Apollo Asteroids, the Opportunities: A Vast Source of Wealth

Thousands of asteroids orbit throughout the solar system. A majority of these are located in a belt between the orbits of Mars and Jupiter, but a considerable number occupy other orbits. Some of these orbits regularly cross the orbit of the Earth, and the asteroids occupying them are generally known as Apollo objects. There may be over 100,000 such objects with a diameter greater than 100 meters. Of these, over 1000 may have diameters greater than 1 km. (only about 50 or so have been officially cataloged to date, and these are, of course, the more easily observed larger specimens).

These minor planets will become a major focus of attention in the future. Their relative nearness to Earth provides both unprecedented opportunities, and an unprecedented threat.

The asteroids have long been considered as a potential source of materials for use both in space and on Earth. Many studies have been done on mining asteroids, and numerous methods have been examined for accomplishing this using both near-term and long-term technologies. A brief overview (without going into technical details):

Refining methods are varied, depending on the material being refined and other factors, but usually involve using solar energy focused by large, lightweight reflectors. Transportation can be accomplished in varied ways, as well. The Apollo asteroids can be reached, even with manned vehicles, by ordinary chemical rockets. At present, though, it appears that more advanced propulsion methods will be required to properly exploit their resources. These methods include mass drivers, solar sails, and steady-state and pulsed nuclear systems. Most mining concepts involve refining the materials on site and shipping the finished product to the location where it will be used. However, advanced propulsion systems open the option of moving the asteroid itself to an orbit around the Earth (possibly in one of the Lagrangian points) in order to more easily work on it. This would probably only be cost-effective if the asteroid was unusually rich in resources (such as some nickel-iron type asteroids, discussed later in this article).

More extraterrestrial mining proposals have dealt with materials from the Moon, rather than the asteroids. The reasons for this have to do with the considerably shorter transit times between the Earth and Moon, and a more complete knowledge (due to sample returns) of the makeup of the lunar surface.

In the long run, though, asteroid mining may be easier and more profitable than lunar mining. Tranportation costs are an important factor. A certain amount of delta-V is required to leave low earth orbit, rendezvous with an asteroid (or land on the Moon), and return. Many of the Apollo asteroids have delta-V requirements that are actually less than those for a lunar landing, due to the delta-V needed to fight the lunar gravity. As far as transit times and distance are concerned, once a steady-state shipping "pipeline" is established from an asteroid mining site, this will cease to be a serious problem.

In addition, the energy requirements of the actual mining process may make asteroid mining more attractive than lunar mining. An asteroid is likely to contain a higher abundance of valuable metals than the lunar soil, and more of these metals are in a free state rather than tied up in oxides like they are on the Moon. It is estimated that up to ten times the energy may be required to refine a final product from metal oxides than from free metals. In addition, this energy is more accessable at an asteroid. As mentioned, solar energy is considered a prime source of energy for space mining processes. An asteroid has constant solar energy available whereas a refinery on the lunar surface would normally be in darkness two weeks out of every four.

To be fair, the final trade-offs between lunar and asteroid mining cannot be made without further information. Future technology breakthroughs in propulsion, mining techniques, or energy production could alter the equation. In addition, more information is needed on the composition of the Moon and asteroids. Samples from the Moon are still too limited to draw final conclusions, but at least there are samples. As yet, no samples at all have been obtained from an actual asteroid.

However, the composition and other physical characteristics of asteroids can be deduced by a number of methods other than sampling. These include spectral analysis, albedo measurements, and mass calculations from orbital analysis. The most useful information has been acquired by the detailed examination of meteorites, many of which are assumed to have compositions similar to those of asteroids, or even be pieces of shattered asteroids themselves.

The classification of meteorites (and by inference asteroids) by composition is complex, but we can break them down into three basic types: ordinary chondrites, carbonaceous chondrites, and metallic or nickel-iron. The composition of these three classes is detailed in Table I:

TABLE I

REPRESENTATIVE COMPOSITIONS OF DIFFERENT TYPES OF METEORITE MATERIALS
(in weight percent unless otherwise noted)

MATERIAL	ORDINARY CHONDRITES	CARBONACEOUS CHONDRITES	NICKEL-IRONS
Fe (Iron)	6.27	0	90.78
Ni (Nickel)	1.34	0	8.59
Co (Cobalt)	0.046	0	0.63
FeS	5.89	3.66	Variable
SiO_2 (Quartz)	39.93	27.81	-
TiO_2	0.14	0.08	-
Al_2O_3	1.86	2.15	-
MnO	0.33	0.21	-
FeO	15.44	27.34	-
MgO	24.71	19.46	-
H_2O	0.27	12.86	-
C (Carbon)	0.03	2.48	Variable

TRACE ELEMENTS

Mo (Molybdenum)	1.6 ppm	-	13.0 ppm
Au (Gold)	0.18 ppm	0.17 ppm	1.15 ppm
Ag (Silver)	0.102 ppm	0.250 ppm	0.020 ppm
Pt (Platinum)	1.0 ppm	-	20.0 ppm

(Reprinted from January, 1978 Commercial Space Report (then titled The Foundation Report)

Studies indicate that the population of Apollo asteroids is probably composed primarily of ordinary chondrites, along with some carbonaceous chondrites and a few nickel-irons. This census involves a certain amount of uncertainty, since the number of surveyed asteroids is still somewhat small, and there are factors that can make the count misleading. As only one example, carbonaceous chondrites generally reflect less light, and so are less likely to be observed and may be more numerous than present observations indicate.

Carbonaceous chondrites have little free metal, but are rich in volatiles such as water. This may make such asteroids extremely valuable in the inner solar system, where water seems to be rare other than on planetary surfaces. Some scientists predict that the Apollo carbonaceous chondrites may not contain much water. The Apollo-type orbits bring these asteroids relatively close to the sun, which could boil away the useful volatiles. After all, this is what happens to comets, which are essentially asteroid-like bodies encased in frozen gases. A comet which passes the sun too many times is boiled down to its rocky core, and becomes an asteroid, or, if the core is composed of many chunks of rock and gravel, a meteor cloud. The answer awaits on-site inspection.

The nickel-iron asteroids contain large quantities of pure metals in a free state. It is speculated that their composition is similar to what one would find if you could mine the core of the Earth. Table I shows nickel-irons to contain, of course, primarily elemental iron and nickel. There are also large amounts of so-called "strategic" metals, such as cobalt, the platinum-group metals, and others. In fact, nickel-iron asteroids contain a higher percentage of platinum-group metals than any material found in nature on Earth.

The ordinary chondrites are mostly minerals, with some metals and volatiles included. They probably represent the average Apollo asteroid not only in numbers, but in structure as well.

The Apollo asteroids are a potential treasure trove of raw materials. Speculation on the value of some typical asteroids is quite enlightening. Take for example three asteroids, one of each type, about half a mile in diameter apiece (a very average size for an asteroid).

At a specific gravity of about 2, our carbonaceous chondrite would weigh in at about 601 million short (2000 lb.) tons. The ordinary chondrite, with a specific gravity of about 2.3, would be a little heavier at 692 million tons. The nickel-iron, with a specific gravity of about 8, tips the scales at an impressive 2.4 billion tons. Now, we apply some math to see what we can get out of these rocks (assuming their compositions to be similar to those listed in Table I).

As mentioned before, the primary value of our sample carbonaceous chondrite is that it contains water--about 77.3 million tons of it. To put this in perspective, in liquid form this would fill a cube about a quarter mile on each side. Cracked into its oxygen and hydrogen components, it would yield enough propellant to fuel over 76,500 Space Shuttle External Tanks, certainly enough to be useful in fueling a large number of deep space vehicles.

It is interesting to note that if these deep space vehicles burn oxygen and hydrogen at the same 6:1 mix ratio used by the Shuttle (instead of the 8:1 ratio at which oxygen and hydrogen burn completely to water) one would have over 16 million tons of oxygen left over. If the hydrogen were used by itself as a propellant in nuclear rockets, the oxygen glut would become even worse. As a matter of fact, with oxygen apparently easily available on the Moon and Mars as well, it may become a problem figuring out what to do with it all. Contrary to traditional science fiction, hydrogen will be much more valuable than oxygen (at least until the outer planets and their moons can be exploited). Hydrogen is not only useful as a fuel, but would be essential in utilizing the asteroids' available carbon (about 17 million tons worth in our sample carbonaceous chondrite) to build complex molecules in space chemical industries.

Our sample ordinary chondrite also contains a useful quantity of water, almost 2 million tons. However, the ordinary chondrites and the nickel-irons are most lucrative as a source of metals. Again applying the figures from Table I, and adding some figures on terrestrial resources, we can create Table II:

TABLE II

COMPARISION OF ASTEROID AND TERRESTRIAL RESOURCES

(all numbers in short tons [2000 lbs. or 907.18 kg.])

	IRON	NICKEL	COBALT	PLATINUM [1]	GOLD	SILVER
World Reserves [2]	7.28×10^{10}	5.40×10^{7}	3.00×10^{6}	33,100	37,500	286,600
Some Major Sources		26%: New Caledonia	70%: Zaire, Zambia, Cuba	79%: South Africa 19%: USSR	53%: South Africa 18%: USSR	
Ordinary Chondrite Asteroid	4.34×10^{7}	9.27×10^{6}	3.18×10^{5}	692	124	71
Percent of World Reserves	0.06%	17.17%	10.6%	2.09%	0.33%	0.02%
Nickel-Iron Asteroids	2.18×10^{9}	2.07×10^{8}	1.52×10^{7}	48,100	2,770	48
Percent of World Reserves	2.99%	383.33%	506.67%	145.32%	7.39%	0.02%

NOTES:

1) "World Reserves" figures for platinum include all platinum-group metals (platinum, palladium, rhodium, ruthenium, iridium and osmium). Figures for asteroids are for platinum alone. Asteroid figures for all platinum-group metals would be even larger.

2) "World Reserves" figures are from the 1985 World Almanac and Book of Facts, and are defined as "that portion of a resource that can be economically extracted or produced at the time of determination". Obviously, a massive introduction of asteroid resources could alter this figure. For example, if prices for a resource are reduced by an increase in supply, the quantity of reserves that can be "economically extracted" would be reduced as well.

As we can see, it's Jackpot Time. In the case of the nickel-iron asteroid, the amount of nickel and cobalt contained amount to respectively four and five times the known reserves of the planet Earth. At present, as also shown in the table, the United States relies for many strategic metals almost entirely on imports from none-too-stable areas of the world. For example, the U.S. annual consumption of cobalt is about 7,500 tons. The need to import it has had a heavy impact on politics in the past. Yet even the resources of an ordinary chondrite (318,000 tons of cobalt) would obliterate these import requirements, and alleviate any political problems associated with them. It is likely that this improvement in our national security, resulting from an economic windfall rather than military might, would be more than worth the initial costs and problems involved in extraterrestrial mining operations.

Calculation of the dollar value of one (1) asteroid delivered F.O.E. ("Free On Earth"--with thanks to Cordwainer Smith) will be left as an exercise for the reader. A calculator capable of expressing itself in scientific notation is recommended. However, keep in mind that the increased supply is bound to have a negative effect on the price. It is said that if all the pure platinum ever mined and refined throughout history were melted into a cube, that cube would be about 14 feet on a side (approximately 1,800 tons). If true, one can see that introducing 48,000 tons of the metal (which would form a cube, incidentally, about 41 feet on a side) is not going to have a salutory effect on prices in the platinum market (at least from the sellers' viewpoint).

The price situation with gold is not quite as serious. All of the gold ever mined on Earth would theoretically form a similar cube about 56 feet on a side (about 110,000 tons). One can see that the amount of gold contained in our nickel-iron asteroid (2,766 tons) would form a cube only 17 feet on a side--only about three percent of all the refined gold in existence in the world (hardly seems worth the trouble, does it?)