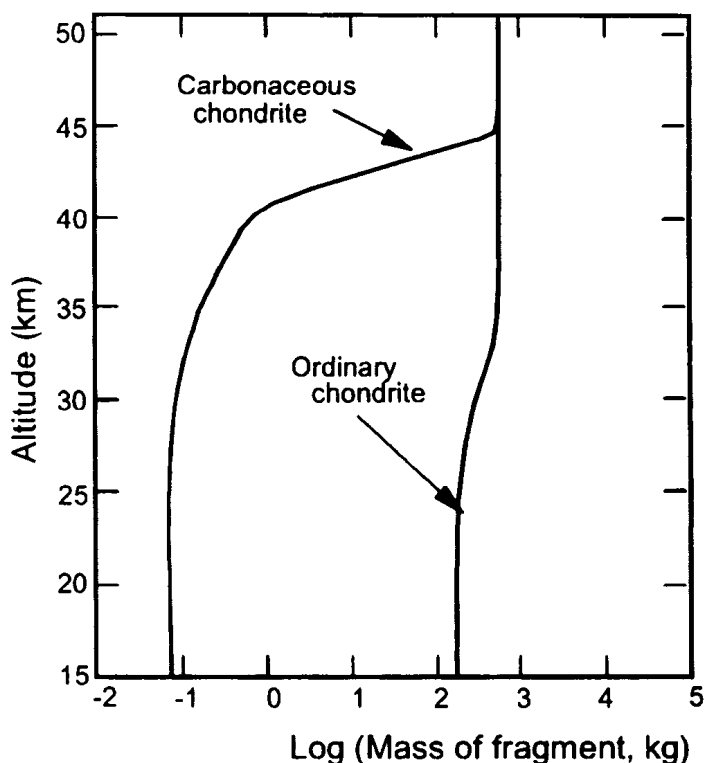


Figure 5. Altitude in the atmosphere against the mass of the surviving fragment of a body initially 1000 kg (Baldwin 1971). The fragmentation of carbonaceous meteorites (CI and CM chondrites) is approximately 1000 times greater than that of ordinary chondrites (H, L and LL chondrites) leading to a 1000-fold bias in favour of ordinary chondrites on Earth.

material that was raised relative to other local features often, but not always, in crater bottoms that have come to be known as “ponds” (Robinson et al. 2001). The NEAR-Shoemaker spacecraft revealed a wide range of environments in which meteorites might have formed.

There are a great many examples of how returned samples from known context might resolve long-standing questions in meteorite and asteroid studies and thus our understanding of conditions and processes in the early solar system. Two of the most fundamental questions in meteorite studies are (1) how did chondrules form, and (2) how were the various metal to silicate ratios produced. These questions relate to the formation of the chondrite classes in as much as every class has unique combination of metal-silicate ratio and chondrule and metal abundances and sizes (Glavin et al. 2000). Many researchers have argued that chondrules are impact melt droplets produced when a meteorite impacted the parent body, while others have argued that a process in the nebula produced the chondrules, perhaps lightning, perhaps one of many other proposed mechanisms. If it were found that samples rich in crater ejecta were rich in chondrules, while

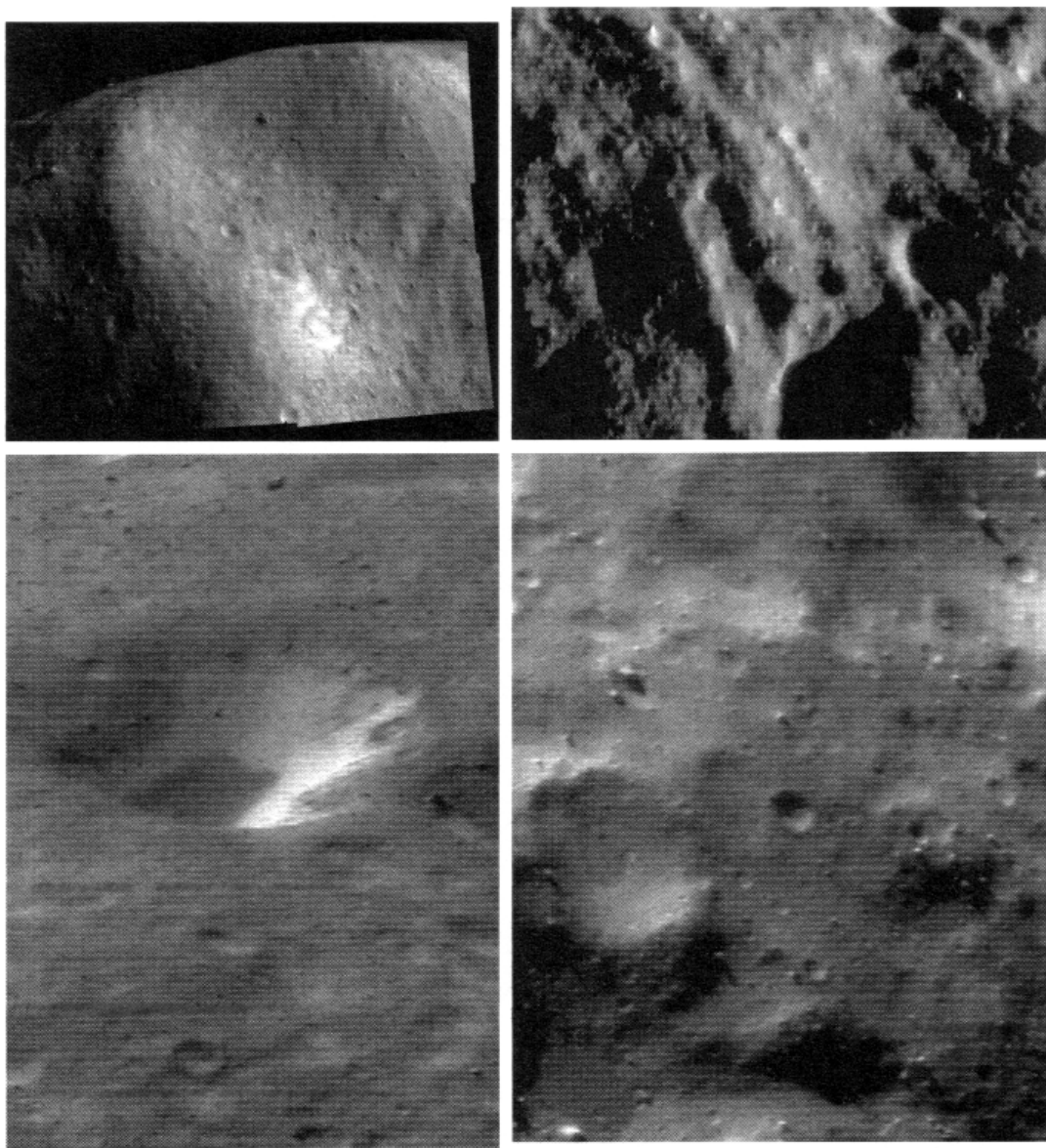


Figure 6. Surface textures on Eros, boulders, grooves, craters, and regolith (NASA). In addition, NEAR discovered flat areas of fine-grained material referred to as “ponds”.

samples from the interior or inter-crater plains were free of chondrules, then it would be clear that chondrules were impact melts. Until we do fieldwork on asteroids and bring back samples we will not know for sure if chondritic asteroids have interiors made of weak unconsolidated dirt or whether they contain chondrules throughout. Similarly, many authors have argued that metal silicate ratios reflect some unknown process that occurred in the solar nebula. However, if metal-silicate ratios on asteroid surface samples varied in some way, say with depth in the regolith or distance from major impact sites, then we might conclude that processes on the surface of the asteroids caused the metal silicate ratios. These are just two examples of specific questions that would be addressed with fieldwork and returned samples from chondritic asteroids. There are many more. Consider what was learnt from fieldwork and laboratory study of returned lunar samples. Without these tools we should still be arguing about whether volcanic action had created any of the lunar features that we now recognize to be impact craters and ejecta blankets. Until we do comparable field work on asteroids and study returned samples from selected sites we will not know which come from bodies that were heated to form cores, mantles and crusts. We will not know which S asteroids if any were partly melted or wholly melted and remixed by impacts.

Samples from the surface of asteroids will also enable us to characterize space weathering on asteroids, just as lunar samples enabled us to understand space weathering on the Moon. While one might expect certain similarities, differences due to the higher impact rate and velocity on asteroids and differences in target chemistry, especially the presence of volatiles, are to be expected. In fact, space weathering effects in samples returned from asteroids of different classes could be compared to such effects for lunar samples in an excellent example of comparative planetology. A fundamental understanding of space weathering would facilitate the interpretation of spectra for all asteroids. We return to this below.

1.4. The value of returned samples, or “Why return asteroid samples when we have in-situ techniques?”

The depth and breadth to which asteroid samples can be studied in terrestrial laboratories will always be many times greater than will be available from in-situ techniques as even the most cursory glance at the literature will demonstrate. The first report of the Tagish Lake meteorite in the technical literature included data for 78 elements using 10 techniques - most of them requiring sophisticated procedures that could only be performed on Earth (Table 1) (Brown et al. 2000). By comparison, in-situ analysis by the Pathfinder mission to Mars yielded data from 7 elements using one technique (Table 2) (Rieder et al. 1997). Aside from the volume of the data, the quality of data obtained in the laboratory was superior.

Not only can better data be obtained in the laboratory, but there are certain kinds of measurement that cannot yet be performed on robotic spacecraft but which are crucial to an understanding of the samples. The classic example is dating. About ten kinds of age can be determined by laboratory methods, while as of today none are available for in-situ measurements. Depending on the type of

Table 1. Analytical data for the Tagish Lake meteorite (Brown et al. 2000).

	Method	Concentration (ppm)		Method	Concentration (ppm)
H	Prt-Gm	1.5 ± 0.3 wt%	Cd	AQ-ICPMS	0.82 ± 0.16
Li	TD-ICPMS	2.5 ± 0.2	In	AQ-ICPMS	0.075 ± 0.005
Be	TD-ICPMS	0.052 ± 0.003	In	F-ICPMS	0.060 ± 0.007
B	Prt-Gm	0.8 ± 0.1	Sn	F-ICPMS	0.92 ± 0.09
C	C-IRA	3.6 ± 0.2 wt%	Sb	LL-INAA	0.17 ± 0.03
Na	LL-INAA	4450 ± 60	Te	AQ-ICPMS	1.5 ± 0.3
Mg	WRA-ICP	10.8 ± 0.5 wt%	I	SL-INAA	<0.2
Al	WRA-ICP	0.99 ± 0.03 wt%	Cs	F-ICPMS	0.146 ± 0.006
Si	WRA-ICP	11.4 ± 0.4 wt%	Ba	F-ICPMS	3.6 ± 1.2
P	TD-ICP	927 ± 50	Ba	TD-ICPMS	7.4 ± 0.8
S	C-IRA	3.8 ± 0.2 wt%	La	F-ICPMS	0.31 ± 0.02
Cl	SL-INAA	560 ± 90	La	LL-INAA	0.33 ± 0.03
K	TD-ICP	650 ± 50	Ce	F-ICPMS	0.81 ± 0.06
Sc	LL-INAA	7.2 ± 0.3	Pr	F-ICPMS	0.111 ± 0.007
Ti	WRA-ICP	520 ± 56	Nd	F-ICPMS	0.58 ± 0.03
V	F-ICPMS	57 ± 3	Sm	F-ICPMS	0.19 ± 0.02
V	SL-INAA	51 ± 1	Sm	LL-INAA	0.20 ± 0.02
Cr	LL-INAA	2840 ± 150	Eu	F-ICPMS	0.072 ± 0.004
Mn	WRA-ICP	1450 ± 150	Gd	F-ICPMS	0.24 ± 0.02
Mn	SL-INAA	1530 ± 77	Tb	F-ICPMS	0.049 ± 0.005
Fe	LL-INAA	19.3 ± 0.9 wt%	Dy	F-ICPMS	0.30 ± 0.04
Co	LL-INAA	517 ± 9	Ho	F-ICPMS	0.064 ± 0.006
Ni	LL-INAA	1.16 ± 0.08 wt%	Er	F-ICPMS	0.20 ± 0.02
Cu	TD-ICP	116 ± 5	Tm	F-ICPMS	0.032 ± 0.002
Zn	TD-ICP	253 ± 9	Yb	F-ICPMS	0.203 ± 0.009
Ga	F-ICPMS	8.4 ± 0.3	Yb	LL-INAA	0.21 ± 0.02
Ge	F-ICPMS	30 ± 2	Lu	LL-INAA	0.034 ± 0.006
As	LL-INAA	1.74 ± 0.06	Hf	F-ICPMS	0.18 ± 0.02
Se	LL-INAA	14.3 ± 0.4	Ta	F-ICPMS	0.022 ± 0.006
Br	LL-INAA	2.8 ± 0.2	Re	AQICPMS	0.056 ± 0.004
Rb	F-ICPMS	2.0 ± 0.2	Os	FA-INAA	460 ± 18 ppb
Sr	F-ICPMS	9.4 ± 0.5	Ir	FA-INAA	547 ± 10 ppb
Y	F-ICPMS	1.7 ± 0.1	Pt	FA-INAA	1.22 ± 0.05
Zr	F-ICPMS	6.0 ± 1.3	Au	LL-INAA	0.19 ± 0.03
Nb	F-ICPMS	0.31 ± 0.15	Tl	TDICPMS	0.090 ± 0.004
Mo	AQ-ICPMS	1.13 ± 0.09	Pb	AQICPMS	2.9 ± 0.8
Ru	FA-INAA	1.08 ± 0.09	Bi	AQICPMS	0.09 ± 0.02
Rh	FA-INAA	0.25 ± 0.02	Th	F-ICPMS	0.040 ± 0.008
Pd	FA-INAA	0.98 ± 0.09	U	F-ICPMS	0.008 ± 0.004

Table 2. Analytical results for the Mars surface rocks as determined by instruments on the Pathfinder spacecraft (Rieder et al. 1997)

	Method	Concentration
Na ₂ O	APXS	3.2 ± 1.3 wt%
MgO	APXS	3.0 ± 0.5 wt%
Al ₂ O ₃	APXS	10.8 ± 1.1 wt%
SiO ₂	APXS	58.6 ± 2.9 wt%
SO ₃	APXS	2.2 ± 0.4 wt%
Cl	APXS	0.5 ± 0.1 wt%
K ₂ O	APXS	0.7 ± 0.1 wt%
CaO	APXS	5.3 ± 0.8 wt%
TiO ₂	APXS	0.8 ± 0.2 wt%
FeO	APXS	12.9 ± 1.3 wt%
<i>Sum</i>		<i>92.7 wt%</i>

material, the dating method, and certain interpretations, laboratory techniques can determine the time interval the end of nucleosynthesis and agglomeration, the duration of agglomeration, time of accumulation, crystallization ages, time since the onset of inert gas retention, the age of major heating and degassing events, the time of metamorphism, time of aqueous alteration, the duration of exposure to cosmic radiation, the time on Earth, and for Antarctic meteorites the duration of burial and the time on the surface of the ice.

Returned samples also have the potential to be archived for future reference, pending new techniques and new ideas. The Apollo lunar samples archived at the Johnson Space Center have been the subject of a great many studies using equipment not dreamed of when the samples were collected. Most notable are probably micrometer scale variations in isotopic properties.

It is sometimes argued that one needs only to collect data of a quantity and quality needed to address specific questions and that if in-situ data are adequate for the problem then the additional expense of obtaining better data is not justified. This is true, and there are many science questions for which in-situ data has been sufficient to make major advances. But this is not true of questions relating to the composition, mineralogy, petrology, and isotopic properties of primitive solar system materials where the full arsenal of data is required. The problems are complex and diverse, and not amenable to a few very simple measurements made by simple automated instruments. This has been demonstrated repeatedly in meteorite studies - in-situ techniques could never have discovered extinct nuclides or complex diversity in elemental and isotopic properties of chondrules, for instance. The NEAR Shoemaker spacecraft carried instruments to characterize the mineralogy and chemistry of Eros from close orbit but was not able to answer the fundamental questions, such as the Mg/Si or Fe/Si ratio of the surface, the presence and type of chondrules, the ratio of metal to silicates, the oxygen content or the oxygen isotopic ratios of the surface materials (McCoy et al. 2001). It is doubtful that instruments specifically designed for in-situ measurements on the surface would have fared much better.

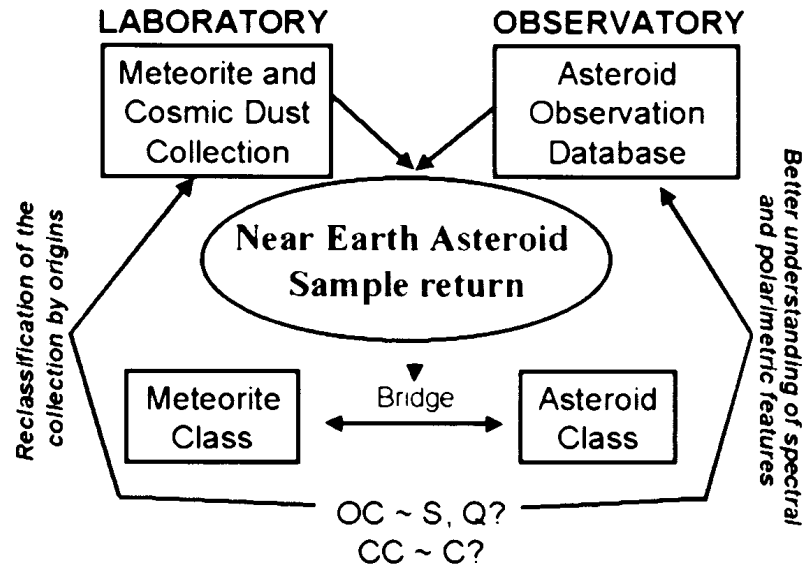


Figure 7. Near-Earth asteroid samples will provide information about the asteroids from which they came, but additionally will provide new understanding that will feed back into the whole of meteorite and asteroid studies.

1.5. A cultural problem and in-situ analysis - do what you do best regardless of the demands of the Science.

There is a cultural problem that must be overcome in placing an appropriate value on asteroid sample return, which is that because sample return has only recently become viable the planetary science community has a long history of finding ways to get round this. There are a great many techniques for in-situ analysis that have been painstakingly developed over the last thirty years that we would like to see fly even though they are not the way to do good science. This tends to cloud the issue and for the difficulties of sample return to be exaggerated.

1.6. The multiplying effect

While the samples returned from near-Earth asteroids will be of great scientific value in themselves, there will actually be a “multiplying effect” in the science return since they will form a bridge between rock samples investigated in great detail in the laboratory and the astronomical objects that have until now only been observed from great distances through a telescope. Thus the data from returned samples will provide new insights into meteorite formation and history

that will improve the interpretation of all meteorite data, and data from the returned samples will also help in our interpretation of astronomical spectra for asteroids (Figure 7). Only sample return from asteroids previously studied by remote observations and in-situ measurements can bridge the gap between ground observations of minor bodies and laboratory analyses of meteoritic samples. There will be an influx of new data and a refreshing reevaluation of ideas on a scale that has not been seen since the return of lunar samples by the Apollo program.

1.7. A natural “next step” in solar system exploration

Perhaps the strongest argument for an NEA sample return mission is that it is the natural next step in solar system exploration in the logical and systemic investigation of the building blocks of the solar system. After centuries of telescopic observation of these primitive solar system objects, numerous fly-bys, a mission to orbit an asteroid, and now a landing, sample return is the inevitable next step. Consider the well tried and tested traditional method of scientific exploration of a geological field site. The area is mapped, making use of aerial photographs and perhaps even remote sensing data, sometimes geophysical data obtained, then the geologist goes into the field to obtain detailed mapping, and then finally the geologist takes samples that can be brought back to the laboratory for detailed study. The only equipment they take into the field is normally a hand lens and a note book, and perhaps a magnet and a bottle of acid. The quipment of modern science is best kept in the laboratory. The analogous line of investigation for the examination of asteroids is to obtain astronomical spectra (map), fly rendezvous and orbital missions (fieldwork), and then take samples. We are entering the decade of sample return. The Stardust and Genesis missions are scheduled to return samples. The Johnson Space Center has a fully operational Astromaterials Branch equipped to process the samples and pass them into the science community, and the NASA Cosmochemistry Program has generated a large community of sample analysts equipped with some of the most sophisticated equipment on Earth.

While we can be confident that there is a good chance the samples will shed new light on fundamental questions, exploring new terrains always stirs new insights and new questions that could not have been predicted. The return of samples from the Moon resulted in a complete overturn of ideas about the origin of the Moon and its history. The existence of a magma ocean was not predicted and few would have predicted the widespread acceptance of an impact origin for the Moon prior to the return of Apollo samples. Thus while it is difficult to write it into budget requests, the best reason to return samples might be that we can expect the unexpected.

1.8. So can it be done?

It is often said that sample return from asteroids is “high science, high risk”. In other words, the scientific value of returning new samples of primitive solar system material from known context on known asteroids is beyond question, but that the mission is a challenge to current technology. The NEA Sample Return Panel suggests that while this was true a few years ago, events of the last year or two have changed this. The events are:



Figure 8. The Deep Space 1 technology development mission demonstrated the reliability of solar electric propulsion and the required automatic navigation techniques in deep space (NASA). Using a new technologies, the spacecraft performed a flyby mission of asteroid Braille and then comet Borelly. Useful images of Braille were not obtained, but the first image of a comet nucleus since that of Halley's Comet fifteen years ago was obtained. Solar Electric Propulsion has been in use in low-Earth orbit for many years, but this was the first use in deep space.

- The success of the Deep Space 1 mission and the new confidence it places in Solar Electric Propulsion. As a result of the end of the primary mission phase of Deep Space 1, JPL recommended and NASA Headquarters approved new specifications for the NSTAR SEP thrusters that bring a number of asteroid missions into the capability of current technology using small missions (Figure 8).
- The spectacular rate of discovery of near-Earth asteroids. Almost 80% of the 1600 known asteroids in near-Earth orbits were discovered in the last two years (Figure 9). Among them are about 30 in orbits that have lower Δv than the Moon. In a pilot study for the Hera mission, Leon Gefert has identified over 60 trajectories (Sears et al. 2001) that would take a NEAR-type spacecraft powered by SEP thrusters to three asteroids and return to Earth.

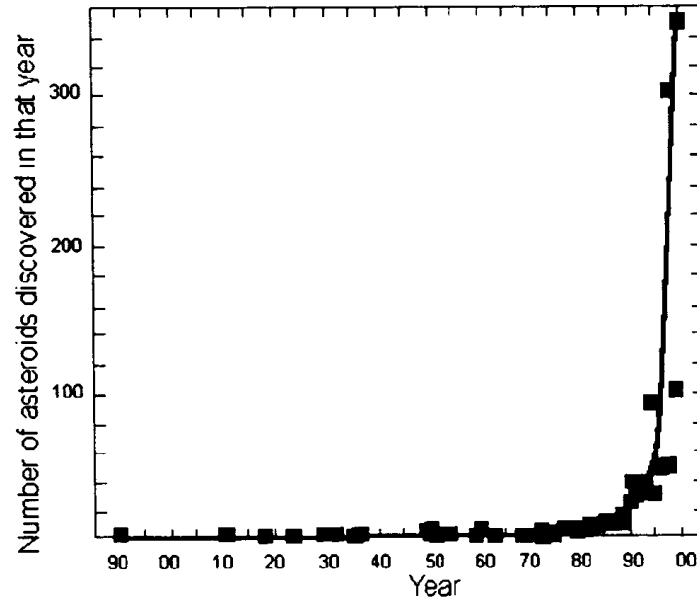


Figure 9. Rate of discovery of near-Earth asteroids has increased considerably in recent years. A large number of low-energy targets now exist for a near-Earth asteroid sample return mission.

- The spectacular success of the NEAR-Shoemaker mission. In many respects, NEAR was a dry run for an NEA sample return mission, accomplishing many crucial operations flawlessly. These were, going into orbit around an asteroid, maintaining a stable orbit for a year, maneuvering repeatedly with high precision while in orbit, and finally landing (Figure 10) (Williams et al. 2000, Fujiwara et al. 2000).
- The pending launch of the technology development mission MUSES-C. The Japanese MUSES-C mission is not a science driven mission but it will return a few grams of sample from a NEA. It will rendezvous with NEA 1998 SF36, station keep, descend to the surface momentarily, fire a projectile into the surface, collect the ejecta in a cone that will channel it into a container inside a sample return capsule, return to Earth for a recovery in the USAF Utah test range (Fujiwara et al. 2000). The published budget for MUSES C is \$150M, but this does not include personnel costs, however it is clear that the mission would fit within the Discovery Program cap of \$250M.

The crucial steps in asteroid sample return are (1) getting to the asteroid, (2) maneuvering in the vicinity of the asteroid, (3) taking the sample, (4) returning the sample to Earth. The first is not a problem given the large numbers of NEA and the availability of SEP. We now have considerable experience and confidence in maneuvering in the vicinity of asteroids through the NEAR experience, and while this was not exactly the same as hovering to take a sample, work by Scheeres and others associated with the NEAR mission and Japanese

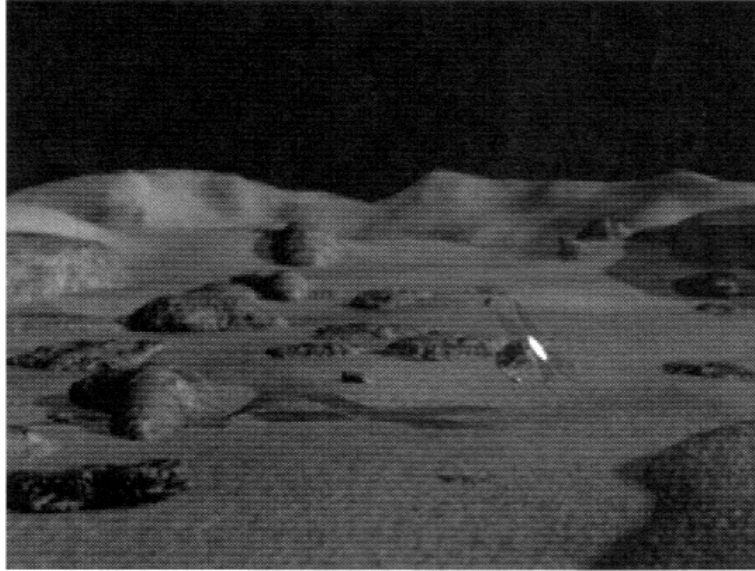


Figure 10. The NEAR-Shoemaker spacecraft about to land on Eros (NASA). Although the spacecraft was intended as an orbiter, after a year in which a large number of maneuvers were performed the NEAR team were able to make a soft landing on the asteroid.

colleagues working on MUSES-C mission has resulted in algorithms for controlling a spacecraft during hovering operations (Williams et al. 2000, Scheeres et al. 2000, Fujiwara et al. 2000). Sample return from space has been commonplace since the film canisters from spy satellites were captured in the air over the Utah test range. More recently, sample return procedures have been developed for Stardust and Genesis missions and workers at NASA Langley have developed even simpler methods of sample return from deep space by direct reentry.

The most challenging aspect of near-Earth asteroid sample return is taking the sample. There are a number of sample collection techniques with flight heritage, such as the automated drill cores of the Luna missions and the trowels of Viking and Surveyor. For human missions there are a number of techniques developed by the Apollo mission. Of course, the MUSES-C team have already developed a technique for sample collection which is flight-ready. In addition to this, the Lockheed Martin Astronautics company have developed a large collector which relies on a fly wheel and screw and Honeybee Robotics have developed a collector that uses two counter-rotating auger bits on the end of a flexible rod that can be withdrawn to haul the sample into the spacecraft (Figure 11) (Allen and Lindstrom 2000, Yano et al. 2000, Nygren 2000, Rafeek and Gorevan 2000, Rafeek et al. 2000). The 750 g collector can reliably pick up 5-10 g and a 5 kg version could probably pick up 500 g.

Any sample return mission must address planetary protection issues to avoid cross contamination from possible living entities contained on or in returned samples. Samples falling naturally to Earth will have received sufficient radiation dose to sterilize them, and this is probably true of samples obtained

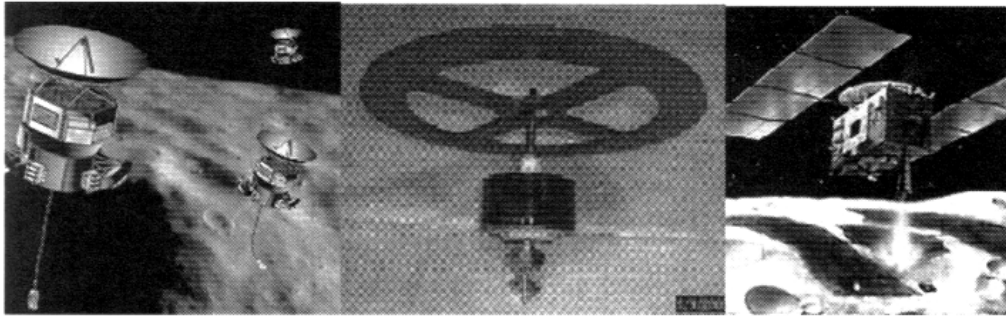


Figure 11. Three methods for collecting samples from an asteroid that do not involve landing. (left) Honeybee Robotics has designed a sampling head which involves counter-rotating drill heads attached to a rod which bounces across the surface. (middle) Lockheed Martin Astronautics have designed apparatus that involves a large screw and fly-wheel that are jettisoned after sample collection. (right) The Muses C collector fires a cannon into the surface and collects the ejecta.

from the surface of most asteroids, but it will not be true of samples taken from depth. Fortunately, NRC panels have considered this matter at great length and suggested that sample return from most asteroids will not require any special containment or handling based on planetary protection concerns (NRC 1994). However, special handling and containment is warranted for P- and D-type, and perhaps for F-type asteroids (the asteroids probably containing free organic compounds) until such time that more information is available about them. In general, samples returned from asteroids are not likely to pose a serious threat to Earth. Nevertheless it will be necessary to be sensitive to planetary protection issues during the initial design of any mission returning samples to Earth (Clark 2000).

1.9. Why sample NEAs, rather than main belt asteroids?

Clearly, the energetics of reaching NEA with spacecraft are less demanding than main belt asteroids and thus will be accessible to scientific research sooner than main belt asteroids. As already mentioned, some are easier to get to than the Moon. Available evidence suggests that NEA are representative of the main belt, at least the distribution of asteroids over the spectral classes is the same for NEA as it is for the main belt so the potential science returns are greater. NEA have suffered an event not experienced by the main belt, namely transfer from the main belt to the near-Earth vicinity, but there is no reason to expect that this has changed their mineralogical or chemical properties and they are still pristine material from the earliest days of solar system history. Since they are fragments of primary bodies, they expose the interior of that object.

However, there are actually reasons why we would prefer to explore NEA before going to the main belt. They are part of the near-Earth space environment, and NASA's current plans for exploring the solar system with robotic and human missions involve a steady progression outwards, from low-Earth orbit, to the Moon, to Mars, to main belt asteroids, to the outer solar system. NEA

exploration fits neatly between the exploration of the Moon and the exploration of Mars. Missions to NEA would have shorter durations than missions to Mars, and would be technically less demanding. Second, NEA could ultimately provide local and relatively cheap resources (water, for instance) for the International Space Station or lunar colonies (Lewis 2000). Third, NEAs include potential Earth-impactors and there is widespread interest in identifying and characterizing asteroids that could potentially impact Earth.

2. Key Science Questions

- Primitive solar system processes. What are the processes occurring in the primitive solar system and accompanying planet formation? How can we distinguish meteorite parent from nebular processes? How does this information relate to existing data and prevailing ideas based on meteorites? What are the lessons to be learned about interpreting data for meteorite classes whose parent body look-alikes have not been visited. If there is new primitive material in the asteroids that is not surviving atmospheric passage, then exciting surprises are to be expected.
- Presolar grains and the relation between the Sun and adjacent stars. New kinds of primitive materials means a whole new range of possibilities for discovering new kinds of presolar material: new types of pre-solar grains, new types of interstellar molecules. To date, interstellar materials have been limited to refractory minerals and compounds have been restricted only to the most primitive of the meteorites. Presolar materials in primitive meteorites are the only direct link we have between stars in the vicinity of the solar system and the Sun and the solar system.
- What are the organic materials in as yet unsampled primitive materials and are there lessons for our understanding of the origin and distribution of life in the solar system? There will almost certainly be volatile organic compounds present in the new types of primitive solar system materials discovered by NEA sample return missions. Characterizing these will yield information about the formation and evolution of prebiotic molecules necessary for life on planets. Does this information require reevaluation of current conclusions based on meteorite organics?
- How did asteroids and meteorite classes form and have their present properties? How do the major elemental, mineralogical and isotopic properties asteroid samples (1) vary with asteroid class and (2) compare with the meteorite classes. What does this say about the origin of meteorites and their relevance to the formation and history of the solar system and processes occurring there?
- How do the elemental, mineralogical and isotopic properties of the asteroid samples vary with geological context on the surface? How uniform is the asteroid, and if it is inhomogeneous, how do the variations relate to variations in meteorite properties? What can be learned from studying the asteroid samples in context about possible parent body effects in

meteorites? What does this imply for nebula conditions inferred from meteorites?

- The space environment. What processes, physical, mineralogical, elemental and isotopic, can be identified as happening on the surface of these small airless bodies as a result of exposure to the space environment. What are the nuclear effects and what is the exposure age of the surface, what is the gardening rate, what are the cosmic ray dose rates, how do these compare with data for Apollo lunar samples? What do these data imply for human radiation doses in the 1 AU region of the solar system? What do these data imply for space weathering on different types of surface, and how does the process compare with those on the Moon? Can we see both radiation effects and mineralogical effects on all bodies? What do these observations imply for the interpretation of astronomical spectra for asteroids?
- What is the internal nature of asteroids? Can anything be learned from the nature of asteroid surface materials about the nature of the interior and therefore the low bulk densities of the asteroids, one of the major problems in asteroid science?
- What can the science community contribute to the human exploration and development of space and mitigation of the impact hazard?

3. Findings and Recommendations

3.1. Supporting facilities

NASA already has in place a facility for astromaterials curation at the Johnson Space Center (Allen and Lindstrom 2000). The facility has over thirty years experience of handling extraterrestrial materials in a way acceptable to the scientific community and society-at-large. They are currently working with teams for the Genesis and Stardust missions, and they are responsible for handling Antarctic meteorites and Apollo samples. In addition, information developed for Mars sample return missions (Race et al. 2001) can provide extensive information in preparation for handling and analyzing future returned samples from asteroids.

3.2. Costs

Judging from the cost of the Japanese MUSES-C mission, asteroid sample return from multiple asteroids in a single mission could be accomplished within the Discovery price cap, especially if there is a modest increase in the cap or an augmentation to the funds by overseas partners.

3.3. Supporting programs

The Panel believes that the near-Earth asteroid sample return should be considered primarily as a science-driven project suitable for the Discovery program. However, it could also be considered as a technology development mission and submitted to the New Millennium Program or as an impact mitigation mission for submittal to the United States Air Force who have been given the mandate

NASA Space Science Enterprise Goals											
Science Goals	1	2	3	4	5	6	7	8	9	10	NEA Sample Return
1. Understand how the structure of our Universe (galaxies, stars and planets) emerged from the Big Bang											
2. Test physical theories and reveal new phenomena throughout the Universe, especially through the investigation of extreme environments.											
3. Understand how both dark and luminous matter determine the geometry and fate of the Universe											
4. Understand the dynamical and chemical evolution of galaxies and stars in the exchange of matter and energy among stars and the interstellar medium											
5. Understand how stars and planetary systems form together											
6. Understand the nature and history of our Solar System, and what makes Earth similar to and different from its planetary neighbors											
7. Understand the mechanisms of long- and short-term solar variability, and the specific processes by which Earth and other planets respond											
8. Understand the origin and evolution of life on Earth											
9. Understand the external forces, including comet and asteroid impacts, that affect life and the habitability of Earth											
10. Identify locales and resources for future habitation within the Solar System											
11. Understand how life may originate and persist beyond Earth											

Figure 12. Figure from NASA's 1997 "Space Science Enterprise Strategic Plan" illustrating the goals of the space science program and how each mission addresses them (NRC 1997). To this diagram we have added the contributions of a mission to take and return samples from near-Earth asteroids (NEA Sample Return). Other missions include 1) Solar Terrestrial Probes, 2) Bohr Probe, 3) Europa Orbiter and Pluto/Kuiper Express, 4) Mars Surveyor, 5) Next Generation Space Telescope, 6) Space Interferometer Mission, 7) Terrestrial Planet Finder, 8) Far-Infrared Submillimeter Telescope, 9) Gamma-ray Large Array Space Telescope, and 10) Constellation X-ray.

by congress to consider impact mitigation. NASA has the mandate to characterize potential earth impactors, but does not have a specific mission program for that purpose.

The community responsible for extraterrestrial material (meteorites, cosmic dust, Apollo samples) research is funded primarily by NASA's Cosmochemistry program. Another argument for near-Earth asteroid sample return is that a large, well-coordinated and well-funded community already exists for the analysis of the returned samples and existing resources would be adequate for their characterization. Lagging, however, is major equipment, and a sample return mission should assign resources for updating the aging instrumentation in the field.

3.4. Priority relative to other activities

The NEA Sample Return Panel argues that the return of samples from near-Earth asteroids is a mission of highest priority relative to other solar system activities currently under study as part of the NRC decadal review. The scientific value of studies of these small solar system objects has been recognized by NASA in the “Space Science Enterprise Strategic Plan” (Figure 12) (NRC 1997). Seven of the 11 goals laid out in the strategic plan can be uniquely addressed by sample return. These are:

- a. Understand processes occurring during planet formation from evidence contained within primitive asteroids.
- b. Understand stellar evolution and the relationship between stars and planet formation from pre-solar grains they contain.
- c. Shed light on the origin of molecules necessary for life from organic compounds.
- d. Detect chemical processes that preceded life on Earth from chemical trends in the samples. This can help us also understand the possibilities of life on other planets.
- e. Determine the record of solar activity for bodies in known orbits, from solar wind and solar energetic particles trapped in these surface materials.
- f. Enable the design of devices to deflect potentially hazardous objects and predict the effects should they reach Earth’s atmosphere from both small body sample return and the data from the encounters.
- g. Identify asteroid resources to facilitate human exploration and the development of space.

In addition, another NASA document, “Mission to the Solar System: A Mission and Technology Roadmap”, which lays out technology development and missions that are required to accomplish the strategic plan, advocates sample return from small solar system objects (Figure 13) (NRC 1996) in fact, of the 18 “portrait” missions listed in the Roadmap, all but one have either been flown or their goals are being addressed in some way. The exception is a mission to recover samples from small solar system bodies.

Missions to recover samples from near-Earth asteroids, the only feasible targets for macroscopic sample return with currently technology in the small mission budgets, addresses some of the most fundamental questions in planetary science - questions relating to the origin of the solar system and all materials in it - which underpin many of the activities currently under consideration.

3.5. Specific recommendations

- Samples should be obtained from NEAs with two specific objectives in mind. (a) To collect primitive material not represented in the terrestrial meteorite flux. To this end, emphasis should be on C-type asteroids. (b) To collect samples from a variety of geological contexts that are likely to

Roadmap Introduction	
Roadmap Missions: An Overview	
<i>Technologically Challenging High Science, Exciting & Inspiring</i>	
<i>Building Blocks and Our Chemical Origins</i>	<i>Evolution of Earth-Like Environments</i>
<u>Pluto/Kuiper Express</u>	<u>Mars Sample Returns</u>
<u>Primitive Body Explorers*</u>	<u>Mars Water and Mineralogy Mapper</u>
<u>Small-Body Sample Return</u>	<u>Mars Mobile Science Labs</u>
<u>Giant Planet Deep Probes</u>	<u>Venus Geoscience Aerobots</u>
	<u>Mars Geoscience Aerobots</u>
<i>Pre-Biotic Chemistry in the Outer Solar System</i>	Venus Atmospheric Probes
<u>Europa Ocean Explorer</u>	Venus Surface Science Labs
<u>Titan Biologic Explorer</u>	
Europa Landers	<i>The Solar System as a Large-Scale Natural Laboratory</i>
<i>Formation and Dynamics of Earth-Like Planets</i>	<u>Neptune Orbiter</u>
<u>Mercury Orbiter</u>	<u>Saturn Ring Observer</u>
<u>Lunar Giant Basin Sample Return</u>	<u>Jupiter Polar Orbiter</u>
<u>Io Volcano Observer</u>	Outer Planet Multiprobes
<u>Mars Surface Network</u>	Mercury Magnetospheric Multi-Sats
Venus Surface Mission	Comet Coma/Tail Multi-Sats
"Portrait" missions underlined	
* Multi-flyby "Visitors", Large Asteroid Orbiter; "New Comet" Encounter	

Figure 13. An overview of missions intended to address the major questions in NASA's space science program as described in the document "Mission to the Solar System: A Mission and Technology Roadmap" (NRC 1996).

shed light on the origin of the chondrite and asteroid classes. To this end, emphasis should be on S-type asteroids, probably those that most closely resembling the ordinary-chondrites, namely the S(IV) asteroids.

- Sufficient samples should be obtained from a number of asteroids so as to reasonably bracket the material in the main belt, i.e. include the major classes. We suggest that three asteroids is appropriate for an initial mission, but recognize that in the long run a program of systematic exploration of the asteroids with multiple missions and multiple programs will be necessary.
- Sufficient total mass of sample should be obtained so that the full armory of terrestrial techniques can be applied and still have sufficient material for long-term archiving. This means that about 500 g - 1 kg of each asteroid should be returned.
- Samples should be obtained from all the scientifically significant sites on the asteroids so that the effects of processes occurring on the asteroid surface can be identified.

- Material should be distributed to the scientific community through a process that recognizes the depth and breadth of techniques available and sensitive to newly emerging techniques.
- Material should be archived on the assumption that the asteroid will never be visited again and in such a way its scientific value is not compromised, yet it should remain accessible to researchers with scientific justification.
- A systematic program of NEA sampling should be international in scope and involve multiple missions. An excellent start has been made by the technology development mission MUSES-C. It would be appropriate to follow this up by a science driven mission to multiple asteroids.

4. Maintaining Capabilities for the Future

Samples need to be subjected to sufficient preliminary examination to ensure that information reaches appropriate researchers and that appropriate research is done.

Samples need to be need to be distributed to the scientific community in a way that ensures maximum scientific return from the samples. Thus while care should be taken to ensure that the samples are not used irresponsibly, an effort should be made to see that all scientists with the appropriate credentials receive samples.

A significant fraction of the material (one-quarter?) should be placed in long-term storage pending further developments and instrumentation.

NEA sample return is an excellent example of how a single mission can make major contributions to the space science strategic plan, but how integrations with other NASA missions and the international programs can yield a total science return that is greater than the sum of the return from the individual missions. In this sense, the achievements of one mission will be perpetuated through future missions. The MUSES C mission will visit one asteroid and return less than a gram of material, yet it will have demonstrated the technology and provide first-look samples of an S asteroid. NASA could contribute the next step by funding a science driven mission to return amounts of material that will enable the full range of measurements to be made, possibly visiting several asteroids. The European Aurora program is an example of a future program that could eventually return samples. These three missions could represent an excellent opportunity of international collaboration for optimum science by coordinating targets and minimum risk and cost, by sharing technology and expertise.

5. Human Space Activities

The current vision for the orderly exploration of the solar system favored by NASA involves an orderly growth outwards from low Earth orbit, to the Moon, to Mars, the Main Asteroid Belt and then the outer planets. There is a big technological gap between missions to the Moon and Mars which can usefully be filled by missions to NEA. Gene Shoemaker advocated manned missions to NEA

two decades ago (Shoemaker and Helin 1978), and at the NEA workshop Bret Drake described recent studies by mission planners at JSC of NEA missions as a useful way to test Mars-bound technologies (Drake 2000). The missions would be of shorter duration (about one year), simpler and cheaper no gravity well or atmosphere at the target, greater launch opportunities to numerous potential NEA targets, and lower energy would be required than for a mission to Mars. The International Space Station might make such missions even more economic. Robotic missions are the precursors of all manned missions and NEA sample return missions would be robotic precursor missions for the human explorations and development of space.

6. Education and Public Outreach

The Public Outreach possibilities of NEA missions are considerable because of the relevance to the impact hazard and popularization of the topic by its relevance to the termination of the dinosaurs and several recent movies. On the strategic and political front there is considerable interest in impact prediction and mitigation and society has every right to expect that the scientific community will make a significant contribution to these efforts. We can do so, while still addressing the demands of fundamental planetary science, by near-Earth asteroid sample return (Drake 2000).

The Education possibilities of integrating a Near-Earth asteroid sample return mission into K-12 education curricular are also numerous. The orbital mechanics involves knowledge of gravitational theory and simple solar system structure, which can be used to help teach basic mathematics and astronomy at many grade levels. The nature of the samples can be integrated into seventh and eighth grade earth science courses, while the impact hazard aspects of the mission can be integrated into history of life on Earth and concepts of time. Solar electric propulsion can be used as a means of teaching 11th and 12th grade physics of moving charges in electric fields and solar cells are an excellent introduction into solid state physics. There are few missions that relate to such diverse aspects of the K-12 school science and mathematics curriculum.

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