**MULTIPLE ASTEROID SAMPLE RETURN: THE NEXT STEP.** Derek W. G. Sears, Cosmochemistry Group, University of Arkansas, Fayetteville, Arkansas 72701.

It is clear that the asteroids provide a unique opportunity to study primitive solar system material and a wide variety of processes occurring early in the history of the solar system [1]. Some asteroids may be extinct comets, and therefore provide an opportunity to study outer solar system material [2]. Some are potential earth impactors [3] and some could be an important source of natural resources for space stations or lunar or Martian colonies [4]. While some information on the structure and composition of asteroids is being obtained by remote sensing [5,6], a full and complete investigation of surface materials requires samples to be examined in the laboratory. Traditionally, the major concerns over asteroid sample return were whether it was necessary since we had representative samples of asteroids in our laboratories in the form of meteorites, that there was too much uncertainty as to which asteroid to sample, and that the mission was technically too challenging [7]. I argue these concerns are no longer valid and that a reasonable exploration strategy for asteroids, analogous to that used by field geologists on Earth, requires sample return as the logical next step.

*Are meteorites representative of asteroids?* We cannot assume that meteorites are representative of material in the asteroid belt because at least two major selection effects determine the meteoritic material reaching the earth's laboratories; (1) the processes required to transfer meteorites from the asteroid belt to Earth, (2) passage through the Earth's atmosphere.

Recent discussions of thermal drag effects on orbits (the Yarkovsky effect) suggests that a wide variety of material should pass through 1 AU [9], and it is certainly true that a wide variety of meteoritic material exists in our collections, especially the Antarctic collections [10]. However, the cosmic ray exposure age distributions [11] and, in the case of the L chondrites, their argon-argon ages [12], display peaks indicating that perhaps one-half to two-thirds of a class shared a common shock-heating event usually presumed to be fragmentation or ejection from their parent objects. When experimental uncertainties in isotopic abundance, shielding corrections, gas-loss before or after the major event, and multiple fragmentation of the parent body and the fragments after ejection are taken into account it seems likely that all of the major classes of meteorites are coming just a few asteroids. Thus meteorite data tell us that the major factor in determining the nature of the terrestrial meteorite flux is either the stochastic impact events that fragmented asteroids and sent material to earth or the location of the source asteroids near resonances, the asteroid belt's "escape hatches" [13]. It is worth noting that 6 Hebe, that has been proposed as the H chondrite source asteroid, is located on both a Jupiter and a Saturn resonance [14]. Thus 95% of the meteorites falling on Earth are probably coming from three or less asteroids.

Calculations performed during the development of spacecraft heat shields predict major differences in the ability of meteorites to survive atmospheric passage. In fact, meteorites with the mechanical strength of CI and CM chondrites, whose spectral reflectivity resemble that of the C asteroids, should fragment 100-1000 times more than the ordinary chondrites [15], which are the major meteorite class reaching the surface of the Earth (Fig. 1). Furthermore, it is possible that asteroid densities are even lower than CI and CM chondrites [16]. Thus only the most robust asteroidal samples can penetrate the Earth's protective atmosphere.

The spectral classifications for asteroids also suggest major differences in the distribution of asteroids and meteorites over their classes (Fig. 1). Even allowing for potential space weathering, only 11% asteroids can be potential ordinary chondrite parent bodies (i.e. the S(IV) class), and less than 1% (the Q class) have spectra that are a perfect match to major ordinary chondrite meteorite classes (Fig. 1 [17,18]).

Meteorites are clearly not representative of the material in the asteroid belt.

*Uncertainty as to which asteroid to sample.* On the other hand, spectral classes provide an excellent method of meaningful target selection. The two major classes of asteroid (C and S type) and the scientifically important V type asteroids, that are probably fragments from Vesta, could be sampled by three missions to near-Earth asteroids.

*The mission is technically too challenging.* The number of known near-Earth asteroids is very large [19] and many are energetically more favorable to reach than Mars or even the Moon [8], yet they have the same class distribution as the main belt (Fig. 1) and offer much easier opportunities to sample the same materials. Table 1 lists the near-Earth asteroids with energetics more favorable or less favorable but comparable with Mars and, where known, the frequency of opportunities to launch between 1990-2010.

An extraordinary amount of data exists for meteorites, but a major difficulty is the lack of information about meteorite sources. I suggest that a relatively small number of asteroid sample returns will lead to an understanding of a few fundamental properties of meteorites that will considerably enhance both meteorite and asteroid science [8]. A ground truth knowledge of the nature of surface materials and surface processes on asteroids will greatly enhance our understanding of meteorites, all of which are surface products of various kinds. It will also help resolve one of the most important questions in asteroid science which is the nature of the S asteroids and the importance of space weathering.

The time-honored method of exploring a new field location in terrestrial geology is to map the site, collect samples and return them to the laboratory. I would suggest that an analogous approach to asteroid exploration is to "map" the belt using reflectivity spectra, to use those spectra as a basis for selecting asteroids to explore, and, as in the terrestrial case return the samples to the laboratory on Earth for complete analysis. In situ analysis is most appropriate for global studies, but analysis in the laboratory is considerably superior for the variety of techniques available, the superior precision and the ability to archive samples pending the development of new techniques and procedures.

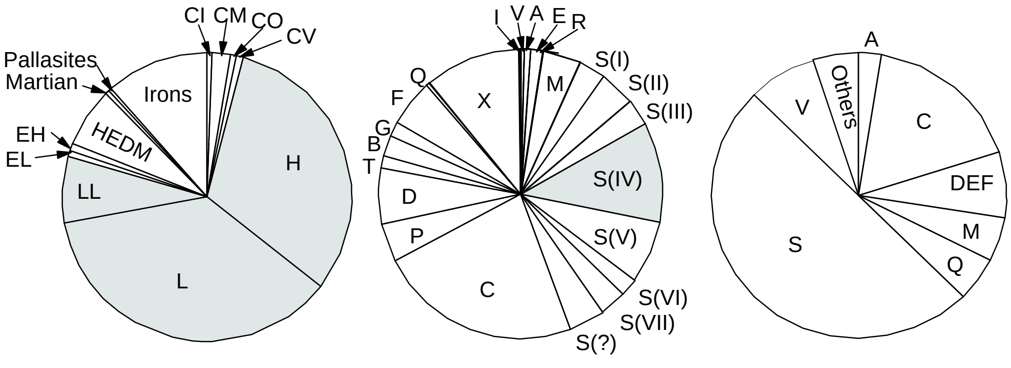
[1] Binzel R. P. *et al.* (1989) *Asteroids II*, Univ. Arizona Press, 1258 pp. [2] Weismann P. R. *et al.* (1989) In *Asteroids II* (R. P. Binzel et al., eds.) pp. 880-920. [3] Gehrels T. ed. (1994) Hazards due to Comets and Asteroids. Univ. Arizona Press, 1300 pp. [4] Kowal C. T. (1996) *Asteroids: Their Nature and Utilization,* Wiley, 172 pp. [5] Veverka J. *et al.* (1989) In *Asteroids II* (R. P. Binzel *et al*., eds.) pp. 970-993. [6] Cheng A. F. *et al.* (1997) *J. Geophys. Res.* **102**, 23,695-23,708. [7] Morrison D. (1978) *Asteroids: An Exploration Assessment.* NASA Conf. Publ. 2053. [8] Shoemaker E. M. and Helin E. F. (1978) In *Asteroids: An Exploration Assessment.* (D. Morrson ed.), pp. 245-256. NASA Conf. Publ. 2053. [9] Farinella P. *et al.* (1997) *Icarus* **132**, 378-387. [10] Grossman J. N. (1994) *Meteoritics* **29**, 100-143. [11] Marti K. and Graf T. (1992) Ann. Rev. Earth Planet. Sci. **20**, 221-243. [12] Bogard D. D. (1995) *Meteoritics* **30**, 244-268. [13] Greenberg and Nolan (1989) In *Asteroids II* (R. P. Binzel *et al*., eds.) pp. 778-804. [14] Farinella P. *et al.* (1993) *Celest. Mech.* **56**, 287-305. [15] Baldwin B. and Shaeffer Y. (1971) *J. Geophys. Res.* **76**, 4653-4668. [16] Consolmagno *et al.* (1998) *Meteorit. Planet. Sci*. **33**, 1221-1229. [17] Gaffey M. J. *et al.* (1993) *Meteorit. Planet. Sci*. **28**, 161-187. [18] Gaffey M. J. *et al.* (1993) *Icarus* **106**, 573-602. [19] McFadden L. *et al.* (1989) In *Asteroids II* (R. P. Binzel *et al*., eds.) pp. 442-467. [20] Williams J. G. (1989) In *Asteroids II* (R. P. Binzel *et al*., eds.) pp. 1034-1072. [21] Lau C. O. and Hulkower N. D. (1985) AAS/AIAA Astrodynamics Specialist Conf. Paper AAS85-352. [22] Sears D. W. G. and Dodd R. T. (1988) In *Meteorites and the Earth Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 3-31. [24] Tholen D. J. (1989) In *Asteroids II* (R. P. Binzel *et al*., eds.) pp. 1139-1150.

Table 1. Near-Earth asteroids with energetics more favorable or comparable with Mars and number of launch opportunities between 1990-2010.

| Asteroid | Class | Δv* (km/s) | No† |
|---|---|---|---|
| *Energetically more favorable than Mars* | | | |
| 1982 DB | -- | 4.97 | 13 |
| 1943 Antares | S | 5.33 | 14 |
| 3361 Orpheus | -- | 5.53 | -- |
| 3757 1982 XB | S | 5.78 | 13 |
| 3908 1980 PA | V | 5.71 | 20 |
| 1980 AA | -- | 5.78 | 21 |
| 3988 1986 LA | -- | 5.83 | -- |
| 1977 VA | XC | 5.92 | 19 |
| *Energetically comparable to Mars* | | | |
| 433 Eros | -- | 6.10 | -- |
| 1988 XB | -- | 6.38 | -- |
| 1976 AA | -- | 6.20 | -- |
| 1988 SM | -- | 6.20 | -- |
| 2062 Atens | S | 6.21 | -- |
| 1980 YS | -- | 6.22 | -- |
| 1987 SF3 | -- | 6.23 | -- |
| 352 McAuliffe | -- | 6.25 | -- |
| 3288 Seleucus | S | 6.25 | -- |
| 2061 Anza | TCG | 6.26 | 14 |
| 1627 Ivar | S | 6.29 | 16 |
| 1972 RB | -- | 6.38 | 16 |
| 1988 TA | C | 6.40 | -- |
| 1980 WF | QU | 6.51 | -- |

* Calculated by J. Akridge using the orbital parameters of [20] and methods of [8]

† Ref. [21]



Meteorite classes Main Belt Asteroids Near-Earth Asteroids

Fig. 1. Pie charts showing the class distributions for meteorites [23], Main Belt Asteroids [24] and Near-Earth asteroids [24]. Where available, the subdivisions of asteroid class S, S(I) - S(VII), are indicated [18].