

NEAR-EARTH ASTEROID SAMPLE RETURN MISSIONS

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ABSTRACT

We are at a unique point in our exploration of the solar system in which missions to obtain samples from Near-Earth Asteroids (NEAs) are both required by the progress of asteroid and meteorite research and are technologically feasible. Recent successes with the Deep Space 1 and NEAR-Shoemaker missions have resolved many of the technical challenges and the spectacular rate of discovery of new NEAs have provided an abundance of energetically favorable targets of a variety of compositional types. A sophisticated world-wide network of research and analysis laboratories and excellent curatorial facilities are already in place, and a protocol exists for ensuring adequate planetary protection. The breadth and depth of data that can be obtained from returned samples greatly exceeds that possible with *in situ* analysis, samples can be archived for future techniques and analysts, and crucial information will be available on source and context for the returned samples. The samples will provide new insights into the interpretation of the large amount of existing data about meteorites and asteroids and the origin of our solar system, the use of NEAs as natural resources to support the human exploration and development of space and the mitigation of asteroid impact on Earth.

INTRODUCTION

The beginning of the 21st Century will witness a major evolutionary change in Solar System exploration as the first samples returned by a space mission since the Apollo moon rocks will reach Earth. Launched in February 1999, Stardust mission, will return dust samples from comet Wild 2 in January 2006. On July 30th, 2001, the Genesis mission will be launched which will return samples of solar wind to Earth in September 2004. Then on November or December 2002 ISAS will launch Muses C that will return samples from asteroid 1998 SF36 to Earth in June 2007. Momentum is building for sample return from small solar system objects, comets and asteroids^{1,2}. The near-Earth asteroids are relatively easy to visit with spacecraft, include objects from the main and comets, and

are important as potential Earth impactors.

At a workshop at the University of Chicago in 1978, when research on the Apollo lunar samples was in full swing, there was considerable support for sample return from asteroids³. However, there were also concerns about technical complexity and there were arguments that sample return was unnecessary because we have meteorites that are fragments ejected from asteroids. Much has changed since the Chicago workshop. The state of meteorite and asteroid research, has reached a point where sample return is a scientific imperative. Furthermore, the technical advances of the Deep Space 1 and NEAR-Shoemaker missions to asteroids, and the recent spectacular increase in the rate of discovery of near-Earth asteroids (Fig. 1), mean that sample return from asteroids is technologically feasible.

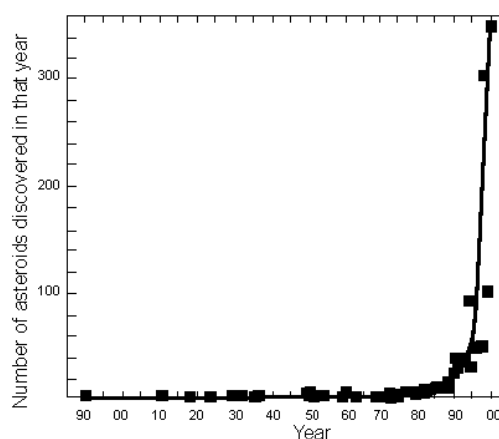


Fig. 1. Rate of discovery of near-Earth asteroids has increased considerably in recent years.

THE SCIENTIFIC CASE

Asteroids and comets are the primitive objects of the solar system and an integral and uniquely important part of our solar system. To date, the only samples of asteroids available for scientific studies are the meteorites, and the primitive meteorites – those that are unaltered relics of initial condensable fractions of solar nebula material - hold the secrets to many questions in solar system studies^{4,5}. Thus primitive meteorites are by far the most intensely

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studied rocks on Earth and, after two centuries of study, an enormous amount of information has been accumulated.

The scientific value of studies of these small solar system objects has been recognized by NASA in the "Space Science Enterprise Strategic Plan". Another NASA document, "Mission to the Solar System: A Mission and Technology Roadmap", lays out technology development and missions that are required to accomplish the strategic plan, advocates sample return from small solar system objects.

Seven of the 11 goals laid out in the strategic plan can be addressed by sample return. These are:

- Primitive asteroids contain evidence for processes occurring during planet formation.
- The pre-solar grains they contain help us understand stellar evolution and the relationship between stars and planet formation.
- Organic compounds they contain can shed light on the origin of molecules necessary for life.
- Chemical processes that preceded life on Earth can be detected from chemical trends in the samples that can help understand possibilities of life on other planets.
- Solar wind and solar energetic particles trapped in these surface materials will contain a record of solar activity for bodies in known orbits.
- Small body sample return (and the data from the encounters) will enable us to design devices to deflect potentially hazardous objects and predict the effects should they reach Earth's atmosphere.

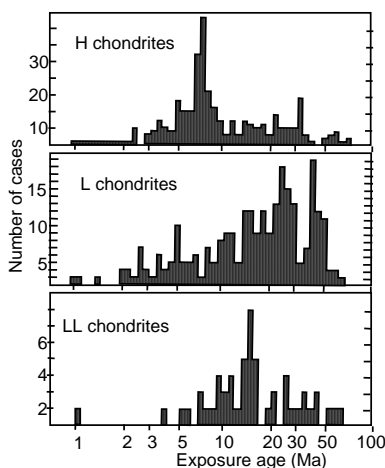
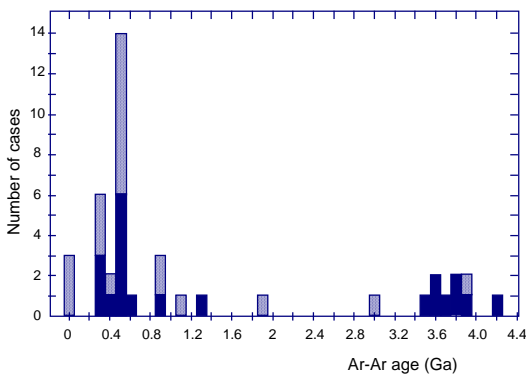


Fig. 2. (Top) Argon-argon ages for L chondrites and (bottom) cosmic ray exposure ages for ordinary chondrites. The peaks in the distributions of these ages indicates that a major disruption of a common parent body (asteroid) occurred at these ages that caused a resetting of the chronometers by gas loss

- Robotic missions to NEA will be pathfinders for human missions that might use asteroid resources to facilitate human exploration and the development of space.

COSMIC JETSAM

Many of these science objectives can be successfully addressed using meteorites, but despite many years of effort, and a considerable body of data, there is still no agreement on many issues. For example what is the origin of the chondrules, the major component of the silicate portion of most meteorites, or what caused the different proportions silicate and metal which is thought to be so important that it is the basis of chondrite classification. This uncertainty over some of the fundamental questions of chondrite genesis is in large part because we lack one key type of information. Meteorites are cosmic jetsam. We lack information on source and context.

The situation is somewhat analogous to the geologist relying only on the pebbles washed up on a beach or strewn along a riverbed. A geologist would insist in visiting the outcrops generating the rocks that were to

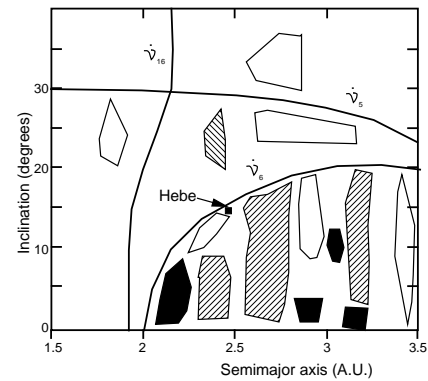


Fig. 3. Plot of inclination against semi-major axis for asteroids showing the location of resonances and asteroid 6 Hebe.

become pebbles. He would also expect to find materials that did not wash out and survive the transport process, and he would expect to learn much from the geological context

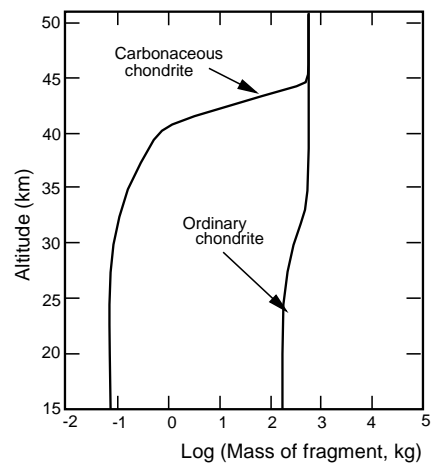


Fig. 4. Fragmentation of a meteorite entering the Earth's atmosphere. The fragmentation of carbonaceous meteorites (CI and CM chondrites) is approximately 1000 times greater than that of ordinary chondrites (H, L and LL chondrites) leading to a 1000-fold bias in favor of ordinary chondrites on Earth.

of the samples, such as their placement in the strata. An analogy is that although we can collect comet debris in our atmosphere, we need the Stardust mission to bring back unaltered dust from a known comet.

The processes influencing the type of meteorites reaching Earth are threefold. First, we are at the mercy of the impact events that ejected fragments from their parent asteroid. We know this not only because many meteorites show petrographic evidence for intense shock, but also because of their age distributions (Fig. 2). The largest meteorite class, the L chondrites, have a preponderance of meteorites with Ar-Ar ages around 500 million years. Similarly, the second largest meteorite class, the H chondrites, show a tendency to display cosmic ray exposure ages of 8 million years, suggesting a major break up of their common parent body at that time.

Second, our sample is influenced by the need to find a way of getting the ejected fragments to Earth and this favors material near one of the orbital resonances with the giant planets. It has been suggested, for instance, that the H chondrites are coming from asteroid Hebe which is situated near the 1:2 resonance with Jupiter and the ν_6 resonance with Saturn (Fig. 3).

Third, and by far the most process influence the meteorites coming to Earth is that only particularly tough material can survive atmospheric passage. It seems most likely that the truly primitive material of the solar system is highly fragile (Fig. 4). Of all the material reaching Earth, the most solar-like, and in a sense the most primitive meteorites, are the so-called CI chondrites that are 20% water. It seems that as many as half of the asteroids resemble the CI chondrites, yet only a few percent of the meteorites falling on Earth are CI chondrites. The density of all the asteroids measured to date are remarkably low ($0.7\text{-}2.6\text{ g/cm}^3$), and generally below the CI chondrite value of $\sim 2.5\text{ g/cm}^3$ and much lower than the ordinary chondrites which are $\sim 3.5\text{ g/cm}^3$.

Thus there are several reasons for concluding the cosmic flotsam reaching the Earth is not representative of material in the asteroid belt. We are getting a very jaundiced view of primitive solar system material.

Compositional information on asteroids can be obtained from the spectra of reflected sunlight. Matching these spectra from those obtained from meteorites is a possible means of relating meteorites to their sources, and this method has had some spectacular successes. For instance, we know that the small igneous class of basaltic meteorites probably came from the asteroid Vesta. However, this method has proved very difficult when applied to the major meteorite class, the chondrites, and for many years scientists have referred to the "paradox" (Fig. 5). The most common meteorite types appear to be rare in the asteroid belt and the most common asteroid types appear to be rare or absent in the meteorites. Trying to find ways of resolve the paradox, has lead to suggestions that the surface of asteroids undergoes considerable "space weathering" similar to that observed for the moon, although surface compositions and the space environment of the moon and asteroids are very different.

VALUE OF CONTEXT

Studying cosmic jetsam means that not only do we not know what type of asteroid the meteorite is from, we do not know whether they 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 on asteroids. Such information is critical to unlocking the scientific potential

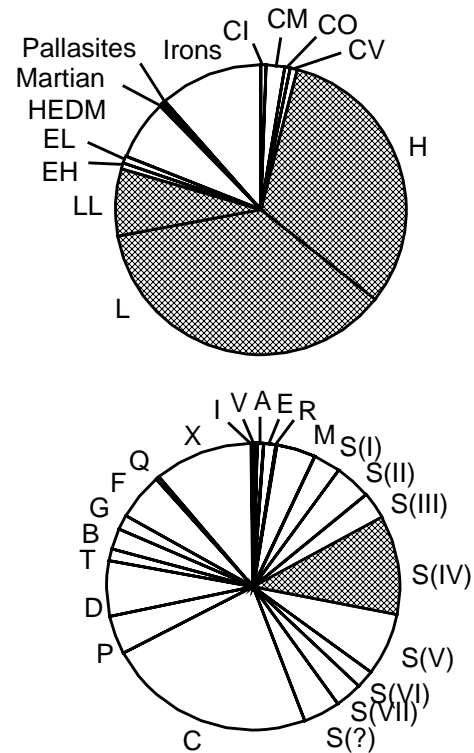


Fig. 5. The distribution of meteorites (upper) and asteroids over the classes. Ordinary chondrites (H, L and LL) match the spectra of Q asteroids although it is suggested that some S asteroids may have ordinary chondrite surfaces that have been altered by processes in space.

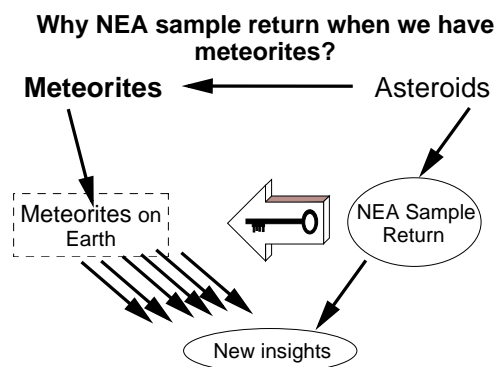


Fig. 6. Logic flow diagram arguing that the information obtained from returned asteroid samples. In addition to being of considerable value themselves, will have a greatly enhanced value because of the insights they provide on existing data for meteorites (and asteroids).

of the meteorites. The NEAR-Shoemaker spacecraft presented a whole new world of structures and features and a number of scenarios in which meteorites could have formed.

There are a great many examples of how returned samples from known context might resolve long-standing question in meteorite 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 caused, ratios that are responsible the various chondrite classes?

Many authors have argued that chondrules are impact melt droplets produced when a meteorite impacted the

parent body. Others argue that an unknown process in the nebula produced the chondrules, perhaps lightning, perhaps other processes possibly involving the Sun. If it were found that samples rich in crater ejecta were rich in chondrules, while samples from the interior or inter-crater plains were free of chondrules, then it would be clear that chondrules were impact melts. Similarly, some many authors have argued that metal silicate ratios reflect some unknown nebula process. However, if metal-silicate ratios in asteroid surface samples varied in some simple way, say with depth in the regolith or distance from major impact sites, then it would appear that the metal silicate ratios were caused by processes on the surface of the asteroids.

Table 1. Analytical data for the Tagish Lake meteorite¹¹.

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

Table 2. Analytical results for the Mars surface rocks as determined by instruments on the Pathfinder spacecraft¹².

Method	Conc.	
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 %
Sum		92.7 wt %

THE MULTIPLYING EFFECT

Returned asteroid samples would enable a direct comparison between the spectra observed for the asteroid with data obtained in the laboratory and thus enable new insights into the interpretation of astronomical spectra for all asteroids. At the same time, an ability to relate detailed petrologic observations to the geological context, the samples will provide new insights that will help interpret data for all meteorites. Thus the returned samples might be regarded as a key in unlocking the secret of the meteorites presently in our collections and this would greatly amplify the value of such missions. This idea is described as a cartoon in Fig. 6.

SAMPLE RETURN VS. *IN SITU* STUDIES

Sample return is more complex than *in situ* measurements, but there are a certain type of study- elemental and isotopic chemistry, mineralogy and petrology, studies of the rocks themselves- that can only be

done by examining the rocks in the laboratory. *In situ* methods for such rock analysis will always be vastly inferior to those that can be performed on returned samples. Analysis in the laboratory has the advantage over *in situ* methods of an unlimited range of techniques, vastly superior precision, the ability to archive samples for future investigation as instrumentation is developed, and laboratory analysis permits flexible responses to surprise results. Isotopic analysis for dating and characterizing samples requires particularly extensive sample preparation that can only be done in terrestrial laboratories. The Apollo program is an excellent case study of the impact which sample return can have on our understanding of planetary systems.

Two recent papers point out the differences in the depth and breadth of laboratory studies and *in situ* studies of extraterrestrial materials. When the Tagish Lake meteorite fell in Canada on January 18th 2001, and the report appeared in *Science* seven months later, there were analyses for 78 elements obtained by 10 different analytical techniques (Table 1). A few years ago analyses of the martian surface by *in situ* techniques appeared in the same science journal included results for 10 elements obtained by one instrument (Table 2). The precision of the laboratory analysis was typically double that of the *in situ* analyses, but the analyses of the martian rocks were sufficient to establish that they were andesites. However, there were difficulties in correcting for surface dust, which illustrates another common problem with *in situ* analysis, the lack of adequate sample preparation.

Of course, it could be argued that a small amount of relatively imprecise might be enough to answer certain questions, but this is not the experience of geochemistry and cosmochemistry where a great many researchers with different backgrounds tend to pose the questions in different ways and the questions change as information and ideas clarify. Sample science is a matter of finger-printing, and the more detailed the finger-print, and the more fingers printed, the more likely it is that the finger-prints will be uniquely fitted by an explanation.

In situ measurements are clearly essential certain types of analysis. Global geophysical measurements, for instance, will always need to be made *in situ* just as they are on Earth where samples are unlimited.

THE TERRESTRIAL MODEL

Perhaps the best guide to how to study small solar system objects is provided by the terrestrial geologist about to explore a new field, or a new continent. A terrestrial geologist would not try to deduce the petrogenesis of rocks from river deposits rather than visiting the outcrops. The terrestrial geologists' methods are well-tried and tested and have withstood the test of time. He or she would map the field, occasionally with the help of aerial photographs, choose sample areas, collect samples, and then return them to the laboratory for analysis. Samples of particular interest usually end up in a university or national museum for study by future generations. The terrestrial geologist would not transport their laboratory, and the laboratories of their collaborators, into the field, tucked in a backpack. In studying asteroids,

or any small solar system body, we should follow the same recognized strategy. We should obtain reflectivity spectra (the equivalent of first-order mapping by remote methods), select interesting asteroids (the equivalent of identifying a scientifically significant region), map them with orbiting spacecraft, collect samples, and then return those samples to the laboratory for complete analysis.

TECHNICAL DETAILS

The technical requirements of an asteroid sample return mission are (1) an outward and return trajectory suitable to current fuel and propulsion technology, (2) the

Table 3. Asteroids having criteria suitable for sample return.

	class	rot (h)	H
Icarus	S	2.273	16.4
Geographos	S	5.223	15.6
Cerberus	S	6.81	16.84
Aten	S	40.77	16.8
Bacchus	n.a.	14.9	17.1
Ra-Shalom	C	19.79	16.05
Tantalus	n.a.	2.391	16.2
Phaeton	F	4.08	14.6
Orpheus	n.a.	3.58	19.03
Amun	M	2.53	15.82
Cruithne	n.a.	18.14	15.1
7822 (1991 CS)	n.a.	2.39	17.4
7889 (1994 LX)	n.a.	2.741	15.3
17511 (1992 QN)	n.a.	5.99	17.1
1989 UQ	n.a.	7.733	19
1989 VA	n.a.	2.514	17.8
1994 CB	n.a.	8.676	21
1978 CA	n.a.	3.756	18
1994 AW1	n.a.	2.519	17.7
1998 KY26	n.a.	0.178	25.5

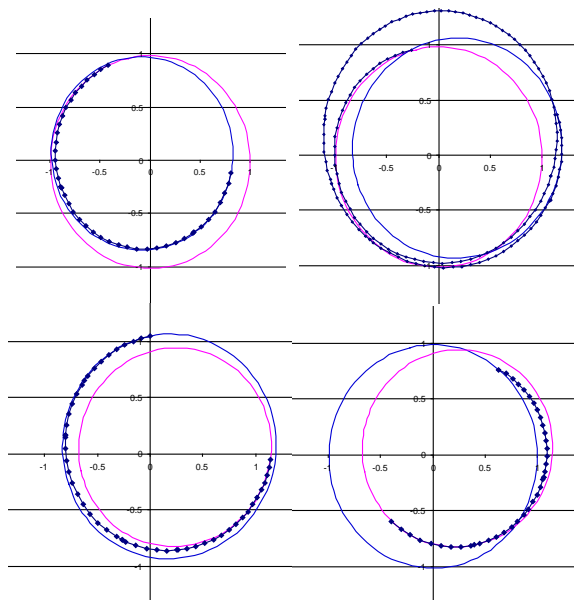


Fig. 7. An example of a trajectory that visits three NEA and returns samples to Earth in 4.8 years; Earth to 1999-AO10, 1999-AO10 to 2000-AG6, 2000-AG6 to 1989-UQ, 1989-UQ to Earth. The large number of recent NEA discoveries means that a large number of such trajectories are possible.

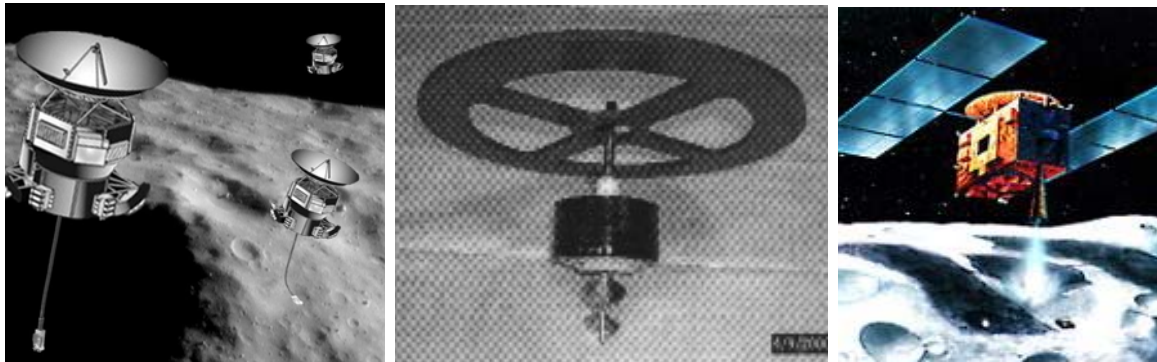


Fig.8. Three methods for collecting samples from an asteroid that do not involve landing. (a) Honeybee Robotics has designed a sampling head which involves counter-rotating drill heads attached to a rod which bounces across the surface. (b) Lockheed Martin Astronautics have designed apparatus that involves a large screw and fly-wheel that are jettisoned after sample collection. (c) The Muses C collector fires a cannon into the surface and collects the ejecta.

ability to maneuver the spacecraft in the close vicinity of the asteroid and (3) the ability to collect and store the sample. Returning the sample to Earth seems relatively straight forward using the methods adopted by the Stardust, Genesis and Muses C missions.

Two developments of recent years have improved our prospects for determining feasible trajectories to asteroids, especially near-Earth asteroids. NASA's Deep Space 1 technology development mission has demonstrated the practicality of solar electric propulsion (ion propulsion) for long duration deep space missions. This mission has demonstrated that the engines can be relied on to provide sufficient throughput of fuel and sufficient mission time that many asteroids can be quickly reached. Secondly, the flood new near-Earth asteroid discoveries mean that the number of possible targets is very large. Thus it was possible for the Hera mission, a proposal to take samples from three near-Earth asteroids, to easily identify a trajectory that visits three asteroids and returns to Earth in 4.5 years using three propulsion units of the sort used by Deep Space 1, with only two firing at a time (Fig. 7).

Our experience with the NEAR-Shoemaker mission demonstrates a high degree of confidence in the new techniques required to maneuver spacecraft around asteroids⁶. Theoretical treatments for a variety of maneuvers around small asteroids have been developed,

Table 4. Sample collecting instruments on space missions and mass collected.

Mission	Date	Type*	Collector	Mass
Apollo 11, 12, 14-17	'69-73	M	Rake, drill /corer (3 m), hand smpls	~380 kg
Luna 16, 20, 24	'70-76	RL	Corer	~450 g
Stardust	'99-07	RFB	Aerogel	> 10mg
Muses-C	'02-06	RL	Cannon	~10 g
Genesis	'01-04	L1	Si arrays	~5 ng

* M, manned missions; RL, robotic lander; RFB, robotic fly-by of comet Wild 2; L1, the satellite spends 2 years at L1.

including: close stable orbits, low-altitude flyovers, landing trajectories and hovering, stated in order of increasing difficulty. However, this work indicates that asteroid shape, size, density, and rotation state are crucial parameters that must be known to implement these operations, thus these data must be available before detailed maneuvers can begin. Additionally, design of the entire spacecraft and mission can be simplified if constraints on these asteroid parameters can be estimated early in the mission development phase.

Asteroids present new difficulties and new opportunities. Their small size, high rotation rates and irregular shape and the abundance of dust make landing difficult, but at the same time their microgravity on surface makes hovering feasible.

A number of sample collection devices have been flown on previous space missions, trowels/claws, drillers/corers, percussive devices, penetrators, and passive surfaces (Table 4). MUSES-C uses a cone to collect ejecta from an artificial impact during its touch-and-go sequence onto the asteroid surface, taking advantage of its microgravity condition. Honeybee Robotics of New York⁸

Asteroid deflection methods

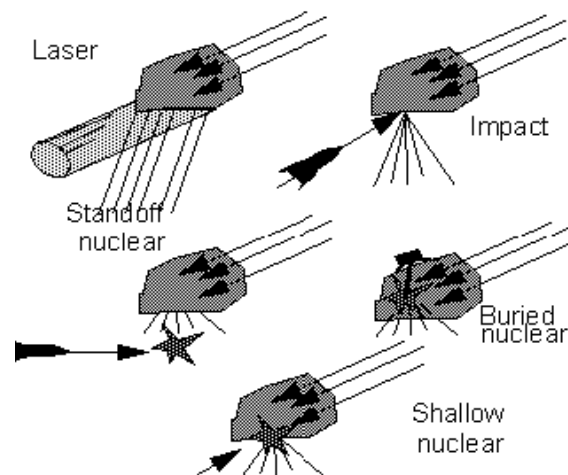


Fig. 9. Possible means of deflecting a potential Earth-impacting NEA.

and Lockheed-Martin Astronautics⁹ are developing other devices that can sample without landing (Fig. 8).

Similarly there has been considerable progress in designing methods to prevent contamination of the visited asteroid by terrestrial organisms, the transfer of organisms to Earth, or the contamination of one asteroid sample with another (Table 5). There are national recommendations covering these concerns, but they require that such issues are addressed from the outset of mission planning. Experience with terrestrial ecosystems demonstrates that natural transfer is not equivalent to anthropogenic transfer, for example radiation doses experienced by meteorites during transfer are high enough to destroy living material while this would not be true for samples returned by missions (NRC, 1998).

HUMAN EXPLORATION AND DEVELOPMENT OF SPACE AND RESOURCE UTILIZATION

Human flights to Mars are an ultimate aim of the space program, yet costs and complexity are considerable. Mission planners at the Johnson Space Center have been investigating human missions to NEAs as a useful way to test Mars-bound technologies. The missions would be of shorter duration (one year vs. three years), simpler (no gravity well or atmosphere at the target), launch windows are numerous, and lower energy would be required than for a missions to Mars. The International Space Station might make such missions even more economic.

There is considerable discussion in the literature of the use of asteroids, especially near-Earth asteroids, as natural resources, This is another respect in which the increasing number of known NEAs is important because of improved accessibility. Recovering precious metals has been discussed, so has the recovery of industrially important metals like iron, nickel and cobalt, and their possible use as propellants and structures. Using asteroid regolith to bury human habitats might be a simple and effective means of radiation shielding. However, probably the greatest value of these objects is as sources for volatile compounds, most especially water, for human habitats (Lewis, 2000). Numerous programs exist to explore these ideas, and these will all profit from the availability of returned samples because it is highly unlikely that the meteorites have the same physical properties as material on the surface of asteroids.

IMPACT MITIGATION

The impact hazard is receiving increasing attention from scientific communities and governments and is one reason for the increased rate of detection of new NEAs. We now know that major extinction events of life on Earth can be attributed to major impacts and effort has been expended to identify methods of deflecting an impactor bound for Earth. There have been many methods proposed, such as detonating nuclear explosives near the asteroid or buried in the asteroid, at shallow or great depth, of firing lasers at the asteroid or impact with a fast moving spacecraft (Shafer *et al.*, 1994). It is impossible to identify the most suitable method without knowing much more than we do now about the nature of the asteroid and its surface materials. Clearly, a laser would interact very differently with an asteroid that is 20% water and one that

Table. 5. Planetary Protection Category V, Earth return from NEA.

Degree of concern	Inbound
<i>Restricted Earth return (P, D, F asteroids)</i>	
	-No impact on Earth or the Moon
	-Sterilization of returned hardware
	-Containment of any sample
Procedures	Outbound
	-Per category of target planet/outbound mission
	-May require Active Bioload Control (depending on target asteroid and whether life-detection mission)
	Inbound
	<i>Restricted Earth return (P, D, F asteroids)-</i>
	-Detailed documentation
	-Continual monitoring of project activities
	-Preproject advanced studies/research
	-Possible sample containment
	<i>Unrestricted Earth return (other asteroids)</i>
	None

is bone dry. Nuclear explosives would affect a tough asteroid differently from a porous asteroid that is more capable of absorbing explosive energy. Returned samples would enable some of these options to be better evaluated.

CONCLUDING REMARKS

Sample return from asteroids will happen in the next few decades and the scientific return will be comparable or greater than that of the Apollo lunar samples. Near-Earth asteroid sample missions are an excellent opportunity for international collaboration, because of cost and complexity of the missions and because of the widespread interest in the samples. However, because of number and diversity of near-Earth asteroids we should be careful to consider the complementary role different missions and we should be careful to consider the roles of remote sensing and *in situ* measurements. For many years asteroid sample return missions have been considered difficult to impossible, but this has changed with the Deep Space 1 and NEAR-Shoemaker missions and the spectacular rate of discovery of new near-Earth asteroids.

The scientific community could contribute to the next phase of solar system exploration by providing the following data on NEAs

- orbits,
- spectral class,
- spin state
- size,
- Δv

Including information on Δv for each asteroid in the major asteroid compilations would enable interested astronomers to focus their attention on the asteroids most likely to be the target of missions.

We are entering a phase where we can expect new insights on a scale that has not been possible in the 200 years since asteroids were discovered and meteorites first came under scientific scrutiny. We are entering the era of

sample return. Several space missions are leading the way in this new effort, among them the Muses C mission that will actually return asteroid samples. The number and diversity of asteroids is very great, and a coordinated international multi-mission effort is required. But the scientific returns will be unprecedented.

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