Asteroid Resources*

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There are three types of possible asteroidal materials that appear to be attractive for exploitation:

1. Volatiles
2. Free metals
3. Bulk dirt

Because some of the near-Earth asteroids are energetically more accessible than the Moon [require a round-trip total change in velocity (ΔV) less than 9 km/sec (though the trip time would be measured in years, not days)], such an asteroid might be chosen as the source of any useful material, even if that material was also available on the Moon. Provided that the asteroid was minable, it might therefore be chosen as the source of bulk dirt needed for shielding in low Earth orbit (LEO) or elsewhere in near-Earth space.

And the near-Earth asteroids may offer materials that are rare or absent on the surface of the Moon. Some of them are spectrally similar to ordinary and carbonaceous chondrites. These meteorites contain free metals and volatiles at a concentration about 100 times that in the lunar soil. Thus, if an asteroid was found to have one of these compositions and to be accessible and minable as well, it would be a very attractive source of such needed materials.

An asteroid of the composition of an ordinary chondrite could be processed to provide very pure iron and nickel for use in structures in LEO. The principal byproducts would be cobalt, the platinum group metals, and other useful elements such as gallium, germanium, and arsenic. These are all materials of high value and utility in an industrial economy. Some might even be valuable and useful enough to merit being returned to the surface of the Earth (though the high cost of space transportation has ruled out economical return of gold and even diamonds, thus far).

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* The editor acknowledges the critical help of John Wasson, for figure 11 and its interpretation; Lucy McFadden, for the spectral classifications of the near-Earth asteroids and other clarifications; and Michael Lipschutz, for the relationship between meteorites and asteroids and other information. Wasson's figure comes from his book *Meteorites: Their Record of Early Solar-System History* (New York: W. H. Freeman and Co., 1985), p. 29. McFadden and Lipschutz are the lead authors of two chapters in the 1989 book *Asteroids II*, ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: Univ. of Arizona Press). McFadden's "Physical Properties of Aten, Apollo and Amor Asteroids" is coauthored by David J. Tholen and Glenn J. Veeder. Lipschutz's "Meteoritic Parent Bodies: Nature, Number, Size and Relation to Present-Day Asteroids" is coauthored by Michael J. Gaffey and Paul Pellas.

Volatiles, such as water and carbon dioxide, obviously useful in any space settlement, could be found in an asteroid that resembles a carbonaceous chondrite or one that consists of the nucleus of a former comet. Water content by weight for these materials may range from 5 percent for C2 chondrites through 10 percent in C1s to about 60 percent in typical cometary nucleus material. The abundance of organic matter in C1s is about 6 percent by weight, and nitrogen, sulfur, and chlorine are readily available. Attractive bonuses from C1s are that on the order of 10 percent of their weight may be magnetite* and about 2 percent is nickel-rich sulfides. As an alternative to returning asteroidal volatiles to LEO, the in situ extraction of water on an asteroid may be justifiable.

The Asteroid-Meteorite Relationship

Spectroscopic comparisons of asteroids with laboratory samples of meteorites show that the dominant minerals in meteorites are also the principal components of asteroid surfaces. Indeed, many asteroids have reflectance spectra that are identical with those of known classes of meteorites. See table 14. However, many asteroids appear not to belong to known classes of meteorites (although they are made of the same major minerals). Further, there is little relation between the abundance of meteorites of a given type and the abundance of asteroids of the corresponding spectral class. Of course, the large majority of the asteroids studied are in the asteroid belt, beyond the orbit of Mars, while the objects that fall on Earth must have very different orbits. It is instructive to note that the commonest class of meteorites falling on Earth, the ordinary chondrites, is apparently absent in the asteroid belt, but at least one spectroscopic match for ordinary chondrites can be found among the small, poorly studied near-Earth asteroids.

We have known for many years that the Earth receives in the meteorites a biased sampling of the asteroid types as spectral reflectance classifies them. The main problem is that the most

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* M. Hyman and M. W. Rowe, 1983, "The Origin of Magnetite in Carbonaceous Chondrites," abstract in Lunar & Planetary Sci. XIV (Houston: Lunar & Planetary Inst.), pp. 341-342.

TABLE 14. *Asteroid Types: Surface Mineralogy and Meteoritic Analogs from Reflectance Spectroscopy*[a]

Type	(No.)[b]	Inferred surface mineralogy	Possible meteoritic analogs
A	(4)	Olivine or olivine-metal	Olivine achondrites or pallasites
B	(6)	Hydrated silicates + carbon/organics/opaques	CI1-CM2 assemblages and assemblages produced by aqueous alteration and/or metamorphism of CI/CM precursor materials
C	(88)		
F	(13)		
G	(5)		
D	(26)	Carbon/organic-rich silicates?	Organic-rich cosmic dust grains?
P	(23)		CI1-CM2 plus organics?
E	(8)	Enstatite or possibly other iron-free silicates	Enstatite achondrites
M	(21)	Metal (possibly trace silicates)	Irons (possibly with silicate inclusions)
		Metal + enstatite?	Enstatite chondrites?
Q	(1)	Olivine + pyroxene + metal	Ordinary chondrites
R	(1)	Pyroxene + olivine	Pyroxene-olivine achondrites
S	(144)	Metal +/- olivine +/- pyroxene	Pallasites with accessory pyroxene Olivine-dominated stony-irons Ureilites and primitive achondrites CV3/CO3 chondrites
V	(1)	Pyroxene +/- feldspar	Basaltic achondrites
T	(4)	Possibly similar to types P/D	

[a] Table taken from Michael J.Gaffey, Jeffrey F. Bell, and Dale P. Cruikshank, 1989, "Reflectance Spectroscopy and Asteroid Surface Mineralogy," in *Asteroids II*, ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: Univ. of Arizona Press), p. 114.

[b] Number of asteroids classified as this type by David J. Tholen in his Ph. D. thesis, Asteroid Taxonomy from Cluster Analysis of Photometry, Univ. of Arizona, 1984.

abundant meteorites (the ordinary chondrites, which comprise almost 3/4 of the meteorites we have found on Earth) have rare asteroidal analogs and the most abundant asteroids (spectral type S, which comprises about 1/3 of all the asteroids that have been classified and over 1/2 of the near-Earth asteroids that have been classified) have rare meteoritic analogs. (See figure 8 for the type distribution of the near-Earth asteroids.) The explanation for this mismatch is among the most intriguing subjects being addressed by meteoriticists and asteroid spectroscopists.

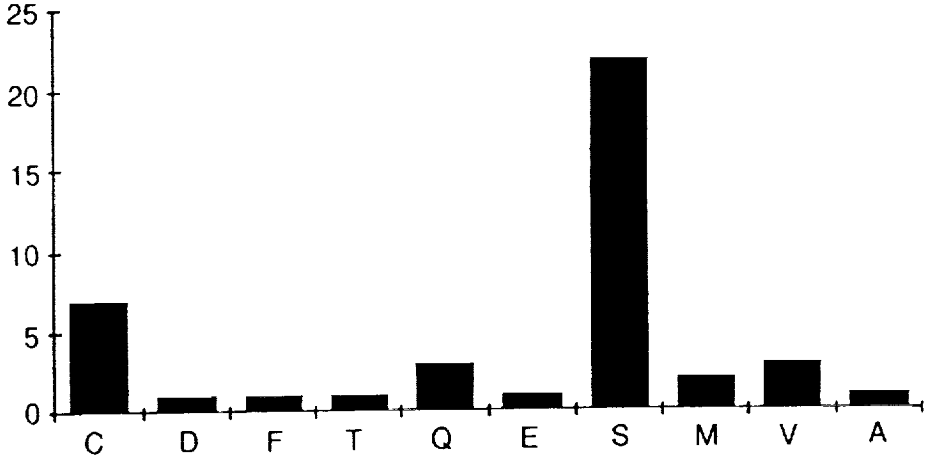
We know that asteroid discoveries are biased in favor of the brighter objects; that is, those that are large or close (in the inner as opposed to the outer belt) or have a high albedo. We know that meteorite finds are biased in favor of those that can survive atmospheric entry. There may be an accidental bias in the meteorite population: that is, they could be the products of the fragmentation of only a few, unrepresentative parent asteroids. The ordinary chondrites could come from only parts of larger asteroids. These meteorites could come from somewhere other than the asteroid belt. There may be a

Figure 8

Spectral Type Distribution of Observed Near-Earth Asteroids

This distribution, as determined by David J. Tholen using the Eight-Color Asteroid System, has not been corrected for observational bias. The asteroid types are defined in table 14.

From Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder, 1989, "Physical Properties of Aten, Apollo and Amor Asteroids," in Asteroids II, *ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: University of Arizona Press), p. 448.*



time bias; comparison of the well-preserved meteorites found in the Antarctic with the more weathered meteorites found elsewhere (which presumably fell within the last 200 years) suggests that Antarctica may have sampled a different meteoroid population in the past than is being sampled by contemporary, non-Antarctic falls and finds.

Thus, although we must be aware that, as Lipschutz says, "the meteorites are an incomplete and unrepresentative sample of the asteroid belt" (and of intermediate parent bodies such as the near-Earth asteroids), the volume of data on the meteorites so far exceeds the volume of data on the near-Earth asteroids that we are compelled to assume for the time being that the meteorites are adequate representations of the near-Earth asteroid population.

In this paper, I will present a brief overview of the entire range of meteorite compositions, with emphasis on the occurrence of interesting resources. I will focus on materials useful in space, especially volatiles, metals, and raw "dirt." Those few materials that may have sufficiently high market value to be worth returning to Earth will also be mentioned.

Meteorite Classes

Figure 9 shows the general scheme for classification of meteorites. This scheme unifies the more than 30 known classes under the three principal headings of *stones, stony-irons*, and *irons*. Primitive solid material, in which the major rock-forming elements have about the same relative abundances as in the Sun, accounts for the subset of stony meteorites called *chondrites*. All other classes of meteorites are the results of melting and density-dependent geochemical differentiation of primitive material. Chondrites fall on Earth far more often than all these other meteorite types combined.

The prospect of mining differentiated asteroids is not encouraging. Volatiles are probably rare or absent, and free metals will probably have drained into a massive monolithic core. Conversely, chondritic asteroids, both those with high volatile content and those with high free-metal content, are attractive targets.

The various classes of chondrites differ greatly in mineralogy, oxidation state, and volatile content (fig. 10) as a consequence of having formed at different temperatures. The content (by weight) of volatile-rich, low-temperature carbonaceous (C1) chondrites is up to 20 percent water chemically bound in clay minerals, up to 6 percent organic matter, and up to 11 percent magnetite. Nitrogen is present in the organic matter, and sulfur may be found as sulfides, elemental sulfur, and water-soluble sulfates. Carbonates and halides are abundant. All members of the C1 subtype of carbonaceous chondrites are very easily crushed; so are the members of the C2 subtype. But the crushing

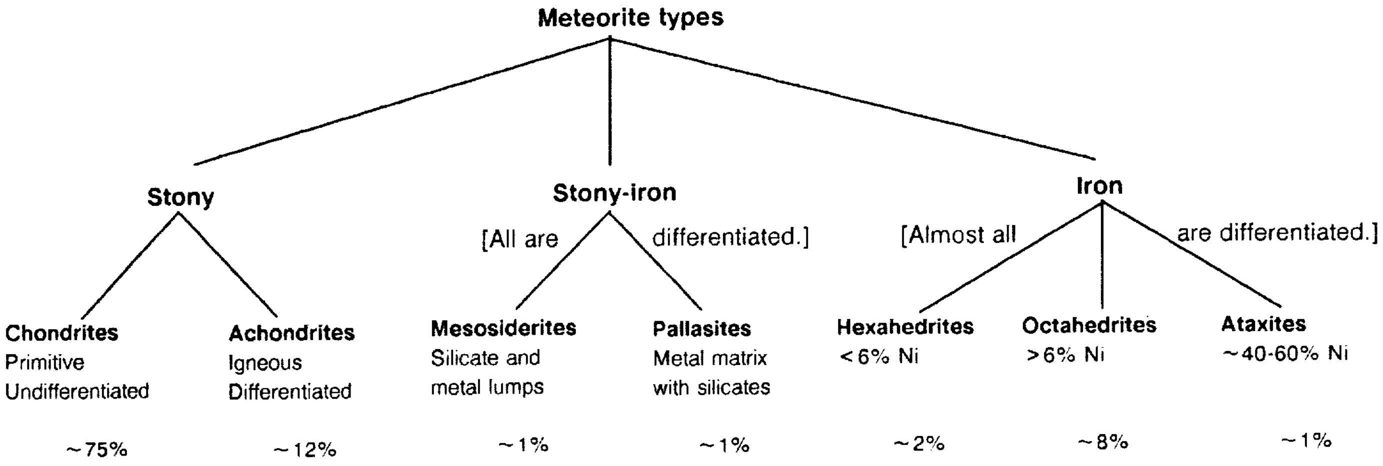


Figure 9

***Meteorite Types** (and Presumably Types of Near-Earth Asteroids)* strength of all other meteorite classes, including the C3 subtype, varies.* Carbonaceous chondrites make up on the order of 1 percent of all meteorite falls.

Equally rare, the enstatite (E) chondrites display markedly different compositions. All the E chondrites are in a state of extraordinary chemical reduction. Iron oxides are wholly absent and iron is found only as the sulfide troilite (FeS) and in iron-nickel-cobalt alloys. The dominant mineral is enstatite, the very pure magnesium orthosilicate. These meteorites are so strongly reduced that as much as 1 percent by weight of the metal phase in enstatite chondrites is elemental silicon in solid solution with the iron and nickel. Accessory materials such as calcium sulfide (the mineral oldhamite), magnesium sulfide (niningerite), titanium nitride (osbornite), manganese sulfide (alabandite), silicon oxynitride (sinoite), and even potassium- and titanium-bearing sulfides are found in the E chondrites or in their differentiated counterparts, the E achondrites.

However, more than 95 percent of the chondrites that fall on Earth (about 3/4 of all known meteorites) lie between the extremes represented by the E and C chondrites. These intermediate "ordinary" chondrites are subdivided into three groups according to the total amount of iron they contain and the proportion of that iron (and of the siderophilic elements) that is found as free metal: the H group with high iron content (much of it metallic), the L group with low iron content (less of it metallic), and the LL group with low iron and low free metal content. Table 15 and figure 11 show the compositional relationships among the five major classes of chondrites.

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*Michael Lipschutz, personal communication with the editor

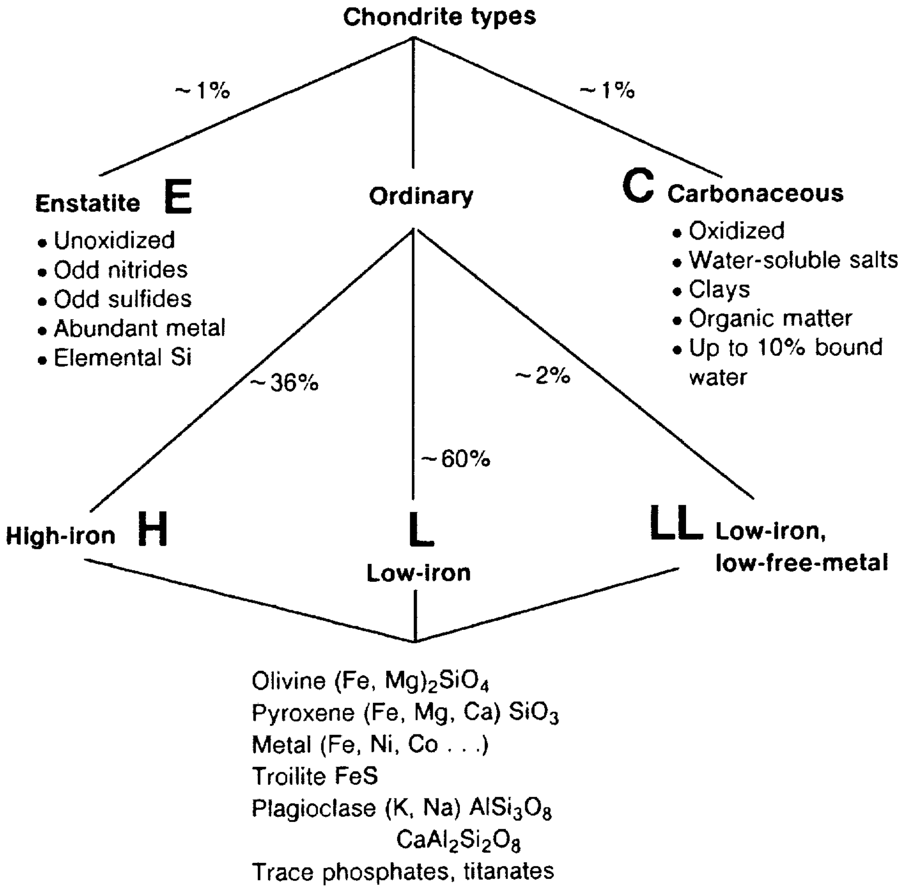

Figure 10

Classes of Chondritic Meteorites
(With Percentages of All Chondrites That Belong to Each Type)

TABLE 15. *Chemical Compositions (Weight %) of Two Enstatite Chondrites and of the Other Chondrite Groups*[a]

Class	Enstatite (E)		Ordinary		Carbonaceous (C)		
Group			H	L (& LL)[b]	C1	C2	C3
Component (wt. %)							
Si	16.47	20.48	17.08	18.67	10.40	12.96	15.58[c]
Ti	0.03	0.04	0.06	0.07	0.04	0.06	0.09
Al	0.77	1.06	1.22	1.27	0.84	1.17	1.43
Cr	0.24	0.23	0.29	0.31	0.23	0.29	0.35
Fe	33.15	22.17	27.81	21.64	18.67	21.56	24.92
Mn	0.19	0.12	0.26	0.27	0.17	0.16	0.16
Mg	10.40	13.84	14.10	15.01	9.60	11.72	14.29
Ca	1.19	0.96	1.26	1.36	1.01	1.32	1.57
Na	0.75	0.67	0.64	0.70	0.55	0.42	0.41
K	0.09	0.05	0.08	0.09	0.05	0.06	0.06
P	0.30	0.15	0.15	0.15	0.14	0.13	0.12
Ni	1.83	1.29	1.64	1.10	1.03	1.25	1.36
Co	0.08	0.09	0.09	0.06	0.05	0.06	0.08
S	5.78	3.19	1.91	2.19	5.92	3.38	2.09
H	0.13	trace	trace	trace	2.08	1.42	0.26
C	0.43	0.84	trace	trace	3.61	2.30	0.76
Fe^0/Fe_{tot}	0.70	0.75	0.60	0.29	0.00	0.00	0.10
Samples	1	1	36	68	3	10	12

The Fe entry in this table includes iron in metal, silicate, oxide, and sulfide phases.
The amount of metallic iron can be determined from that number and the ratio Fe^0/Fe_{tot}.
The amount of oxygen is not shown but is the remainder to make up 100 percent.

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[a] Table modified from Robert T. Dodd, 1981, *Meteorites: A Petrological-Chemical Synthesis* (Cambridge University Press), p. 19.

[b] Dodd grouped the low-iron (L) and low-iron, low-metal (LL) chondrites in his analysis.

[c] Weighted average for Dodd's five CO chondrites and seven CV chondrites.

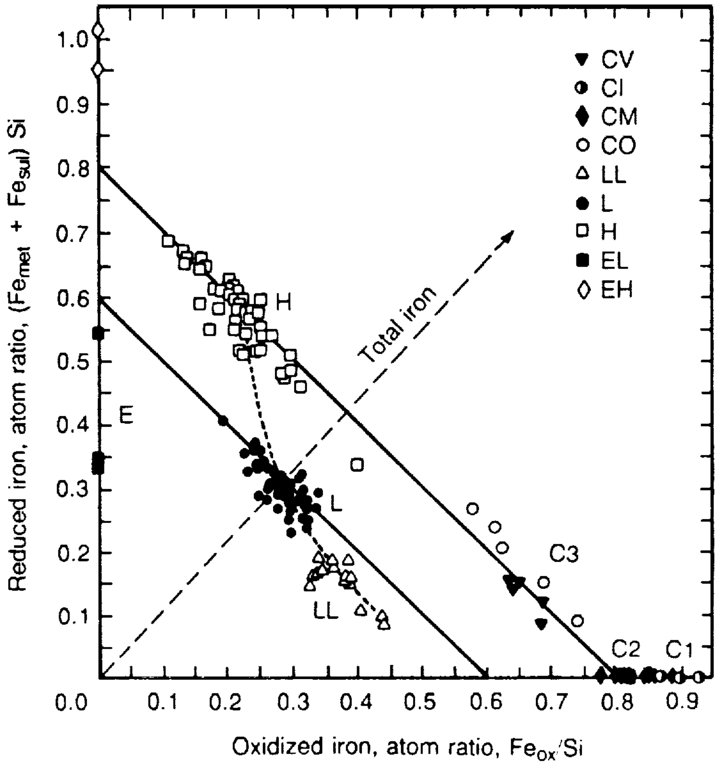

Figure 11

Reduced vs. Oxidized Iron in the Five Classes of Chondritic Meteorites

Reduced iron (metallic iron and that present as FeS) in chondritic meteorites is plotted against oxidized iron (that present in silicates and, in CM and CI, as Fe_3O_4). Lines having slopes of -1 correspond to constant total Fe/Si ratios; two are shown for reference purposes. The highly reduced enstatite (EH and EL) chondrites plot along the left axis; the highly oxidized CM (C2) and CI (C1) chondrites, along the bottom axis.

Modified from John T. Wasson, 1985, Meteorites: Their Record of Early Solar-System History *(New York: W. H. Freeman and Co.), p. 29.*

The most highly oxidized ordinary chondrites (LL) and the most volatile-poor and unoxidized of the carbonaceous chondrites (C3) contain by weight only 16 percent free metal. But, because the less abundant components of the metal (nickel, cobalt, and the platinum group metals) are harder to oxidize than iron, they have been concentrated in the metal grains. Thus, the metal grains in these more oxidized chondrites contain far greater concentrations of these metals than do the metal grains in, say, the E chondrites. Nickel ranges from about 6 percent of the metal in E chondrites to 60 percent in the C3 chondrites, and cobalt and the platinum group follow suit. In each class of chondrites, the concentration of the more valuable elements in the metal phase is highest in the smallest grains.

Table 16 shows the concentrations of a number of elements in the magnetically separable (metallic) component of chondritic meteorites. It can be seen that the fourfold overall depletion of the metallic elements in the LL chondrites relative to H chondrites is accompanied by only a twofold depletion in their platinum group content. It is thus not terribly important which class of ordinary chondrites is exploited for these elements. Magnetic extraction of iron-rich phases (magnetite, FeS, etc.) might be applied to a C1 chondrite, which is lacking in free metal, since C1 chondrites contain by weight up to 11 percent magnetite and about 2 percent nickel-rich sulfides. However, it has not yet been shown that such a separation process is practical.

TABLE 16. *Concentrations of Components of the Metal Phases of Ordinary Chondrites*

	Class		
	LL	L	H
Concentration (% by wt.) of total metal in meteorite:	4 (±1)	9 (±2)	16 (±3)
Nickel conc. (% by wt.) in metal	25 (±5)	15 (±3)	10 (±2)
Cobalt conc. (% by wt.) in metal	1.2 (±0.2)	0.7 (±0.1)	0.5 (±0.1)
Concentration (ppm) in metal:			
Platinum group metals			
Platinum	21 (±5)	13 (±1)	11 (±2)
Ruthenium	12 (±1)	8 (±1)	5.7 (±0.6)
Osmium	10 (±2)	6 (±1)	4 7 (±0.4)
Iridium	10 (±2)	5 (±1)	4.8 (±1.2)
Rhodium	1.0 (±0.2)	0.6 (±0.1)	0.5 (±0.1)
Other elements of interest			
Gallium	1 to 15	6 to 30	?
Germanium	200 (±30)	110 (±30)	?
Arsenic	1.2 (±0.2)	1.7 (±0.2)	2.1 (0.2)

Meteorites as Sources of Volatiles and Metals

If the resources of primary interest are volatiles, then, among meteorites, the carbonaceous chondrites are the target of choice. The concentrations of hydrogen, carbon, nitrogen, and sulfur in C1 chondrites are more than 100 times those in the lunar regolith: the C1s contain (by weight) 4 to 6 percent carbon, about 0.3 percent nitrogen, 6 percent sulfur, and 10 to 20 percent water (1 to 2 percent hydrogen). Most of the carbon, nitrogen, and sulfur is, like the hydrogen, compounded, though there may be some pure carbon.

If metals are the principal resource desired, then all classes of chondritic meteorites are of great interest. The abundance of free iron in a typical chondrite is much higher than on the lunar surface, where only meteoritic fragments can be found. And the amount of metallic nickel in a typical chondrite is about 100 times the nickel content of lunar regolith. As figure 11 shows, there is real variation in the Fe_{total}:Si atomic ratio [from about 0.4 in LL and some E chondrites (the EL subtype, including Indarch) to about 1.0 in C1 and some other E chondrites (the EH subtype, including Khairpur)], but the large majority of the chondrites landing on Earth (the L and H groups) have Fe_{total}:Si atomic ratios of 0.6-0.8. As shown in figure 11, the C3 chondrites and C2 chondrites contain fully as much total iron (relative to silicon) as the H chondrites; the amount of free metal in the chondrite, however, varies from about 1 percent in the C3s to about 20 percent in the H group.

Figure 12 shows the total concentrations of water and free metal in the major classes of chondrites.

Mechanical Properties of Meteorites

Meteorites have seldom been subjected to tests of bulk physical properties. There is a great variation in crushing strength and porosity, with C1 chondrites apparently most porous (more than 10 percent of their volume is pores) and weakest (crushing strengths of only a few bars). The ordinary chondrites have measured strengths ranging from 60 to 2600 bars (1 bar = 10^5 N/m^2). Iron meteorites range in strength up to 3600 bars at room temperature. At low temperature and in the presence of hydrogen, these are subject to embrittlement and should be much easier to crush. However, iron asteroids, if found, would present significant processing challenges.

Meteorites are the subset of nonterrestrial projectiles that survive entry into the atmosphere. Thus, they have been selected for strength. Stony fireballs often break up at high altitudes and yield no meteorites. Typical strengths for such fireballs are about 40 bars. The famous Tunguska object

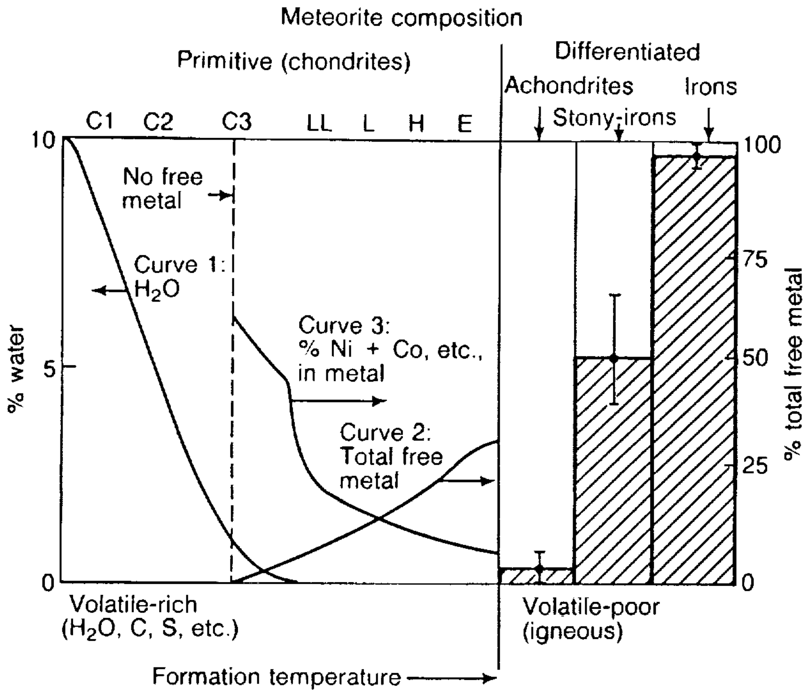

Figure 12

Volatile and Metal Variations in Meteorites

Curve 1, as measured on the left scale, shows the concentration of water in different types of chondritic meteorites. The carbonaceous chondrites contain the most water and become progressively less hydrous in going from type C1 to type C3. The ordinary chondrites (LL, L, and H) contain even less water. Most of the other common volatile species (carbon as CO_2, sulfur, etc.) are also present in significant amounts only in the meteorites that contain significant water.

Curve 2, as measured on the right scale, shows the total free metal in these same meteorite types. The total free metal (that is, the metallic elements that are not combined as oxides, silicates, etc.) generally increases as water decreases. As curve 3 (measured on the right scale) shows, the concentration of nickel, cobalt, and the platinum group elements within the metal phase is generally highest in meteorites having the lowest amounts of free metal.

The amount of free metal in differentiated meteorites is shown by the shaded areas as measured on the right scale.

that detonated over Siberia in 1908 completely ruptured under an aerodynamic pressure estimated at 200 bars. Fireballs associated with the orbits of known comets break up at loadings of 0.1 to 1 bar. This may be a very important and relevant datum, since some near-Earth asteroids are thought to be extinct comet nuclei. Beneath surface dust mantles, such asteroids may be 60 percent or more ice.

The available data on the crushing strengths of Earth-crossing bodies are summarized in table 17.

TABLE 17. *Crushing Strengths of Lunar Materials and Various Types of Meteors*

		Crushing strength, bars (1 bar = 10^5 N/m^2)
Moon		
	Regolith—precrushed	0
	Rocks (anorthosite, basalt)	~2500
Meteors		
	Irons —room temperature	3600
	—low temperature (Brecher)	< 1000
	Stones—measured (L)	> 60 < 2600
	Fireballs that yield stones (Lost City, Innisfree)	> 200
	Tunguska explosion	200
	Fireballs	
	PN40503	30
	EN160166	50
	Cometary fireballs	> 0.1 < 1

Asteroid Orbits

Eleanor Helin has recently summarized for the Spacewatch Report the orbital data on the asteroids crossing the Earth's orbit and closely approaching the Earth. An updated version of this list (through 1984)* is given in table 18. The orbital eccentricities of these asteroids range from 0.182 to 0.894, with an average (and most probable) value of 0.55. Inclinations range from a low of 1.4 degrees for 1982 DB up to over 68 degrees. Those asteroids which take the least energy to reach from Earth must have low inclinations *(i)* and eccentricities *(e)* and should have semimajor axes not too different from Earth's. Asteroids with orbital periods greater than 1 year are usually easiest to reach if their perihelion distance is near 1 astronomical unit (AU), the mean Earth-Sun distance. A simple but useful approximation rule is that an asteroid will be accessible with a round-trip total change in velocity (ΔV) of less than 6 km/sec if $20e + i$ is less than 14 and the perihelion distance is between 0.8 and 1.15 AU. The first criterion is met by 8 of the 63 known near-Earth asteroids, and 7 satisfy both criteria. Of these, five have round-trip ΔV's under 6 km/sec, and two are just over the limit. For comparison, the ΔV for ascent from low Earth orbit (LEO) to the lunar surface is 6 km/sec one-way and 9 km/sec round-trip. The most favorable asteroid, 1982 DB, requires less than 4.6 km/sec for a round trip.†

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*A further updated list (through 1988) is available in the chapter by McFadden, Tholen, and Veeder in *Asteroids II*.

† It should be noted, however, that we do not have a spectral type for 1982 DB. Two (1982 XB and 1943 Anteros) of the other four asteroids listed in table 19 have been classified (as S). Only one other (3908 1980 PA) of the asteroids meeting these criteria for accessibility has been classified (as V).

TABLE 18. *Near-Earth Asteroids—Atens, Apollos, and Amors*
[After Eleanor Helin in Spacewatch Report]

Name/number[a]	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccentricity	Inclination	Spectral type[b]
3200 Phaethon	1983	0.14	2.47	1.30	0.894	22.8	F
1566 Icarus	1949	0.19	1.97	1.08	.827	23.0	S
2212 Hephaistos	1978	0.36	3.97	2.16	.835	11.9	SG[c]
1974 MA	1974	0.42	3.13	1.78	.762	37.8	
2101 Adonis	1936	0.44	3.30	1.87	.764	1.4	
2340 Hathor	1976	0.46	1.22	0.84	.450	5.9	CSU[d]
2100 Ra-Shalom	1978	0.47	1.20	0.83	.437	15.8	C
1954 XA	1954	0.51	1.05	0.78	.345	3.9	
1984 KB	1984	0.53	3.88	2.21	.760	4.6	S
3362 Khufu	1984	0.53	1.46	0.99	.469	9.9	
1982 TA	1982	0.53	4.07	2.30	.769	12.1	
1864 Daedalus	1971	0.56	2.36	1.46	.615	22.1	SQ
1865 Cerberus	1971	0.58	1.58	1.08	.467	16.1	S
Hermes (1937 UB)	1937	0.62	2.66	1.64	.624	6.2	
1981 Midas	1973	0.62	2.93	1.78	.650	39.8	
2201 Oljato	1947	0.63	3.72	2.17	.712	2.5	
1981 VA	1981	0.63	4.22	2.46	.744	22.0	
1862 Apollo	1932	0.65	2.29	1.47	.560	6.4	Q
1979 XB	1979	0.65	3.88	2.26	.713	24.9	
2063 Bacchus	1977	0.70	1.45	1.08	.349	9.4	
1685 Toro	1948	0.77	1.96	1.37	.436	9.4	S
1983 LC	1983	0.77	4.50	2.63	.711	1.5	
2062 Aten	1976	0.79	1.14	0.97	.182	18.9	S
2135 Aristaeus	1977	0.79	2.40	1.60	.503	23.0	
1983 VA	1983	0.81	3.67	2.24	.636	15.4	
3361 Orpheus	1982	0.82	1.60	1.21	.322	2.7	
6743 P-L	1960	0.82	2.42	1.62	.493	7.3	
1983 TF_2	1983	0.82	3.62	2.61	.387	7.8	
2329 Orthos	1976	0.82	3.99	2.40	.658	24.4	
1620 Geographos	1951	0.83	1.66	1.24	.335	13.3	S
1959 LM	1959	0.83	1.85	1.34	.379	3.3	
1950 DA	1950	0.84	2.53	1.68	.502	12.1	
1866 Sisyphus	1972	0.87	2.92	1.89	.540	41.1	
1978 CA	1978	0.88	1.37	1.12	.215	26.1	S
1973 NA	1973	0.88	4.04	2.46	.642	68.1	

TABLE 18 *(concluded)*.

Name/number	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccen-tricity	Incli-nation	Spectral type
1863 Antinous	1948	0.89	3.63	2.26	0.606	18.4	SU
2102 Tantalus	1975	0.91	1.67	1.29	.298	64.0	
1982 BB	1982	0.91	1.91	1.41	.355	20.9	E
6344 P-L	1960	0.94	4.21	2.58	.635	4.6	
1982 DB	1982	0.95	2.02	1.49	.360	1.4	
1979 VA	1979	0.98	4.29	2.64	.627	2.8	CF
3671 Dionysius	1984	1.01	3.41	2.21	.544	13.7	
3757 1982 XB	1982	1.01	2.70	1.86	.454	3.9	S
3122 1981 ET_3	1981	1.02	2.52	1.77	.422	22.2	
2608 Seneca	1978	1.02	3.93	2.48	.587	15.6	S
3908 1980 PA	1980	1.04	2.82	1.93	.459	2.2	V
1980 AA	1980	1.05	2.73	1.89	.444	4.2	
2061 Anza	1960	1.05	3.48	2.26	.537	3.7	TCG
1915 Quetzalcoatl	1953	1.05	3.99	2.52	.583	20.5	S
1943 Anteros	1973	1.06	1.80	1.43	.256	8.7	S
1917 Cuyo	1968	1.06	3.23	2.15	.505	24.0	
3551 1983 RD	1983	1.07	3.12	2.10	.488	9.5	V
1221 Amor	1932	1.08	2.76	1.92	.436	11.9	
1980 WF	1980	1.08	3.38	2.23	.514	6.4	QU
1981 QB	1981	1.08	3.39	2.24	.518	37.1	
1983 RB	1983	1.09	3.35	2.22	.490	18.0	
3288 Seleucus	1982	1.10	2.96	2.03	.457	5.9	S
1982 YA	1982	1.11	5.09	3.10	.641	33.2	
1627 Ivar	1929	1.12	2.60	1.86	.397	8.4	S
1580 Betulia	1950	1.12	3.27	2.20	.490	52.0	C
2202 Pele	1972	1.12	3.46	2.29	.510	8.8	
433 Eros	1898	1.13	1.78	1.46	.223	10.8	S
887 Alinda	1918	1.15	3.88	2.52	.544	9.1	S

[a] When first discovered, asteroids are given a provisional designation which consists basically of the year and two letters. The first letter refers to the half-month interval in which it was discovered; the second, to the chronological order of its announcement within that particular half-month interval. So, for example, 1982 DB was the second (B) asteroid discovered during the second half of February (D) in 1982. After the orbit of an asteroid has been well enough determined that it can be found again, it is given a sequential number and, when its discoverer can think of one, a name. Names seem to be needed for Amors 3757 1982 XB, 3122 1981 ET_3, 3908 1980 PA, and 3551 1983 RD, so readers with lovely ideas may submit them to the International Astronomical Union, Commission 20 (Positions and Motions of Minor Planets, Comets and Satellites).

[b] See table 14 for the definitions of these spectral types and possible meteoritic analogs of them.

[c] When more than one spectral type is listed, the indication is that the data are ambiguous or noisy.

[d] U = Unclassified.

The best possible target would be a body that can be reached simply by achieving escape velocity from Earth and which is about to collide with the Earth (so that no return propulsion is required). The round trip ΔV from LEO for this unattainably ideal case is about 3.4 km/sec. A reasonable estimate of the number of near-Earth asteroids with radii of 1 km or more yet to be discovered is 1000 to 4000. Estimating that 10 percent of them will be in accessible orbits (round-trip total ΔV < 6 km/sec), some 100 to 400 1-kilometer-size bodies should be available for exploitation. The number of bodies with radii of 100 m to 1 km is probably several hundred times as large.

The martian satellites Phobos and Deimos are less attractive in terms of the energy needed to reach them than the near-Earth asteroids but still more accessible for exploitation than the surface of the Moon. Like the Moon, Phobos and Deimos apparently have a regolith and lack an atmosphere. Three independent sources of information—thermal inertia measurements and photographs made from Mariner 9 and Viking and ground-based radar measurements—indicate the presence of a lunar-like regolith that is tens of meters deep in some places. Measurements of the densities of Phobos and Deimos, their albedo (dark), and their spectral reflectance are similar to those for carbonaceous chondrite meteorites and the possibly organic-rich D- and P-type asteroids. However, ground-based photometry of Deimos made during the 1988 opposition of Mars shows no 3-micron water band in its spectrum, and data from the Soviet spacecraft Phobos 2 must be thermally modeled before these images and spectra can provide information on the presence of water on Phobos. Thus, to associate the composition of Phobos and Deimos with any meteorite type would require a mission capable of taking a chemical inventory of these satellites.*

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*Lucy McFadden, 1989, in vol. VI of Exploration Studies Technical Report, published by the Office of Exploration, Johnson Space Center, NASA TM-4170, pp. 2-6 & 2-7.

The ΔV requirements for the outbound (LEO to surface of body) and inbound (surface of body to LEO) legs and the trip times for asteroidal, lunar, and martian trajectories are compared in table 19. Note that the Mars system is mainly useful for supplying resources to support Mars endeavors. However, return of martian satellite materials to LEO is somewhat more attractive energetically than return of lunar materials to LEO (return ΔV's about 40% lower).

TABLE 19. *ΔV's and Trip Times Between LEO and the Surfaces of the Moon, Selected Asteroids, Mars, and Phobos/Deimos**

Body	Outbound		Inbound	
	ΔV, LEO ⟶ surface, km/sec	Time of flight, days	ΔV, surface ⟶ LEO, km/sec	Time of flight, days
Asteroids:				
1982 DB	4.45	210	0.06	480
1982 XB	5.30	220	0.22	470
1982 HR	5.30	180	0.26	320
1980 AA	5.40	690	0.36	450
1943 Anteros	5.27	390	0.39	290
Moon	6.00	3	3.10	3
Mars	4.80	270	5.70	270
Phobos/Deimos	5.60	270	1.80	270

*All returns to LEO are via aerocapture. All arrivals in the Mars system are also via aerocapture in the martian atmosphere.

Asteroids as Targets for Resource Exploitation

Although both meteoriticists and asteroid spectroscopists are puzzled over the lack of correspondence between types of meteorites as analyzed in the laboratory and types of asteroids as measured by remote sensing of their surface mineralogy, there are indications in these spectral reflectance data that some of the near-Earth asteroids resemble the volatile-rich carbonaceous chondrites. So useful would volatiles, including water and carbon dioxide, be in space settlements that additional support for the effort to find and characterize more of these asteroids seems warranted. (See the preceding paper by Mike Gaffey.)

Though we have no spectral typing of the most accessible asteroid, 1982 DB, the fact that a round trip to it or one of several other near-Earth asteroids requires less energy than a round trip to the surface of the Moon is another reason to keep looking for an asteroid that is both accessible and of a desirable composition. Should such a candidate for resource exploitation be found, then we would want to send a reconnaissance mission to it to determine if it is really a mining prospect. (See Rich Gertsch's subsequent paper on asteroid mining.)

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