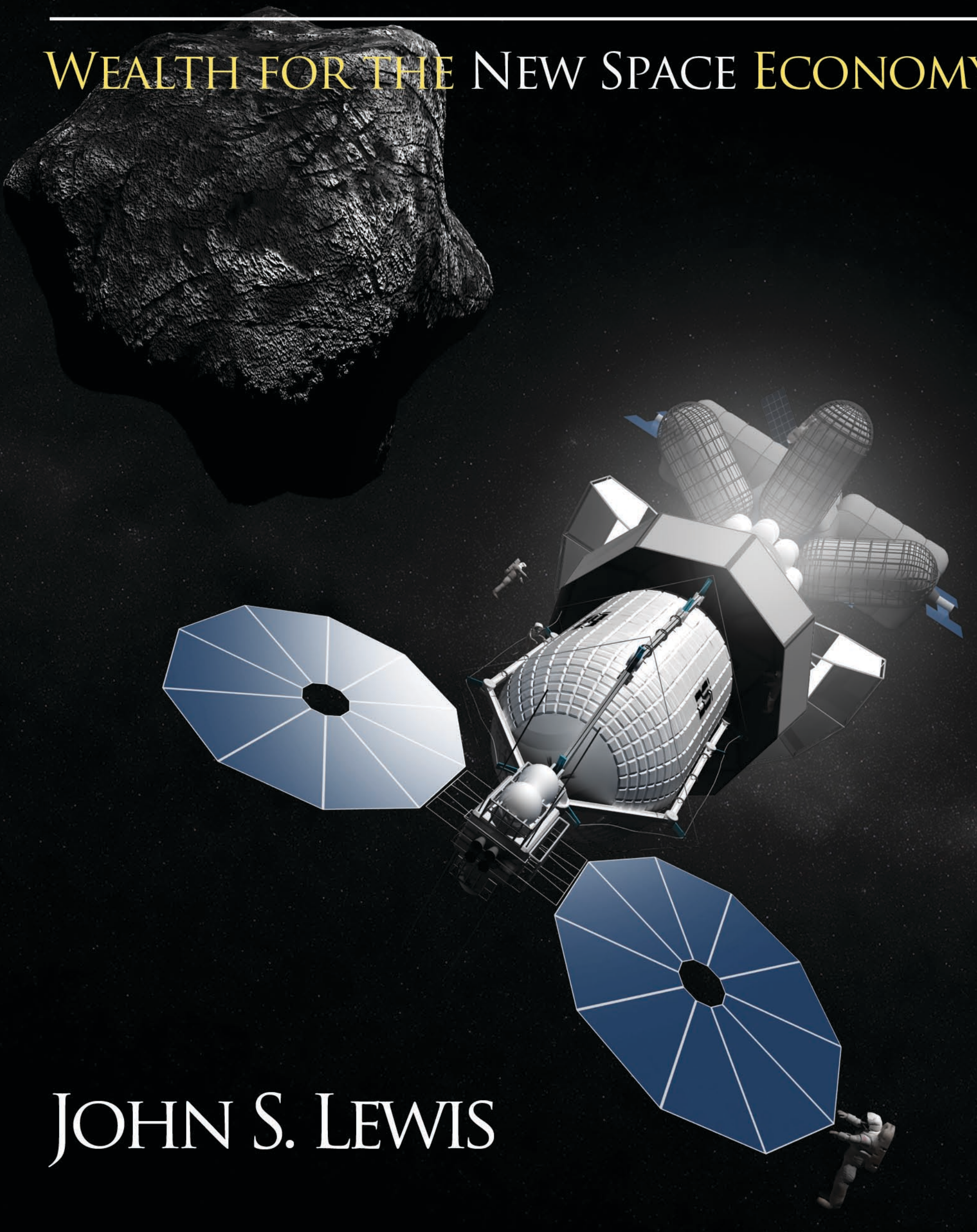
ASTEROID MINING 101

WEALTH FOR THE NEW SPACE ECONOMY



JOHN S. LEWIS

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Preface

By Rick N. Tumlinson

The best way to predict the future is to invent it.

--Dr. Forrest C. Shaklee

You live in a time when there are companies who want to fly into space and mine asteroids.

Think about it.

Real companies with staffs of talented engineers, scientists and businesspeople, funded by very smart and in some cases incredibly wealthy people who are themselves very successful business people, who want to send machines and possibly people to fly millions of miles out into space and "dig up" the rocks floating there in order to make even more money.

Who could have predicted this? Well, the father of American rocketry, Robert H. Goddard did. The father of Russian rocketry, Konstantin Tsiolkovsky, did—and both saw this future over a century ago! But nothing was done: technology was too immature; the cost was prohibitive; imagination was lacking. Clearly, they were crazy. *The New York Times* said as much in an editorial on "Moon-mad" Goddard's craziness published in 1926.

In *any* other time this would have sounded crazy. To many people it still does. Probably, even when it begins to happen, many will still think it's crazy. In fact, even as they benefit from the wealth and possibility that is created as we harvest the resources of space and create a new renaissance, many will think such things and the people who do them to be crazy.

And it is. And yes, we are.

Exactly the kind of crazy that has led to every major scientific and economic revolution since some crazy hair-covered hominid (class of '00) decided to pick up a naturally provided stick or rock to see if it might help protect them from large hungry creatures with pointy teeth.

Or a few million years later, a less hairy yet equally crazy descendant dropped a seed into a hole he had made with a similar stick or rock to see if he could actually grow the grains and berries that kept them fed in bad times. Or the distant ancestor who found little pieces of hard, shiny bronze in the ashes of his cooking fire and set about trying to make the stuff intentionally.

This is the kind of crazy that applies thought and imagination to observations of the real world, inventing new ways to defend ourselves or to increase the abundance of our vital supplies – by using the tools available in crazy new ways.

It is this kind of crazy that takes a brilliant mind from the observation of dead rocks in space and their relationship to the development and evolution of planets and the solar system through the revelation that such objects not only pose an imminent and ongoing threat to our civilization, but that they can be defended against, and more, these same objects can be used to save our planet and help us expand our domain into the universe.

This is John S. Lewis.

And this is his time.

Within the last three decades something important and incredible has finally begun to happen. The rockets and space systems we thought reserved for the use of governments and soldiers have found new purposes, and new masters, people who want to use them to go beyond the purposes of science and state and turn them into tools that can be used for other goals, such as flying people and machines out to the frontier for fun and profit – oh, and to live. Weapons of mass destruction morph into both weapons of mass protection and heavenly chariots delivering untold wealth to Earth and Earth's children.

Well before the idea that an Elon Musk or Jeff Bezos could build and own their own fleets of spaceships, in fact well before either of them had the idea they could own their own car, John Lewis was exploring the solar system from his office at MIT and then the University of Arizona, and coming to the realization that the solar system was not some neatly arranged set of planets with a well-placed band of asteroids in its middle, but was full of errant chunks of rock and ice flying in all directions and wreaking havoc on these celestial objects in often unpredictable and sometimes incredibly spectacular ways. His book ***Rain of Iron and Ice*_**laid out these ideas, and in harrowing detail carried us through the life of a world that is the hapless bull's-eye in a cosmic shooting gallery—a realization made far more harrowing by the recognition that the bull's-eye is us.

In it, he tied together thousands of eye witness reports of meteor strikes on the Earth, and showed how not only would there be no life here without these objects, but also how life and history have been affected by them, and how, if we remain passive, life and history may come to an end when one of them takes us by surprise.

In parallel to this evolution of thought, John was also realizing that these same objects must carry the very materials and supplies the human race could use to rise beyond its home on Earth and expand into space, not only making humankind essentially un-killable, but prosperous and vital in ways that stagger the imagination.

The idea of using space resources to do things in space was not new, but no one had pulled it together in such a focused, scientifically credible and easy to understand way as Dr. Lewis did in his book ***Mining the Sky*.** The perfect sequel to ***Rain of Iron and Ice***, this volume laid out a clear and concise approach to developing an economy and industrial base using space resources, with reality-based numbers, scientifically supportable research and solid, common sense explanations.

Early on in his work building these concepts into the core of a new vision of our relationship to space, we joined forces with Dr. Gerard K. O'Neill and physicist Freeman Dyson to give them life in the form of encouraging action in the next generation. O'Neill had written a game-changing book of his own called ***The High Frontier*** that laid out a clear and compelling case for developing human communities in space, and with Dyson at his side they fathered the Space Manufacturing Conferences in Princeton, New Jersey. There they formed a coalition to move these ideas from the mere pages of books and papers out into the world, and to enable young minds of the time to enter their conversation and actually engage in the craziness themselves. It was the TED and South by Southwest of its time in terms of space, where young minds and crazies could come together with their peers and heroes and lay out ideas that were, as we used to say "not ready for prime time."

This is where I and the others who now pursue our own dreams of opening the frontier first came together. And it was there where we first were given what I call Permission to Dream that we might actually be able to go out there and do those things. It was at these meetings that we began to develop the depth of understanding and connect the dots that would enable us to realize that the dream of expanding human civilization into space was not only feasible, but imminently so, and yes, imperative.

It is from the core concepts laid out by Dr. Lewis that we were able to translate Dr. O'Neill's vision into the reality of a set of basic steps that could lead us to establishment of companies and teams that would really begin to make it happen.

And it was a result of their ability to listen to us, interact with us in ways that were firm and yet encouraging that created in us a self confidence and fired our passions with the heat of urgency so that we could go out into a world that sees us as crazy to do exactly what the people in that world need us to do. This core group of mentors could have locked us out, could have played the academic game of elitism, but they did not. They almost delighted in lighting our fires, and their kindness and willingness to listen to our crazy ideas was critical to starting us on the critical path we needed to take to begin to make it happen today. Along the way, those in this core group, who now range from top NASA leaders and scientists to successful businesspeople and entrepreneurs, were able to fire the minds and imaginations of others, people who had made huge amounts of money in fields like computers, software, payment systems, real estate and entertainment, until, just as the old ways of doing space began to reach their end, these new leaders were able to rise and create the new companies and projects you see today.

And thus we are able to talk of flying out to asteroids to harvest them. Because the dream of doing such things, planted by people like Dr. Lewis, took root in our minds and those with whom we interacted and so on until now they have created the rockets and spaceships and technologies that will allow us to go out and harvest asteroids…

We have right now on this planet people who by themselves have said they will build and fly passenger rockets to Mars in our lifetime. We have in the world right now today the technologies to shrink a computer that used to take an entire building into the size of part of a wristwatch, and to put that system and a million others in the hands of people around the world working together in a million ways to create new ideas and technologies at a rate that seems to increase by the minute.

Crazy? Wait a few hours… oh, and as you're waiting, read this book.

If you have read the other books I have mentioned, you are already on the way to understanding what it is we are doing when we say we are going to harvest the resources of space. If not, get ready for a bit of both work and mind blowing possibility. In ***Asteroid Mining 101*** Dr. Lewis moves from a survey of possibilities to the specific concepts and information one needs to be able to turn a dead rock in space into the tools and supplies of life. You will learn more about the types and forms of asteroids than you thought possible, and while in past times such knowledge may have seemed a bit abstract, keep in mind that because of John, there are people getting paid out there right now to make this stuff happen, and soon enough, the idea that you are or know an asteroid miner will be the same as in another time when one might have known someone who programmed those new things called computers.

This book is not easy. It is serious and you will have to work a bit to understand all it has to offer. But if you do the work and spend the time you will graduate into the class of crazies who change the future – or at least understand us, and what is happening as we change tomorrow.

Good luck, and welcome to the revolution!

Rick N. Tumlinson

I. Introduction

The emerging asteroid mining industry has extremely ambitious intentions. It is within the realm of possibility that their work may usher in a change in global economics as profound as the Industrial Revolution. As may be expected, press reports dealing with asteroid mining have been numerous, ranging in scope from short and breezy to broad and serious, and in quality from accurate to impressionistic to simply uninformed.

There is good reason to be curious about what may be the biggest game-changer in human economic history. And there is good reason to look closely at the underlying science and engineering that form the foundation of this work.

My personal involvement in this field gives me license to talk about the subject without hiding behind clever catch-phrases or vague generalities. It also carries the responsibility to avoid overselling the field. I do this by including critical assessments of the ideas I put forward. You presumably did not buy this book to be hyped by some huckster. If you did, I hope you will be sorely disappointed and not recommend the book to like-minded friends.

There is seldom a perfect place to begin a century-long ongoing story, but I choose to start with the writings of the Russian rocket pioneer Konstantin Eduardovich Tsiolkovsky (1857-1935). At age 10 he suffered a severe case of scarlet fever that left him nearly deaf. He used an “ear-trumpet” for the rest of his life, but the immediate effect of his loss of hearing was to terminate his formal education. Possessed of a brilliant and original mind, he embarked on a program of self-education that quickly led him into physics and engineering. He became obsessed first with lighter-than-air flight, and later with rocket propulsion. By 1900 he had formulated a roadmap for expansion of mankind into the Cosmos. This roadmap was revised and reprinted many times over the years, but the core document consisted of the “14 Points” he articulated in 1903. The first seven points concerned basic rocket propulsion technology, all of which were achieved by 1964. But the final seven points stretched out into a distant and remarkable future. These points were:

8. development of spacesuits for use outside spacecraft (first achieved in 1965),

9. space agriculture to provide the food needed by space travelers,

10. Earth-orbiting self-sufficient space colonies,

11. use of solar power for transportation in space (Solar Electric Propulsion, 1965),

12. exploitation of asteroid resources to achieve autonomy from Earth,

13. offloading of heavy industry from Earth to space, and

14. the perfection of mankind and society.

Of the nine points already realized, it is noteworthy that all were achieved by 1965—and not a single one since that date. It is interesting that Tsiolkovsky had no illusions about how easy it would be to bring about his vision. His novel *On the Rocket: In the Year 2000* envisioned manned space travel being first achieved in that year, brought about by a team of what we would today call venture capitalists. When, in his later years, Tsiolkovsky became a hero of the Soviet state, they somehow failed to mention that prediction. But manned spaceflight did not have to wait for the year 2000: Yuri Gagarin flew into orbit in 1962. And, sad to say, even now the perfection of mankind and society is still a way off.

Now it is well past the year 2000, and venture capitalists with dreams about space are making daily news. Whether it is offering private satellite launch services, selling tickets for suborbital flights, servicing the International Space Station, building hotels in orbit, landing on the Moon, or even mining asteroids, space travel has escaped from the iron grip of governmental control and is intent on becoming a generator of profits and of tax revenues, not a sinkhole for our tax dollars.

Of these commercial endeavors, mining asteroids seems farthest away, yet paradoxically has the longest history. The very phrase “asteroid mining” reminds aerospace technologists of Tsiolkovsky, science fiction readers of the asteroid miners of E. E. “Doc” Smith and Frederick Pohl, and almost everyone of terrestrial mining. But familiar mining operations on Earth give a poor and misleading idea of what mining asteroids will entail. Mining and mineral processing on Earth assume the presence of air and water and Earth-normal gravity, huge diesel-powered excavators and earth-movers, and often strip-mining of vast volumes of overburden to access thin veins of highly concentrated ore. We who want to mine asteroids must learn to operate without air except what we can make; without water except what we can extract; without gravity except what artificial gravity we can make; even without conventional ore bodies.

Earth, unlike the large majority of asteroids, melted very early in its history. The solid raw materials out of which Earth and the planets formed, once grown into bodies nearly the size on Mars, melted extensively due to a combination of the gravitational potential energy released by their accretion and the cumulative buildup of heat from the decay of radioactive isotopes inherited from the pre-planetary cloud. The melted rock separated at first into two liquids with very different compositions and densities, one a dense liquid composed of metals and sulfides, and the other a silicate melt. As accretion slowed and the radioactive heat source decayed away, cooling of these two melts led to partial crystallization and further separation by density into distinct layers with very different compositions. This process is called "geochemical differentiation". Differentiation of the dense metal-plus-sulfide melt, driven by crystallization of metallic alloy of iron, nickel, and other chemically similar elements, separated into an even denser solid metallic core and a residual sulfide-rich melt. These are today's metallic inner core and liquid outer core. The silicate melt, driven by crystallization of dense minerals containing iron oxides and by release of low-density volatile elements, separated into a dense lower mantle, a less-dense upper mantle, a crust dominated by low-density silicates with high contents of sodium, calcium, aluminum, potassium, and silicon, and, on top, oceans of water and an atmosphere of uncondensed gases.

This history assures that all those chemical elements that can readily enter into the core, including free metals and many sulfides, are very strongly concentrated into the core—and very severely depleted in the crust upon which we live, and into which we mine. **Our very concept of precious and strategic metals reflects which elements have been efficiently buried thousands of kilometers beneath our feet.**

Geochemical recycling processes, largely dependent upon very hot liquid water, are responsible for extracting and concentrating the pittance of these elements that remain in the crust, depositing them in veins that are concentrated enough for economically profitable mining. Those materials that can be extracted profitably are called “ores”.

But, as we shall see, most asteroids have never melted and differentiated. The action of liquid water is seen in very few meteorites, and never in those that have differentiated. This means that the terrestrial concepts of having to remove vast masses of uninteresting overburden, and of ore veins that must be found and followed deep within hard rock, are largely irrelevant to asteroid mining. Undifferentiated asteroids consist of a fine-grained mixture of all the materials that went to make Earth’s core, mantle, and crust. All those “precious” and “strategic” materials we have defined from an Earthly perspective are present everywhere. As an example, ***the concentration of the “rare” and “precious” platinum-group metals in a random piece of an average asteroid is several times higher than in the richest known ore bodies in Earth’s crust*****!**

Now, for the first time in human history, the capabilities of aerospace engineering, originally largely developed for military purposes; the laboratory study of meteorites; and the astronomical study of asteroids have combined to give us knowledge of-- and access to-- reservoirs of resources beyond our wildest dreams. This comes at a time when the press reminds us daily of the finite resources of Earth’s crust and the depletion of easily accessible ores, projecting a dismal and inescapable future for us all.

This book is the story of why asteroid mining is so timely. We will survey the nature of asteroids and of the meteorites that tell us of their detailed composition and history. We will discuss at some length the opportunities for using resources from space and the types of uses to which those resources can be put. And we will attempt to restore a vision of the potentially limitless future before us, in which nothing is guaranteed, but almost anything is possible.

II. The Solar System: Complex and Overlapping

When we move to a new house, the first thing we do is explore it and our back yard. A little later, we explore our neighborhood, and eventually our new town, with an eye to seeing what it has to offer. So it is with the planet on which we live.

Just a few hundred years ago, mankind became aware that Earth was not the only material body in existence. Soon thereafter it was discovered that Earth was not the center of creation, but instead was just one of several large planets that orbited around the Sun. Two centuries ago astronomers found the first asteroids, showing that our neighborhood was a much more complex and lively place than we had imagined. Others showed how to measure the distances to other stars, making it clear that our Sun was only one of countless stars in the Milky Way, each one a potential center for a planetary system of its own. One century ago we found out that Earth was visited by many asteroids, making Earth and the asteroids interacting parts of Solar System ecology. At the same time, deep-space astronomers found that the Milky Way was just one of countless galaxies, each with hundreds of billions of stars. And in the last 20 years we have discovered not just a few, but hundreds of planets in orbit around nearby stars. We have gained not only a much deeper understanding of Earth's place in the Solar System, but also have come to appreciate the complexity and diversity of other stellar systems. We now see the Solar System as our back yard; we have sent spacecraft to every planet and even to the limits of the Sun's sphere of influence. Let us now take a tour of our back yard to refresh our understanding of what is there.

The Solar System comprises the several classes of primary bodies that orbit around the Sun and those smaller secondary bodies that orbit around them. **Table II.1** gives the essential data on the structure of the planetary system, as also portrayed in **Figure II.1**

Table II.1
Orbits of the Planets

Planet	Semimajor Axis, a (AU)	Eccentricity e	Inclination i (°)
Mercury	0.3871	0.20563	7.0044
Venus	0.7233	0.00678	3.3945
Earth	1.0000	0.01670	0.0000
Mars	1.5237	0.0934	1.8499
Jupiter	5.2042	0.0479	1.3056
Saturn	9.5751	0.0520	2.4859
Uranus	19.31	0.0500	0.7727
Neptune	30.2	0.0040	1.7725

Closed (periodic) orbits are ellipses. The *shape* of an ellipse can be described by two numbers, the mean radius of the ellipse (its *semimajor axis*) and its deviation from circularity (its eccentricity). The eccentricities of closed orbits range from 0 for circular orbits to 1 for the limiting case of a parabolic orbit. An eccentricity of 0.9999 would be an extremely elongated ellipse, similar to the orbit of a long-period comet. In addition to the shape of the orbit, it is often necessary to describe the *orientation* of the orbit in three dimensions. This requires giving the inclination of the plane of the body's orbit to the central plane of the Solar System (an orbit that lies in the same plane has an inclination of 0; a body that is traveling in the same plane as the planets but in the opposite direction would be assigned an inclination of 180 degrees). In addition, we must specify where the body's orbit crosses through the central plane, the "*longitude of the ascending node*". (A "node" is the point where one orbit crosses a specific plane and "ascending" means "traveling from south to north".) By analogy with longitudes on Earth, celestial longitudes are measured relative to an arbitrary but universally agreed-on reference point, the Greenwich Observatory on Earth and the Vernal Equinox, the point on the celestial sphere where the Sun is located on the first day of spring, in space. We also have to specify the direction of the long axis of the orbit. This is done by giving the "*argument of perihelion*", which essentially tells us the longitude of the point on the orbit that is closest to the Sun, the *perihelion* point. With these five numbers we have fully described the shape of the orbit and its orientation in space. All we need now is to specify where on that orbit the body is at a particular time. This number bears the somewhat puzzling name of "*true anomaly*", which is the angle between the point of perihelion passage and the position of the planet on its orbit. Thus a true anomaly of 180 degrees would refer to a planet that was in the point on its orbit opposite perihelion, which is at opposite end of the long axis of the orbit, the point of greatest distance from the Sun, or *aphelion*, at the specified reference time ("epoch").

The most massive of the Sun-orbiting primary bodies are the gas giant planets Jupiter, Saturn, Uranus and Neptune. Lower in rank by mass,

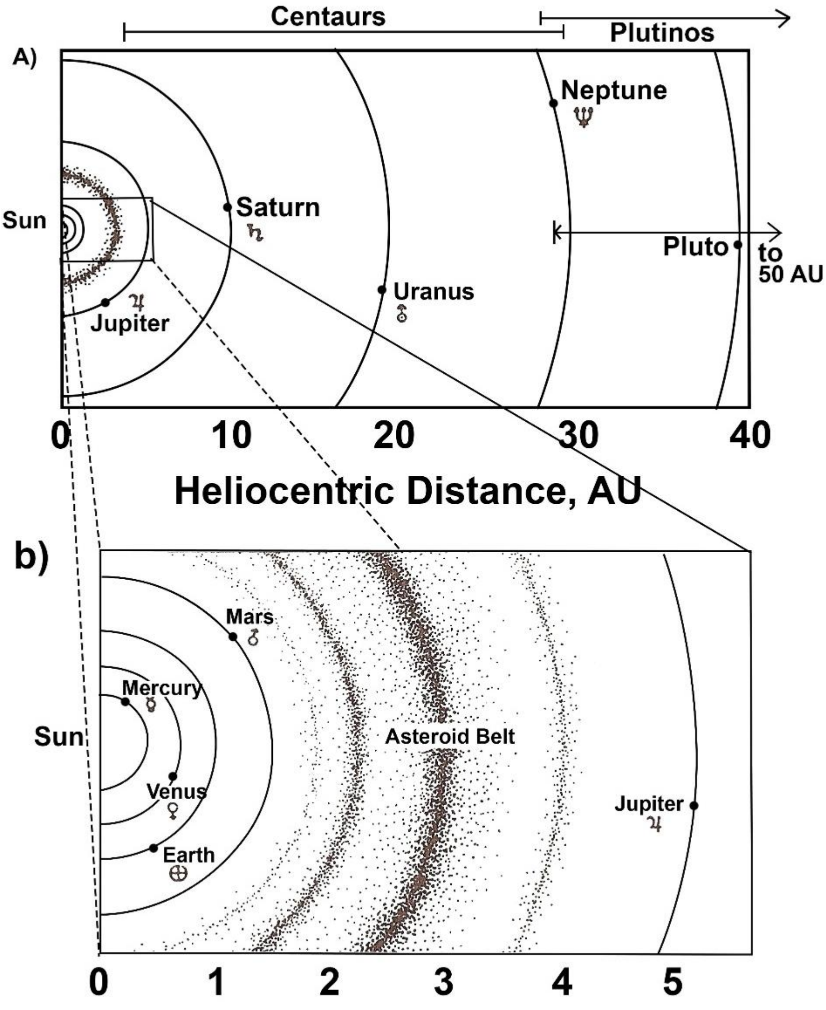

Figure II.1 Structure of the Solar System. The orbits of the planets and of the Asteroid Belt are shown to scale. Part a) shows the Solar System out to Pluto; part b) shows detail in the inner Solar System.

Credit: Deep Space Industries – John S. Lewis

and much closer to the Sun, are the inner or terrestrial planets Mercury, Venus, Earth, and Mars. As in Table II.1, The mean distances of the planets from the Sun are normally given in units of Earth's mean distance from the Sun, 1 Astronomical Unit (1 AU; 149,597,870.7 km).

Also directly orbiting the Sun **(Figure II.1)** is the broad band of the main Asteroid Belt, which occupies a ring outside the orbit of Mars and inside the orbit of Jupiter. Belt asteroids fall into several orbital families, and the distribution of orbital periods is highly structured, with several narrow intervals of orbital period essentially devoid of occupants. Some asteroids have orbits that penetrate into the inner Solar System, allowing them to cross the orbits of the terrestrial planets. Any asteroid that approaches within 1.300 AU of the Sun is called a Near-Earth Asteroid, or NEA. Many NEAs have orbits that take them as far from the Sun as the heart of the Asteroid Belt, 2.2 to 3.3 AU from the Sun; some travel out to Jupiter's orbit 5.2 AU from the Sun, and even beyond. At the opposite extreme, some NEAs have orbits that lie entirely inside Earth's orbit. The distribution of asteroids versus orbital distance (a, in AU) or period (P, in years) shown considerable structure, with certain orbits whose orbital periods are harmonically related to Jupiter's orbital period being virtually unpopulated (see **Figure II.2**).

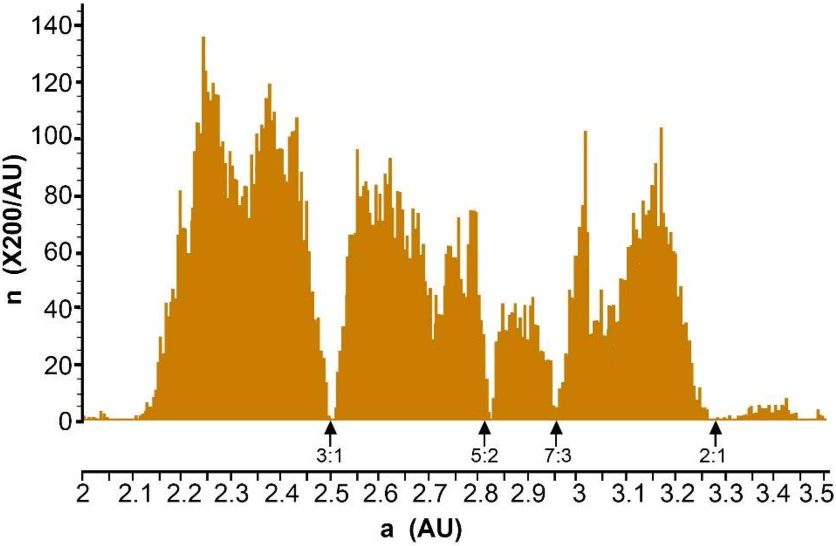

Figure II.2 Structure of the Asteroid Belt. The distribution of asteroid population density vs. mean distance from the Sun (orbital semimajor axis a, in AU) shows severe depletion of those asteroids that have orbital periods that are harmonically related to (resonant with) Jupiter's orbital period. These Kirkwood gaps are locations from which asteroids can be expelled by the periodic perturbations caused by Jupiter's gravity.

Credit: Deep Space Industries – John S. Lewis

Figure II.3 The NEAR Shoemaker mission photographed near Earth asteroid 433 Eros in February 2000.

Credit: NASA

The main Asteroid Belt also has outliers beyond the Belt's outer confines, including the Hilda family at 4 AU from the Sun, and two clusters of asteroids that actually orbit on the orbit of Jupiter near points 60° ahead of and behind Jupiter, 5.2 AU from the Sun (and thus also 5.2 AU from Jupiter). These are called the Trojan asteroids: originally they were intended to be named after characters in Homer's *Iliad*, divided by location into the Trojans and the Greeks. Unfortunately for this clever idea, incautious use of the *Iliad* led to an inadvertent mixing of the two camps which made the intended distinction moot. In recent years the number of known Trojan asteroids has grown so large as to exhaust the nomenclatural resources of the *Iliad*.

Analogous to the relationship between NEAs and the terrestrial planets, there are also certain small Sun-orbiting bodies from the outer Solar System that have orbits that cross one or more of the orbits of the giant planets. These bodies are known as *Centaurs*.

Beyond the orbit of Neptune lies the realm of trans-Neptunian objects (TNOs), including the *plutinos*, whose mean distance from the Sun is greater than that of Neptune, but which follow orbits that cross Neptune's orbit. Pluto itself is one member of this family, the one that is most easily observed from Earth. Beyond the plutinos we have the *cubewano* family. These distant bodies are historically described as Kuiper Belt objects after planetary astronomer Gerard P. Kuiper, who first proposed their existence.

Far beyond the Kuiper Belt, following orbits of random inclination and high eccentricity, is the *Oort cloud* of long-period comets, named after Dutch astronomer Jan Oort, who first deduced the cloud's existence. These comets typically have orbital semimajor axes on the order of 10,000 AU and periods of millions of years. Occasionally, perhaps once or twice per year, a member of the Oort cloud, having been perturbed by the gravitational influence of a passing star, will pass spectacularly through the inner Solar System. These *long-period comets* are outliers from the main comet population that pass deep into the inner Solar System on each orbit around the Sun (once every few million years), and therefore are observed only once by astronomers. In addition, there are *short-period comets,* which may have orbital periods as short as three years. They often have orbits that take them out to the orbit of Jupiter: it is extremely likely that they owe their present orbits to gravitational perturbations that occurred during close approaches to Jupiter. Because they can be seen on many passages around the Sun, their periods are known, and they are therefore often termed *periodic* comets. All comets are extremely difficult to observe unless they approach the Sun relatively closely, where solar heating evaporates ices from their surfaces and produces distinct, and often memorable, displays of gas and dust called comet tails. Fresh long-period comets that approach the Sun closely may put on spectacular shows, with tails that sometimes exceed 100 million km in length. Short-period comets that have passed many times through perihelion, their point of closest approach to the Sun, may eventually exhaust their supply of near-surface ices and cease to produce tails. They then are visually indistinguishable from asteroids. Indeed, some NEAs follow orbits that are characteristic of short-period comets, with aphelia (greatest distance from the Sun) that lie on the orbit of Jupiter.

Small bodies which orbit directly around primary Solar System bodies are numerous and fall into several distinct groups according to their compositions, locations, and orbital properties. These bodies, sometimes called "moons", are the natural satellites. Artificial satellites are usefully termed "spacecraft" to avoid confusion. Mercury and Venus alone among the planets have no known natural satellites. Earth has one, the Moon. The Moon is one of seven large, almost planet-sized, satellites in the Solar System. Mars has two small satellites, Phobos and Deimos. Jupiter has four giant satellites, Io, Europa, Ganymede, and

Callisto, usually called the Galilean satellites in recognition of their original discovery by Galileo Galilei early in the 17th century. Io is a rocky body with extensive sulfur volcanism, Europa has a thin ice shell surmounting a global ocean perhaps 50 km deep, and Ganymede and Callisto are mostly composed of ice. Ganymede is larger than the planet Mercury. Jupiter also has several small inner satellites that orbit between the top of Jupiter's atmosphere and Io, and a vast population of small outer moons, some in prograde orbits (moving in the same sense as the planet's spin) and some in retrograde orbits with periods longer than two years.

Saturn's satellite family includes one giant satellite, Titan, a little larger than Mercury. Titan has a dense atmosphere of nitrogen, methane, and other gases and lakes and seas of liquefied atmospheric gases on its surface. Saturn has nine other mid-sized satellites, ranging from about 200 to over 1400 kilometers in diameter. It also, like Jupiter, has several small inner satellites and families of small prograde and retrograde outer satellites.

Uranus has five mid-sized satellites (diameters about 400 to 1600 km) with a swarm of small inner satellites and another swarm of outer retrograde satellites. Neptune has one large satellite, Triton, which has a trace atmosphere and a very peculiar retrograde orbit. The Neptune satellite system also contains a number of small prograde bodies interior to Triton's orbit and one prograde midsized satellite, Nereid, outside Triton's orbit.

Pluto, not to be left out, has a midsized satellite, Charon, which is locked in a triple resonance with Pluto: the spin period of Pluto, the spin period of Charon, and the orbital period of Charon are all the same. Charon has more than half the diameter of Pluto. Pluto also has several small outer satellites. Like Charon, many other satellites of the outer planets, including all the Galilean satellites of Jupiter, are rotationally locked onto their parent planet.

There is no reason to believe that our present catalog of Solar System bodies is close to complete. In recent years, driven by advances in the sensitivity of electronic detector technology, the number of known satellites of the outer planets has grown substantially, and continues to grow. More surprising, a number of satellites of small bodies have also been discovered. Many Belt asteroids, NEAs, Centaurs and trans-Neptunian objects have been found to have satellites. Pluto is not the only plutino to have a moon. The count of satellites in the Solar System rises constantly, and it is a safe bet that many more are yet to be found.

Discoveries extend not only our quantitative catalogue of the numbers of known bodies, but also our qualitative understanding of the structure and contents of the Sun's family. If we turn our calendars back to 1800, the Solar System was a much simpler place: Earth's Moon; the four Galilean satellites of Jupiter and the five brightest satellites of Saturn (discovered in 1655 through 1686) were well known. Uranus had recently been discovered (1781), soon followed by the discovery of two of its satellites (1787). Just before the turn of the century, two more satellites of Saturn were added (1789). No asteroids were known; none of the small inner and outer satellites of the Jovian planets were known; the Centaurs, Kuiper Belt, and Oort cloud of comets were wholly unsuspected. Yet there was reason to celebrate and feel pride in the host of new discoveries of the previous 20 years. The next century literally dawned with the discovery of a wholly new class of Solar System bodies: the Italian astronomer Giuseppe Piazzi discovered the first known asteroid, Ceres, on 1 January 1801, the first night of the 19th century. By 1807 the Belt asteroids Pallas, Juno, and Vesta had been added to the list. Except for asteroid discoveries, matters rested there for the next 45 years; an observer might have felt justified in concluding that the work of cataloging the Solar System was done. But the planet Neptune was discovered in 1846, and its large satellite Triton was found a few days later. Saturn's satellite Hyperion was added in 1848, and two more satellites of Uranus, Ariel and Umbriel, were found in 1851. In 1877 the Martian satellites Phobos and Deimos were added. Jupiter's small inner satellite JV Amalthea, discovered by Barnard in 1892, the first known Near-Earth Asteroid, Eros (1898), and Saturn's satellite Phoebe (1898), finished off the 19th century list.

The 20th century was opened by the discoveries of four small outer satellites of Jupiter (1904-1914). Clyde Tombaugh discovered Pluto in 1930; two more small satellites of Jupiter were added in 1938, and several NEAs were found in the 1930s. The NEA Hermes flew by Earth at a distance of only 0.005 AU in 1937, alerting us to the potential for devastating asteroid collisions with planets. Gerard Kuiper discovered Uranus' satellite Miranda in 1948 and Neptune's small satellite Nereid in 1949. The remainder of the 20th century contained discoveries of many more small satellites, powerfully assisted by the *Voyager* spacecraft flybys of the giant planets and by great advances in electronic detection and imaging systems on Earth and in near-Earth space, on the *Hubble Space Telescope*. The first Centaur, Chiron, was discovered in

1977, and many more have been added since 1992. Since the Kuiper Belt was discovered in 1992, well over 1000 *Kuiper Belt Objects* (KBOs) have been catalogued.

The clean division of small Solar System bodies into discrete families has motivated theoretical modeling of their orbits, including the evolution of these orbits over long periods of time. These studies revealed that the mean lifetime of an NEA is about 30 million years, and that the main mechanisms for loss of these bodies were impact on a terrestrial planet or perturbation into Jupiter approaching orbits, from which the body could strike Jupiter, or could be ejected from the Solar System, or even fall into the Sun. Other studies examining the dynamical evolution of the Asteroid Belt found that certain specific locations in the Belt, called the Kirkwood gaps, corresponding to resonances with Jupiter, were unstable. These resonances have precise orbital periods, and therefore correspond to precise orbital semimajor axes: the actual distance of the asteroids from the Sun at any point in time is irrelevant. Since the orbital eccentricities of Belt asteroids are typically around 0.3, most asteroids cross one or more resonances on each orbit: an instantaneous picture of the locations of all the asteroids shows no gaps and no hint of the existence of these resonances: only a plot of number versus a or P shows gaps. Bodies wandering into these resonances could be kicked into high-eccentricity orbits that effectively transform them into NEAs. Thus both sources and sinks for the NEA population were documented. The NEA population is clearly in a state of dynamic overturn, with bodies being lost and recruited continually. Both the impact history of Earth and the fall of asteroidal debris (meteorites) are reflections of System-wide dynamical processes. Clearly anything that impacts Earth must be in an orbit that crosses Earth's orbit. Asteroids in such orbits are NEAs; comets that impact Earth can be members of either the short-period (which can have frequent opportunities to hit Earth) or long-period family (which typically have no more than one opportunity per million years, and may never have passed this way in earlier times).

Other studies showed that the outer, loosely-bound satellites of the giant planets could readily be captured from, or lost into, heliocentric orbits. Jupiter's Trojan asteroids can wander out of the Lagrange points and pursue "horseshoe" orbits that carry them back and forth between the two stable Lagrange points, or even make them available for capture as transient outer satellites of Jupiter. The other giant planets are also able to have their own Trojan asteroids: both Uranus and Neptune have known Trojan asteroids, and even Earth and Mars have them.

The short-period comet Wilson-Harrington, discovered and lost in 1949, was rediscovered in 1979 masquerading as an NEA, with no signs of cometary activity. By then several NEAs had been discovered following orbits closely similar to those of periodic comets. These bodies may reasonably be regarded as extinct, or at least dormant, periodic comets, whose supplies of near-surface ices have been exhausted by prolonged solar heating over many perihelion passages, leaving them without the ability to generate gas or dust tails to attest to their cometary origins.

Many comets entering the inner Solar System can be dynamically linked to the high-eccentricity subset of KBOs called “scattered disk objects”. Centaurs, whose orbits cross those of one or more of the gas giants, unavoidably experience severe gravitational perturbations of their orbit when they pass close to one of those planets. Some may be abruptly kicked into orbits that pass through the inner Solar System. A 100-km Centaur exposed to severe solar heating and tidal forces may break up into a vast swarm of up to a million 1-km comet nuclei, bombarding the inner planets with an intense shower of comet impacts. Direct impact of a 100-km Centaur on Earth would deliver about 10,000 times as much impact energy as the asteroid that struck Earth at the end of the Cretaceous Era, causing the famous end-Cretaceous extinction event.

Another orbital class of Trans-Neptunian Objects is the plutino family, of which Pluto itself is the type example. These bodies, which cross only the orbit of Neptune, are locked into stable orbital resonances with Neptune which prevents them from ever approaching Neptune closely. Most of these bodies, like Pluto, are in a 2:3 orbit resonance (very close to $a = 39.7$ AU), in which they orbit the Sun twice for every three Neptune years. Non-resonant bodies in similar orbits would encounter Neptune from time to time and be destroyed or perturbed into eccentric and unstable orbits such as those followed by the Centaurs. Beyond Pluto there are also many bodies with orbital semimajor axes between about 41 and 47 AU and low eccentricities. These bodies are referred to as the “Kuiper Belt” or as “cubewanos”, a whimsical reference to the type example, 15760 1992 QB1. The largest known Kuiper Belt body (1995 SM55) has a diameter of 813 km, and the population of the Kuiper Belt is estimated as 100,000 bodies, for an aggregate of about one Earth mass. Finally there is a population of “scattered disk objects” (“SDOs”) with $a > 41$ AU and eccentricities ranging from about 0.2 to 0.9. Some have aphelia beyond 200 AU, and some have inclinations as high as 40°. These bodies presumably owe their large eccentricities and inclinations to strong interactions with Neptune. The SDOs may be as numerous as the Kuiper Belt bodies. Bodies ejected by close encounters with a Jovian planet into the scattered disk population may evolve into Centaurs and eventually, after another encounter with Jupiter or Saturn, become periodic comets. In principle, an 800-km ice ball could evolve into an Earth-crossing orbit: impact with Earth would deliver roughly *one million times* the energy of the asteroid impact that ended the Cretaceous Era—and would deliver to Earth a mass of water roughly equal to the total mass of Earth's oceans.

Thus the "pigeonholing" of Solar System bodies has had considerable historical utility, but in the light of present-day reality the boundaries between classes can be diffuse. A body may change classes from time to time. Materials in the Solar System may over time migrate far from their place of origin. All this makes for a much more complex and much more interesting picture. When we encounter the evidence from studies of meteorites, we should not be surprised to find a stunning diversity of compositions and histories, all arriving on Earth from their temporary residences in the NEA swarm—and ultimately sampling a wide variety of remote and exotic locations.

III. Breakthroughs in Asteroid Prospecting

Traditional deep space robotic missions are expensive, which means they are packed with as many sensors as possible, which raises their complexity and cost even more. Because these spacecraft are so valuable, two to five years are spent on design and extensive testing, increasing costs still further. The spacecraft and launch vehicle for the NASA-funded OSIRIS-REx mission to the asteroid Bennu will gather a rich set of data from multiple instruments as well as small samples for return to Earth. But its wide-ranging goals results in a spacecraft weighing a ton and half, and a mission cost of $1 billion.

Now there's an alternative approach that foregoes the broad science abilities and ultra-high reliability of traditional robotic missions. A handful of sensors are packaged into small spacecraft assembled from standardized cubes measuring four inches (10 cm) on a side. A single cube masses two pounds, while assembling three to six units creates "3U" or "6U" CubeSats massing 12 to 25 pounds (12 kg). Hundreds of 1U to 3U CubeSats have been released into low Earth orbit for communications, surveillance, and science tests.

Universities and small companies have built CubeSats lacking propulsion and long-distance communications capabilities for less than $200,000. Launches are inexpensive as well, as CubeSats can hitch space-available rides on rockets carrying multi-ton primary payloads. To keep these small probes from cluttering low Earth orbit and becoming hazardous, U.S. rules require them to naturally deorbit from atmospheric drag in 25 years or less. Many reenter in only a few months if they are released at a low altitude.

The current CubeSat revolution adds capable propulsion to kick these tiny probes out beyond the Moon into deep space, and provides them with upgraded radios or laser units to enable robust communication back to Earth. Deep space CubeSats also require technologies to cope with sudden solar flares, a danger not faced by low Earth orbit spacecraft protected by the Earth's magnetic field. Because journeys out to near Earth asteroids can take six months to two years, deep space CubeSats need to be more reliable than their short-lived Earth-orbit predecessors. Finally, actually seeing and closing on a small charcoal-colored asteroid in the darkness of space is far more difficult than orienting a spacecraft toward the giant and brilliantly illuminated Earth. While all these additional challenges do raise expenses, one-way asteroid prospecting missions using small spacecraft are still very affordable.

Asteroids that come almost as close to the Sun as Earth (coming in to at least 1.3 AU, or 1.3 times Earth's average distance from the Sun) are classified as near Earth asteroids (NEAs). More than 11,000 have been discovered with more than 1100 added every year, out of perhaps one to two million such objects not yet charted. However, to be easy targets for prospecting and harvesting, an asteroid also must come relatively close to Earth and have a roughly circular orbit like Earth. These characteristics for easy harvesting also make them potentially hazardous asteroids (PHAs) – those that are mostly likely to impact Earth at some point. NASA has identified almost 1500 PHAs, with about 10 percent measuring more than ten football fields in diameter, large enough for mass extinctions on Earth. None are currently known to be on an impact trajectory, but most PHAs have yet to be discovered. A vibrant asteroid mining industry will help illuminate the deep dark and give us better warning of the still-unseen apocalyptic rocks headed our way.

Scouting Missions Reveal the Unseen

Small prospecting missions will begin to answer key questions about asteroid resources and asteroid threats. For example, the only detailed photographs of NEAs are of those 500 meters and larger in diameter. All of the photographed NEAs have been rubble piles, loose gatherings of boulders, pebbles and regolith (shattered rock) held together by the asteroid's own weak gravity.

Some theories predict that smaller asteroids will tend to be solid monoliths, which would call for entirely different harvesting methods than rubble piles, and different deflection strategies if they were threats to Earth. Low-cost scouts will be able to build up an inventory of close-in images to discover if the solid monolith theory is correct. Traditional space probes are too expensive to collect data on a realistic sample of NEAs.

An example of low-cost NEA scouting missions is the FireFly design produced by Deep Space Industries. This 6U CubeSat masses about 25 pounds and carries cameras and other sensors to characterize the structure and composition of its target. Each FireFly campaign is comprised of three similar spacecraft launched as hitchhikers on different primary missions, spread over a six- to twelve-month period and likely headed to three different asteroids.

With two fallback spacecraft already in the pipeline, the initial spacecraft can be designed, built, and tested at an accelerated pace, cutting one to two years off the normal development schedule with the consequent savings in manpower and facilities rent. Most spacecraft failures occur very early in a mission, often in the form of failure to separate from the launch vehicle, failure to deploy an antenna or solar panel, or a sudden-death wiring glitch. The second and third copies of FireFly can be corrected and sent on to launch. Commercial and science customers pay on the basis that at least one FireFly succeeds.

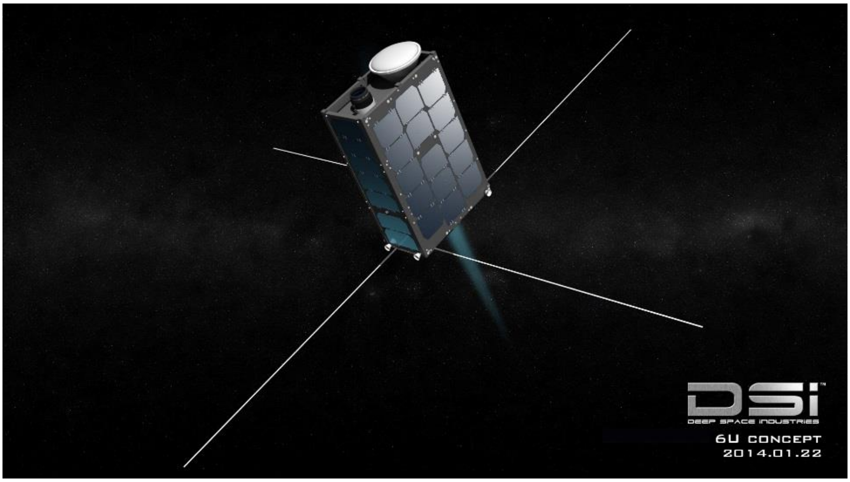

Figure III.1 The FireFly campaign will deploy sets of three CubeSat-style spacecraft to prospect at near Earth asteroids.

Credit: Deep Space Industries – Bryan Versteeg

Arks to Carry Dozens of CubeSats

As noted earlier, many universities and small companies have the skills to design and fabricate low Earth orbit CubeSats but there are hurdles to making them fit for deep space operation. One solution is to package several LEO-style CubeSats into a small carrier spacecraft, enabling wider involvement in the new age of asteroid mining and prospecting. A carrier can be loaded with a dozen or so CubeSats – from one unit to three units each – to give them a ride out to the target so they don't need big thrusters. At the asteroid, the carrier is the shared communications link back to Earth, so the CubeSats only need short-range radios with cheap omnidirectional antennas.

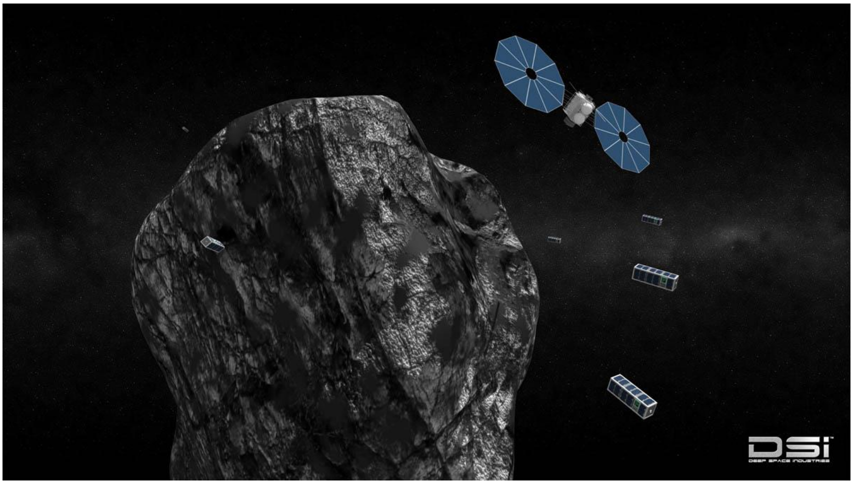

Figure III.2 The Mothership of Asteroid CubeSats offered by DSI delivers multiple low-cost CubeSats for joint investigations of NEA targets.

Credit: Deep Space Industries – Bryan Versteeg

By unleashing the creativity of frugal researchers around the world, the ark approach increases the potential scientific and commercial discoveries. In most cases, having a swarm of diverse instruments will make the readings gathered by any single instrument more meaningful through greater context. The ark also can provide enhanced situational awareness for the swarm members, reporting their own position as seen from a stand-off distance, and the positions of the other CubeSats. It also allows a 3D viewing perspective that no single spacecraft can achieve.

Returning a Piece of the Deep Dark

Spacecraft three to four times larger than FireFlies will be able to collect small rocks and regolith from target asteroids. Analyses done by the astrodynamics team at Deep Space Industries have found several NEAs for which round-trip voyages are feasible using small spacecraft capabilities. The calculations are complicated, as the energy required to reach a target changes every year as the orbital positions of the Earth and the NEA shift relative to each other.

Additionally, the most efficient trajectories often involve swinging by the Moon on the outbound or inbound legs, or both. Lunar swing-bys require the spacecraft to arrive in a relatively small range of velocities and at very low altitudes – often no more than 100 kilometers above the Moon's uneven terrain. Probes going too slowly will be captured and

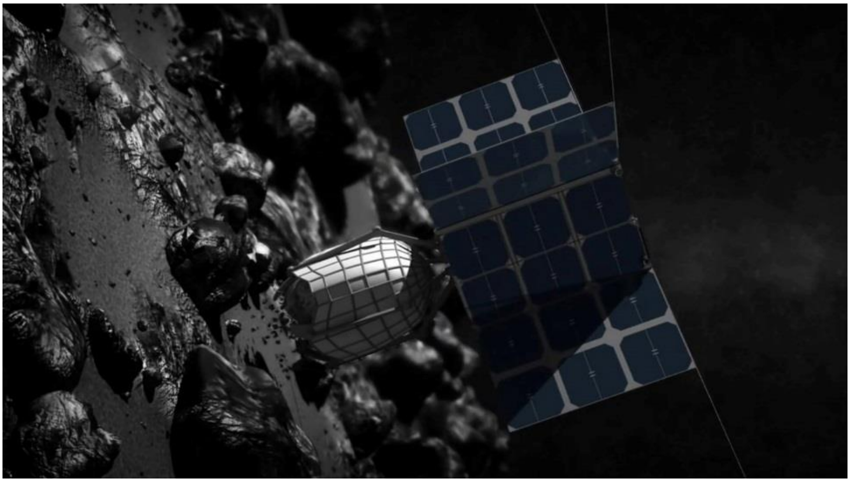

Figure III.3 DragonFlies will select promising small boulder, rocks and regolith for return to Earth for intensive analysis.

Credit: Deep Space Industries – Bryan Versteeg

crash. Probes going too fast will speed by the Moon too quickly for the lunar gravity have any appreciable effect. Factoring in lunar assists makes finding the best targets a complex challenge.

For profitable asteroid mining, shorter transit times will get return on investment faster but they come with two penalties: cutting sailing times requires more propellant, and it also forces the spacecraft to hit narrower launch windows. As one example, a six-month cruise to 1991 VG with a six-month return leg must start during one or two weeks in mid April 2017. Otherwise the total energy needed to achieve rendezvous in six months rapidly triples and quadruples and goes off the chart. By contrast, allowing a one-year transit to 1991 VG opens up a six-month launch window stretching from December 2015 to June 2016. During much of that, the energy required to reach VG 1991 in one year is half that needed for a six-month sprint.

The 1991 VG trade off is shown in the Figures below. The vertical axis shows the energy required for each leg of the flight, measured in kilometers per second of velocity. The starting point for the outbound leg is right after achieving Earth escape with no forward velocity, and the ending point for the return is arriving at the edge of Earth's gravity field with zero velocity. Of course, an actual mission would arrive back at the edge of Earth's gravity field with some forward velocity so it can move to its next maneuver, whether that is a direct descent to Earth or rendezvous with an orbiting facility. Figure III.4 shows the one-year-out and six-month-back scenario. Figure III.5 shows the narrow

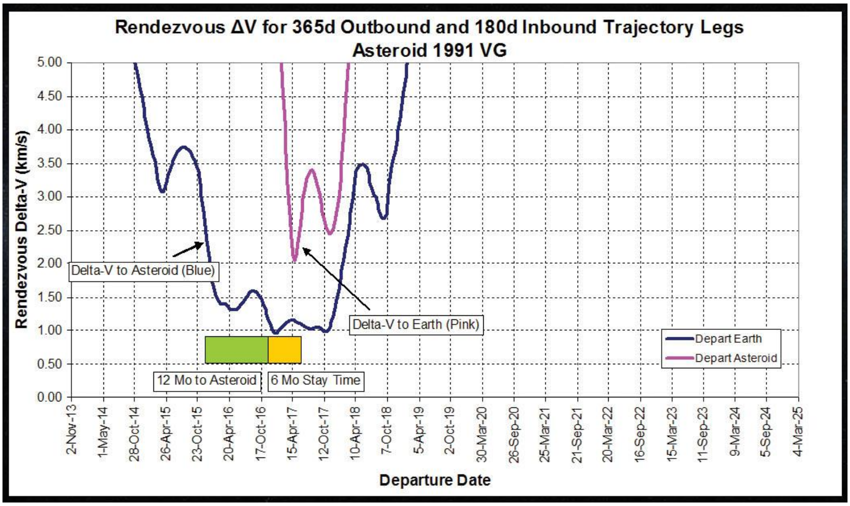

Figure III.4 Propulsion requirements are lower for a round trip to asteroid 1991 VG assuming one-year outbound voyage instead of a six-month period, compared to the propulsion budget in Figure III.5.

Credit: Deep Space Industries – Daniel Parcher

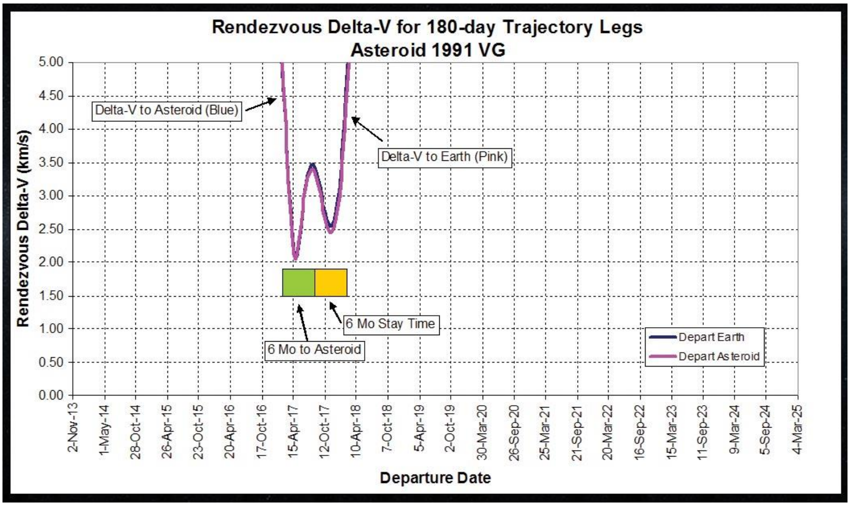

Figure III.5 Designing a faster mission to achieve speedier conclusions has the effect of narrowing the launch window severely and requiring a higher-performance propulsions system.

Credit: Deep Space Industries – Daniel Parcher

window and higher required propulsion of the faster six-month scenario.

Because low-cost asteroid probes will be hitching rides on major missions, the launches will take place when the primary customer wants, not when it is optimal for the hitchhiker. Long launch windows make it possible to withstand slips in the schedule of the primary satellite, which often happen as hardware problems are discovered, or even just suspected because a similar spacecraft had a problem after reaching orbit. The alternative is to find many potential targets, each with launch windows that overlap so there always is a NEA available for prospecting.

Once at a NEA, sampling will require a degree of intelligence on board the probe due to the time lag between giving commands from Earth and seeing the action carried out. While such delays might be as short as 15 to 30 seconds in the best of alignments between Earth and the asteroid, the lag more likely will stretch to several minutes. Operators at mission control will utilize “supervised autonomy” or “sliding autonomy” where general commands will initiate broad action goals – “center the spacecraft over that rock” – rather than specific thruster burns and spacecraft orientations. The next command might be “descend to one meter and hold” so that mission control can study the selected rock at close range. Then “grasp rock and attempt to ascend” could follow. Asteroid missions will be unlike game console quick-twitch challenges.

Depending on mission design, asteroid samples can be returned directly to Earth using an entry capsule or dropped off at an orbiting installation or waiting spacecraft.

IV. Meteorites: Poor Man's Space Probes

Meteorites are of crucial importance in our efforts to understand asteroids: they are samples of Solar System materials from a wide variety of locations and many different parent bodies. They are the key to understanding both the hazards of large impact events on Earth and the potential of resources carried by nearby asteroids. And best of all, they come to us free of charge, unlike the spacecraft missions described in the previous chapter.

Cosmic bodies of a wide range of compositions and sizes hit Earth daily. To speak clearly about this bombardment process requires some definitions of terms.

Let's start out in space. Solid rock-plus-ice bodies with kilometer dimensions, orbiting around the Sun, are normally called *comet nuclei.* The word "comet" of course implies observed or potential cometary activity, such as generation of a gaseous atmosphere (coma) and gas and dust tails. A short-period comet nucleus whose surface has been baked so long, and been so warm, that volatile ices have been depleted from its surface will cease to show cometary activity and will be termed an asteroid. Traditionally, the word *asteroid* was applied to rocky bodies larger than 1 km in diameter and smaller rock bodies in space were call *meteoroids*. However, thinking of a 1001-m body as an asteroid and a 999-m body as a meteoroid is clearly arbitrary and useless. Probably for this reason, any small Sun-orbiting rocky body discovered by astronomers has come to be called an asteroid, even though some of them are only a few meters in diameter. A further distinction was made at the upper end of the size scale, where bodies larger than 1000 km were often called *planetoids*. Others would reserve the name "planetoid" for bodies that are of sufficient size that they are roughly spherical, or which have undergone sufficient internal heating to generate a differentiated core/mantle/crust structure. Those who wish to make qualitative semantic distinctions on the basis of minor quantitative differences must find our modern knowledge of the Solar System unsettling.

A large rock that strikes Earth is called an asteroid; a small rock that survives entry into Earth's atmosphere and is recovered on the surface is a *meteorite*. Professional students of meteorites, called *meteoriticists*, have identified over 20,000 separate fall events, of which only a small fraction were observed to fall. A number of these events dropped multiple individual meteorites over a local area called a *strewn field,* usually a rough ellipse with a long axis along which the fragments are crudely sorted by mass. The total number of meteorite fragments that have been recovered is probably close to 200,000, of which as many as 100,000 were contributed by the fall of the Pultusk meteorite, which fell in 1868 in Poland. That single fall contributed about 9 tonnes of recovered material, of which the largest individual stone was a mere 9 kg.

Systematic searches for meteorites began with canvasing of farmers in the central United States, concentrating on alluvial farming areas where native rocks are essentially unknown. Rocks found by farmers in their fields often were put to use as doorstops, of which an astonishing number were found to be meteorites. In recent decades meteorite searchers have found great success in other areas where distraction by terrestrial rocks is rare, especially on the ice sheet of Antarctica and in sand deserts.

Meteors, however, are in essence optical phenomena, brief flares seen in the sky when high-velocity grains hit the atmosphere with sufficient energy to vaporize themselves. Many meteors are associated with cometary dust trails, Earth's passage through which generates "meteor showers". Some dust trails and meteor showers originate from asteroids, apparently dust blasted off the asteroid by impacts of much smaller bodies. Prominent asteroid-derived meteor showers include the Taurids (from the asteroids 2201 Oljato, 3270 Dudley, 6063 Jason, and 5025 Palomar-Leiden) and the Geminids (from 3200 Phaethon). Meteors, whether cometary or asteroidal, have never been recovered intact, and there is no statistical association of meteorite falls with meteor showers.

Many meteors have been tracked during their brief but brilliant career. The typical speed for a meteor as it enters Earth's atmosphere is 20 to 30 kilometers per second. Meteors become luminous at altitudes of about 100 km, where they first encounter air dense enough to have a strong effect on them. It should be clear that a body falling from 100 km altitude at a speed of, say, 30 km/s cannot last more than a few seconds. Indeed, most meteors are so fragile that they evaporate completely in less than a second, though strong rocky meteors entering the atmosphere at a very shallow angle may persist for 10 seconds.

Qualitatively similar to meteors, but quantitatively in a wholly different league, are the spectacular phenomena called *fireballs* or *bolides*, after the Greek word for javelins. I have personally witnessed fireballs brighter than the full Moon, and some daytime fireballs have even outshone the Sun. Military spacecraft dedicated to observing rocket launches and watching for atmospheric nuclear explosions, which keep virtually all of Earth under observation virtually all the time, have seen and reported hundreds of brilliant fireballs caused by entry of space rocks into Earth's atmosphere. In addition, photographic meteor tracking station networks in the United States, the Czech Republic, and Canada have observed a number of brilliant fireballs, some of which have even dropped meteorites on the ground. These records are of great value because they permit triangulation of the path of the entering object in sufficient detail to allow calculation of the heliocentric orbit the body was pursuing at the moment it encountered Earth.

Little is known about the chemical compositions of meteors (not to be confused with meteorites). On the rare occasions that "burnup" (vaporization) of a meteor has been observed by astronomical spectrometers, the light emitted usually proves the presence of abundant carbon. An occasional meteor spectrum reveals the presence of iron and nickel, and emission lines of calcium, magnesium, sodium, and other abundant rock-forming elements are often seen. We know that, statistically, the large majority of all meteors and fireballs have very little strength and break up very high in the atmosphere. Equating the calculated aerodynamic ram pressure on these bodies at the point of breakup (from the known density profile of the atmosphere and the observed entry velocity) to the crushing strength of the material, we find that most of them have crushing strengths between a few dynes per square centimeter and 10,000 dynes per square centimeter (roughly 0.01 atmosphere pressure). **They therefore have strengths more similar to the dust balls you find under your bed than to rocks you find in your garden.** The small minority of bolides that show crushing strengths of 1 to over 1000 atmospheres are the only ones from which meteorite falls have been observed.

Fireballs that drop meteorites almost always are accompanied by loud aerial explosions. In many cases, a brilliant flash of light lasting several seconds is first seen. Sometimes there are multiple flashes, corresponding to stepwise explosions of ever-smaller fragments of the entering body. Many seconds, even a few minutes, after the visible flash the explosion (or series of explosions) is heard on the ground. The minimum entry velocity for a fireball is governed by Earth's escape velocity, 11.2 kilometers per second. (A fireball entering horizontally at the equator in the direction of Earth's rotation can enter at as little as 10.6 km/s.) This means that all entering bodies are traveling at speeds far above the speed of sound in air, at a Mach number of at least 35 (Mach 35 means 35 times the speed of sound). This is not merely supersonic; it is hypersonic. The air is violently shocked, heating it and the surface of the entering body to temperatures well above 10,000 degrees, not simply melting but completely vaporizing the surface material. The shock wave set up by the passage of the fireball travels to the ground at Mach 1 (about 0.3 kilometers per second), so the sound of an explosion at a slant range of 30 km will reach the observer about 100 seconds after the breakup flash.

A recent spectacular example of an aerial explosion of an entering body is the Chelyabinsk event of 15 February 2013. The peak brightness of the bolide exceeded that of the Sun. Hundreds of images of the fireball, many with excellent-quality position and direction documentation, have permitted accurate reconstruction of its entry trajectory. Many small meteorites were recovered from the landing area shortly after its fall.

Solid materials will survive an aerial explosion if they are strong enough. The stronger the material, the more will survive, and the larger the surviving fragments will be. The weakest classes of meteorite recovered, the CI chondrites, which have crushing strengths usually between 1 and 10 bars[1], are often found only as small fragments, of which the largest is rarely more than a few centimeters in diameter. Intermediate-strength rocks may fall as stones that are tens of centimeters in size. And the very strongest iron meteorites may reach the ground as pieces over a meter in diameter, with masses sometimes in excess of 10 tonnes.

Bodies with larger sizes (100 to 1000 meters) and masses, not easily decelerated by passage through the air, may reach the ground with some significant fraction of their original speed and energy still intact. If they strike the ground at a speed larger than the speed of sound in the target material they will drive a strong shock wave into the ground, causing a violent explosion that may destroy both the impactor and its target. The explosion will excavate a crater, scattering fragments of the impactor and a 100- to 1000-times larger mass of shattered target rock over a wide area and leaving a crater with a raised rim. An excellent example of such a crater is Meteor Crater in Arizona, from which hundreds of metallic meteorites have been recovered. Of course it was

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[1] The bar is a metric unit of pressure, roughly equal to one atmosphere; one bar pressure is reached at a depth of about 10 meters in water.

not made by a meteor—if we were naming it today we would refer to it as an asteroid impact crater.

Very large impactors (say, 1 to 10 kilometers in diameter), regardless of their strength, will retain nearly all of their original energy up to the point of impact with the surface. Virtually all of the impactor will be vaporized, and the crater ejecta will be dominated by a mass of shattered and melted target rock up to about 1000 times the mass of the original impactor. Such an event was the dinosaur-killing Chicxulub impact, which excavated a crater 180 kilometers in diameter on the northern flank of the Yucatán peninsula in Mexico. The explosive power liberated by that event was roughly that of 250,000,000 megatons of TNT. That's 250 trillion tons—250 teratons, or about *40,000 tons of high explosive for each person on Earth*.

What to do when a meteor is streaking through the sky

Few people have witnessed the entry of 10-meter rocks, and you would not want to be close enough to witness the fall of a 100-meter rock. If you should be fortunate enough to experience a brilliant fireball, with or without a meteorite fall, there are several things you should note and record. First, note the position and motion of the fireball in the sky, including angle of elevation of the fireball above the horizon, its speed and direction. Document your own vantage point: a photograph taken where you were standing, especially if marked up with the fireball path, brightness, color, sound effects, and other data, could be immensely helpful. In any case, in daytime you should make a precise note of the time and your location, and the object's path relative to landmarks. At night, note the path of the object relative to the stars and planets. Count out the time from the flash of light for several minutes: if you hear a boom or series of booms, note their time(s).

If you should witness the fall of a meteorite, you should of course document the event as in the previous paragraph. You should take care to protect the freshly fallen rock from contamination. Record, or photograph if possible, the landing site. Since most contamination of meteorites is by contact with the ground, exposure to rain or standing water, or careless handling, your best course of action may be to pick up the meteorite and wrap it with the cleanest material available: cloth or, even better, a sealable plastic bag. Use the wrapping, not your unprotected hand, to pick up the meteorite.

Figure IV.1 Fusion crust formed on an ordinary L-chondrite meteorite during entry.

Credit: Amethyst Galleries, Inc.

You should then contact a nearby Natural History Museum or university Geology Department (few Astronomy departments have any familiarity with meteorites: they are responsible for asteroids and comets, not rocks). Fresh, uncontaminated meteorites have high scientific value; old, weathered, or contaminated meteorites may still have some commercial value, but they are not at the peak of the market.

Freshly fallen meteorites usually have a distinctive black glassy *fusion crust* produced during hypersonic flight through the atmosphere. Heating during atmospheric entry may remove anywhere from a few percent to a large majority of the mass of the entering body, depending on the strength of the material and its entry velocity and angle. This process of erosion, called *ablation*, is caused by the combined effects of melting, vaporization, and scouring by aerodynamic friction. Only the last remnant of melt, usually with distinctive flow markings, is retained as fusion crust. That crust is usually seen as a black, glassy layer less than 1 mm thick.

Because of the severe heating experienced during entry and the very high temperature of the ablating vapor and liquids, it is reasonable to wonder whether freshly fallen meteorites might not be dangerously hot. In fact, stony meteorites are quite poor conductors of heat. Studies of trapped gases in stones show that at a depth of only 1 mm below the fusion crust there was negligible heating. Within minutes after its fall the surface of a meteorite cools to the temperature that the interior of the stone had in space; often frost will grow on its surface. Irons, however, being far superior in their thermal conductivity, may be warm or even hot to the touch. Reports of fires being set by meteorites, if true, must be due to irons.

A new meteorite, once its authenticity has been determined by a meteorite expert, is assigned a name that identifies the mapped town or geographical feature nearest to the location where it was found. Examples include Bacubirito, Tucson, Odessa, Revelstoke, Norton County, Orgueil, Black Mountain, Tagish Lake, Great Fish River, and so on. Occasionally two unrelated meteorites are found in the same area, leading to names such as Hale Center No. 1, Grady 1933, or Akron 1954. Meteorites found at unrelated places that happen to bear the same name or unrelated meteorites found at the same locale are given common-sense explanatory names, such as Edmonton Canada and Edmonton Kentucky, Gladstone iron and Gladstone stone.

Three major meteorite types

Meteorites can be coarsely divided into three compositional and structural classes by simple inspection and observation of their gross properties, especially density. These classes are *irons, stony-irons*, and *stones*. Irons are almost pure (~99%) metallic iron-nickel alloy, a natural stainless steel with a density of about 7.5 grams per cubic centimeter. Stones are dominantly composed of silicates, often with small particles of metal and sulfides, with densities typically less than about 3.7 but more than 2 g/cm^3. Stony-irons, not surprisingly, are composed of roughly equal proportions of metal and stone, with densities close to 5.5 g/cm^3.

Breaking open or cutting a meteorite to make its interior structure visible and accessible to examination with a hand lens permits a somewhat more detailed categorization. Some stones have an intimate mixture of silicates, metal, and sulfides that coexist without evidence of melting and separation by density. Because of the absence of evidence of strong heating and melting, these meteorites are said to have primitive textures. Most such meteorites contain small (~1 mm or less) glassy spheroids called *chondrules*, from the Greek word for a seed or drop. By generalization, all meteorites with primitive textures,

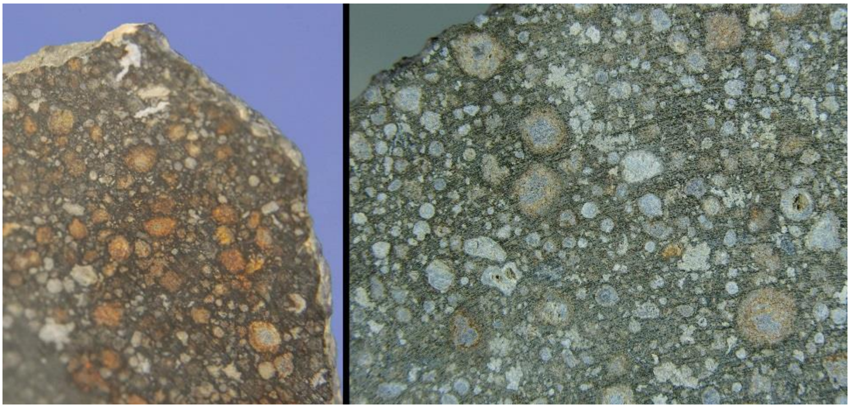

Figure IV.2 Stones are one of the three major meteorite groups, and can be further classified as chondrites if they have glassy spheres called chondrules as shown above.

Credit: Aerolite Meteorites LLC

Figure IV.3 Stones without chondrules are classified as achondrites, one of the seven major meteorite groupings.

Credit: Amethyst Galleries, Inc.

irrespective of the abundance of chondrules in them, are called *chondrites*.

Some stones, however, are essentially pure silicate with only tiny trace amounts of metal and sulfides, with textures that strongly imply solidification from a melt under conditions in which dense metals and sulfides were separated from the silicates. Since these differentiated bodies are always devoid of chondrules, they are called *achondrites*.

Figure IV.4 Pallasties are members of the stony-irons meteorite grouping. This sample of pallasite shows olivine crystals.

Credit: Amethyst Galleries, Inc.

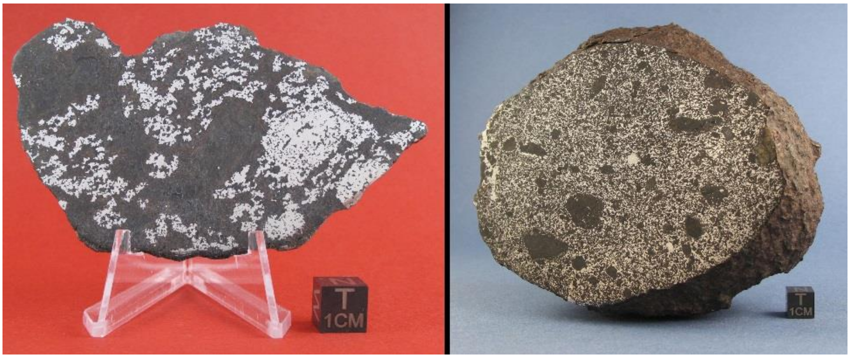

Figure IV.5 The mesosiderites grouping of the stony-iron meteorites has only scattered pockets of metal.

Credit: Aerolite Meteorites LLC

Stony-irons can likewise be easily separated into two types with very different internal structures. Some, having a continuous matrix of metal (as is easily determined by measuring the electrical conductivity between distant points on the meteorite's surface), are called *pallasites*. About a third of all stony irons, those that have a very different structure consisting of chunks of metal dispersed discontinuously among chunks of silicate, are called *mesosiderites*.

The irons, upon being (laboriously) cut, polished, and etched with acid to reveal their crystal structure, can readily be subdivided into three broad physical and chemical categories. One class of irons, typically

Figure IV.6 Iron octahedrites clearly show their high metal content.

Credit: Amethyst Galleries, Inc.

Figure IV.7 Meteorite hunter Geoff Notkin displays an iron ataxite sample.

Credit: Aerolite Meteorites LLC

containing 5.5% nickel, has the structure of metallurgists' alpha iron, which bears the mineralogical name of *kamacite*. The alpha-iron phase has a body-centered cubic lattice structure, and a cube, to geometers, is called a hexahedron. Thus these meteorites are called *hexahedrites*. Most irons, however, contain 6 to 14% nickel, more nickel than can be accommodated in the alpha-iron structure. These meteorites consist of an intergrowth of crystals of alpha (low-nickel) iron and gamma (high-

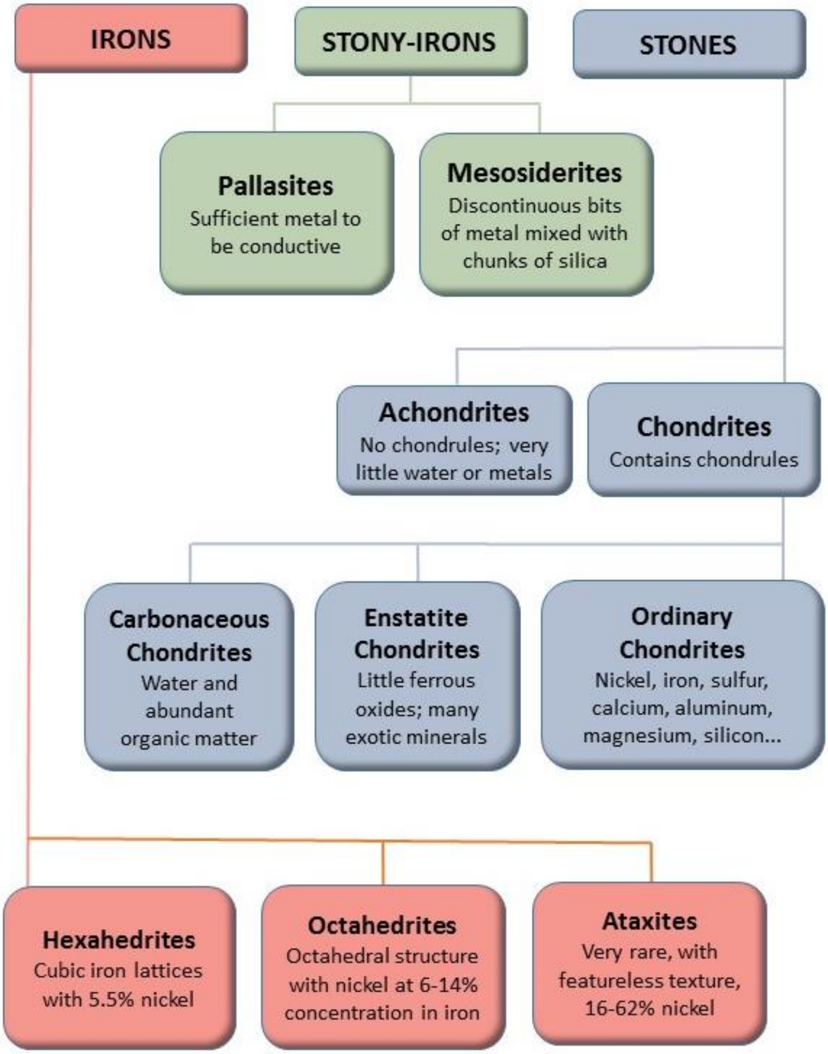

Figure IV.8 Seven major meteorite types (pallasites, mesosiderites, achondrites, chondrites, hexahedrites, octahedrites and ataxites), with chondrites further divided into three subtypes.

Credit: Deep Space Industries

nickel) iron. The gamma-iron phase bears the mineral name *taenite*. The kamacite-taenite crystal intergrowth patterns exposed by cutting, polishing, and acid etching show octahedral symmetry, leading to the name *octahedrites* for these irons. There is a third, much rarer class of irons with high nickel content, generally greater than 16% nickel, and running as high as 62% nickel in the Oktibbeha County iron. These generally consist of a very fine-grained intergrowth of kamacite and taenite called *plessite*. The visual impression of these meteorites, which lack the striking large-scale banded structure of octahedrites, is that there is no noticeable texture, from which they derive their name, the nickel-rich *ataxites*.

This somewhat more discriminating subdivision of meteorites is far from the whole story, as we shall soon see. But it provides a broad overview of the main types of meteorites which will be useful as we progress.

Meteorites are also frequently divided into two broad categories called *falls* and *finds*. Since it is clearly necessary that any meteorite in our collections both fell and was found, this convention requires explanation. A *fall* is any meteorite that was *observed to fall*; a *find* is any meteorite that was not observed to fall, but was simply *found on the ground*.

One of the first lessons about meteorites is the fact that the finds and falls of these seven broad types of meteorites (chondrites, achondrites, pallasites, mesosiderites, hexahedrites, octahedrites and ataxites) have very different statistics, requiring thought about sources of bias and discrimination between them. The statistics for these types are given in **Table IV.1**:

Table IV.1
Frequencies of Meteorite Types among Finds and Falls

Meteorite Type		Percentage of Finds		Percentage of Observed Falls	
Stones			52.3%		94.1%
	Chondrites	51.3%		90.7%	
	Achondrites	1.0%		3.4%	
Stony-Irons			5.4%		0.7%
	Mesosiderites	1.6%		0.4%	
	Pallasites	3.8%		0.3%	
Irons			42.1%		5.2%
	Hexahedrites	12.0%		1.6%	
	Octahedrites	29.0%		3.4%	
	Ni-rich Ataxites	1.1%		0.2%	

Where the frequency of finds of a given meteorite type is much larger than the frequency of observed falls, the discrepancy is principally due to the superior survivability of that meteorite type on Earth's surface. Note that irons, made of natural stainless steel, are eight times more common among finds than among observed falls. Pallasites, which combine that same corrosion resistance with highly distinctive appearance, show an even larger enhancement among finds. Mesosiderites, of somewhat lower strength and resistance to weathering but distinctively high density, are about four times as common among finds as among observed falls. Stones collectively are less abundant among finds than among falls because of the dilution of their proportion by highly survivable metallic meteorites; however, the proportions of chondrites and achondrites, both of which are subject to weathering and lack impressively high and distinctive densities, are also different. The ratio of chondrites to achondrites among finds is over 50:1, whereas among observed falls the ratio is about 25:1. This discrepancy is due to the fact that weathered chondrites and weathered achondrites have very different appearances: chondrites are very dark in color and weather to produce black and red oxides of iron; the principal minerals of achondrites are light in color, metallic iron is rare or absent, their densities are close to those of terrestrial crustal rocks, and weathered achondrites look very much like weathered terrestrial rocks. Thus weathered chondrites are usually easier to recognize than weathered achondrites. The statistics suggest that half of the achondrites seen by meteorite searchers are not recognized as meteorites.

It must be stressed that the above statistics refer to *numbers* of recovered meteorites, not total mass. The stronger types (irons and pallasites) are more resistant to aerodynamic breakup during atmospheric entry, and hence contribute an even larger proportion of mass than their numbers suggest. The largest known stones are about 1 tonne; the largest known iron is about 60 tonnes.

The seven types of meteorites we have so far encountered are further subdivided on the basis of chemical and mineralogical composition and structure into over 50 distinct groups, suggesting that the meteorites of which we have samples may originate on roughly 50 different parent bodies. We shall survey most of these types later in this chapter, treat them is greater detail in Appendix A, and discuss their relationships to particular asteroids in Chapter IV.

The two powerful selection effects on meteorite recognition and recovery, differential survival of atmospheric entry and differential resistance to weathering, both act to bias our estimates of the actual population of the asteroidal parent bodies of the various types. Of the two sets of statistics, clearly the observed falls (which lack the differential weathering bias) are a better guide to the populations of meteoroids and asteroids in space. Even so, observations of fireball breakup in the atmosphere show that very fragile material, incapable of surviving entry as a recoverable meteorite, is at least as common in nearby space as the relatively strong, competent material we have in our meteorite collections. Thus even the statistics of fresh meteorite falls are subject to a significant bias favoring stronger materials.

Abundances of the Elements

Meteorites are derived originally from material with roughly the same elemental composition as the Sun. The Sun, like all Main Sequence (hydrogen-burning) stars, is overwhelmingly composed of hydrogen (H) and helium (He).

For compactness and efficiency we usually refer to the elements by their one- or two-letter symbols: most symbols are fairly simply related to their English names, but a few elements known by the Romans bear symbols that reflect their names in Latin. One important example is Fe for ferrum, the Latin word for iron. The names and symbols of the elements are included in **Table IV.2**

After H and He, the ice-forming volatile elements oxygen (O), carbon (C), and nitrogen (N) are next in abundance, along with nearly incondensable neon (Ne). These are followed in abundance by the principal rock-forming elements silicon (Si), magnesium (Mg), iron (Fe), and sulfur (S). These in turn are several times more abundant than calcium (Ca), aluminum (Al), sodium (Na), titanium (Ti) and potassium (K). Elemental abundances, whether derived from spectroscopic studies of the Sun or from laboratory chemical analyses, are usually reported as number of atoms relative to silicon.

Meteorites, being dominantly rocky material, are strongly deficient in the more volatile elements compared to the solar material from which the Solar System is derived. Their relative proportions of rock-forming elements are determined not only by their temperature of formation, but also by any melting and density-dependent differentiation process that may have permitted separation into core- mantle-, and crust-like layers. These elements enter into naturally-occurring crystalline compounds called *minerals*. Those volatile elements which do not form stable solids at temperatures prevalent near the Sun – neon (Ne), argon (Ar), krypton (Kr), and xenon (Xe) – are severely depleted in meteorites relative to those that do, such as sulfur (S), oxygen (O), nitrogen (N), carbon (C), and hydrogen (H). Far from the Sun, where it is very cold, even these gases may enter into minerals as, for example, gas hydrates such as $Ar \cdot 7H_2O$.

Ice, as a natural crystalline substance, is a mineral. Volcanic glass (obsidian) and coal, which are natural but not crystalline, are therefore not minerals. We shall survey the most abundant meteoritic minerals in the next section.

The cosmic abundances of selected elements are given in **Table IV.2**. These abundances are appropriate for the Sun, the original raw material of the Solar System, and most Population I stars (which are late-forming, Sun-like stars, made of recycled material from generations of previous stars). Jupiter appears to have similar composition, except that the lightest elements, hydrogen and helium, have been depleted several-fold, presumably by escape during the earliest phases of planetary formation.

Some trends are obvious from this Table: the light elements hydrogen and helium, the "permanent volatiles", are overwhelmingly abundant; the next three elements – lithium (Li), beryllium (Be), and boron (B) – are very rare because they are both poorly synthesized in the Big Bang and unstable in the interiors of stars; the volatile elements C, N, O, Ne, etc. are common and more abundant than the dominant rock-forming elements Si, Mg and Fe. Generally the heavier the element, the rarer it is. Elements with even atomic numbers are more abundant than those with odd atomic numbers; the iron-group elements (which have the most stable nuclei of all) have enhanced abundances relative to their neighbors. Uranium and thorium, the heaviest naturally occurring elements, and two of the most important radioactive heat sources, are extremely rare in nature.

The other important radioactive heat source responsible for heating planetary interiors is the potassium isotope ^{40}K. Many other radioactive nuclei are available as "clocks" for measuring the timing of geological events, but are not sufficiently abundant to be important sources of heat. Certain short-lived radionuclides, such as ^{26}Al, may have been important heat sources during the earliest days of the Solar System, but they decayed rapidly and are now essentially extinct.

Table IV.2
Abundances of the Elements
(Number of atoms relative to 1 atom of silicon)

Element	Atomic Number	Abundance
H hydrogen	1	27900.
He helium	2	2700
O oxygen	8	23.8
C carbon	6	10.1
Ne neon	10	3.1
N nitrogen	7	3.1
Mg magnesium	12	1.1
Si silicon	14	1.000
Fe iron	26	0.9
S sulfur	16	0.51
Ar argon	18	0.10
Al aluminum	13	0.085
Ca calcium	20	0.061
Na sodium	11	0.057
Ni nickel	28	0.049
Cr chromium	24	0.014
P phosphorus	15	0.010
Mn manganese	25	0.009 6
Cl chlorine	17	0.005 2
K potassium	19	0.003 8
Ti titanium	22	0.002 4
Co cobalt	27	0.002 2
Zn zinc	30	0.001 3
F fluorine	9	0.000 84
Cu copper	29	0.000 522
V vanadium	23	0.000 293
Ge germanium	32	0.000 119
Se selenium	34	0.000 062
Li lithium	3	0.000 057
Kr krypton	36	0.000 045
Ga gallium	31	0.000 038
Sc scandium	21	0.000 034
Sr strontium	38	0.000 024
B boron	5	0.000 021
Br bromine	35	0.000 011 8
Zr zirconium	11	0.000 011 0
Rb rubidium	37	0.000 007 1
As arsenic	33	0.000 006 6
Te tellurium	52	0.000 004 8
Xe xenon	54	0.000 004 7
Y yttrium	39	0.000 004 6
Ba barium	56	0.000 004 5
Sn tin	50	0.000 003 8
Pb lead	82	0.000 003 2
Mo molybdenum	42	0.000 002 6
Ru ruthenium	44	0.000 001 9
Cd cadmium	48	0.000 001 6
Pd palladium	46	0.000 001 4
Pt platinum	78	0.000 001 34
Ce cerium	58	0.000 001 10
I iodine	53	0.000 000 90
Nd neodymium	60	0.000 000 83
Nb niobium	41	0.000 000 70
Os osmium	76	0.000 000 67
Ir iridium	77	0.000 000 66
Ag silver	47	0.000.000 50
24 elements less than		0.000 000 50
Th thorium	90	0.000 000 045
U uranium	92	0.000 000 018

Geochemical Affinity Classes

Any chemical element can be classified by its geochemical affinity for entry into particular classes of compounds. Those elements that are readily reduced to the elemental state, such as iron, nickel, cobalt, platinum, gold, and so on are described as *siderophiles* (“metal-lovers”). Those which readily enter into stable sulfides, such as iron, nickel, copper, zinc, lead, etc. are termed *chalcophiles* (“sulfur-lovers”). Those which preferentially enter into silicates, such as iron, magnesium, calcium, aluminum, sodium, potassium, etc. are called *lithophiles* ("rock lovers"). Note that iron is capable of all three kinds of behavior in nature, depending upon its circumstances.

Since iron and magnesium are both approximately as abundant as silicon, their behavior is of paramount importance. Magnesium on Earth is an unambiguously lithophile element; iron in Earth's crust, which is subject to the hydrating and oxidizing effects of water and free oxygen, is usually a lithophile or chalcophile. The Mg^{2+} and Fe^{2+} ions are not only very abundant, but have the same ionic charge and nearly identical ionic radii. They therefore can substitute freely for each other in any silicate mineral. They are said to be *compatible* elements. Rock-forming elements that have different ionic charges and radii than Mg^{2+} and Fe^{2+} do not substitute readily for them: they are termed *incompatible lithophiles*.

The volatile elements discussed above are often referred to as *atmophiles*.

Meteorite Minerals

We have seen that Earth, as a differentiated planet, has hidden certain groups of elements in its core or mantle. Since most meteorites (the chondrites) are undifferentiated, they contain far higher concentrations of some siderophile and chalcophile elements than can be found in Earth's crust. Thus our terrestrial standards of what constitutes a rare, precious, or strategic material may be quite irrelevant to meteorites. Likewise, many minerals stable on Earth's surface, and the ore bodies in which they are found, result from the presence of water and oxygen, and consequently are rare or wholly unknown in meteorites, which originate on parent bodies that have no atmospheres, and which seldom contain liquid water.

Although well over 100 minerals have been found in meteorites, most of the mass of the common types of meteorites is made up of a modest number of minerals formed by the most abundant rock-forming elements. Some of these are familiar on Earth; some are not. Most of the known meteorite minerals are rare trace or accessory constituents of a few unusual meteorite composition groups. The seven most abundant minerals are usually the only ones that are have a detectable effect on the color and reflection spectrum of a meteorite or asteroid. They are not the only minerals of resource interest; they are simply the only ones that can be detected and identified by remote observations.

The four most abundant rock-forming elements, oxygen (O), silicon (Si), magnesium (Mg) and iron (Fe), form several very stable and abundant minerals. The behavior of these four elements is crucially important for understanding terrestrial planets, asteroids, and meteorites: together these our elements and their compounds make up the large majority of the mass of Earth and asteroids.

Both silicon and magnesium react readily with oxygen to form stable oxides. The normal form of Si is as minerals containing the SiO_2 molecular unit, and magnesium forms the MgO molecule. Iron, which has a relatively smaller affinity for oxygen, can form metallic Fe as well as oxides. In almost all meteorite groups, the most stable oxide of iron is FeO (ferrous oxide). The minerals these four elements form are metallic iron and the two very important "ferromagnesian" minerals pyroxene and olivine. *Olivine* is a solid solution of Mg_2SiO_4 (forsterite) and Fe_2SiO_4 (fayalite). The compositional extremes of any solid solution (here forsterite and fayalite) are called the *end-members* of the solid solution series. In meteorites with a low degree of oxidation, there is little FeO compared to MgO, producing olivine of nearly pure forsterite composition. Where FeO is more abundant (and where the amount of metallic iron has been proportionately reduced by partial oxidation to FeO) the relative amounts of FeO and MgO are closely comparable. *Pyroxene* is also formed by combination of SiO_2, MgO and FeO. Pyroxene solid solutions of $FeSiO_3$ (ferrosilite) and $MgSiO_3$ (enstatite) are common; however, the pure $FeSiO_3$ end member is slightly unstable in isolation, and does not exist in nature. Note also that, because of the strong lithophilic behavior of Si and Mg, the most abundant element in rocks *by number of atoms* is usually oxygen.

The relative proportions of olivine and pyroxene depend on the degree of oxidation of iron. The situation is most easily envisioned if we picture equal exactly equal numbers of Si, Mg, and Fe atoms, and start in a chemically reduced state in which all the iron is present as Fe metal. Then Mg, Si, and O combine completely and exclusively with each other to make $MgSiO_3$, enstatite. The silicates then would consist entirely of the enstatite end member of pyroxene, and no olivine will form: making olivine requires an excess of 2+ cations (Mg^{2+} and Fe^{2+}) over silicon, which, in this chemically reduced state, we do not have.

Partial oxidation of Fe metal to FeO increases the ratio of 2+ ions to silicon, which is reflected not only as the appearance of ferrosilite in pyroxene solid solution, but also the appearance of olivine. Further oxidation of Fe metal to FeO produces ever more ferrosilite-rich pyroxene, ever more fayalite-rich olivine, and ever higher abundances of olivine relative to pyroxene. In this simplified system, complete oxidation of iron will produce equal numbers of SiO_2, MgO and FeO units. The ratio of 2+ ions to Si is then 2:1, not 1:1 as in enstatite, and all pyroxene (px) would be converted into olivine (ol) containing equal amounts of forsterite and fayalite. This would correspond to an olivine composition of $MgFeSiO_4$.

Until the mid-20th century all chondritic meteorites were considered to be results of progressive oxidation of Fe to FeO: the olivine-to-pyroxene ratio, the FeO-to-MgO ratio in olivine and pyroxene, and the declining Fe metal abundance were simply results of a single process. The linkage of these processes was known as *Prior's rules*. Since FeO formation is due to reactions oxidizing iron metal during cooling, the most olivine-rich (and metal-poor) meteorites would be attributed to lower formation temperatures. Exhaustion of metallic iron would occur near 500K (227°C).

This wonderfully simple picture is made more complicated by the existence of other, somewhat less abundant, elements and by fractionation between Fe and Si. The chief offender is sulfur, whose cosmic abundance is about 40% of the abundance of iron. At about 680 K (407°C) in a cosmic-composition gas, at a point where Fe oxidation to FeO is only partially completed, FeS would form as the mineral *troilite*. The iron that enters into FeS formation would be tied up in a stable mineral and would therefore no longer be available for oxidation to FeO. One consequence of this behavior is that complete conversion of pyroxene into olivine is prevented because FeS formation leaves insufficient FeO to complete the process.

Another complication is introduced by considering the presence of calcium (Ca). The ionic size of Ca^{2+} does not allow it to fit easily into the olivine crystal lattice (except in traces at very high temperatures), but it can form a silicate, $CaSiO_3$ (wollastonite; wo), which can to some degree enter into a solid solution with enstatite and ferrosilite. Thus pyroxenes in nature are three-component (ternary) solid solutions. The Fe-Mg solution series crystallized in the orthorhombic system, called *orthopyroxene*, can accommodate moderate concentrations of wollastonite. Nearly pure $FeSiO_3$ (the part of the composition range not found in meteorites), which is unstable, spontaneously separates into FeO (wüstite) and SiO_2 (quartz). When the solubility limit (about 20% wo) of wollastonite in the Mg-Fe pyroxene is exceeded, a more Ca-rich pyroxene phase forms as crystals of diopside [$CaMg(SiO_3)_2$] or, in extremely FeO-rich environments, hedenbergite [$CaFe(SiO_3)_2$]. Higher wollastonite contents, over about 80%, would result in formation of *clinopyroxene*, which crystallizes in the triclinic system.

The next three elements to add to the mix are aluminum (Al), sodium (Na), and potassium (K). These elements are geochemically coherent, linked by the formation of aluminosilicates called *feldspars*. In Earth's crust, where hydrothermal processes have produce relatively high concentrations of potassium, the feldspars commonly separate into a sodium/calcium feldspar phase called *plagioclase*, a solid solution of $NaAlSi_3O_8$ (albite; ab) and $Ca_2AlSi_2O_8$ (anorthite; an), and a potassium-rich phase with composition $KAlSi_3O_8$ (orthoclase; or). In most meteorites, where the K abundance is much lower than that of Na or Ca, the potassium feldspar can be fully dissolved in the plagioclase and does not normally form a separate phase. Thus meteoritic feldspar is usually a single mineral; terrestrial occurrences typically involve two coexisting feldspars, a "soda-lime" feldspar (plagioclase) and a "K-spar" of orthoclase composition.

Certain minerals, many with mica-like layered lattice structure, contain essential water: their structures *require* the presence of water to stabilize them. The several water-bearing minerals with layered structure are usually lumped together under the heading of *phyllosilicates*. More detail on this family is given in Appendix A.

Titanium, with an abundance similar to that of potassium, may form TiO_2 (rutile) or $FeTiO_3$ (ilmenite) in accessory amounts. In meteorites, ilmenite is always a minor mineral.

Nickel is normally present as a solute in the iron metal: the metal in chondrites and irons typically averages about 92% Fe, 7% Ni and 1% Co, although, as we shall soon see, there is a considerable range of variability. As we have seen, addition of Ni to Fe metal results in the possibility of having two coexisting metal phases with different Ni contents: we shall discuss this further in our detailed survey of iron meteorites in Appendix A.

Table IV.3 presents a short list of meteoritic minerals chosen to include the major phases which dominate the total mass and volume of meteorites. A much more detailed listing of meteorite minerals is presented in Appendix B. In this table, where two mineral names are given for a particular formula, they denote materials of the similar chemical composition but different crystal structures. These are the only minerals that are abundant enough to be detected in the reflection spectra of asteroids.

Table IV.3
Dominant Minerals in Meteorites

Mineral Name	Formula	Notes
Kamacite	(Fe, Ni)	<6% Ni: In ordinary chondrites, irons, stony irons
Taenite	(Fe, Ni)	>6% Ni: “
Troilite	FeS	“
Olivine	$(Mg,Fe)_2SiO_4$	Usually contains more Mg than Fe
Pyroxene	$(Mg, Fe, Ca)SiO_3$	Often forms two coexisting minerals, one Ca-rich (clinopyroxene) and one Ca-poor (orthopyroxene)
Feldspar	$NaAlSi_3O_8/CaAl_2Si_2O_8/KAlSi_3O_8$	
Phyllosilicates		Various clay-like minerals, all containing water
Magnetite	Fe_3O_4	Found only in the most oxidized C chondrites

Meteorite Composition Groups

Of the seven types of meteorite mentioned earlier, the large majority of the individual objects are primitive (unmelted, undifferentiated) chondrites. Because of their number, a vast body of laboratory data on their mineralogy and chemistry exists. Because of their diversity, each class deserves special treatment and consideration. Since much of this information is highly technical, it will be presented in Appendix A. Readers having a general familiarity with chemistry and geology would do well to read that Appendix now; others would be better advised to delay reading the Appendix until completing this chapter.

Appendix A will subdivide these seven broad meteorite types into many narrowly defined groups, beginning with the chondrites. We will follow the same order as previously utilized, identifying groups first by composition and second by degree of internal thermal evolution. The compositional details for these meteorite classes are of great importance in determining their potential as resources.

For present purposes, it will suffice to treat the three major subdivisions of irons and the two types of stony irons without further discrimination. It must be mentioned, however, that most achondrites are generally similar to terrestrial basalt (pyroxene, olivine, and feldspar) and are referred to as *basaltic achondrites*, whereas a group of very dark achondrites called the *ureilites,* another group of highly reduced *enstatite achondrites*, and several other minor classes are known. The chondrites are mostly composed of kamacite and taenite metal, the iron sulfide troilite, olivine, pyroxene and feldspar. The three main families that consist of these minerals are called the *ordinary chondrites*: they differ in the proportions of these mineral, the overall iron content, and the degree of oxidation of iron, being known as the H (high-iron), L (low-iron) and LL (very low iron) chondrites. Other important families of chondrites are the two classes of highly-reduced *enstatite chondrites* (with negligible oxidized iron content and many rare and exotic minerals) and several distinct types of highly oxidized and water-rich *carbonaceous chondrites*, notable for their high abundance and rich diversity of organic matter.

For those desiring further detail on meteorite research, an excellent guide to the basic data on individual meteorites is Monica M. Grady's *Catalogue of Meteorites.*

Meteorite Orbits

It is important to know the compositions of meteorites, but such knowledge becomes useful only when we know what asteroids, or what region of space, these meteorites come from. Several meteorite falls have been so well documented by photographic tracking that the pre-atmospheric trajectories of the entering bodies could be determined accurately. These entry conditions can then be used to calculate the orbits that these meteorites were pursuing before their encounter with Earth. It must be understood that meteorites arriving on NEA-type orbits may be either fragments ejected from NEAs by impacts, or meteorite-sized fragments from Belt asteroids that have wandered into Jupiter resonances and thence into NEA-type orbits. It also must be understood that a meteorite orbit that crosses Earth and travels out to, say, 3 AU at aphelion cannot be said to have "originated" at 3 AU. The first effect of a body's drifting into a Jupiter-resonant orbit is to pump up the eccentricity of the orbit while maintaining the same orbital period. Once the eccentricity is high enough to cross the orbit of one or more of the terrestrial planets, further strong perturbations by those planets can, and often will, obscure the nature of the original orbit.

These meteorite orbits are especially useful when we find that they are closely similar to the orbit of a particular Near-Earth Asteroid. We then require a comparison of the spectrum of the meteorite with that of the asteroid. When a good match is found, it then becomes urgent to compare the spectrum of the NEA with the spectra of asteroids out in the Asteroid Belt. Only then can we construct plausible histories for these bodies.

Pre-atmospheric orbits have been determined, or at least estimated, for the meteorites listed in **Table IV.4**. The composition data given in the Table are explained in Appendix A.

Table IV.4
Orbits of Meteorite Falls

Meteorite	**Date of fall ddmmyyyy**	**a AU**	**e**	**i °**	**Mass and Type***
Farmington, Kansas**	1890	2.4	0.6	?	89.4 kg L5 chondrite
Pribram, Czechoslov.	07 04 1959	2.42	0.67	10.4	5.7 kg H5 chondrite
Lost City, Oklahoma	03 01 1970	1.66	0.41	12.0	17 kg H5 chondrite
Dhajala, Gujarat, India*	28 01 1976	2.3	0.6	28	60 kg H3 chondrite
Innisfree, Alberta	05 02 1977	1.87	0.47	12.3	4.6 kg LL5 chondrite
Peekskill, New York	09 10 1992	1.49	0.41	4.9	12.4 kg H6 chondrite
Tagish Lake, Canada	18 01 2000	2.0	0.56	2.0	10kg anom. C1 chondrite
Morávka, Czech Rep.	06 05 2000	1.85	0.47	32.2	1.4 kg H5 chondrite
Neuschwanstein, Germany	06 04 2002	2.4	0.67	10.4	6 kg EL6 chondrite
Almahata Sitta, Sudan	07 19 2008	1.31	0.31	2.54	11 kg anom. ureilite
Sutter's Mill, California	22 04 2012	2.7	0.8	?	1 kg CM chondrite
Chelyabinsk, Russia	15 02 2013	1.73	0.57	4.2	10? kg LL5 chondrite

** Types explained in Appendix A*

** No imaging data available on these fireball trajectories; lower-quality orbital data*

The Farmington meteorite fell in Kansas on an unrecorded date in 1890. It has an exceptionally low cosmic ray exposure age, suggesting an immediate origin as a fragment from an Apollo asteroid. There is no photographic documentation of the fall trajectory (because it fell in

1890!), and the reconstructed pre-atmospheric orbit of Farmington must be regarded as plausible but conjectural.

The first observed fall for which good photographic tracking data were available was the Pribram meteorite, which fell in Czechoslovakia in 1957.

The Lost City meteorite, an H5 chondrite whose entry was observed by the Prairie Meteorite Network of photographic tracking stations in 1970, had an orbit that was resonantly affected by both Jupiter and Saturn, causing the eccentricity of the orbit to be cyclically pumped up and down. The meteorite would have been in an orbit with sufficient eccentricity to cross Earth's orbit only about 12% of the time.

The Innisfree meteorite fall in 1977 was tracked by a Canadian photographic network.

The orbit of the Dhajala meteorite was calculated from visual observations, not from photographic tracking. The calculated orbital parameters given in **Table IV.4** are those usually quoted, but it must be understood that these numbers are very imprecise. The original paper on Dhajala's orbit quotes the semimajor axis as 2.3±0.8 AU and e = 0.6±0.1, compatible with perihelia q ranging from q = (2.3-0.8)(1-0.7) = 0.45 AU to (2.3+0.8)(1-0.5) = 1.5 AU, an obvious absurdity, since q must be less than 1.017 AU in order for the body to collide with Earth. The significance of this orbit determination should not be overestimated. Note also that the aphelion distance allowed by these numbers can be as high as Q = (2.3+0.8)(1+0.7) = 5.27 AU, which would make Dhajala a Jupiter-crosser, a suicidal state of affairs.

Tagish Lake, an anomalous C1 chondrite, had an entry mass on the order of 100 tonnes, with a composition suggestive of extremely primitive material and a reflection spectrum similar to D-type asteroids from the outer reaches of the Asteroid Belt. About 10 kg of fragments were recovered. The orbit of Tagish Lake is embedded in the μ-Orionid meteor stream, a debris trail associated with the S-type Apollo NEA 4183 Cuno, a poor match. Both Earth-based and orbital imagery were used to calculate the orbit.

The fall of the Morávka meteorite in the Czech Republic was videotaped by three witnesses and the sonic boom signature was heard at a number of stations.

Figure IV.9 One of the thousands of small pieces recovered from the 2013 Chelyabinsk, Russia, bolide.

Credit: Aerolite Meteorites LLC

The Neuschwanstein meteorite, which dropped fragments in Germany and Austria, was tracked by photographic stations there and in the Czech Republic. The orbit found for this EL6 chondrite was essentially identical to that of the Pribram H5 chondrite which fell nearby some 43 years earlier. The lack of any chemical or petrological similarities between the two falls is most easily attributed to them both being fragments ejected by a collision between EL6 and H5 parent asteroids (see Appendix A for explanation of these classes).

The meteorites dropped by the spectacular Chelyabinsk bolide are generally quite small: although nearly 3000 pieces have been recovered, the total recovered mass is only a few kilograms. Pieces of the meteorite are still being found. Studies of the aerial explosion of the Chelyabinsk bolide estimate a total mass of about 10,000 tonnes and an explosive power of 400 to 500 kilotons of TNT.

On 7 October 2008 the Near-Earth Asteroid 2008 TC3, discovered only hours earlier, entered Earth's atmosphere over the Sudan. It was the first predicted asteroid impact in history. The explosion, with a yield of 1 to 2 kilotons of TNT, dropped over 600 recovered fragments of the rare ureilite achondrite type, with admixtures of several distinct kinds of chondritic material. The recovered samples and the asteroid itself have spectra that fit the definition of an F-type asteroid. Recently a similar event involving the newly-discovered NEA 2014 AA has provided a second example of the successful prediction of the impact of a small (several meters diameter) asteroid. This fall occurred far from land over the South Atlantic, where recovery of meteorites was impossible.

The Sutter's Mill meteorite in California was observed by weather radar and by acoustic monitoring stations as well as by photographic and video means. Roughly 1 kilogram of small fragments has been recovered. The meteorite was a carbonaceous chondrite with an exceptionally high entry velocity, 28.6 kilometers per second. The airburst had an estimated explosive yield of about 4 kilotons of TNT.

Note that, since the year 2000, three of the six falls with documented orbits are dark carbonaceous objects, either C chondrites or ureilites. Note also that irons and stony irons do not appear on the list, as would be expected from their rarity. Modern search and tracking technology make rapid recovery of meteorite falls much easier, which greatly enhances the likelihood of recovering very fragile meteorites before they are disintegrated by weathering. Thus the most recent falls are more faithful representatives of the incoming flux of meteorites than earlier statistics on falls, and vastly more relevant to the real impact flux (and thus the real NEA population) than the statistics on finds.

Further Clues to the Places of Origin of Meteorites

On Earth we encounter many minerals and rock types that are not stable at the low pressures found in the upper crust, but instead require high formation pressures. The most familiar example is diamond, which is unstable at pressures lower than about 25 kilobars, and spontaneously reverts to graphite, a lower-density polymorph of carbon that is a widespread minor mineral in Earth's crust. [The bar is a metric unit of pressure, roughly equal to one atmosphere: meteorologists normally report atmospheric pressure in bars or millibars. One bar pressure is reached at a depth of about 10 meters in water; 10 kilobars is reached at a depth of about 30 km in rock.] Beautifully clear, crystalline (gem-quality) diamonds, sometimes over 1 cm in diameter, require prolonged exposure to high pressures and high temperatures to grow to such size and attain such purity. For them to survive on Earth's surface, they must be cooled down so quickly that they do not have time to adjust to lower pressures and recrystallize as graphite. We therefore find diamonds on Earth's surface only where they have been transported up from great depths very quickly by explosive volcanic eruptions (diatremes). These volcanic diamond-bearing source rocks are called *kimberlites*.

Thus the presence of large clear diamonds in a meteorite would constitute *prima facie* evidence for the formation of the meteorite deep inside a parent body at pressures on the order of 30 kilobars, similar to the pressure at the base of Earth's crust. Diamonds are indeed found in ureilites and some irons, but their character is very distinctive: they are typically tiny and black, what are called carbonado diamonds. They are found in association with severely shocked minerals; experiments have demonstrated that severe mechanical shock, with peak pressures of at least tens of kilobars, can and does make such carbonado diamonds from a wide variety of carbon-rich materials, ranging from graphite to peanut butter. The mechanical shock occurring during an impact between two asteroids not only can briefly attain very high pressures, but the expanding debris cloud from such an impact cools down on a time scale of seconds, freezing in the effects of the transient high-pressure phase.

Diligent searches for high-pressure minerals in asteroids have found only shock-produced features and phases. No evidence for prolonged high pressures (greater than a kilobar) has ever been found. Now consider the largest asteroid, Ceres: its central pressure is about 400 bars. In other words, even total disruption of a Ceres-sized asteroid would not expose minerals that had been subjected to hydrostatic pressures of a kilobar. In the 19th and early 20th centuries it was common to assume that the Asteroid Belt was the remains of a disrupted Earth-sized planet that once orbited near the present orbit of Ceres. That such a planet should once have existed was deduced from Bode's "Law" of planetary distances, which has been demonstrated to fail in several crucial ways, not least in failing to describe the orbits of the outer planets. A second serious objection to the planetary-disruption theory was that the total mass of the Asteroid Belt was found to be less than twice the mass of Ceres, less that 0.0006 Earth masses, or about 5% of the mass of Earth's Moon, far too small to make a credible planet. The third objection was that there was no evidence in meteorites for minerals formed at high static pressures.

Another concern was that the growing evidence from meteorite studies made it clear that only a small fraction of meteorites had ever experienced temperatures high enough for thorough melting and differentiation, and that such melting had occurred 4.5 billion years ago, essentially right on the heels of the formation of the Solar System. The discovery of a few odd meteorites that had solidified only 1.5 billion years ago threatened to reopen the debate, but it was soon found that these meteorites contained adsorbed gases with the distinctive chemical signature of the atmosphere of Mars: they were Martian surface rocks that had formed late in Solar System history and had been blasted off Mars by a comet or asteroid impact into orbits around the Sun.

By the time astronomical technology had advanced to the point of being able to measure the spectra of asteroids and compare them to the laboratory spectra of various meteorite groups, the expectation that meteorites came from asteroids, and had never been part of a planet, was already established. The question then became, "Which asteroids do the various meteorite groups come from?" This will be our concern in the following chapter.

Implications for Fledgling Asteroid Miners

There are several important messages inherent in our tour of the world(s) of meteorites, both here and in Appendix A:

1. Minerals available in nearby space are seldom familiar as terrestrial ores,
2. Mining and ore-enrichment techniques useful on Earth are therefore seldom useful in space,
3. The compositional variety of meteorites is very broad,
4. Many elements are available only in very limited concentrations or in very narrow ranges of meteorite types,
5. The primitive (chondritic) classes are by far the most abundant,
6. The chondrites fall into three distinct families, ordinary, enstatite, and carbonaceous, with very different ore potential,
7. The volatile elements needed for life-support and propellant production are specific to carbonaceous chondrites,
8. The metal phase of LL chondrites is the richest in rare minor elements among all chondrites,
9. Metallic meteorites, however rich in composition, present severe processing problems,
10. Enstatite meteorites contain rare metal sulfides from which extraction of several metals is technically feasible.

V. Meteorite-Asteroid Connections: NEA Sources and Fate

The orbits of those meteorite falls that have been tracked in detail are all closely similar to the orbits of Near-Earth Asteroids. This is not a profound insight into their nature: it is logical necessity that all meteorites encounter Earth from orbits that cross Earth's orbit. Such orbits have finite lifetimes that are very short compared to the age of the Solar System. But recognition of these facts raises several important questions:

1. Which asteroids are the sources of meteorites?
2. Which meteorite group comes from which asteroid?
3. Where do NEAs come from and how are they replenished?
4. What is the fate of the present NEA population?

Spectral Types of Asteroids

There are two prominent systems of assigning spectral classes to asteroids, that proposed by David Tholen and the SMASS system of Schelte Bus and Richard Binzel. Even those spectral classes that appear with the same name in both systems may differ slightly in their definitions. Here we will simplify these systems to a sort of common denominator.

Each asteroid spectral class is designated by a letter of the alphabet. Some of these letters are mnemonic (C for carbonaceous; S for stony; M for metal), but the number of classes is large enough to frustrate the desire for a transparent mnemonic system to accommodate all of them; indeed, the number of recognized classes threatens to exhaust the entire alphabet!

The order of letters in the alphabet, being assigned for reasons having little to do with the nature of the spectrum, is a far less useful system of categorization than ordering the groups by albedo, spectrum, and composition. **Once an asteroid is discovered, the first datum bearing on its material composition is its albedo**, the fraction of incident sunlight that is reflected rather than absorbed. (In other words, is it made of dark or light materials?) Thus grouping spectral classes by albedo is both easy and useful.

Albedo is determined by comparing the total reflected light intensity to the total thermal infrared emitted intensity. The reflected visible-light flux is proportional to the cross-section area of the asteroid and to its albedo: $F_{vis} = aA$, where a is the albedo and A is the cross-section area. All the visible light *not* reflected is absorbed and then re-emitted as thermal infrared (heat) radiation: $F_{IR} = (1-a)A$. For newly discovered asteroids, and for almost all small asteroids, the cross-section area A is unknown. But the ratio of these two fluxes, $F_{vis}/F_{IR} = a/(1-a)$, is sufficient to determine the albedo. For example, if we measure a flux ratio of visible to IR radiation of 4:1, then $a/(1-a) =4$, and $a = 4 - 4a$, so $5a =4$ and $a =0.8$. This is a highly reflective material, such as salt flats or titanium dioxide white-paint pigment. In reality, even the most reflective asteroids only reach albedos near 0.64, and thus have a flux ratio of $F_{vis}/F_{IR} = a/(1-a) = 0.64(1-0.64) = 1.8$. Since all other asteroids have lower albedos, IR fluxes that are larger than the visible fluxes are not only possible, they are common. Most asteroids, like most politicians, give off more heat than light.

At the other extreme, some rare asteroids have albedos below 0.035, meaning that 0.965 (96.5%) of the incident light is absorbed. Then the ratio of visible to IR fluxes, $F_{vis}/F_{IR} = a/(1-a)$, is $0.035(1-0.035) = 0.0362$. The ratio of IR flux to visible flux is1/0.0362, or 27.6:1!

This strongly suggests that the best way to search for most dark asteroids is in the infrared, not in visible light.

The incident sunlight has its peak intensity at a wavelength of about 0.6 micrometers (yellow light). The spectrum of the emitted heat radiation depends on the temperature of the emitting surface. The intensity distribution over wavelength is a broad, roughly bell-shaped curve, called the Planck function. The wavelength at which the intensity of emitted radiation is greatest depends on temperature according to the equation $2960 = l_{max}T$, where the wavelength l_{max} at the peak of the emission curve is given in micrometers and the temperature is the absolute temperature, the temperature above absolute zero, in Kelvins. So on a nice warm day on Earth, or a scorcher in Seattle, 296K (23 ^{o}C; 81 ^{o}F) the wavelength of peak emission of radiation is 10 micrometers. For an outer-Belt asteroid with a temperature of 148K the emission peak is at 20 micrometers.

Also, even without spectral resolution, the total emitted thermal flux is proportional to the 4th power of the temperature of the emitting surface: $F_{thermal} = sT^4A$, where s is a universal constant called the Stefan-Boltzmann constant and A is the area of the emitting surface. Thus if we know the total emitted infrared emission from an asteroid and also have measured its cross-section area, we can calculate its albedo. If we have spectral resolution, however, the thermal infrared spectrum permits us to measure l_{max} and calculate both the temperature and the cross-section area, from which we calculate the albedo.

Note that, once we know the albedo, we can use either the IR or visible-light data to calculate the cross-section area of the asteroid, and hence its average radius. **Thus any method of determining albedo is also a means of measuring the asteroid's size.**

<u>Bad data warning:</u> The reader is cautioned that older (pre-1970) sources of astronomical data frequently presented tables of asteroid diameters and masses that were arrived at by assuming that asteroids had the same albedo as the Moon and the density of that astronomer's favorite class of meteorites. Such estimates, in effect, assumed that all asteroids had albedos that real asteroids do not have. Such tables also often contained data calculated from different and incompatible guesses about albedo and density, with largely random results. **Figure V.1** illustrates why this approach was not appreciably more successful than casting runes or examining sheep entrails, because virtually no asteroids actually exist that have "average" albedos.

What about an asteroid of very irregular shape, tumbling through space so that the cross-section area it presents to us is constantly changing? Then we will see both the visible and IR brightness varying in synchrony. The periodic cycle of visible brightness is called the "light curve" of the asteroid, which provides us with a direct measurement of its rotation period. And what of an asteroid that is quite nicely spherical, in obedience to Plato's requirement for celestial bodies, but has large regional variations in albedo? We will then see the ratio of fluxes vary cyclically with the rotation period, with the albedo constantly changing, but the calculated cross-section area remaining constant. One striking example of such behavior is Saturn's moon Iapetus, which varies in albedo by nearly a factor of seven with each revolution.

Larger asteroids, and small asteroids that make fortuitously close passes by Earth, may provide enough light so that the spectrum of the asteroid can be measured. Rather than simply lumping all visible light together, and all infrared light together, we can disperse the light according to wavelength and look for the absorption signatures of minerals.

Classically this dispersion was done using prisms and visual observation; then more recently using diffraction gratings and photographic emulsions. But at the red end of the visible spectrum, and in the infrared, where most of the distinctive mineral absorption features are found, photographic films are so insensitive that no useful spectral information could be gained.

Early data on spectra of asteroids were collected by stellar astronomers using a three-filter system, passing ultraviolet (U), blue (B) and visible (V) light respectively. The UBV filter system was useful in determining the spectral classes of stars, but of limited utility when applied to asteroids; it was, however, widely available.

Modern spectral measurements are made using narrow-band filters (filter photometry) or Fourier-transform spectroscopy with sensitive electronic detectors such as CCDs. It is by such means that the present-day spectral classes of asteroids are determined, both in Earth-based and spacecraft-based studies.

The spectral classes are grouped together here according to albedo. The relationship of asteroid taxonomic class to albedo in **Figure V.1** clearly displays the dichotomization of virtually all asteroids into two groups of low (0.03 to 0.09) and high (0.12 to 0.30) albedo. We shall call the dark (usually carbonaceous) classes the C-cadre and the bright (stony) classes the S-cadre. A few rare asteroids are even brighter, with albedos ranging up to about 0.64. Note that asteroids assiduously avoid having the same albedo as the Moon (about 0.1): asteroid diameters calculated by assuming that all asteroids have the same albedo as the Moon will be either much too small or much too large.

For anyone harboring the archaic assumption that all asteroids are the same, and that once you've seen one you've seen them all, it is worth mentioning that the four brightest asteroids (catalog numbers 1 through 4) belong to four different spectral classes.

The most important features in the spectra of asteroids and meteorites are broad absorption bands due to FeO, centered near wavelengths of 1 and 2 micrometers in the near infrared. The 1-micron bands produced by FeO-bearing pyroxene and FeO-bearing olivine have slightly different wavelengths and very different band shapes, which permits determination of both the FeO content and the relative abundances of these minerals. The 2-micron band of ferrosilite in pyroxene has no

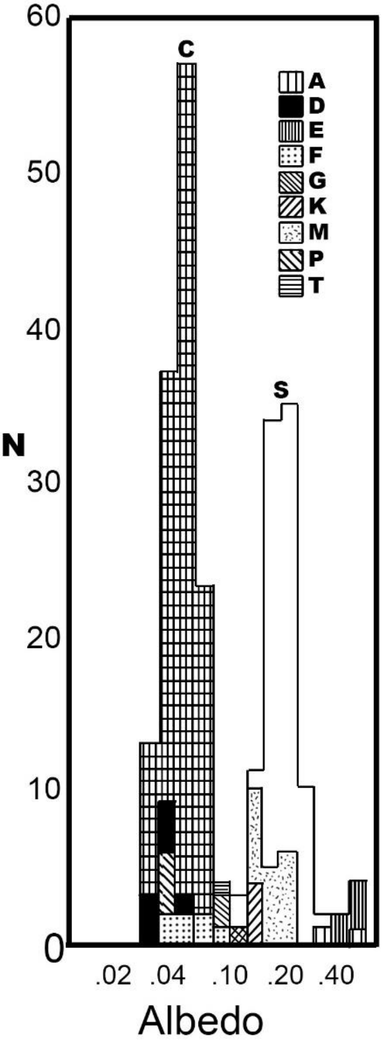

Figure V.1 Albedo Distribution of the Belt Asteroids. The distribution of albedos and taxonomic classes of Belt asteroids falls into two distinct classes: dark, albedo < 0., comprising classes B, C, D, F, G and P (collectively called "C cadre") and bright, with albedo > 0.1, comprising classes K, M, and S ("S cadre"). The very bright A and E classes (albedo > 0.3) are sometimes lumped with the S cadre. The various classes are overlaid, not stacked, in this diagram.

Credit: Deep Space Industries – John S. Lewis

counterpart in the spectrum of olivine. Also very important, but much harder to observe, is the "water band" centered near 3 micrometers wavelength. Water in various forms (ice, hydrated salts, -OH silicates, etc.) absorbs in that region, but, as with FeO, the shape and center of the absorption band depends on which mineral the water is in. Since the reflected sunlight peaks at about 0.6 micrometers and the re-emitted thermal radiation peaks in the thermal infrared at 10 to 20 micrometers wavelength, there is a broad region in between these peaks in which there is a local minimum in the light intensity: this is the near-infrared, from about 1 to 5 micrometers, where it happens that most useful spectral features of minerals, such as those containing FeO and water, are located.

Table V.1
Asteroid Spectral Taxonomic Classes

Class	Description	Example
C-cadre (albedo<0.1)		
D	Extremely dark; common among Trojans	624 Hektor
P	Extremely dark; comet affinities	324 Bamberga
F	Dark, denser than C	704 Interamnia
C	Dark, carbonaceous chondrite	10 Hygeia
B	Dark, altered	2 Pallas
G	Dark, altered; some polar ice	1 Ceres
T	Dark, altered, possibly dry	114 Kassandra
S-cadre (0.1<a<0.4)		
K	Rare category, like CV and CO chondrites	221 Eos
M	Metallic iron-nickel	16 Psyche
S	Silicaceous/stony (a)chondrite	3 Juno
Q	Strong FeO bands, like ordinary chondrites	1862 Apollo
Bright Outliers (albedo>0.4)		
A	Strong olivine signature	446 Aeternitas
E	Enstatite (a)chondrite--no FeO	44 Nysa
V	Basaltic achondrite	4 Vesta
R	Rare type between A and V	349 Dembowska
Catchall-group with flat spectra		
X	(bland M, E, P, etc. spectrum but poor albedo data)	
Borderline cases with intermediate spectra		
Any two- or three-letter designation such as CB or MS		
U	An outlier of any of the above taxonomic groups; an Unknown	

Origin of NEAs

Some NEAs have orbits that are so unstable that they cannot survive in their present orbits for more than a few tens of thousands of years; others, whose orbits are far from Jupiter resonances and do not approach any of the terrestrial planets closely (due to high inclinations and orbital nodes that are not close to the orbits of Earth or Venus), may have lifetimes on the order of 100 million years (100 ma). An average expected lifetime over the entire NEA population is about 10-30 ma.

These times are very short compared to the age of the Solar System (4,550 million years), which means that some mechanism must be responsible for replenishing the population of NEAs. The logical source for Near-Earth Asteroids is the Asteroid Belt, and both their spectra and orbits confirm that the overwhelming majority of NEAs come from the Belt. To understand how this happens, we need to seek out mechanisms that could remove a meteoroid or asteroid from the Belt and divert it into an NEA orbit.

Two features of the Belt provide valuable clues in this search. First, in 1857, Daniel Kirkwood, a professor at Jefferson (since 1865 called Washington and Jefferson) College in Pennsylvania, became interested in asteroid orbits. He noticed that, although a plot of the distribution of instantaneous heliocentric distances of all known asteroids showed no interesting structure, a plot of their population vs. semimajor axis (or, equivalently, orbital period) showed profound structure, with deep, essentially unpopulated minima in the distribution at distances where the orbital periods were harmonically related to Jupiter's period (see Figure II.2). Asteroids that wander into such orbits experience repeated mutually reinforcing gravitational perturbations by Jupiter, which can rapidly pump up their orbital eccentricities and put them into planet-crossing NEA-type orbits. Most obvious were the 3:1, 5:2, 7:3, and 2:1 resonances, but over a dozen narrow gaps are now recognized. The 4:1 resonance essentially defines the inner edge of the main Belt, and the 2:1 resonance defines the outer edge. He also proposed that the gaps in Saturn's rings were due to orbital resonances with the moons of Saturn, and was the first to suggest that meteor showers were caused by cometary dust.

Later, in 1918, the Japanese astronomer Kiyotsugu Hirayama, based on his careful study of the orbits of asteroids, determined that asteroids formed distinct clusters when their orbital element (a, e, i) were plotted in three dimensions. It was later found that each Hirayama family cluster contained many members with indistinguishable spectra, as would be expected if they were fragments resulting from the collisional disruption of a single large asteroid.

In 1961-2 the Russian dynamicist Mikhail Lvovich Lidov and the Japanese astronomer Yoshihide Kozai independently discovered an effect in which a small body, in this case an asteroid, can undergo a periodic oscillation in its orbital elements, in effect trading off inclination with eccentricity, which may drive an asteroid into close encounters with other (terrestrial) planets, breaking the resonant relationship. This Lidov-Kozai mechanism, so long as only the Sun, Jupiter, and asteroid are involved, conserves the quantity *L*, defined in terms of e and i as

$$L_z = \sqrt{(1 - e^2)} \cos i.$$

The general result is that small bodies in highly inclined orbits will experience an extreme variation in eccentricity, to the point of causing their perihelia to drop inward toward the primary body of the system. By this mechanism, asteroids and short-period comets strongly perturbed by Jupiter can evolve over a few million years into highly eccentric NEA-type orbits, even Sun-grazing and Sun-impacting orbits. This effect is completely independent of the mass of the asteroid (except only that its mass must be much less than that of Jupiter!), meaning that 10-m meteoroid-size rocks and 10-km asteroids are subject to the same evolutionary effect, differing only in the rate at which these bodies are redirected (small bodies are vastly more numerous).

As the orbital eccentricity increases for such high-inclination asteroids, their perihelion distances edge slowly toward the Sun. Whenever the perihelion of the migrating asteroid is close to the semimajor axis of one of the terrestrial planet, there is a period of tens of thousands of years in which the asteroid, at its perihelion, will graze or slightly cross the orbit of the planet, affording an opportunity for that planet to have a strong influence on the asteroid's motion. When an asteroid develops sufficient eccentricity to cross the orbits of one or more planets, this relationship can be broken by interaction with the planets and *L* is no longer conserved. That perturbation may be sufficient to break Jupiter's lock on the body and cause it to merge into the general NEA population if, and only if, the asteroid's line of apsides lies close to the planet's orbital plane. Otherwise the asteroid may be far out of the planet's orbital plane at the time of crossing, and the effects may be minimal.

At the opposite extreme, NEAs with very low-inclination orbits are compelled to pass very close to the actual orbits of each planet whose orbit they cross. These are the asteroids that have the highest probability of collision with a planet. In the statistics of NEA orbits, it is well established that asteroids with inclinations of less than a few degrees have short calculated lifetimes and are markedly less abundant than those with slightly higher inclinations. The implications are clear: if you want to survive crossing a freeway on the plains, it is far safer to be a bird (out-of-plane, above the traffic) than a rabbit (in-plane, amidst the traffic).

The weight of evidence implies that NEAs are indeed derived mostly from the main Asteroid Belt by means of Jupiter's gravitational perturbations. A small proportion of them are extinct or dormant short-period comets also placed in near-Earth orbits by Jupiter. An even smaller proportion, probably limited to 10-m or smaller objects in very Earth-like orbits, may be ejecta from violent impacts of NEAs and comets on the Moon. The overwhelming majority of NEAs must be samples of the Belt, but they were kicked out of a few resonances: they are therefore very non-democratic, non-random samples of Belt material from several very specific locations where Jupiter's resonant effects are largest.

There are three distinct mechanisms by which a Main Belt asteroid can migrate into a resonant orbit. The first is a change in orbital period caused by an impact of a smaller body. The second is the effect of solar radiation pressure, which, because of the aberration of the direction of incident sunlight caused by the asteroid's orbital velocity, always acts to retard the orbital speed of the asteroid and cause it to spiral inward. This weak force is called the Poynting-Robertson effect. Third, and usually most important, is the momentum imparted by the emission of thermal radiation from the asteroid, primarily into its afternoon sky. For a prograde rotating asteroid (rotation in the same direction as the orbital motion) this force acts to accelerate the asteroid's orbital motion and causes it to retreat to more distant orbits; on a retrograde rotator, it acts to slow the orbital motion and causes it to spiral inward. This third force is called the Yarkovsky effect. Generally, small asteroids are collision fragments and have random orientations of their spin axes, causing about half to spiral inward and half to migrate outward. Large asteroids are generally more likely to have prograde rotation. The accelerations produced by both the Poynting-Robertson and Yarkovsky accelerations are proportional to the cross-section area of the asteroid (r^2) and inversely proportional to their masses (r^3); hence smaller asteroids are more easily moved.

Fate of NEAs

As we can see, the fate of any given NEA is related to its orbital elements in complex ways. Because of the frequent opportunities for perturbations by planets, NEA orbits can change markedly over time. An NEA whose orbit closely approaches Jupiter may be ejected from the

Solar System or collide with Jupiter. Strong interactions with Jupiter can also drop the perihelion of an NEA orbit into the Sun, or into a close Sun-grazing orbit in which it will be torn apart by solar tidal forces or eventually evaporate after a number of perihelion passages. Of course, depending on the momentary orbital parameters, collision with any of the terrestrial planets may be possible. Low-inclination NEAs have much more frequent close encounters with planets, and will generally have the shortest lifetimes. NEAs in orbits that do not presently cross Earth (the Amor family) may be perturbed by Jupiter or Mars into Apollo-type Earth-crossing orbits, and bodies with orbits wholly interior to Earth may likewise be perturbed by Venus into Earth-crossing Aten-type orbits. Because of their larger mass and cross-section area, Venus and Earth are far more effective at destroying NEAs than Mars and Mercury: among the terrestrial planets the collision rate is highest for Earth, then Venus, followed by Mars, Mercury and the Moon. The role of the Moon in all this is fairly trivial. One frequently encounters assertions such as "the Moon helps protect Earth from cosmic bombardment", but in actual fact only about 1 in every 100,000 asteroids headed for Earth would encounter the Moon on the way in.

About 30% of all NEAs, probably without preference for spectral class, will end their career by colliding with Earth. There, in a manner closely determined by their size, strength, entry velocity and entry angle, they will be destroyed in airbursts high in the atmosphere, break up into meteorite-sized rocks, or reach the ground intact to cause violent surface explosions and excavate craters. The very weak ones will disintegrate into dust and vapor and will not drop recoverable meteorites; the very largest ones will reach the ground still traveling at orbital velocity, carrying so much energy that they will be almost completely vaporized in the impact explosion.

Figure V.2 shows the distribution of airburst altitudes and yields for a computer simulation of a typical 100-year period, supplemented with the observed data for the Tunguska (1908) and Chelyabinsk (2013) explosion. See the figure caption for further explanation. Note that many Chelyabinsk-sized airbursts occur per century; Tunguskas should occur at the rate of one every few centuries.

We are now ready to explore the NEA population in detail, in search of bodies that are promising sources of valuable materials and are accessible to spacecraft launched from Earth.

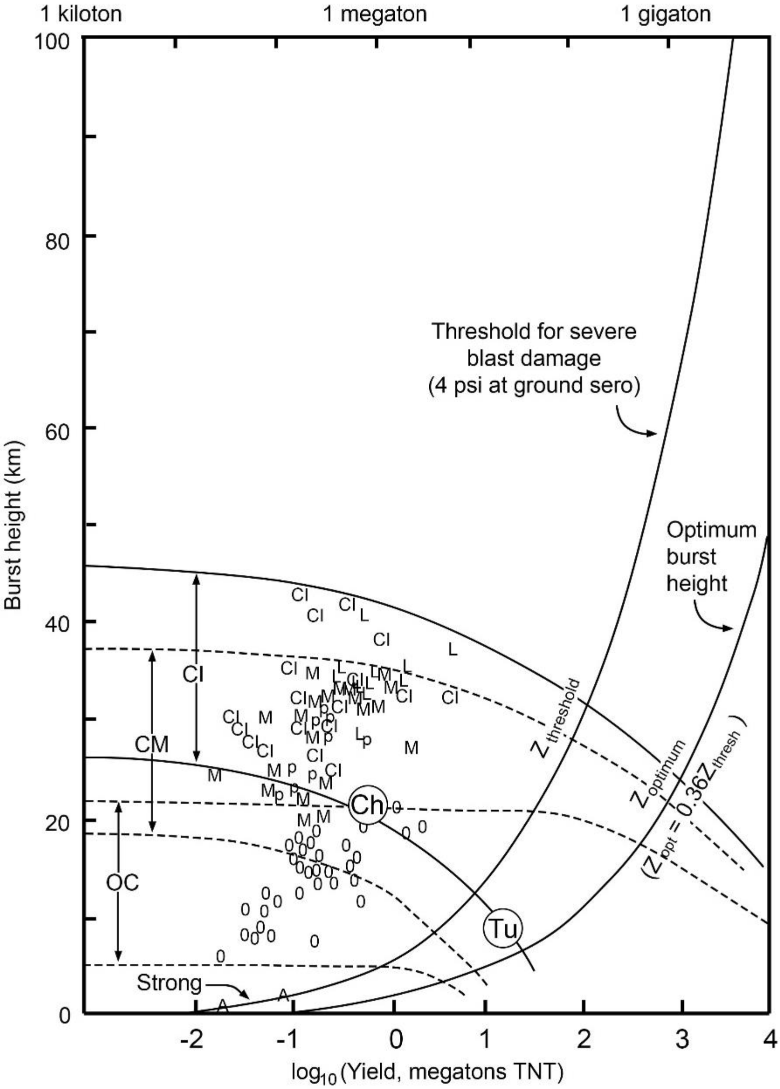

Figure V.2 Airburst Altitudes and Yields for a Typical 100-year Period. A computer simulation of the bombarding population for one century, with the Tunguska and Chelyabinsk airbursts added for comparison. For each year in the simulated century, the disruption altitude and explosive yield of the largest entering body is given. The symbols give the composition (and hence the strength) by class of the impactors: CI = CI chondrites, M = CM chondrites; O = ordinary chondrites; A = achondrites; L = long-period comet debris; P = periodic comet. For comparison, the Tunguska airburst of 1908 is marked with Tu and the Chelyabinsk airburst of 2013 is marked as Ch. The $Z_{threshold}$ curve marks the onset of severe structural damage at the ground; $Z_{optimum}$ is the optimum burst height from the nuclear weapons literature (the airburst altitude at which the maximum area is devastated by a blast with a given yield).

Credit: Deep Space Industries – John S. Lewis

VI. Near-Earth Asteroids

NEA Orbital Classes

We have already met the three important classes of NEAs, defined in relation to their orbital properties. The most important criterion for residents of Earth is whether a given asteroid crossed Earth's orbit. Earth's orbital semimajor axis is (by definition) 1 AU, but the eccentricity of Earth's orbit, though small, is not zero: in fact, $e = 0.017$. Therefore Earth's perihelion distance is $q = a(1-e) = 0.983$ AU and its aphelion distance is $Q = a(1+e) = 1.017$ AU. Using this information, we can more carefully define the NEA orbital classes:

1. **Atens:** those asteroids that spend most of their time inside Earth's orbit and cross Earth's orbit from inside (they get at least far enough from the Sun to reach Earth's perihelion) and have orbital periods less than one year. ($P < 1$ year; $a < 1$ AU; $Q > 0.983$ AU),
2. **Apollos:** those asteroids that have orbital periods greater than one year and cross Earth's orbit from outside ($P > 1$ yr; $a > 1$ AU; $q < 1.017$ AU)
3. **Amors:** those asteroids that approach within 1.300 AU of the Sun but do not cross Earth and have orbital periods longer than 1 year ($P > 1$ yr; $a > 1$ AU; $1.017 < q < 1.300$ AU. Almost all known Amors are Mars-crossers.

The discovery conditions are very different for these three classes: Atens spend most of their time on the Sunward side of Earth, Apollos can fly by very close to Earth, and Amors can never be closer than 0.017 AU. Many Amors never get closer to Earth than 0.2 to 0.283 AU at perihelion. As a result, the statistics of their relative abundances must be considered incomplete. Of the 11,000 NEAs known as of May 2014, 7.7% are Atens, 54.4% are Apollos, and 37.8% are Amors. It is likely that Amors are much more abundant than Apollos, but there is a deficiency of discoveries of small Amors in our lists because many must never approach Earth closely enough to be discovered.

In addition to these three well-established classes, there is another group called variously the Atira, Apophele, or Arjuna asteroids, which follow orbits entirely inside Earth's orbit. They never cross Earth's perihelion ($P < 1$ year; $Q < 0.983$ AU). Only 14 have been spotted thus far.

NEA Magnitudes and Sizes

At this writing, some 863 NEAs larger than 1 km in diameter are known, out of a total population estimated as 980. It must be made clear that these are for the most part not measured diameters; they are calculated from the assumption that asteroid sizes correlate simply and directly with their standard brightness, “standard” meaning the brightness they would have if observed when exactly 1 AU from the Sun and 1 AU from Earth. The brightness of a heavenly body is always measured in magnitudes, a traditional measure of relative brightness going back to pre-telescopic naked-eye astronomy.

The traditional magnitude scale talked of the brightest stars as “stars of the first magnitude”, noticeably fainter but still bright stars as “stars of the second magnitude”, and so on, down to the practical limit for naked-eye observations, “sixth magnitude”. When it finally became possible to measure the light flux from these stars, it was found that a 5 magnitude difference between the apparent brightness of two starts corresponded almost perfectly to a factor-of-100 difference in their light fluxes. Thus a 1st-magnitude star delivers 100 times as much visible light to Earth as a 6th magnitude star. Later, when it became clear that stars were at very different distances from Earth, it became necessary to specify that these magnitudes were actually “*apparent* visual magnitudes”, and not intrinsic properties of the stars.

The development of astronomical photography made it possible to measure the distances of many thousands of nearby stars by observing the apparent displacement of each star against the background of much more distant stars as Earth executes its orbit around the Sun. The displacement was measured in seconds of arc (“), each second of arc being 1/60 of a minute (‘) of arc, and each minute being 1/60 of a degree (^{o}). This displacement is called the star’s parallax, p. The closer the star, the larger the parallax: distance is inversely proportional to the parallax measured in seconds of arc; $d = 1/p$. The obvious unit of distance then was 1/”, called by astronomers a parsec (from “per second of arc”). By simple geometry, 1 parsec is equal to 206,264.8 AU.

Measurements of the distances of these stars made it possible to use the apparent magnitude of a star to calculate its intrinsic brightness, but required that astronomers agree on a standard distance. By consensus, stars are given “absolute magnitudes” that specify how bright the star would appear from a standard distance of 10 parsecs. The absolute magnitude of the Sun is 4.83, meaning that it would have an apparent magnitude of 4.83 when viewed at a distance of 10 parsecs, or 4.83 -

5.00= -0.17 when viewed from 1 parsec away. But viewed from Earth, only 1 AU away, the Sun's apparent magnitude is an impressive -26.73.

Since asteroids are tiny and extremely faint compared to stars, and since their brightness depends not only on their distance from us but also on their distance from the Sun, a more convenient standard distance was called for: that standard is, as we have seen, 1 AU from the Sun and 1 AU from Earth. By this convention, an "average" 1 km asteroid 1 AU from Earth and 1 AU from the Sun would have an absolute magnitude (H) of 17.75. A typical asteroid with a diameter of 100 meters would have a cross-section area 100 times smaller, and hence would appear 5 magnitudes fainter, H = 22.75. Several prominent asteroid search programs, such as LINEAR, have detection limits at about that level.

It should be mentioned that the notion of an "average" asteroid is rather naïve; NEAs (and their Belt parents) differ widely in their properties.

Table VI.1 summarizes the largest and most massive NEAs, specifically those larger than 3 km in diameter. The diameters given are the mean diameters; these bodies are generally best represented as triaxial ellipsoids, not spheres.

Table VI.1
The Largest NEAs
(diameter > 3 km)

Number/Name	**Diameter (km)**	**H magnitude**	**Albedo**	**Spectral Class**	**Mass** (kg)
1036 Ganymed	38.5	9.45	0.18	S	$100\text{x}10^{15}$
433 Eros	22.0	11.16	0.18	S	$18\text{x}10^{15}$
3552 DonQuixote	18.7	13.0	0.02	D	$6.4\text{x}10^{15}$
1627 Ivar	9.1	13.2	0.16	S	$1.3\text{x}10^{15}$
1866 Sisyphus	8.5	12.24	0.14	S	$1.1\text{x}10^{15}$
1580 Betulia	5.4	14.53	0.08	C	$0.17\text{x}10^{15}$
3200 Phaethon	5.1	14.60	0.11	B	$0.16\text{x}10^{15}$
1980 Tezcatlipoca	4.3	13.92	0.25	SU	$0.14\text{x}10^{15}$
887 Alinda	4.1		0.23	S	$0.12\text{x}10^{15}$

Note the dominant role of 1036 Ganymed, which is more than 10 times as massive as any other NEA. (Do not confuse 1036 Ganymed with Jupiter's planet-sized satellite JIII Ganymede.) Ganymed is in a relatively inaccessible Amor orbit which never crosses Earth, and is composed of S-type material, giving it low mining interest. Assigning a density of 3.5, the mass is calculated to be 100x10^{15} kg. (Recall that many tabulated diameters and masses of asteroids in the older literature incorporate either absurd assumptions about densities or computational errors.) Beyond this "top nine" the next NEA in order of mass would be 1685 Toro, with a mass of 0.047x10^{15} kg. A good estimate of the total mass of the NEA population would be 128x10^{15} kg, meaning that Ganymed alone accounts for 78% of the total of all NEAs, and the biggest two account for more than 92% of the total. Those two, Ganymed and Eros, are both S asteroids. Note that 3 of the next 7 are C-cadre asteroids (B, C and D), of which the large majority (72%) of the mass is provided by carbonaceous materials. Thus is it is perfectly true that the large majority of the mass of the NEA swarm is relatively low-value (volatile-poor) S-type (Ganymed and Eros), but it is equally true that most of the mass of the remaining NEAs is carbonaceous, with abundant organic matter, water, and other useful materials.

The D-class asteroid 3552 DonQuixote not only has an extremely low albedo (0.02) but belongs to a spectral class associated with outer-belt comet-like material. Its orbit is also very suggestive of cometary affinity: its orbital eccentricity is 0.713, with a perihelion 0f 1.216 AU and an aphelion of 7.247 AU, about halfway between Jupiter and Saturn. Its orbital inclination is very large, 30.84 degrees. Because it is a Jupiter-crosser, it is exceptionally vulnerable to strong perturbations by Jupiter, as a result of which it could easily become an Earth-crossing (Apollo) asteroid. It is almost certainly an extinct periodic comet. It is one of the hardest NEAs to reach from Earth, and also the one with the most attractive composition.

The next NEA in the table is 1627 Ivar, an Earth grazing S-type Amor asteroid with modest eccentricity (0.397) and inclination (8.447^{o}). Next, 1866 Sisyphus, is a binary S-type Apollo asteroid that has been studied by radar from Earth.

1580 Betulia is a C-type Amor with a perihelion of 1.126 AU and an eccentricity of 0.488. It has a very high inclination, 52.1^{o}, which makes it an exceptionally difficult target for a rendezvous or landing mission.

3200 Phaethon is a B-class Apollo asteroid, suggesting that it is a thermally-processed C-type asteroid. Its orbit is also unusual, with an eccentricity of 0.890 and a perihelion distance of only 0.140, far inside the orbit of Mercury, affording it an excellent excuse for having been thermally altered. Its aphelion is in the inner Asteroid Belt. Its inclination is 22.17°, high enough to make it a difficult target for spacecraft visits.

1980 Tezcatlipoca is an Amor asteroid with a spectral class of SU, implying that it is an outlier of the S group. It is an Earth-grazer, with perihelion of 1.086 AU (Earth's aphelion is 1.017 AU). It too has a high inclination, 26.86°. Finally, 887 Alinda is an Amor asteroid that is also the namesake of a family of asteroids with similar orbital parameters (a close to 2.5 AU; e = 0.52 +/- 0.12) and orbital periods of about 4.1 years, in a 1:3 resonance with Jupiter and very close to a 1:4 resonance with Earth. This is one of the resonances that slowly pump up the orbital eccentricity, leading to ever more opportunities for close flybys of the terrestrial planets, and ever-increasing chances of breaking the Jupiter resonance. The famous Potentially Hazardous Asteroid 4179 Toutatis is a member of the Alinda family.

NEA Albedo and Spectral Class Statistics

There are several sources of data on the albedos and spectral classes of NEAs. The classical process of determining asteroid albedos begins with visible-light detection of the new asteroid, such as the example of LINEAR mentioned above, determination of its absolute visual magnitude H, observation of the asteroid in the thermal infrared, comparison of the visual and infrared brightness, and calculation of the albedo. Alternatively, one might examine the visible and near infrared (not thermal infrared) spectrum, assign a spectral class, and then adopt an albedo consistent with this low-resolution spectrum. Many NEAs studied in this manner have rather flat and featureless spectra that are compatible with several composition classes that have very different albedos: the M (metallic), E (enstatite) and C, D or P (carbonaceous) asteroids may differ greatly in albedo, but be indistinguishable from their spectra. These are called X-class asteroids, a designation that can be resolved only if actual thermal infrared or radar data become available. Consider two NEAs categorized as X-class; an E asteroid of albedo 0.48 and a carbonaceous asteroid of albedo 0.03. For them to have the same H magnitude, the dark asteroid must have 16 times the cross-section area of the more reflective E asteroid. It therefore is 4 times as large in radius, 64 times as large in volume, and (because it is less dense) about 30 times as large in mass as its brighter counterpart. Since small asteroids are far more abundant than large asteroids, a disproportionate number of the bodies of a given visual magnitude will be small, high-albedo bodies, and a minority will be large, massive, dark bodies. (Small dark bodies will belong to a much fainter magnitude class.) The smaller number of large, dark asteroids may have more mass than all the bright little ones of the same H magnitude combined.

The several Earth-based asteroid detection programs (Spacewatch, LINEAR, NEAT, LONEOS, Catalina Sky Survey, Pan-STARSS, and others) have all searched in visible light, assessing the visual H magnitude of each body. Then, by assuming an average albedo of 0.14, this H-magnitude number has been used to calculate the cross-section area of the asteroid, which, because of the high likelihood that the real object is either considerably brighter or considerably darker than albedo 0.14, introduces the large mass uncertainties outlined above. Adding thermal infrared data dramatically improves the situation: *simultaneous* visible and thermal infrared flux measurement of these asteroids provides an actual determination of the albedo, permitting assignment of the body to a spectral class and suggesting a density for the material. For any given H magnitude, very dark bodies are seriously under-represented. Many attempts have been made to correct for this discovery bias, with rather broad agreement that 20 to 30% of the members of the general NEA population must be dark. **As much as 50-60% of the mass in the NEAs would then be water-rich carbonaceous asteroids.** Since virtually all asteroids are brighter in the thermal infrared than in visible light (because they have albedos less than 0.5), clearly the best way to search for them would be in the infrared.

For asteroids discovered by infrared observations, for which this discovery bias does not exist, the resulting estimate of the relative populations of S and C bodies is quite similar to the numbers estimated from bias-corrected visible-light discoveries. The WISE mission, observing at several bands in the thermal infrared, can determine both a total thermal flux and a “color temperature”, and hence a rough albedo, of large numbers of asteroids, including hundreds of NEAs. Each NEA orbital class (Atens, Apollos, Amors) studied by WISE shows a double-peaked albedo distribution with a distinct minimum at about an albedo of 0.1. The proportion of dark asteroids is smallest (about 10%) for the Atens, which have the smallest mean distances from the Sun, intermediate (about 35%) for Apollo Earth-crossers, and highest

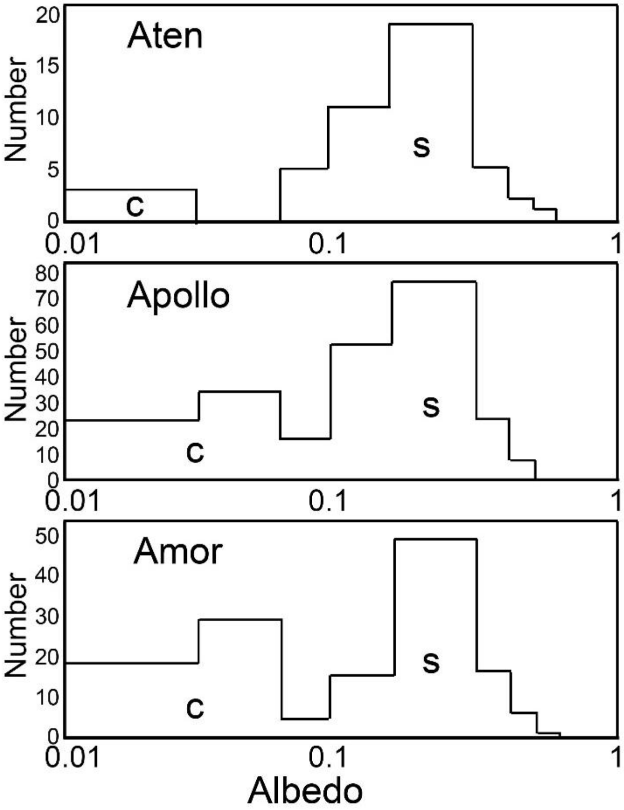

Figure VI.1 Visible-light Albedo Distributions of the NEAs from WISE Data. The albedo distributions of all NEA orbital classes are, like those of Belt asteroids (given in Figure IV.1), bimodal. The C-cadre (B, C, D, G, P, etc.) dark asteroids are most common in the Amor population and rarest among the Atens. The S-cadre (S, Q, M, etc.) bright asteroids are most prevalent among the Atens.

Credit: Deep Space Industries – John S. Lewis

(nearly half the population) for Amors. The WISE data on the albedo distributions of the NEA orbital classes are shown in **Figure VI.1.**

Accessibility of NEAs

The accessibility of an NEA from Earth depends upon the asteroid's orbital elements and on the nature of the intended mission, whether flyby, rendezvous, or landing. Of these, the easiest is a flyby mission. The criterion for ranking an asteroid's accessibility is the energy required to get from Low Earth Orbit (LEO), usually taken to be a typical space station orbital altitude of about 400 km (for example, the International Space Station). (Note: The energy required to launch a deep-space mission is often described by spaceflight professionals in terms of the velocity excess the spacecraft must have relative to Earth, the *hyperbolic excess velocity*, and reported as the mission launch energy requirement, C3. Since energies are proportional to V^2, C3 is defined as $C3 = V_{oo}^2$, in units of km^2/s^2. To reach Earth's exact escape velocity requires C3 = 0; a mission that requires a hyperbolic excess velocity of 15 km/s would have a C3 of 225 km^2/s^2.)

For our purposes, it is simpler and more direct to consider the total *velocity change* needed by a spacecraft to get from LEO to its target. This quantity is called *delta V*, which has the usual velocity units of m/s or km/s. (Recall, however, that the amount of **energy** required is proportional to the square of the velocity change.)

The delta V required to get from the ISS to a soft landing on the surface of the Moon is about 5.95 km/s, varying slightly depending on the exact distance of the Moon from Earth at the time of the flight and the orientation of the flight path relative to the direction of the Sun. To simply fly by the Moon without landing, or to strike the Moon without braking to a soft landing, is much easier, requiring a delta V of about 3 km/s. In LEO, to escape from Earth's gravitational sphere of influence, and thus enter an independent orbit around the Sun, requires a delta V of 3.22 km/s. Interestingly putting a spacecraft into Geosynchronous Orbit (GEO) at an altitude of 35,786 km above the equator, requires a delta V of 3.9 to 4.3 km/s, depending on the inclination of the LEO starting point, which in turn depends on the latitude of the launch site: the farther the launch site is from the equator, the more energy is required to deflect the plane of the spacecraft's motion into Earth's equatorial plane. Thus any nation (or any rocket) capable of launching a communications satellite into GEO can easily hit the Moon or escape from Earth. In fact, the delta V for our spacecraft departing LEO on the way to fly by (or impact upon) Mars or Venus is only 4.3 km/s.

On rare occasions an asteroid may enter Earth's gravitational sphere of influence (the volume, only approximately spherical, within which the strongest gravitational force is that due to Earth). Such encounters, for purely statistical reasons, almost always involve small asteroids of a few meters to tens of meters in diameter, which, because of their small size, have not been previously discovered and tracked. The time between discovery and closest flyby is often hours to a few days, insufficient time to plan and launch a flyby mission. The delta V to carry out the mission is very small, typically 1 to 3 km/s, but the option to launch seemingly can only be exercised when either the approaching asteroid has an orbit that is already so well known that its approach was expected, or an intercept vehicle is kept ready on the launch pad in anticipation of a fortuitous discovery of a new asteroid on a close-flyby path. Since the overwhelming majority of NEAs are very small, an NEA making a close approach to Earth has almost certainly not been seen before, and its approach cannot be predicted. Fortunately there is a third option that provides vastly improved flexibility: to "store" one or more small spacecraft in orbit around Earth and simply retarget them when an opportunity presents itself. The challenge then is to determine the orbit of the new asteroid so well and so quickly that the spacecraft trajectory can be planned and the engine firing executed in a matter of hours.

For an asteroid outside Earth's sphere of influence, and for a spacecraft stored in Low Earth Orbit, the minimum delta V needed to intercept the asteroid with a flyby spacecraft is about 3.2 km/s. Many NEAs pass close enough to Earth to be accessible by flybys with delta Vs less than 4 km/s, and a few every year can be reached with less than 3..

To rendezvous (match velocities) with an NEA is somewhat more expensive in terms of propulsion energy. But once rendezvous has been achieved, the additional delta V required for a soft landing is usually less than 0.01 km/s! Several NEAs are known for which the total delta Vs to rendezvous are about 4.5 km/s, and hundreds more are available for rendezvous or landing for a delta V of 5.6 km/s or less. By comparison, the delta V required to land on the Moon is about 6 km/s, and that required to land on the Martian moons Phobos and Deimos is about 5.6 km/s. Note the remarkable fact that our nearest neighbor, the Moon, is by no means the most accessible body in the Solar System to land on: even the moons of Mars are easier! Of the 11,000 already-known NEAs, the number of asteroids of all sizes that are easier to land on than the Moon is approximately 2200. Of these, 200 are at least 1 kilometer in diameter. Our catalog of bodies in the 100 to 1000 m size range is still only about 30% complete, but the expected number of these bodies that are easier to land on than the Moon is about 3800. *The Moon, in effect, is less accessible than Phobos, Deimos, and 4000 large (>100 m) NEAs.*

Return to Earth from NEAs

The delta V required to return to Earth from an NEA is often very small because the energy cost of escaping from an asteroid's feeble gravity is tiny. Several NEAs have return delta Vs less than 0.1 km/s. Such a return mission would lift off from the asteroid's surface, adjust its

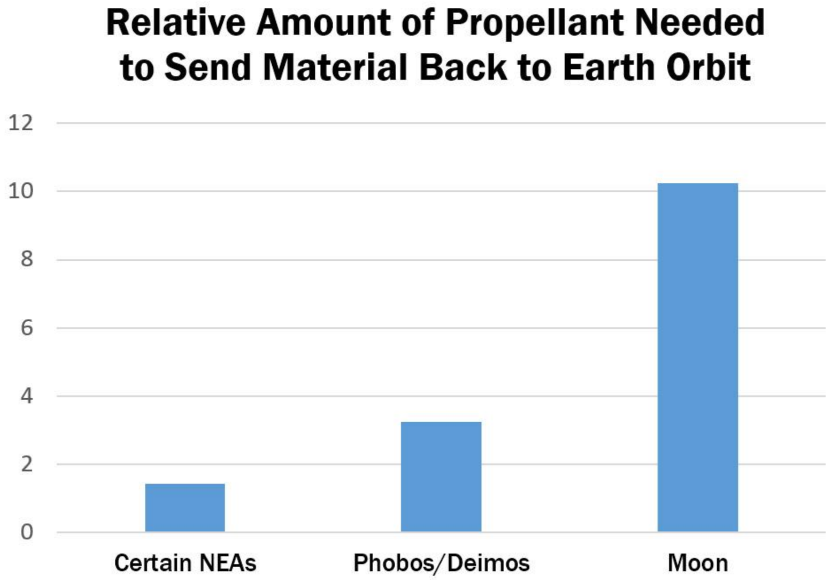

Figure VI.2 Relative amounts of propellant required to launch the same mass of material from different locations to LEO or to Earth impact: materials from NEAs are economical to transport. (On this scale, launch from Earth to LEO would rate a value of about 65!)

Credit: Deep Space Industries – David Gump

already Earth-crossing orbit around the Sun so as to intercept Earth, and coast home. The returning spacecraft can, with an appropriate heat shield, enter the atmosphere directly and parachute to the ground, or graze the upper atmosphere to lose enough speed to be captured into Earth orbit. Successive gentle passes through the atmosphere could then lower the apogee of the spacecraft's orbit and approach LEO, using an engine burn of about 0.1 km/s to circularize the orbit and rendezvous with a space station. It is in the return to Earth's vicinity that the greatest advantage of the NEAs is seen: return to Earth from the Martian moons requires escaping from the gravity field of Mars, reducing the spacecraft's orbital speed around the Sun so as to drop inward to an Earth-crossing orbit, and specifically targeting Earth. This requires an average delta V of about 1.8 km/s, depending in detail on which moon is involved, and where Mars is on its eccentric orbit around the Sun at the time of departure.

The mass of rocket propellant needed for a given delta V is proportional to the mass of material to be returned and *exponentially* dependent on the delta V. For this reason, NEAs can provide excellent mass returns to Earth or to Earth orbit. By comparison, a return mission from the surface of the Moon requires a delta V of about 3.2 km/s, comprising escape from the lunar gravity well and transfer to an Earth-return trajectory. Thus exporting materials from the Moon to Earth is far harder than exporting the same mass of materials from Phobos or Deimos to Earth. The Martian moons in turn are far inferior to the best NEAs for return of asteroid materials to LEO or Earth.

Remote Spacecraft Observations of NEAs

The *Infrared Astronomical Satellite (IRAS)*, launched into polar orbit in 1983, was a joint US/Dutch/British survey of the sky at thermal infrared wavelengths of 12, 25, 60, and 100 micrometers. *IRAS* discovered 3 NEAs and 6 comets, and returned useful data on roughly 2000 already-known asteroids, mostly in the Belt. The success of *IRAS* encouraged the development of an even more sensitive IR mission.

The *Wide-field Infrared Survey Explorer (WISE)*, launched in 2009 and in operation until 2011, had a wide range of astronomical contributions. One spinoff of this mission has been the asteroid infrared data collected in its mapping of the sky. *WISE*, though not targeted on asteroids, nonetheless observed and determined the approximate albedos of hundreds of NEAs belonging to all three orbital families. We have seen that *WISE* data shows that all three groups had population minima at an albedo of about 0.1, confirming the relative absence of "average albedo" asteroids. The proportion of dark asteroids (albedo < 0.1) was highest for the Amors, high for the Apollos, and lower for the Atens. These statistics imply that either the innermost NEAs were sampled preferentially from the inner Belt, or that space weathering such as surface erosion or loss of volatile constituents caused a change in their appearance. Because of uncertainties in the interpretation of the thermal infrared data caused by the unknown visible-light brightness, rotation state, and pole orientation of the observed asteroids, and the consequent crude binning of the data on the darker asteroids, it would be safest to conclude only that the brighter (albedo > 0.1) NEAs observed by *WISE* were more abundant than the darker ones. The contributions of *WISE* observations to elucidation of the structure of the Asteroid Belt, based on observation of about 120,000 Main Belt asteroids, were profound and will be mentioned later.

So successful was the *WISE* main mission that NASA reactivated the spacecraft in 2013 to resume asteroid observations. The results of this extended mission are eagerly awaited by asteroid scientists.

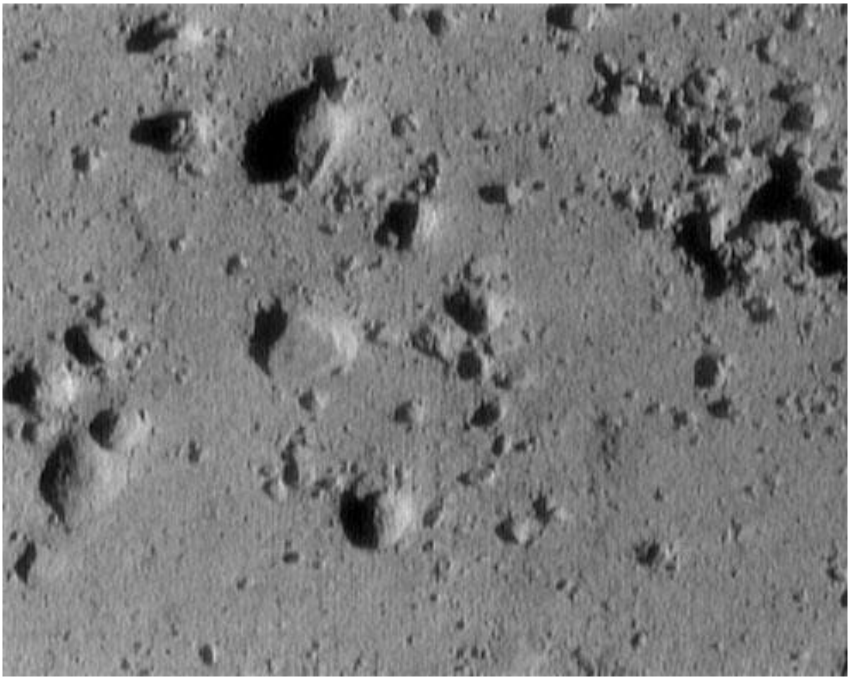

Figure VI.3 Surface of the NEA Eros seen from 250 m Altitude. This scene covers an area of about 7 by 11 meters as imaged by the NEAR spacecraft. The largest rocks are about 1 m in size.

Credit: NASA / Johns Hopkins Applied Physics Laboratory

Spacecraft Visits to NEAs

We have seen that many NEAs are easy to reach from a propulsion standpoint; even rendezvous and landing are easier for about 20% of the NEA population than for Earth's Moon. NASA's *NEAR (Near Earth Asteroid Rendezvous) Shoemaker* mission, launched in 1996, orbited and landed on the S-type NEA 433 Eros, the Japanese national space agency JAXA sent the *Hayabusa* spacecraft to the S-type NEA 25143 Itokawa for a landing and sample retrieval mission in 2003, and the Chinese National Space Agency CNSA retargeted the *Chang'e 2* lunar orbiter (launched in 2010) to fly by the S-type NEA 4179 Toutatis in January, 2013.

NEAR, in approaching and landing on Eros, provided the first close-up imagery of an NEA surface. **Figure VI.3** shows an area of Eros' regolith as seen from an altitude of only 250 meters. The largest rock fragment seen is about 1 meter long. Note that most of the surface is unresolved fine dust. The landing was not part of the original mission plan, but was added during flight as a possible alternative. The last image returned

(**Figure VI.4**), taken only 130 meters from the surface, was still being transmitted when the spacecraft struck the surface of Eros. The large rock in the 6 m wide image is at about 4 m long.

The sampling device on the *Hayabusa* mission failed to operate, but the spacecraft was successfully returned to a landing in Australia. Optical and chemical analyses of the small particles that stuck to the spacecraft show that the pyroxene and olivine grains have consistent ferrosilite and fayalite contents of about 30 mole %, falling squarely in the LL chondrite composition range. The oxygen isotope systematics were also found to be compatible with either an L or LL chondrite provenance. Fortuitously, the samples of Itokawa also shed valuable light on the process of space weathering: the reddening of the spectrum accompanying prolonged exposure to space was linked to the reduction of ferrous iron (Fe^{2+}) to tiny particles of metallic iron (Fe^{0}) by hydrogen implanted in surface grains by the solar wind.

Presently JAXA has plans for a *Hayabusa 2* mission to return samples from a C-type NEA, 1999 JU3. This mission was planned for launch in 2014; however, recent discussion has centered on a possible 2018 launch in order to take advantage of a very attractive opportunity to visit the NEA 4015 1979 VA. This asteroid is an extinct short-period

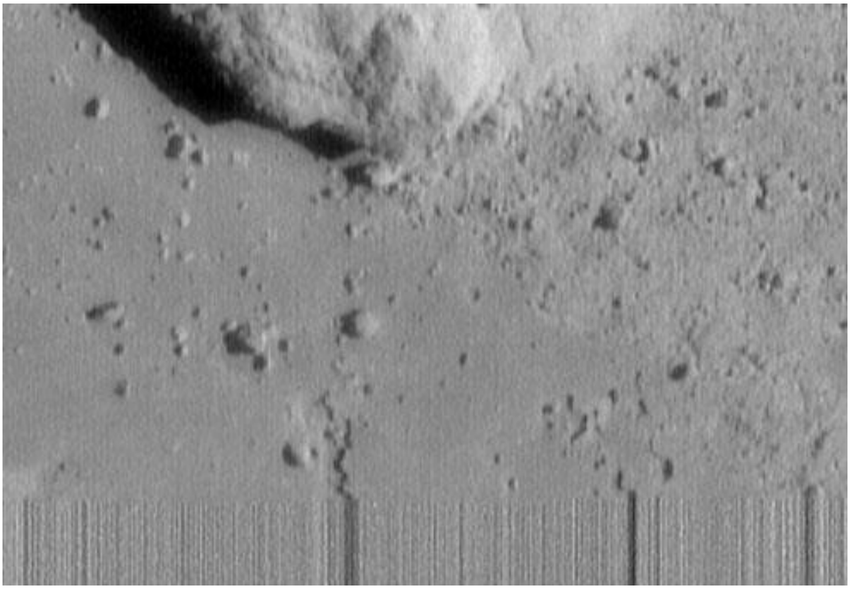

Figure VI.4 Surface of Eros Seen from 130 m Altitude. Pebbles as small as 1 cm are visible on a very smooth, dusty surface. The spacecraft impacted Eros before completing transmission of this image, causing the "lockup" of the image at the bottom of the frame. The largest rocks are about 1 m in size.

Credit: NASA / Johns Hopkins Applied Physics Laboratory comet originally known as Comet Wilson-Harrington. That spacecraft may be rather larger than the original Hayabusa design, leading to a so-far unfunded mission concept called *Hayabusa Mk2*.

The second Chinese lunar orbiter, *Chang'e 2*, orbited the Moon for nearly a year, and then, after completing its planned mission profile with ample reserves of propellant, the spacecraft was moved to the Sun-Earth outer Lagrange (L2) point, where it waited for eight months for reassignment. It was then dispatched to execute a high-speed flyby of the asteroid 4179 Toutatis. Toutatis, an Apollo asteroid, is also a member of the Alinda family with a 3:1 Jupiter orbital resonance (4 year orbital period), which also places it very close to a 1:4 resonance with Earth. Because the orbit is subject to frequent strong planetary perturbation, it defies accurate long-term prediction: it is indeed a "loose cannon" among NEAs. It is classed as a potentially hazardous asteroid because of its frequent close flybys of Earth and its unpredictability on century time scales. In 2004 Toutatis passed by Earth at about four times the distance of the Moon.

Toutatis has as S-type spectrum and a density of only 2.1 g/cm^3. It has an albedo of 0.13, toward the lower end of the range for S asteroids. The density is distinctly lower than the average of 3.5 found for ordinary chondrites, suggesting a rubble-pile structure with about 40% pore volume. Visually, it banana-like shape suggests an origin in the weak coalescence of two different asteroids. Befitting its strange structure, it also has a compound rotation, with a principal-axis rotation period of 5.38 days and an axial precession period of 7.38 days.

Chang'e 2 was sent to make a very close pass by Toutatis at a range of about 3 km from its surface, at a relative speed of 10.73 km/s. Such precision targeting was made possible by radar observations by NASA's Goldstone radar and the giant Arecibo radio telescope, which provided very precise orbital data. The main lunar mission goal was to qualify potential landing sites for the upcoming *Chang'e 3* lander and rover. The Toutatis opportunity, not a part of the original mission plans, was added when it became clear that the fuel margins of the spacecraft were large enough to carry out a high-speed flyby. Because of Toutatis' large orbital eccentricity (>0.6) its velocity near Earth was very high: rendezvous would have required a huge amount of fuel, and was clearly not an available option.

VII. Belt Asteroids

Asteroid mining will start with the NEAs, since reaching them requires less energy than venturing out to the belt between Mars and Jupiter. However, the belt is important as the source of NEAs and it eventually will become a routine part of humanity's available resources.

Nomenclature

Belt asteroids, like NEAs, are given provisional designations such as 1949 FL immediately upon discovery. Once an asteroid's orbit has been determined to satisfactory precision, the asteroid is added to the catalog and given a number such as 7743 1949 FL. The discoverer then has the right to assign a name to the asteroid, subject to the approval of a nomenclature committee of the International Astronomical Union. Asteroid names, initially drawn from classical sources, have long since exhausted that resource. Many have been named to honor culturally prominent individuals, often scientists, or nations, states, universities, and other institutions. The extent of this process can be grasped by citing the asteroids 8749 Beatles, 4147 Lennon, 4148 McCartney, 4149 Harrison, 4150 Starr, 3834 Zappafrank, and 4442 Garcia. Asteroid names are restricted to single words (thus DonQuixote rather than Don Quixote), and are screened to eliminate offensive words and, more recently, even the names of astronomers' girlfriends. There is nothing about the asteroid's name or catalog number that tells where the asteroid is located or what its properties are.

There are now well over 100,000 catalogued asteroids. The estimated number of asteroids larger than 1 km in diameter is 1 to 2 million, but detection of such small bodies from Earth at the distance of the Belt (minimum 1.1 AU) is very difficult. Of course, the darkest asteroids are the hardest to detect in visible-light surveys.

Size and Mass Distribution

The sizes of the ten largest asteroids are rather well known, both from spacecraft imaging and by studies of the occultations of stars by the asteroids. Ceres is by far the largest, a little less than 1000 km in diameter. The ten largest asteroids are listed in **Table VII.1.**

Table VII.1
The Largest Belt Asteroids

Asteroid ID		**Diameter**(km)	**Spectrum**	**Notes**
1	Ceres	952	G	Spherical; modified carbonaceous
2	Pallas	544	B	Spherical; largest member of family
4	Vesta	526	V	Spherical; Basaltic Achondrite
10	Hygeia	429	C	Irreg. 530x407x370 km: 2.1 g/cm^3
704	Interamnia	333	F	350x304x300 km; largest F asteroid
511	Davida	320	C	357x294x231 km
52	Europa	315	C	380x330x250 km; NOT J2 Europa!
15	Eunomia	272	S	357x245x205; Largest in inner Belt
87	Sylvia	271	CX	384x262x232; 2 moons; Cybele family
16	Psyche	253	M	Iron; high radar reflectivity; 6.5 g/cm^3

Since almost all asteroids except the three largest are irregular in shape, estimates of their dimensions, volumes, and densities are highly dependent on observations of occultations of stars. It should be mentioned that most asteroids have only inferred densities that cannot yet be checked directly. The difficulty lies in the measurement of asteroid masses, which for most asteroids can be determined only by a spacecraft mission, from tracking of a natural satellite, or from very difficult measurements of mutual orbital perturbations caused by other asteroids. In the absence of a spacecraft visit or a natural satellite, densities must be inferred, thus introducing uncertainties into the mass estimates. The uncertainties are sufficiently large that the ranking of asteroid sizes is only approximate after the first four in Table VII.1 Within these uncertainties, the total mass of the Asteroid Belt is estimated as 3x10^{21} kg (about 4% of the mass of Earth's Moon), about 10^5 times the total mass of the NEA swarm. Half of the total mass is accounted for by the four largest asteroids.

Orbital Population Statistics

The main Asteroid Belt extends from about 2.1 to 3.3 AU from the Sun. Hierarchical clustering analysis of the a, e, and i[2] data on Belt asteroids from the *WISE* spacecraft has identified as many as 76 families of asteroids with correlated orbital parameters. There is a common misconception, fostered by wildly imaginative artistic renderings of the Asteroid Belt in movies, video games, and periodicals, that asteroids populate space very densely, so that dozens of asteroids can be seen filling the sky from any vantage point within the Belt. There is a second misconception that asteroid families travel around the Sun in clusters, so that members of a given family are always close to each other. Neither is remotely true. Although there may be 2 million kilometer-sized asteroids in the Belt, the volume of the Belt is about 5×10^{25} km^3, giving us 1 asteroid per 5×10^{19} cubic kilometers: a random cubic volume 1 million kilometers on a side in the Belt has only one chance in 50 of containing an asteroid larger than 1 kilometer in size. If you were on an asteroid, you very likely would not be able to see any others.

Asteroid families share similar orbital parameters: similar orbital period, a, e, and i, but the periods within a family are *not identical*: although the family members may have originated in a violent collision at a particular point in time and space, the velocity dispersion of the fragments ensures that they will steadily drift apart.

One unusually compact family, that of 832 Karin, may be as young as a few million years. The different rates of precession of their orbits cause all collision fragments to diverge from the original plane of the orbit of the disrupted asteroid, and the different Poynting-Robertson and Yarkovsky forces on each fragment lead to further dispersal over time scales of hundreds of millions of years. So effective is this dispersal process that fully two thirds of the asteroids in the Belt form a nearly featureless “background” in a-e-i space, presumably the debris from asteroid collisions over a billion years ago. In addition to their orbit parameters, some asteroid families have spectra that link them to the large asteroids from which they were collisionally ejected.

Notable asteroid families that stand out from the general Belt population include:

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[2] The semi-major axis, eccentricity, and inclination of the orbit

1. The Alinda family, linked to 887 Alinda, with mean distance from the Sun (semimajor axis a) close to 2.5 AU, and hence with an orbital period very close to 4 years. Orbital eccentricities lie generally in the range from 0.40 to 0.65, typical of NEAs. The Alinda asteroids with perihelion $q < 1.3$ AU are also Amor asteroids, and those with Earth-crossing orbits ($q < 1.017$ AU) are Apollos. They are located at the inner Kirkwood gap, one of the strongest Jupiter resonances. Because of the their proximity to both the 3:1 Jupiter resonance and the 1:4 Earth resonance they are subject to strong perturbations and evolve rapidly. Any Alinda that makes a close approach to Earth is likely to do so repeatedly every 4 years.

2. Among the several large asteroids that are embedded in families of spectrally similar material, 4 Vesta is a striking example. Most members of this family of Vesta fragments look like Vesta's surface material, but, since Vesta is a differentiated asteroid with a V-class *basaltic achondrite* surface and denser, metal-rich interior, a severe impact event can (and did) excavate deeper material to lend spectral diversity to the family. Some V-class asteroids are present among the NEAs.

3. The large asteroid 2 Pallas has, as first discovered by Kiyotsusu Hirayama in 1928, an accompanying family of small B-class asteroids. These asteroids have orbital semimajor axes a close to 2.75 AU, modest eccentricities e close to 0.28, and exceptionally high (and very distinctive) orbital inclinations i near 33^{o}. The NEA 3200 Phaethon may belong to this family, with which the Geminid meteor shower of mid-December is closely related. These meteors are relatively slow and of low strength, often disintegrating above 40 km altitude.

4. The large asteroid 10 Hygiea is associated with an extensive family of C- and B-type small asteroids with as many as 100,000 members, of which over 1000 are large enough to have been observed and catalogued. The family clusters around $a = 3.15$ AU, $e = 0.13$, and $i = 5^{o}$. The criteria for discrimination of this group are their orbital parameters, the C spectral type being extremely common in the outer Belt and therefore non-diagnostic. One possible scenario is that a B asteroid struck the C-type Hygiea a glancing blow, leaving both types of material in a common family.

5. The Koronis family, named after 158 Koronis, and whose largest member is 208 Lacrimosa, also contains 243 Ida, which was flown

by at close range by the *Galileo* spacecraft *en route* to Jupiter. The orbits of Koronis family members lie close to a = 2.87 AU, e between 0.01 and 0.09, and i = 1.0 to 3.3^{o}. Within the Koronis family is the compact subfamily of 832 Karin, an S-type asteroid, which was disrupted about 5.8 million years ago.

6. The Hilda "family" of asteroids share with their namesake 153 Hilda orbits that are in a 3:2 resonance with Jupiter. The orbits pass at aphelion through the Jovian L4 and L5 Lagrange points and also the point on Jupiter's orbit on the opposite side of the Sun from Jupiter, passing through all of these points every three orbits. There are well over 1000 known D and P asteroids, and some Cs, in this family. Although their orbits attest to dynamical control of their motions, and although they may mostly belong to the same population as short-period comets, there is no evidence that they originate from a single parent body. They therefore are not a family in the same sense as the other families listed above, each of which has a common progenitor.

7. The Thule family, residing in the 4:3 Jupiter resonance, may also be a dynamically selected group with eclectic origins. These orbits are probably short-lived.

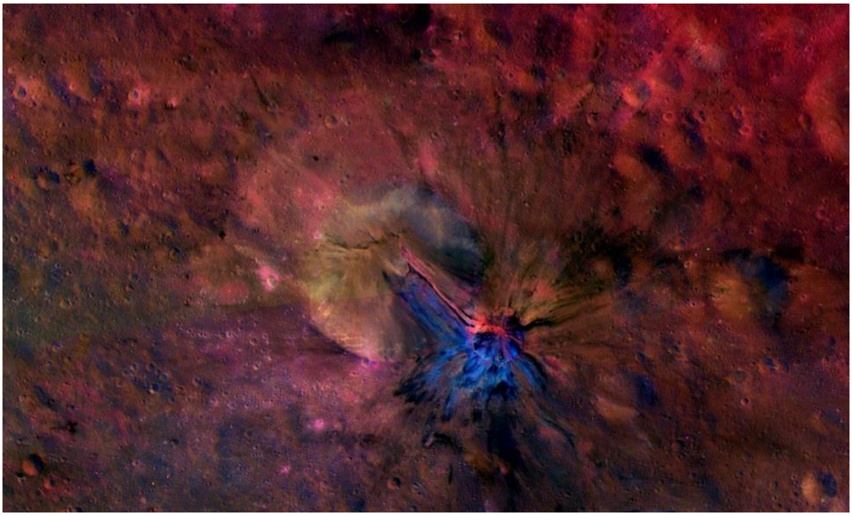

Figure VI.1 This image of the crater Aelia on the proto-planet 4 Vesta was created by assigning ratios of color information from several color filters in visible and near-infrared light to reveal flow structures, possibly made by liquid material created at the impact.

Credit: NASA – Jet Propulsion Laboratory

8. Hungarias orbit near a = 1.9 AU, with low eccentricity (e < 0.18) and inclinations mostly between 18 and 25^{o}. Despite their proximity to the Sun, they are not planet-crossers.

9. Phocaea asteroid orbit near 2.37 AU, with e > 0,1 and i mostly between 20 and 25o. The Phocaeas are separated from the Hungarias by the string 4:1 Jupiter resonance.

Taxonomy of the Belt

Of the seven largest asteroids, five are very dark and apparently carbonaceous in nature. The outer half of the Belt is dominated by C, D and P asteroids, suggesting that about two thirds of the mass of the Belt is volatile-rich dark material.

Access to the Belt via NEAs

Most NEAs have aphelia located in the main Asteroid Belt. Any vehicle, mining device, or processor that rides an NEA to aphelion, using asteroid material for radiation shielding and manufacturing propellant along the way, will pass through the Belt, providing an opportunity for access from that NEA to many other NEAs in similar orbits, and (near aphelion) to any of a large number of Belt asteroids. A Belt asteroid in circular orbit at a = 3 AU near the outer edge of the Belt has an orbital velocity of 17 km/s. An NEA with q = 1 AU (at Earth's orbit) and Q = 3 AU (at the target asteroid's orbit) must have an orbital eccentricity of 0.5, an orbital semimajor axis of 2 AU, and a velocity at aphelion of 12.25 km/s. Thus a delta V of 4.75 km/s would permit a transfer from the NEA to the Belt asteroid. Likewise, a delta V of the same magnitude would permit a vehicle departing from the Belt asteroid to enter a return trajectory that intercepts Earth' orbit (q = 1). From any Belt asteroid, thousands of other asteroids would be accessible with a delta V of less than 2 km/s. Of course, we could also target a body in the inner Belt. A target near the inner edge of the Belt at a = 2.2 AU could be accessed from an NEA with q = 1 and Q = 2.2 (a = 1.6; e = 0.375). The velocity of the NEA at aphelion is 16.4 km/s and the orbital velocity of the asteroid is 23.7 km/s: the delta V for transfer from the NEA to the Belt asteroid is 7.3 km/s.

VIII. Asteroid Resources

Discovering that an asteroid has iron or platinum group metals does not mean the asteroids is valuable. That is only the first step in establishing the worth of the target. The next challenge is to characterize the quality and extent of the desired materials. They may be found only in low concentrations, or found only in certain places on the asteroid.

If the target material is sufficiently concentrated and abundant, the next question is whether methods exist to economically extract, enrich, and process it into useful products. It could be mixed with elements that are difficult to separate from the target resource, or which poison the standard extraction processes.

Once a commercial product seems feasible, asteroid miners then have to identify sites of demand and analyze the transportation costs needed to deliver their products to the sites of demand. With the total costs now estimated, the final determination is whether the asteroid products can be sold competitively against existing sources. Only when profitability has been established can the material being mined be described as an ore.

On Earth, the material needs of human civilization are often described in terms of "demandite", the sum of the elemental abundances of consumables that must be mined to support civilization. The amount of demandite that must be supplied to maintain one person for a year is the *per capita* demandite requirement. The demandite concept is a valuable one, but applying it to human needs off Earth requires a complete rethinking of the concept. In space, the crucial question is how much of each element must be in circulation to maintain one person indefinitely: it is assumed that commodities are not expended, but instead recycled in a closed system[3]. The only external input to this material recycling economy is energy. That energy can, for the moment, be assumed to be solar power; we shall return to this issue later.

To illustrate terrestrial application of the demandite concept, consider **Table VIII.1**, from reports of the U. S. Chemical Manufacturers Association and the U. S. Bureau of Mines. My purpose in displaying

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[3] Completely closed space ecologies do not yet exist. The International Space Station recycles only part of its water and air; food and most other commodities are supplied from Earth.

these data is to focus on what materials are important to modern society, not on the numerical requirements that are specific to Earth.

The most important feature of this table is the absence of water from the list. Water is assumed to be non-consumable, un-expended commodity available in limitless quantities. In space, water is precious and absolutely essential for life support.

The first item in Table VIII.1 is hydrocarbons, here interpreted as including coal as well as crude oil and natural gas. The overwhelming majority of these materials are for energy generation by combustion, a use irrelevant to a solar-based space economy. Similarly, silicon dioxide and calcium carbonate are of great demand on Earth for the manufacture of structural concrete, but this material unhelpfully binds up precious water and has structural properties ill-suited for space.

Table VIII.1
Demandite for the United States (1990)

Element or Compound	**1990 Demand** (% of total moles)
Hydrocarbons	86.77
Silicon dioxide	9.35
Oxygen	0.76
Nitrogen	0.67
Iron	0.64
Sodium	0.44
Chlorine	0.44
Phosphorus	0.35
Sulfur	0.25
Aluminum	0.13
Calcium carbonate	0.10
Potassium	0.07
Copper	0.02
Zinc	0.01
Lead	0.004
Magnesium	0.003

Iron demand is principally for structural steel, a material with high tensile and compressive strength, but vulnerable to corrosion.

Oxygen and nitrogen appear on the list largely because of their industrial uses, quite unrelated to production and maintenance of a breathable atmosphere. Part of the nitrogen demand is manufacture of synthetic fertilizers containing ammonium and nitrate ions.

Rethinking the demandite requirements for human civilization in space produces a very different list. Confining ourselves to the NEA population, we can estimate the per capita demandite requirements for a space-dweller and estimate how many people could be maintained indefinitely by the NEA resources. These calculations are summarized in **Table VIII.2**. Assuming that the system is closed to materials and that the only consumable is solar power, the NEA population could support approximately 400 billion people at a generous level of affluence from now until the Sun enters the red giant phase several billion years from now. The limiting resource is probably nitrogen.

Extending the sphere of human influence to the Main Belt asteroids, an increase of available resources of a factor of roughly 100,000 would be appropriate. The population sustainable by Belt resources, given in **Table VIII.3**, is roughly 1.4x1016 people, more than 1 million times the carrying capacity of Earth.

Table VIII.2
Resources of the Near-Earth Asteroids

Commodity	Mass Present Among NEAs (10^{15} g)	Per Capita Inventory (g/person)	Population Sustainable by NEA Resources (billion people)
Silicates	75,000	140,000,000	530
Ferrous metals	10,000	20,000,000	500
Fe in oxides	10,000		
Cement [1]	1,800	10,000,000	180
Industrial CaO		2,000,000	900
Phosphates[2]	300	2,000,000	150
		200,000	1,500
Water	5,000	10,000,000	500
Carbon[3]	3,000	1,000,000	3,000
Nitrogen[4]	300	700,000	400
Sulfur	1,800	1,200,000	1,500
Sulfides	4,500	1,200,000	3,000

**The Near-Earth Asteroid population is a renewable resource that replaces itself about every 30 million years. Note that the only true "consumable" in this fully-recycling system is solar power.*

[1] Cement is of dubious utility in space, except for wholly internal (non-vacuum-tight) construction. CaO is a useful reagent for pH control and an essential nutrient (line 2).

[2] Phosphate fertilizer usage on Earth is predicated upon toleration of massive loss in runoff from fields. In a 100%-recycling regime, the needed inventory could easily be 10x smaller (line 2).

[3] Carbon inventories assume 100 g of plant carbon per gram of human carbon.

[4] Nitrogen inventories include 1000 m^3 of habitat volume per person at 0.7 atm partial pressure of nitrogen for fire suppression (no alternative gases available) as well as organic nitrogen.

The uses and sources of these various essential commodities in asteroids are easy to identify. For silicates, uses include radiation shielding and agricultural substrate. Although silicates are not the very best radiation shielding, their availability in truly astronomical quantities suggests their use in habitats and colonies. Water would be a better shielding choice for spacecraft and for any habitat that is designed to be moved. And of course, locking up precious water in concrete is not an attractive option in space. In addition to this chemical objection, concrete is desirable for structural use on Earth because of its high compressive strength, and despite its low tensile strength. In the vacuum of space, and on low-gravity bodies and habitats, structural loads are predominantly tensile, not compressive. Concrete may make sense for interior construction only if sufficient water is available.

Table VIII.3
Resources of the Asteroid Belt

Commodity	**Mass present in the Belt (10^{21} g)**	**Per Capita Inventory (g/person)**	**Population Sustainable by Belt Resources (billion people)**
Silicates	2000	140,000,000	15,000,000
Ferrous metals	300	20,000,000	30,000,000
Fe in oxides	300		
Cement[1]	60	10,000,000	6,000,000
Industrial CaO		2,000,000	30,000,000
Phosphates[2]	10	2,000,000	5,000,000
		200,000	50,000,000
Water	300	10,000,000	30,000,000
Carbon[3]	100	1,000,000	100,000,000
Nitrogen[4]	10	700,000	14,000,000
Sulfur	60	1,200,000	50,000,000
Sulfides	150	1,200,000	125,000,000

** Assumes full recycling and full reliance on solar power. See text for detailed discussion.*

[1] Cement is of dubious utility in space, except for wholly internal (non-vacuum-tight) construction.

[2] Phosphate fertilizer usage on Earth is predicated upon toleration of massive loss in runoff from fields. In a 100%-recycling regime, the required inventory could easily be 10 times smaller.

[3] Carbon inventories assume 100 g of plant carbon per gram of human carbon

[4] Nitrogen inventories include1000 m^3 of habitat volume per person plus organic nitrogen.

Although hydroponic culture of food plants has obvious appeal, the reasons for dirt-less agriculture are derived from the perceived necessity of lifting all materials out of Earth's deep gravity well, with associated high launch costs. Thus hydroponics makes sense when used in the context of Earth-launched, Earth-orbiting space stations or colonies. The launch-cost problem does not arise when deriving raw materials from micro-g or milli-g asteroids. There, the silicates are essentially "free" and have no other major uses besides shielding.

In addition, hydroponics make sense for feeding short-stay astronauts on near Earth habitats because these visitors arrive already well-nourished. Perfect nutrient balance in the hydroponic solution need not be achieved because people spend only weeks or months in space, and revert to a normal Earth-side diet upon their return. But to sustain a long-term space population, we would have to compound hydroponic nutrient solutions based upon having a complete and perfect knowledge of what nutrients are required both for ourselves and our food plants. We know that our list of essential trace nutrients is far longer than it was a few decades ago, and there is no reason to conclude that we are presently omniscient. But a diverse plant ecology working upon dirt is highly competent at extracting needed nutrients. There is a temptation to "design" a biosphere rather than import a diverse variety of plants and let the best-adapted survive and thrive, but this approach again assumes omniscience on our part, an assumption that has not served us well in the past.

Ferrous metals are the obvious choice for structural materials in space. Roughly 25% of the asteroid population is iron and nickel, carried by minerals appropriate to the degree of oxidation and hydration of the asteroid. For most NEAs and for the inner half of the Asteroid Belt, the iron and nickel will be found largely as metallic Fe-Ni-Co alloy. We have seen that M-class asteroids, which have reflection spectra, radar reflectivities, and densities characteristic of metallic meteorites, must be about 95 to 99% metal alloy. In the outer Belt and in the C-cadre NEA population, the metal is almost completely oxidized to Fe oxides, FeS, NiS, and more complex minerals containing these entities, such as fayalite in olivine, ferrosilite in pyroxene, clay minerals, and magnetite. The proportion of total ferrous metal minerals is still high: indeed, the Fe:Si ratio in carbonaceous chondrites is actually higher than in any of the ordinary chondrite groups. Aside from the achondrites (such as the V-type asteroids), the ferrous metals are both widely distributed and abundant. Where iron and nickel are present as native metals, the consumption of great masses of reducing agents to extract them from their oxides (the universal practice on Earth) is not needed.

A word is needed here on the absence of non-ferrous metals from this list. Where are aluminum, magnesium, and titanium? The problem is that these elements all form very stable oxides that require vast amounts of energy to extract, purify, and fabricate. Aerospace engineers accustomed to launching payloads from Earth's deep gravity well are rightly concerned about minimizing launch mass, which leads them to require light-weight, strong non-ferrous metals. They therefore accept the high energy cost of manufacture of these metals because it saves them even more energy and expense in launch costs: both ores and reducing agents such as coke and coal are abundant and cheap on Earth. But in space, a given amount of energy would process vastly larger amounts of native ferrous metals than, for example, aluminum. There is no incentive to invest in lightweight nonferrous alloys except for, again, spacecraft and things designed to be moved.

Calcium, calcium oxide, calcium hydroxide, and calcium carbonate all figure prominently in Earth-surface demand. Calcium carbonate, mined from limestone sedimentary rocks as biogenic calcite and aragonite, is kilned at high temperatures (heated by combustion of fossil fuels) to drive off carbon dioxide and make lime, CaO. Hydration of CaO makes "slaked lime", calcium hydroxide, which is reacted with silica to make concrete. We have already pointed out the reasons to avoid or limit concrete use in space.

Phosphates are in demand primarily as nutrients. Phosphate is an essential component of mammalian bones as the mineral apatite [$Ca_5(PO_4)_3(OH,F)$] and in the "backbone" of DNA and RNA. It is also the crucial component of cellular energy production in the molecules ADP (adenosine diphosphate) and ATP (adenosine triphosphate). Nature provides about one phosphorus atom per 100 Si atoms. Phosphorus is found in stony meteorites and carbonaceous chondrites as a variety of phosphate minerals. In irons and M asteroids, phosphorus is usually reduced to phosphides such as schereibersite. There is no shortage of phosphates for agricultural use, and few other competing uses. We set aside 200 kg of phosphate for each person, a very generous allowance.

Water is found in the carbonaceous chondrites and the C-cadre (B, C, D, G, P, etc.) asteroids. A CI chondrite body contains about 20% water by weight. Traces of water can be found as a fine carbonaceous dust in the groundmass of some chondritic meteorites, although that water is partly of terrestrial origin. Water is usually bound as –OH groups and interlayer water in phyllosilicates, although CI chondrites also contain significant water of hydration in salts such as gypsum (selenite) and epsomite. In addition, hydrogen is an essential part of organic polymers, subject to conversion to water by reaction with magnetite and other oxides during strong heating. We require 10 tonnes of water per person to fully populate the water cycle, for agricultural or hydroponic use, for radiation shielding, drinking and cooking water, and water for personal hygiene.

Carbon is an absolute necessity for all known forms of life; indeed, its high cosmic abundance and rich chemistry suggest it as the logical basis for all life in the Universe. Carbon is ubiquitous in meteorites, although its abundance is strikingly high only in the carbonaceous chondrites and ureilites. In CI meteorites, C is found mostly in insoluble, involatile organic polymer in amounts up to 5-6% of the total mass of the meteorite. These same meteorites contain mineral carbonates and traces of water-soluble or volatile organic matter, including carboxylic acids, hydrocarbons, aldehydes, ketones, and amino acids. All metal-bearing meteorites, whether ordinary chondrites, stony-irons, or irons, contain carbides such as cohenite (Fe_3C) as well as dissolved carbon in the metal phase. Strong heating of ordinary chondrites mobilizes carbon so that carbides can react with FeO in the silicates, releasing CO and CO_2. We assume that C-cadre material makes up about 30% of the number and 50% of the mass of the NEAs that are less than 10 km in diameter, or about 1% of the total mass of the NEA swarm. (The S-type NEAs 1036 Ganymed and 433 Eros make up about 95% of the total NEA mass; we are interested in the rest.) As essential as carbon is for life, it makes up only 18% of the mass of the human body. A 60-kg (133 lb) human contains about 10 kg of carbon. Generously allowing a biomass of 100 kg of plant matter per kg of human mass, we require 1,000 kg of carbon in the food cycle per person.

Nitrogen is a particularly interesting case. About 3% of the mass of the human body is nitrogen, most of which is carried in the amino acids that are the building blocks of proteins. Nitrogen is also an essential constituent of the organic bases guanine, cytosine, adenine, and tyrosine, the carriers of the genetic code in DNA. For each human we require 1.7 kg of nitrogen within the body. Including a plant biomass that is 100 times the human body mass, we require 170 kg of biological nitrogen per person. In addition, nitrogen is essential as a fire retardant: life in a pure-oxygen atmosphere is extremely dangerous. Allowing 1000 m^3 of air per person at 0.9 atmosphere pressure, containing about 60% nitrogen, we need 540 kg of gaseous nitrogen per person. We round off these requirements to 700 kg of nitrogen per person.

Sulfur is also an essential ingredient of life. Proteins contain the sulfur-bearing amino acids cysteine and methionine. Sulfuric acid is an important chemical reagent used in metal extraction and processing.

The many trace elements used by life are all present in chondrites with adequate abundances. The metals incorporated in biological porphyrin complexes illustrate this point: Fe for hemoglobin and Mg for chlorophyll are both very abundant; even Cu for decapod (shrimp, crab, etc.) hemoglobin and V for the analogous role in tunicates are available. The vanadium abundance in chondrites is about the same as for copper (the atomic ratio $V/Si = 2\times10^{-4}$), which might constitute a problem for space-faring populations of tunicates or lobsters, but causes the rest of us no inconvenience.

Economic Drivers: Ores in NEAs

We have already surveyed the direct material demands of living organisms. The additional demands imposed by transportation, housing, and protection involve even larger masses of materials.

For propellants, the most abundant "ore" is water. A conventional approach to producing high-performance rockets would require collecting sunlight, using solar cells to convert the solar power into electrical power, and then using the electrical power to electrolyze water into hydrogen and oxygen. This propellant combination has very high performance, the best achievable from a chemical propulsion system without using the rare and extremely corrosive and poisonous oxidizer fluorine (F_2). Both hydrogen and oxygen must be liquefied and transported at extremely low temperatures. They are termed *cryogenic propellants*.

Water can also be used directly as a propellant in any propulsion system that uses an external source of energy to heat the exhaust stream. Examples include solar thermal propulsion (STP), in which a lightweight solar collector is used to reflect and concentrate sunlight onto a refractory thrust chamber, and nuclear thermal propulsion (NTP), in which a stream of water is run through the core of a nuclear reactor to generate superheated steam. This approach differs from conventional hydrogen/oxygen chemical propulsion in several critical ways. First, no cryogenic propellants must be made, refrigerated, liquefied or stored. (Propellants that don't need extreme refrigeration are called "storable" propellants.) Second, these heating methods can produce steam at a higher temperature than can be achieved by combustion, and therefore can deliver a higher specific impulse (a measure of the propulsive efficiency of a rocket engine). Third, the advantages gained by freedom from electrolysis and refrigeration equipment are partially offset by the necessity of carrying the mass of the nuclear or solar energy system.

It is clearly simpler to envision a system that uses storable liquid propellants rather than cryogenic propellants such as liquid oxygen (LOX) and liquid hydrogen (LH_2). A conventional solution to this problem would be to use a propellant combination such as hydrazine (N_2H_4) or a hydrazine derivative such as monomethyl hydrazine ($CH_3N_2H_3$; MMH) as the fuel and nitrogen tetroxide (N_2O_4) or nitric acid (HNO_3) as the oxidizer. On Earth, with its abundant nitrogen, this propellant combination is sufficiently compelling that many U.S., Soviet, and Chinese strategic missiles have been designed to use it, despite how dangerous it is to handle. However, we have seen that nitrogen is in very short supply in space, and is not something that we want to throw away. A less conventional storable chemical rocket system might burn methanol (CH_3OH) with hydrogen peroxide (HOOH), a combination that conserves nitrogen and promises good performance, though it also requires an elaborate chemical factory to manufacture the propellants. By far the simplest storable propellant is water itself, used directly in conjunction with an STP or NTP system.

There is also a great demand for shielding against micrometeoroids and cosmic radiation. To provide adequate micrometeoroid protection two or three layers of thin metal foil will suffice. Stopping energetic protons from the Sun or from primary cosmic rays is a very much more challenging problem. The amount of protection provided by Earth's mostly-nitrogen atmosphere (the amount of shielding we and all other terrestrial life forms have evolved to tolerate) is equivalent to about 1 kilogram of mass per square centimeter of surface area, but nitrogen is not the most effective shielding material. The most effective shielding against the dominant bombarding species (protons) per kilogram is hydrogen, for which the momentum exchange per collision is greatest. It is wildly impractical to surround our spacecraft or habitat with a tank of liquid hydrogen, but fortunately there are other materials which have about the same number of hydrogen atoms per cubic centimeter as LH_2 and are vastly easier to handle: water and methane come to mind, gasoline is not bad, and even paraffin is useful. Given the many uses of water, we would surely want to have tanks of it available—so why not use it for radiation shielding? A protective layer of water massing 500 grams per square centimeter would demand a layer 5 meters thick. This is what we would need while cruising interplanetary space, exposed to both solar cosmic ray bursts and galactic cosmic rays launched into the Solar System by supernova explosions. Deep within the protection afforded by Earth's magnetosphere, in LEO, the amount of shielding would be much smaller. An interplanetary spacecraft, approximated as a sphere 10 m in diameter, would require 3000 cubic meters of water with a mass of 3000 tonnes. The mass of radiation shielding would thus dominate the total mass of the spacecraft and would be totally impractical. This is the central challenge of manned missions to Mars: to provide sufficient shielding to keep the crew alive and safe during solar flares. The solution to this challenge requires that three conditions be met: accurate forecasting of intense flares, a small "storm shelter" to serve as a refuge for the few hours of peak flare activity, and sufficient shielding around the storm shelter to protect the crew. The shielding could be provided by a few square meters of coverage by fuel tanks and a water reservoir, with a total shielding mass on the order of a few hundred tonnes, all of it already needed for other purposes.

We have already mentioned the utility of iron and nickel as structural materials. By means of the gaseous carbonyl process, iron and nickel can be volatilized at relatively low temperatures near 200 °C, separated by fractional distillation of their carbonyls, and selectively deposited. Iron carbonyl decomposition is in fact the source of commercial analytical grade iron, with a purity of 99.9999%. Such iron is so pure that it is virtually free of crystal defects, making it not only extremely strong but also as corrosion-resistant as stainless steel. **Habitats full of water and oxygen could be made out of high-purity iron without fear of rust.** The tensile strength of high-purity iron whiskers grown by chemical vapor deposition reaches 13,000 MPa, about 5 times the strength of piano wire.

Among the byproducts of carbonyl extraction of iron and nickel are cobalt, platinum-group metals, and semiconductor nonmetals. Cobalt can be extracted by a variant of the carbonyl process and used to make high-temperature corrosion-resistant alloys for use in space. The Platinum-Group Metals (PGMs) made available as byproducts of iron, nickel, and cobalt extraction (platinum, osmium, iridium, rhodium, ruthenium and palladium) are sufficiently valuable to be worth returning to Earth. Two fundamental misconceptions about this scheme appear weekly in the press: that we will go into space primarily to mine PGMs for shipment to Earth, and that asteroids are a source of Rare Earth Elements (REEs). The first makes no economic sense: PGMs are a lucrative *byproduct* of a space-based ferrous metals industry. The second makes no chemical sense: the rare earths are not found in asteroidal native metal alloys, and indeed are not found in any plausible ore in any meteorite.

The last category of trace elements in the metal phase or in the accompanying sulfides is the semiconductor elements (selenium, tellurium, arsenic, antimony, gallium, germanium, etc.). In enstatite chondrites and achondrites, and in the iron meteorites derived from them, the metal contains up to several percent *elemental* silicon. Although these elements are far less precious than PGMs, they are a potential source of solar cells to be manufactured and used in space.

Table VIII.4 lists the abundances of a number of PGMs and semiconductor elements. Many of these numbers require explanation.

Table VIII.4
Minor and Trace Elements in Asteroidal Metals*

Material	Atoms/10^6 Si	Concentration Range (parts per million; ppm)	Earth-side Market Price in 2013 ($US/kg)
Ferrous Metals			
Cobalt	60000	5000-64000	27.5
Platinum-Group Metals			
Platinum	1.8	0.07-39	49000.
Palladium	1.4	1.6-50	24100.
Osmium	0.8	0.03-41	12900.
Iridium	0.6	0.4-40	25700.
Rhodium	0.4	0.1-17	36200.
Ruthenium	1.9	0.08-40	2400.
(Rhenium)	0.04	0.004-3.3	4600.
Semiconductor Elements**			
Silicon, 99.9999%		0-25000	20.
Germanium, 99.99%		0.03-2000	70.
Gallium, 99.99%		0.15-87	500.
Indium, 99.99%		0.01 (0.26 in CI)	745.
Arsenic, 99.99%		1.8	3200.
Antimony, 99.5%		0.34	45.
Selenium, 99%		8.0 (53 in CI)	124.
Tellurium, 99.99%		(6.9 in CI)	140.

*See text for discussion and explanations

**Note that nitrogen, phosphorus, and boron are also semiconductor constituents

In the Table, cobalt is a ubiquitous component of asteroidal metal, present in the metallic state in irons, stony-irons, and most chondrites, and as sulfides and oxides in more oxidized chondrites. The concentration of cobalt metal faithfully reflects the degree to which iron has been oxidized out of the metal into FeO and magnetite. Usually cobalt positively correlates with nickel.

The concentration of platinum-group metals (PGMs) in the metal phase reflects both volatility and oxidation state as well as partitioning between kamacite and taenite.

The rare element rhenium, which shares some of the properties of the PGMs, is appended to the list of the six accepted members of the group. The correlation of rhenium with osmium in iron meteorites is extremely close.

The semiconductor elements, including nitrogen (N)-, phosphorous (P)- and boron (B)-doped silicon and germanium, gallium arsenide, indium antimonide, and structurally related compounds can be derived from asteroidal material; however, the volatility of most of these elements favors their retention primarily in the lowest-temperature (carbonaceous) classes of asteroids, in which free metal is rare or completely absent. Arsenic and antimony form stable sulfides, and selenium, tellurium, and germanium substitute freely in sulfides. These elements therefore follow metal not because they are present as solutes within the solid metal, but because metal and sulfide minerals both derive from a metal/metal sulfide melt analogous to that in Earth's outer core. Cooling of that melt leads to exsolution of crystals of metal (kamacite and taenite) and concentration of chalcophiles into the less-dense residual melt.

In this Table, the number given for silicon is the abundance of elemental Si found in the metal phase, and does not include silicates. Elemental silicon, as we have seen, is associated with the high degree of reduction seen in E chondrites and metals derived from them. Gallium and germanium reach high concentrations in some irons; Ga and Ge abundances are lowest in the type IVB irons, the ones that have the highest PGM content. Remote sensing cannot discern whether a given M-class asteroid is rich (or poor) in either semiconductor elements or PGMs. Within any single given iron meteorite type (such as IVA, IVB, or IIIAB) PGMs generally anti-correlate with nickel.

Solar Power

The availability of semiconductor elements in asteroids raises the question of whether they can be put to profitable commercial use. Returning these materials to Earth's surface is not likely to be achievable on a profitable basis because their asteroid-to-Earth transportation costs are likely to be larger than their Earth-surface prices. These materials might be of great utility in manufacturing photovoltaic cells in space if the difficulty and complexity of extracting and processing them in space can be overcome.

Sites of Demand

– or, The Truth About Platinum Mining of Asteroids

The demand for PGMs on Earth, and the complexity of schemes for separating them, strongly suggests that they be returned to Earth as a mixture in their natural proportions. Given an ideal iron meteorite source such as the Butler or Itique irons, concentrations of total PGMs may reach 200 ppm. With an average Earth-side market value of $25,000 per kilogram of mixed PGMs, processing 1 tonne of asteroidal iron-nickel alloy would produce as a byproduct 200 g of mixed PGMs with an Earth-side market price of about $5,000 per tonne of asteroidal iron-nickel metal processed.

This falls far short of the value of asteroidal propellants and metals that can be produced from that same tonne of asteroidal material to replace terrestrial supplies delivered into orbit at great expense. At current launch prices and expected yields of propellants, water, and metal, the in-space value from processing that tonne of asteroid material is approximately $1 million. Compared to the $5,000 of PGMs per tonne of processed ore to serve terrestrial users, it therefore seems quite likely that any scheme that attempts to mine asteroids primarily or solely for their PGM content would be unwise.

The $1 million yield from processing a tonne of asteroid material is only an approximation; some extracted materials will have lower value because additional cost is required to make them into end-user products, and some materials may have higher values, potentially because they can be fabricated into very large structures (giant antennas, trusses, habitats, etc.) that simply cannot be launched on rockets with limited payload volumes.

Earth-side marketing of *byproduct* PGMs from large-scale processing of iron and nickel in space could, however, deliver substantial additional profits if the collection of PGMs does not require significant additional cost beyond the baseline iron-nickel activities. Thus production and import of PGMs from space will almost certainly be contingent upon the prior establishment of a large in-space market for ferrous metals.

Economic Value of Asteroidal Resources

Given the total mass of the NEA swarm of 120×10^{15} kg, it is possible to calculate the Earth-surface market value of its materials at present market prices. The balance sheet includes 37×10^{15} kg of iron worth \$11,000 trillion, 2.5×10^{9} kg of Ni worth \$70,000 trillion, 2×10^{8} kg of cobalt worth another \$70,000 trillion, and 1.8×10^{6} kg of PGMs worth yet another \$70,000 trillion. These numbers are intended to convey the enormity of the NEA resource base, and to make it clear that there is absolutely no prospect of importing even a tiny proportion of these materials to Earth. As we have already seen, the PGMs make economic sense as imports only if there is an in-space demand for ferrous metals, and only if the PGM import rate is tightly controlled so as to avoid a price crash.

If present Earth-surface prices are so irrelevant, one might reasonably ask what prices these same metals would command in space. Present costs of supplying 1 million tonnes of metal to GEO from Earth's surface would run about \$10,000/kg, for a total of \$10 trillion. Building a constellation of Solar Power Satellites in GEO, involving millions of tonnes of structural materials, would require a year's worth of the gross global product—unless the material was native ferrous metal alloy brought downhill into the Earth-Moon system from NEAs. Any asteroid-based supply system that could deliver structures (trusses, antennas, etc.) and other finished products to GEO at a price less than \$10,000 per kilogram of displaced Earth-launched material would be competitive.

IX. Asteroid Mining and Processing

The conduct of mining operations on an asteroid differs profoundly from standard mining practice on Earth. The terrestrial example concentrates on finding an outcrop or core specimen of some promising mineral, then mapping the mineral vein or body in three dimensions. Samples of the vein are analyzed (assayed) to determine their concentration, and elaborate models of the mining process are constructed to determine how much overburden must be excavated to access the mineral body, the cost of excavation and local conveyance, the cost of mineral transportation to the processing site, the enrichment ("beneficiation") of the desired mineral, and the cost of extracting the desired element(s) from the mineral via chemical processes. Certain chemical reagents and fuels, such as air (oxygen), water, diesel fuel and coal may be required, and the costs associated with them must be reckoned. Finally, the cost of delivering the final product to its site of use must be determined. Only if the revenue from sale of the product significantly exceeds the total costs of the operation can the mineral deposit qualify to be called an *ore*. An ore is not a potentially valuable mineral; it is a demonstrably *profitable* mineral.

"Ore Bodies" on Asteroids

The first of many profound differences between terrestrial mining technology and that necessary for mining asteroids lies in Earth's long history as a thoroughly differentiated and continuously recycled planet. Siderophile (affinity for metallic iron) and chalcophile (affinity for sulfur) elements have been efficiently extracted into Earth's core, dense ferromagnesian silicates have been concentrated into the mantle, and a low-density, volatile-rich residual melt rich in alkali metals, silica, water, and other incompatible elements have floated to the top to form the crust, oceans, and atmosphere. Many "precious" and "strategic" metals exist in small traces in the crust thanks mainly to late accretion of asteroidal material after the crust was already formed; the vast majority of Earth's content of these elements resides in the core.

Ore mineralization in Earth's crust is typically caused by the action of hot, and sometimes supercritical, water, which dissolves, transports, and deposits minerals selectively. Mineral deposition frequently occurs along fractures in the country rock or at volcanic or hydrothermal vents. Very commonly these veins are thin, irregular in shape, and difficult to map, and wander through bodies of hard igneous rock. Some commodities, such as coal, are laid down in layers in sedimentary rocks, through which tunnels must be cut or vast amounts of overburden stripped off to gain access to the coal. It is common for known coal veins to be so thin or so deeply buried that they are not worth mining.

The circumstances on asteroids are quite different. Most meteorites have clearly never melted and differentiated. Only CI chondrites betray evidence for the dissolution, migration, and deposition of veins of minerals: these are the thin white veins of carbonate and sulfate minerals that run through CI stones. The isotopic compositions of the sulfur compounds in these meteorites require that the action of liquid water took place at a temperature near or below 0 °C, in the presence of an oxidizing agent. At such low temperatures, few minerals are sufficiently soluble to be transported and concentrated by water transport.

It is therefore easy to see that the terrestrial concept of finding and following veins is generally inapplicable to asteroids. The great virtue of the primitive state of chondrites is that the precious and strategic materials have not been extracted and hidden from view—and from access. The small percentage of asteroids and meteorites that are products of melting and differentiation have mostly suffered devastating collisions that leave large chunks (which we then can describe as small asteroids) of core, mantle, and even crustal material, which are the sources of most irons, stony-irons, and achondrites. The chondrites, for example, without any help from hydrothermal processing, approximate the chemical composition of an entire terrestrial planet: core, mantle, crust, and (in the C chondrites) volatiles are all mixed together without opportunity for differentiation. Thus the concentrations of the precious and strategic metals in any random piece of any random chondritic asteroid are higher than in their richest known ore bodies found on Earth.

Landing on an Asteroid

Spacecraft routinely rendezvous and dock with each other. The development of these techniques dates back to the early *Gemini* and *Soyuz* missions (and unmanned *Soyuz* spacecraft masquerading as *Kosmos*-series "scientific research" spacecraft) of the late 1960s. Assembly and operations of the Soviet *Salyut* and *Mir* space stations with their *Soyuz* and *Progress* visitors, and the manned lunar missions of the American *Apollo* program, depended on orbital rendezvous and docking. So, can we conclude that landing on an asteroid would be nothing special? No.

First of all, the rendezvous and docking operations of the last 45 years have involved controlled vehicles that interacted cooperatively to maintain their relative positions and orientation. One spacecraft would serve as a stable target while the other maneuvered actively to effect the rendezvous and docking. Both spacecraft carried docking adapters, specialized hardware to enable them to lock firmly together with an air-tight seal. Asteroids, however, are neither controlled nor cooperative, and, at least for the time being, are sadly lacking in docking adapters.

Not only do asteroids lack these civilized amenities, they are also wild beasts. Asteroids, especially those smaller than several hundred kilometers in diameter, are often extremely irregular in shape. Their surfaces are a chaotic patchwork of craters, rocks, rubble, and dust. Some areas may be large expanses of stainless steel; others may be deep loosely-packed regolith containing rocks of all sizes, and some may be extremely fragile and unstable “fairy castles” of fine-grained dust. In addition, asteroids rotate on their own schedule, not in accord with pre-planned mission guidelines. The overwhelming majority of NEAs, those that are less than 100 m in diameter, are collision fragments that were originally produced in violently disruptive impact events. They often have rotation periods of a few minutes. Many are so irregular in shape that they partake of tumbling motions that cannot be described in terms of rotation around a single well-defined axis. Such small asteroids are also vulnerable to the effects of direct solar radiation pressure (the Poynting-Robertson Effect) and the forces exerted by asymmetrical emission of thermal energy (the Yarkovsky Effect), so that prolonged exposure to sunlight may affect not only their orbital motion, but also spin them up like pinwheels in the wind. Rapidly rotating small bodies can reach rotation rates so high that the feeble gravity of the asteroid is insufficient to hold them together. Indeed, any rocky body with a rotation period less than about 2 hours (dependent on the body’s density) has an “equatorial” rotation speed that is greater than orbital velocity. The fact that we see so many rapidly rotating small NEAs has suggested to many observers that they must be strong “monoliths”. However, a calculation of the tensile strength required to hold a body together against rotational disruption reveals that even a modest degree of “stickiness” would suffice to preserve them intact. Such cohesion can be provided by polarization forces, in which the + and – ionic charges on the surface of one grain align with or induce complementary – and + charges on an adjacent grain surface, leading to a small net attractive force called the *van der Waals force*. Thus even a rubble-pile asteroid rotating with a period of a few minutes may hold together thanks to this natural stickiness. We have experience with

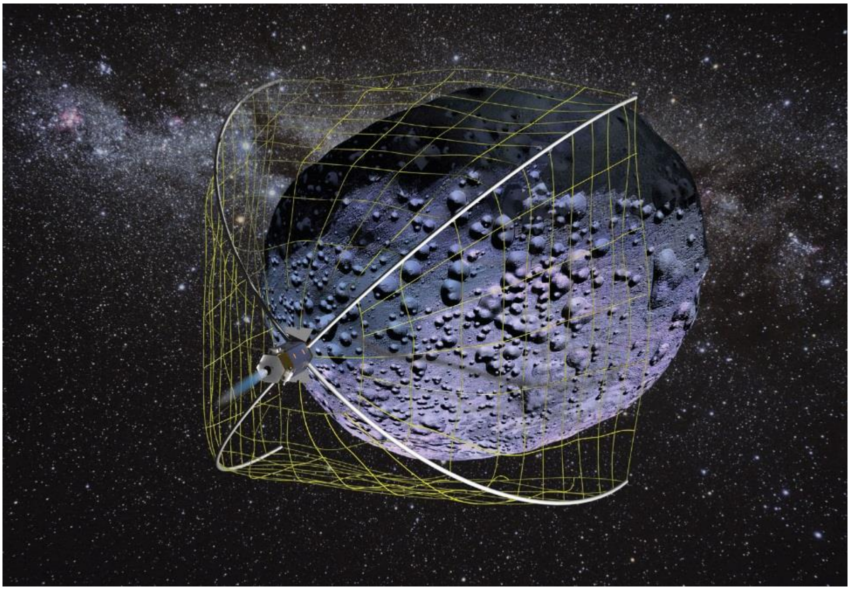


Figure IX.1 One proposed technique to capture and de-spin a small asteroid grasps it with a lightweight mesh structure.

Credit: Tethers Unlimited

sand dunes on Earth, which often attain steep and unstable slopes due to the transport of grains by wind, and we naturally picture steep slopes on asteroids as unstable and treacherous. But sand grains on Earth slip so readily because their contact points are lubricated by air, a commodity not found on asteroids. There are other reasons not to fear having your spacecraft buried by landslides on asteroids: the acceleration of gravity on the surface of, say, a 100-m asteroid would be around 0.1 mm/s^2, making a landslide (even if there were no resisting van der Waals forces) so slow as to be completely boring. On a small rapid-rotator, the situation is even less threatening: over almost the whole surface of the asteroid, any landslide inadvertently triggered by a lander would travel up (and escape), not down onto the lander. Indeed, the lander itself must be anchored to keep it on the asteroid.

Rapidly rotating small bodies have little total rotation energy because of their small mass and rotation velocity: a 10-m asteroid (30 m circumference) with a rotation period of 10 minutes has an equatorial rotation velocity of 3 m/minute, or only 5 cm/s. The amount of chemical rocket propellant that would be needed to completely de-spin a typical 100-m asteroid is only about 1 tonne, and of course the reaction mass may be material extracted from the asteroid, not propellant brought at great expense from Earth. At need, the spin of a small asteroid can be controlled, even locked on to the Sun.

On a “wild”, rapidly spinning, asteroid, there are several adaptive strategies that a would-be asteroid lander could employ. One is to grapple the asteroid and de-spin it. Another is to land at the rotation pole. A third is to anchor the lander by means of harpoons, magnets, or even a wire girdling the asteroid’s equator. The method of choice depends on the properties of the asteroid.

The proposed Keck Asteroid Retrieval Mission (*ARM*) now under study would use a large bag to envelop a small asteroid. The bag is then cinched shut and the electric propulsion system of the spacecraft is used to de-spin the asteroid, preparatory to bringing it back to a stable orbit in the vicinity of the Moon. The target orbit would be chosen so that the asteroid could not de-orbit and strike Earth: rather, its long-term fate if left uncontrolled would be to fall onto the Moon. Possible locations for safe storage of the small asteroid (<1000 tonnes) would be the L1 and L2 Lagrange points in the Earth/Moon system or, even better, a high orbit around the Moon.

Operating on an Asteroid

The surface environment of an asteroid is defined by hard vacuum and very low gravity. A typical 1 km asteroid has a surface gravity of about 0.3 mm/s^2 (0.00003 times Earth’s gravitational acceleration) and an escape velocity of about 1 m/s (surface gravity scales as the product of radius times density; escape velocity scales as the product of radius times the square root of density). Landing on an asteroid and taking off from an asteroid are both easy; indeed, the biggest problem is avoiding inadvertent departures caused by the reaction forces of moving, digging, drilling, etc.

An atmosphere on an asteroid would not only offer a “minable” resource; it could also be used for aerocapture and aerobraking. But there is no permanent resident atmosphere on an asteroid: the thermal velocity of gas molecules at asteroid surface temperatures ranges from about 1 km/s for light gases such as hydrogen and helium to about 100 m/s for heavy gases such as xenon or sulfur hexafluoride. Since these thermal velocities are far in excess of the escape velocity of the asteroid, any gas released from the interior of the asteroid or by an impact event, or vented by a leaking spacecraft, will escape immediately into space. There the gas will quickly become ionized by solar ultraviolet radiation, and the ions will be swept out of the Solar System by the magnetic field in the solar wind at a speed of several hundred kilometers per second. Of course, a mining operation would regard any gases it may release as precious commodities, worthy of careful conservation and not to be carelessly vented into space.

(If the possibility of serious "industrial pollution" by gases is so low, what of dust pollution? Dust kicked up by mining activities at speeds below the asteroid's escape velocity will soon, usually in a matter of 100 minutes or less, fall back onto the asteroid's surface. Any dust that escapes will enter heliocentric orbit, subject to the long-term effects of the Poynting-Robertson force, and eventually spiral into the Sun. It would require a remarkably intensive asteroid mining program to even begin to compete with the natural sources of dust provided by asteroid collisions and cometary activity.)

Obviously processes involving internal combustion engines are irrelevant on a body that provides neither fuel nor air. Mechanical power must be supplied electrically from sources such as batteries, solar voltaic cells, solar dynamic generators, or nuclear reactors. There are (unequal) challenges to all these approaches: batteries are suitable only for short-term use, and become quite massive and, because of launch costs, unaffordably expensive for periods of use longer than a few days. Nuclear reactors are compact and powerful, but incur the wrath of environmentalists who see them as little Chernobyls about to shower down on our heads. Those who remember the uncontrolled fall of the Soviet reactor-powered ocean surveillance satellite *Kosmos 954* in Canada in 1978 have reason for concern. In short, nuclear power supplies, despite their operational advantages, and irrespective of the safety of modern designs, are politically infeasible. There is also the long-term consideration that nuclear reactors in space are not a renewable resource: asteroids, being devoid of any relevant ores, are terrible sources of uranium and thorium, making in-space refueling of a reactor or radioisotope thermoelectric generator (RTG) impossible. Thus we are left with solar-derived electric power. The advantages of such a power source are that it is light, clean, and has a long useful lifetime. Though solar cells degrade over decades of use, there is a possibility that, on the same time scale, we may master the art of extracting semiconductor elements and fabricating solar cells from space-derived minerals. The main drawback of solar cells arises from the need for operations at great distances from the Sun, where the intensity of sunlight is low. In the outer Belt, 3.2 AU from the Sun, the intensity of sunlight is ten times lower than it is at Earth's orbit, near 130 watts per square meter, compared to1350 W/m^2 at Earth. This problem can be partially compensated by using very light-weight thin-film metal mirrors to capture sunlight and concentrate it onto the solar cells. A processing plant riding an NEA from 1 AU (perihelion) out to 3.2 AU (aphelion) and back on each orbit around the Sun would have to adapt to this dramatic periodic variation in solar intensity.

Any installation on the surface of an asteroid that digs into the surface will have to be anchored in some way, lest the reaction force from digging or drilling tip over, move, or launch the facility into space. There are many ideas about how to secure a lander to the surface of a small asteroid, none of which have yet been tested in practice.

The Japanese *Hayabusa* spacecraft, which landed on the asteroid 25143 Itokawa in 2005, was not secured in any way; indeed, the mission design specified only a brief contact with the surface to effect the collection of a surface sample, but, contrary to plan, the spacecraft actually sat on the surface for about a half-hour. A mining mission would require secure attachment to the surface by any of several means. First, a small asteroid could be "harpooned" by a small penetrator attached to a long, light tether. The rotation of the asteroid would wind the tether all the way around the asteroid, the spacecraft being pulled down to the surface by the tether until the vehicle could find and grapple with the lower end of the tether, near the penetrator location. The tether could then undergo a "belt-tightening" to secure the system to the asteroid.

Alternatively, one or more penetrators could be shot into the asteroid's surface near the intended landing point to anchor the vehicle to the ground in a manner similar to the use of tent pegs to secure a tent against wind. The success of penetrators depends on the physical properties of the surface: too strong a surface would simply prevent penetration; too weak a surface would allow penetration but prohibit secure anchoring. Magnetic anchoring is a possibility on most (but not all) asteroids, and has the virtue of being light, but the use of an electromagnet would entail some small continuing electrical current drain. There is also a concern that the vehicle may anchor to a very weak metal-bearing regolith, a dust layer lacking in tensile strength and incapable of holding the spacecraft in place. The use of a wide-mesh "butterfly net" has also been suggested, but seems practical only for very small asteroids because of mass limitations. Clearly further thought and experimentation on these concepts are in order.

Mining

We have already concluded that mining in the usual terrestrial mode, tunneling or stripping overburden to follow a mineral vein, will seldom or never be relevant to mining asteroids. Because of the wide compositional variability of, and enormous strength differences between, different meteorite groups and their corresponding asteroid families, the appropriate mining techniques are correspondingly different.

We have made the point that, from a strictly compositional standpoint, carbonaceous chondrites have the richest resource mix. If volatiles are not our principal target, then ordinary chondrites are a clear choice because they contain all the non-volatile elements in approximately solar (cosmic) proportions. As a further benefit, ordinary chondrites are relatively easy to crush (a few hundred bars pressure needed), and carbonaceous chondrites are the easiest of all classes of meteorites to crush (1 to 10 bars suffices for CI and CM chondrites). But there is no need for the prospective asteroid miner to handle and crush large boulders or country rock on a chondritic asteroid: nature provides ample crushing opportunities in the form of hypervelocity impacts. The pre-crushed material, called regolith, coats the surfaces of larger asteroids, and is sometimes even available on small asteroids that generally experience severe collisional erosion. In general, crushing of hard rock is a difficult process which places severe strain on mechanical equipment. We would do well to try to avoid schemes that rely on crushing hard rock.

Mining achondrites is generally of distinctly less interest. They are almost all (except the ureilites) volatile-poor, and contain only very small traces of free metal. They are not only resource-poor, but, as igneous rocks, they are quite strong. Of all the classes of asteroids, V and other achondrite types have the greatest resemblance to lunar basalts or to the slag discarded in metal processing operations on Earth. One rather specialized attraction of achondritic material comes to mind: the ureilites contain up to 1% of tiny black (carbonado) diamonds, a superior industrial abrasive. It is remotely conceivable that these diamonds would be worth returning to Earth, but it is far more likely that a use will be found for them in space. The existence of ureilites also draws attention to the potential difficulties of crushing and grinding a rock that contains materials that are harder and stronger than our grinding equipment.

Mining M asteroids presents daunting challenges. Large M asteroids, some of them the stripped cores of large asteroids that have met with catastrophic collisions, may present us with intractable metal monoliths tens of kilometers in dimensions. The metal is tough and strong, defying crushing, drilling, cutting, and breaking. There is, however, an interesting aspect to M asteroids that we should keep in mind: the night sides of M asteroids in the inner Asteroid Belt may get cold enough to drop below the brittle-ductile transition temperature of the metal alloy. Below that temperature (which is composition-dependent) an impact event may shatter the metal like glass, opening up the possibility that some of these M asteroids may have a regolith consisting of dust, grains, and larger lumps of stainless steel. Such material would be easy to collect and of a size suitable for processing. M-type NEAs, however, being usually closer to the Sun than the Belt is, are not likely to get cold enough to shatter.

But the initial mining activities on asteroids are much more likely to involve collecting chondritic regolith on S or Q class NEAs. Ordinary chondrite regolith, like the chondrites themselves, contains abundant olivine, pyroxene, kamacite, taenite, troilite, and plagioclase feldspar. The prime attraction here would be ferrous metals, notably iron and nickel. Carbonaceous chondrite regolith, devoid of metal, instead contains organic matter, clay minerals, and magnetite, making water and other volatiles the main attraction, but also permitting ferrous metal extraction from oxides and sulfides. It should be noted that S-type asteroids are surely a heterogeneous sample of several diverse meteorite types, including both chondrites and resource-poor achondrites. It would be an acute disappointment to send an expensive metal-mining mission to an apparent ordinary chondrite asteroid, only to find upon arrival that it is a metal-free achondrite.

Mineral Beneficiation

Beneficiation of a mineral simply means concentrating it. There are two separate considerations connected with beneficiation: the efficiency of collection of the desired mineral, and the degree to which unwanted impurities can be separated from it. Minerals derived from a crushed polymineralic rock, whether it was crushed by a machine or by natural processes, commonly have fragments of other minerals firmly attached to them. To produce a mineral concentrate for processing, we would very much profit from requiring a high degree of *liberation* of the mineral grains; in effect freeing them of useless impurities. This problem of preparing pure separated minerals is ubiquitous; indeed, the problem is even worse on the Moon, where violent impacts generate a significant percentage of molten droplets. Because the Moon's gravitational acceleration is thousands of times larger than that of a 1-km asteroid, these droplets are not lost into space, but are efficiently reaccreted onto the surface of the Moon. These cooling droplets weld to anything they touch, producing mineralogically complex structures called *agglutinates*, a random assortment of rock particles which are firmly welded together by the glass formed by rapid cooling of the droplets of melt. Even in a region of the Moon which is rich in desirable minerals, such as mare basins with their vast content of ilmenite, agglutinates tie up much of the ilmenite in large composite particles from which liberation of reasonably pure ilmenite (or any other mineral) is not practical.

Sorting minerals involves two fundamental kinds of discrimination: that based on what thermodynamicists call "intensive" properties of the mineral (chemical composition, magnetism, density etc.) that reflect its internal molecular properties, and "extensive" properties (size, mass, area) that reflect the extent of the particles. But all kinds of beneficiation involve playing two forces of nature off against each other, often in opposite directions or at right angles to each other. Running a magnet through lunar regolith plays magnetic attraction against gravitational attraction; using a dense liquid to separate two minerals (one denser than the liquid, the other less dense) plays gravitation against buoyancy. Neither process works in zero gravity. Even simple sieving of dirt to sort materials by size depends on gravity. Froth flotation, in which an additive such as a surfactant is used to selectively wet and entrain desired minerals in a foamy layer, also does not work in zero g. For a pure material with a wide range of grain sizes, electrostatic separation (playing electrostatic force against gravity) also fails. It is a universal rule that familiar beneficiation technologies were developed on Earth, where the presence of a substantial gravitational acceleration is taken for granted—and therefore almost universally used and relied upon. This state of affairs has also discouraged pursuit of gravity-free beneficiation techniques.

In a microgravity or zero-g setting, a substitute for gravitation must be identified and used. The nearest we can come is inertia. Magnetic separation (usually magnetism vs. gravity) can be recast by spinning a magnet, for example on the end of a rotor arm or tether, or by vibrating it, to inertially "spin off" or "shake off" the non- or weakly-magnetic dross, much as a wet dog separates himself from water. From Einstein's perspective, one kind of acceleration is as good as another: we must conclude that dogs are Relatively smart.

Another, as yet untested, beneficiation process might involve crossed electrostatic and magnetic fields. It would be easy to test such a technique on the International Space Station, or indeed on any orbital platform, ideally using real asteroidal (meteoritic) materials.

Processing Into Feedstocks

Under many circumstances, chemical techniques may be the preferred method of effecting separation and purification. An example would be the thermal decomposition of hydrated salts or phyllosilicates to release water vapor. Separation and isolation of vapor from solids is a familiar and easy process on Earth; in microgravity such separation is not so easy. Dust is readily entrained in, and easily introduces unwanted impurities into, a product gas stream such as water vapor. Filtration seems an obvious choice to maintain the purity of the gas stream, but any filter fine enough to maintain purity will not only severely limit the gas flow, but will very rapidly become completely clogged by dust. Providing a mechanism to clean such a filter will probably be much more difficult, expensive, and failure-prone than using a "cyclone" dust separator, in which the gas stream is rotated to expel dust from the gas onto the walls of the device. This technique has wide-spread application in the mineral and chemical industries on Earth, and even is used in some commercial home vacuum cleaners.

Once a gas stream has been generated, such as by solar heating of carbonaceous asteroidal material to drive off water vapor, the gas must be cleaned of fine dust and condensed into liquid water. Volatile impurities that condense with or dissolve into the liquid water must be removed before the water can be certified for use inside a spacecraft or habitat. Such impurities might include ammonia, carbon monoxide, methane, hydrogen sulfide, and hydrogen cyanide, as well as other irritating or toxic gases. (Traces of nitrogen and carbon dioxide are likely to be present, but do not constitute a hazard.) The best method of chemical purification will usually be catalytic oxidation, but the details of the process depend on the abundances and proportions of the contaminants.

Complete extraction of volatiles from CI chondrite material would provide a gas mixture containing hydrogen, oxygen, carbon, sulfur, nitrogen, chlorine, and traces of other elements. Moderate heating of CI material causes the organic matter to react with the coexisting magnetite [Fe_3O_4] to release CO and CO_2 and produce free metal, a process known as auto-reduction. The total inventory of extractable volatiles can exceed 46% of the total mass of meteorite material. Ultimate useful products could include water, oxygen, hydrogen, carbon dioxide, hydrocarbons, nitrogen, sulfuric acid, hydrochloric acid, and organic building blocks such as amino acids. The inorganic, involatile residue after extraction of these elements is about 33% native metallic Fe-Ni alloy (another19% of the original meteorite mass), leaving a largely silicate residue totaling 35% of the raw material mass. Acid leach of this residue can extract phosphates, alkali metals, and alkaline earths, adding P, Na, K, Ca and Mg to the list of essential biogenic elements already extracted.

The ferrous metal separated from ordinary chondrites, or from chemical processing of carbonaceous chondrites, is closely similar to the material of iron meteorites: Fe, Ni, Co, PGMs, and several of the most important semiconductor elements. Direct casting of metal from ordinary chondrites, irons, or stony-irons will normal result in dissolving substantial amounts of sulfides, especially troilite, in the melt. Castings with such high sulfur contents are not only very weak, but also extremely vulnerable to corrosion. Some method of purifying the iron and nickel from these classes of meteorites is required to make the ferrous metals useful. One promising technique for purifying these metals is volatilization as the gaseous carbonyls of iron and nickel. This procedure, called the *Mond process*, is effected by exposing the metal to carbon monoxide (CO) gas at a pressure near 100 atmospheres and a temperature of about 100 ^{o}C. The PGMs and semiconductor elements are then left behind as a residue. However, sulfur is notorious as a poison for the carbonyl process, making it imperative to remove sulfur completely before CO processing. The ferrous metals made by auto-reduction of CI chondrites have already been devolatilized before the metals are formed, but the native metals in ordinary chondrites are extensively intergrown with FeS, making their extraction, separation, and purification far more complex and difficult. On Earth, large-scale production of nickel usually starts with a sulfide ore and scrupulously removes sulfur (via roasting in air) before attempting to reduce the nickel to the metallic state for Mond-process extraction. The roasting process releases vast amounts of sulfur dioxide, which makes smelters unwelcome neighbors. Natural processes oxidize and hydrate the sulfur dioxide to make droplets of sulfuric acid, industrial acid rain.

The non-ferrous metals aluminum (Al) and titanium (Ti) are the hardest to extract, because both enter into extremely stable minerals that are difficult to concentrate, purify, and decompose. All processes for extraction of aluminum from feldspar are very energy-intensive. Magma electrolysis on bulk silicate melts will indeed extract metals, including aluminum, and liberate oxygen gas, but the cathode deposit is a complex mixture of several different elements (Fe, Ni, Mg, Si, Ca, Al, etc.) which do not alloy nicely with each other. The separation and purification of this mixture of metals promises to be an expensive and difficult operation.

There are many reasons for identifying volatiles and ferrous metals as the most desirable products from asteroidal feedstocks. The elements H, C, O, Fe and Ni are abundant, useful, and extractable by relatively simple and energy-efficient means. The dominant products for early processing of asteroid material are air, water, hydroponic nutrients, rocket propellants (especially water and storable propellants), high-purity iron, and Fe-Ni-Co steel alloys. An interim use for the residues from extraction of these elements would be as radiation shielding.

The following chart illustrates several of the processes needed to turn raw asteroid material into feedstocks or finished goods. Each of these processes in turn may require steps not specifically identified in the chart, such as the purification described earlier. The chart shows that, over time, a broad array of products can be produced from asteroids and even the tailings that have no industrial worth still have value as radiation shielding.

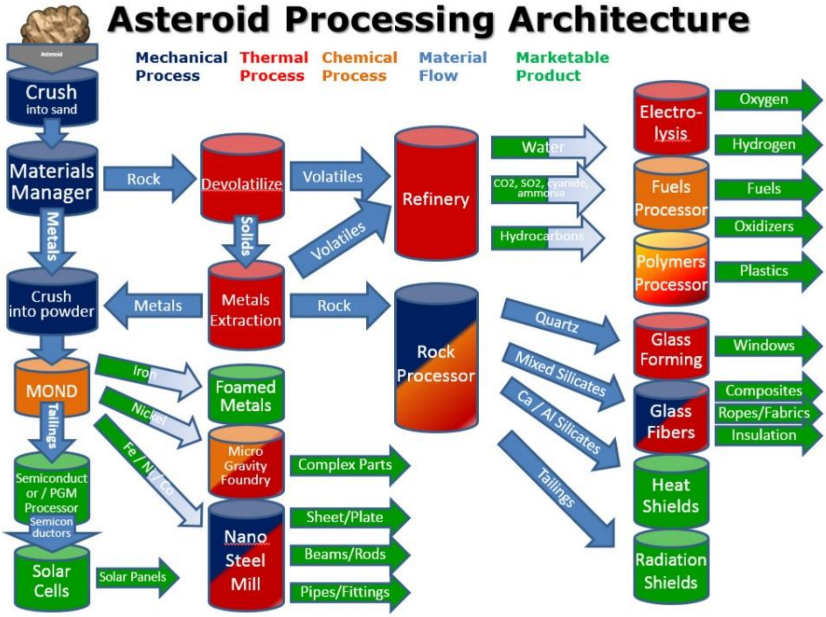


Figure IX.2 Asteroids provide the ingredients for an array of intermediate and finished products.

Credit: Deep Space Industries - Steve Covey, Mark Sonter, John Lewis

Fabrication of Useful Products

Water – Water, produced and purified as outlined above, is an essential prerequisite for space settlements and long-term space missions. It is also the key to the manufacture of several critically important classes of products listed below.

Air – It is essential that air be available independent of resupply from Earth. We rightly recognize the essential role of oxygen, but nitrogen is also of fundamental importance as a fire suppressant. We have seen that electrolysis of asteroidal water is a direct and simple method of manufacturing oxygen inorganically. On a mature space settlement, in which local food production would be required, organic production of oxygen by photosynthesis would supplement and eventually replace electrolysis.

Nitrogen presents a more significant problem. Because of the great stability and high volatility of molecular nitrogen, it is poorly retained by solid minerals and poorly represented in meteorites. The principal sources of nitrogen identified in our survey of meteorites (Chapter IV and Appendix A) are carbonaceous chondrites, which contain about 0.25% nitrogen in the form of organic polymers, and enstatite meteorites and certain related irons, which contain about 0.06% concentrations of nitrogen in nitride minerals such as TiN, Si_2N_2O, and CrN. The figure of 0.25% nitrogen is not very impressive, but it means that one tonne of CI material (a volume of about 0.4 cubic meters) contains 2.5 kg of nitrogen. To reconstitute air, we will need about 1 g of N_2 per liter of artificial air. Thus 1 tonne of CI material will provide about 2.5×10^3 liters (2.5 cubic meters) of air, 6.2 times the volume of CI rock consumed to make it. Ordinary chondrites are far less promising, rarely containing more than 100 ppm (0.01%) nitrogen. Earth itself contains only a few ppm of known nitrogen, of which about 1 ppm is found in the atmosphere and 2 ppm in the crust and mantle. The N content of Earth's core is of course unknown, but iron meteorites contain 1 to over 100 ppm nitrogen, and troilite nodules in irons contain 30 to 200 ppm. A median concentration of 10 ppm N in the core would translate into about 3 ppm N for the entire Earth, suggesting that about half of Earth's nitrogen content is hidden in the core.

Propellants – We have mentioned the direct use of water as a propellant in rockets that derive their energy from a source other than combustion: solar and nuclear power are the obvious options. The most direct scheme for making chemical propellants involves the electrolysis of water into hydrogen and oxygen gas using solar power. The hydrogen and oxygen may then be liquefied for storage for later use, or burned immediately in a H/O rocket engine. Manufacture of storable propellants made of H, C, and O is necessarily more complex, but the ability to store large quantities of these propellants without liquefaction or refrigeration makes them an attractive option. The fuel could be any of a wide range of alcohols, hydrocarbons, or even ethers or ketones. The oxidizer is more of a challenge: the best choice for a storable oxidizer may be high-concentration hydrogen peroxide, HOOH.

For reasons already explained in Chapter VIII, the use of nitrogen in storable fuels and oxidizers is far less attractive in space than it has historically been on Earth. Thus pursuing propulsion systems based on hydrazine derivatives and nitrogen tetroxide would be a far less desirable path than conserving nitrogen for use inside habitats.

Radiation Shielding – The ideal shielding against proton bombardment is hydrogen: the quest for useful shielding favors those materials that have the highest number of hydrogen atoms per cubic centimeter. Water, ice, and liquid or solid methane are superb; water-rich minerals or higher hydrocarbons are very good. Since water is both the most abundant chemical compound in the universe and the material needed with the greatest urgency by space travelers, and since methane requires cryogenic storage, water is the shielding material of choice. Unprocessed water-bearing rock, such as CI chondrites, would also be very useful. On Earth we often think of lead shielding because it puts so much mass in a small volume. But lead and other heavy metals are millions of times less abundant than water in asteroids. Acquiring a large enough mass of lead to provide useful shielding is not practical.

Structural Ferrous Metals – Iron and nickel, extracted and purified as described above, are the materials of choice for construction in space. Their high abundance, occurrence as native metals, and ease of fabrication recommend them in preference to aluminum, magnesium, or titanium, which are far harder to extract and purify. The gaseous carbonyl process not only affords a means of extracting and purifying the ferrous metals, but also offers a highly desirable material for either chemical vapor deposition or laser chemical vapor deposition of iron, nickel, and cobalt. The gaseous carbonyls would be of high utility in 3D printing of specialty parts.

Matching Sources and Demand Sites

We can see ways to provide a wide variety of products, starting with volatiles and ferrous metals, in space. But where are these products needed? Ideally, we should establish not only where these materials are needed, but the quantities in which they are needed and the present cost of meeting those demands from Earth.

Propellants are in demand in LEO for launching into geosynchronous transfer orbit (GTO) and geosynchronous orbit (GEO), to the Moon, the planets, and the asteroids. Propellants are also in demand for station-keeping and orbit maintenance wherever satellites are deployed. High delta-V missions would profit greatly from hydrogen-oxygen chemical propulsion; all station-keeping activities would require storable propellants. We have already stressed the utility of water and water-derived propellants for moving asteroidal materials from their sources to their ultimate site of demand.

Radiation shielding could also be made available in LEO, but is a lesser issue because LEO is a relatively protected environment and astronauts in LEO always have the option pf returning to Earth. Here as elsewhere, water is the preferred shielding material.

A plausible scenario would entail using Solar Thermal Propulsion (STP) with water as the working fluid to return large masses of water via aerocapture to a base and propellant depot in LEO. (Aerocapture is the process of dissipating the excess energy of an incoming payload by passing through the upper atmosphere to slow down to a speed below Earth's escape velocity.) At that refueling base, solar cell arrays would be used to power the electrolysis of water and liquefaction of hydrogen and oxygen, which would be available for all outbound missions.

In GEO, propellants are required by all spacecraft for station-keeping. Manned facilities in GEO also would require massive radiation shielding. A manned presence in GEO would become necessary if large structures such as Solar Power Satellites were built there, which creates in turn a need for water shielding. Manned presence in GEO also creates a need for propellants to drop from GEO into GTO en route to Earth.

Space habitats would of course require structural metals, but the best locations for such habitats cannot yet be determined. The traditional idea of building large habitats at the L4 and L5 points in the Earth-Moon system suffers from the problem that there are no native resources at these locations, and neither Lagrange point seems useful as a way station to any destination.

X. The Long View

Asteroid exploration missions have already flown, and the first retrieval of asteroid surface material has already been accomplished. The present status of already-launched and proposed asteroid missions is summarized in **Table X.1.** The Osiris-Rex mission is planned to return about 60 g of surface material from a 500-meter C-type asteroid in a few years. NASA is presently studying a scheme to retrieve a small (10-1000 tonne) NEA and place it in a stable, safe orbit around the Moon within a decade. This mission, the Keck Institute's Asteroid Retrieval Mission (ARM) project, would involve a single flight using a solar electric propulsion system with terrestrial xenon as the working fluid.

Table X.1 Spacecraft Missions to Asteroids

Spacecraft	**Agency**	**Year**	**Mission**
Galileo	NASA/ESA	1991	flew by 951 Gaspra *en route* to Jupiter
Vesta	IKI (Russia)	1991	cancelled before launch
Galileo	NASA/ESA	1993	flew by 243 Ida *en route* to Jupiter
NEAR	NASA	1997	flew by 253 Mathilde
Cassini	ESA/NASA	2000	flew by 2685 Masursky
NEAR	NASA	2001	orbited and landed on 433 Eros
Rosetta	ESA	2009	flew by 2867 Steins
"	"	2010	flew by 21 Lutetia
Hayabusa	JAXA (Japan)	2010	landed, attempted sample return from 25143 Itokawa
Dawn	NASA	2011	arrival in orbit around 4 Vesta
"	"	2012	departed 4 Vesta *en route* to 1 Ceres
Chang'e 2	CSA (PRC)	2013	flew by 4179 Toutatis
Rosetta/Philae	ESA	2014	to orbit/land on Comet 67P Churyumov-Gerasimenko
Dawn	NASA	2015	to arrive in orbit around 1 Ceres
Osiris-REx	NASA	2016	60-g sample return from C-type asteroid 101955 Bennu
ARM	NASA	2019?	~150 ton Asteroid Retrieval Mission—under study

The purpose of this proposed mission is to establish ground truth on the physical and chemical nature of an NEA for planetary defense and economic utilization purposes, while also providing a science-rich exploration opportunity for manned missions. The retrieved asteroid, once parked in lunar orbit, would be the site of resource extraction experiments, but none of the products to be made there would be used in space operations.

This ambitious mission is not intended to serve as a model for future commercial missions dedicated to retrieving asteroid materials. The list of available targets is severely limited by the fact that the spacecraft cannot retrieve more than about 1000 tonnes. Asteroids of such low mass are typically about 7 meters in diameter. Such small bodies are so faint that they present almost impossible targets for spectral characterization: they must pass exceptionally close to Earth to be bright enough for spectral measurements. There is no way to determine their density and mass without a precursor spacecraft mission, and even that would be extremely demanding. But the retrieval mission would fail if the asteroid turned out to be denser and more massive than expected. This uncertainty drives the mission planners to target even smaller asteroids, for which the problems of mass and density determinations are even more severe.

Since ARM is not intended to be a prototype, and does not take advantage of space-derived propellants, we must look elsewhere for sustainable, long-term mission architectures such as the STP water-based system described in the previous chapter, or any electric propulsion system that can use water as the working fluid.

For Earth-based missions, the fraction of NEAs that are easier to reach than the Moon is 20%. However, once a water-extraction processor is in place on any given NEA, launching from that NEA to other asteroids is relatively easy. Thus the most accessible NEAs, especially the approximately 190 that are larger than 1 km diameter and more accessible than the Moon (outbound delta V from LEO less than 6 km/s), are steppingstones providing access to a much larger population of NEAs. Like Kevin Bacon, essentially all the NEAs are within 4 or 5 degrees of separation from the first-generation set of targets, which were chosen for ease of *direct* access from Earth. Many NEAs that are hard to reach directly from Earth (because of large outbound delta V requirements) follow orbits from which return to Earth intercept is easy.

Most NEAs have aphelia in the Asteroid Belt. A first-generation (or later) propellant extraction facility will pass by Earth's orbit on every trip around the Sun, typically affording superior outbound and inbound mission opportunities every few decades. Those NEAs that are in nearly Earth-resonant orbits will have more frequent mission opportunities. But these same asteroids will also offer opportunities near aphelion on every orbit to transfer to Belt asteroids with delta V on the order of several km/s. These first-generation Belt asteroids in turn afford relatively easy access to thousands of other Belt asteroids. In this manner the sphere of access for mining operations can expand rapidly to encompass virtually the entire Belt, again approaching completion after four or five generations of transfers. The time scale for this diffusion process is one or two centuries, assuming that the production of new processing facilities can be highly automated. If extensive hands-on human presence is required to manufacture these facilities, then the process could take 1000 years. Although C-cadre asteroids (especially C and D spectral classes) pervade the Belt, they are strikingly dominant beyond about 2.8 AU. Most known Belt asteroids have albedos less than 0.1, and the most probable albedo for a Belt asteroid is 0.04. About half the C asteroids in the outer Belt show spectral evidence of the presence of water. Because of the discovery bias against distant and dark asteroids, it is remarkable that the majority of the mass of the Belt, and the large majority of the largest (> 100 km) asteroids are dark bodies in the outer Belt. These bodies promise very high proportions of volatiles, approaching comet-core compositions. We have already noted that the distribution of Belt asteroid albedos is strongly bimodal, with peaks near 0.04 and 0.25 and a deep minimum in the albedo range from 0.10 to 0.15.

In the same way that NEAs can be reached stepwise, moderate-eccentricity Belt asteroids can be ridden to the Hilda asteroid family 4.0 AU from the Sun, or to the Jupiter Trojan asteroids at 5.2 AU. A significant fraction of this population, which mostly belong to the D and P spectral classes, must be extremely volatile-rich, including both periodic comets and ice-rich asteroids that have never experienced strong solar heating and cometary activity, and some models suggest that the total mass of material in the Trojan clouds is comparable to that in the entire Asteroid Belt. Such orbital transfers also apply, with nearly identical delta V requirements, to accessing the outer small satellites of Jupiter. The outermost Jovian satellites have orbital inclinations of about 160 degrees (strongly retrograde), distances of 20 to 25 million km from Jupiter, and orbital periods ranging from 282 to 340 Earth days, with orbital eccentricities ranging from 0.17 to 0.38. Their diameters range from about 4 to 70 km, the largest being JVIII Pasiphae. Spectral data collected by Faith Vilas in the visible and near-infrared suggest water-altered surface materials on Pasiphae, JXII Ananke, JXI Carme, and JIX Sinope, all of which are members of this outermost group of Jovian satellites. Since dynamical studies suggest the transient nature of the orbits of these retrograde satellites, it is reasonable to expect that they, the Jovian Trojan asteroids, and the outer Saturnian satellites might constitute a single population.

Somewhat closer to Jupiter is a family of larger prograde satellites, including JIII Leda, JVI Himalia, JX Lysithea, and JVII Elara. Their orbital semimajor axes lie between 11 and 12 million km from Jupiter, with orbital periods of 238 to 260 days, eccentricities of 0.14 to 0.21, and inclinations of 26 to 30°. Their diameters range from about 16 km for Leda to about 175 km for Himalia. All have spectra related to the C-cadre asteroids, and Himalia, the largest, appears to be an F-class asteroid, one of the C-cadre classes, with an albedo of only 0.03. The mass of Himalia is larger than the total mass of all the other prograde and retrograde distant satellites combined. Elara, the second largest, also is spectrally compatible with the F class. (Both Himalia and Elara were discovered by my 4th cousin Charles Dillon Perrine, a fact that you will surely never find useful.) All four members of the prograde family show evidence of a charge-transfer absorption centered near 0.7 micrometers wavelength, a feature diagnostic of the presence of oxidized iron in phyllosilicates. The high concentration of dark material is also suggestive of why many outer-Belt C asteroids show no detectable 3-micrometer water absorption feature: the black absorber coats and masks the grains of the water-bearing minerals. In the absence of spectral evidence for water, we can only speculate whether ice might be a major constituent of these small Jovian satellites

Beyond Jupiter's orbit, one might hope to find Saturn Trojan asteroids and outer, retrograde satellites of Saturn. However, no Saturn Trojans have ever been found, even though Earth, Mars, Jupiter, Uranus and Neptune all have them. Saturn's distant small satellites (beyond the orbits of Titan, Hyperion, and Iapetus) show a chaotic mix of prograde and retrograde orbits. The largest of these outer satellites, SIX Phoebe (that's Saturn-nine Phoebe, not 6 Phoebe) is a 220-km body in a retrograde orbit. There are many small bodies at distances of 15 to 23 million kilometers from Saturn, including several small retrograde satellites near 20 million km, many with orbital eccentricities of 0.17 to 0.54. Orbital periods range up to over 1300 Earth days. Uranus boasts not only Trojan companions, but also five small, distant retrograde satellites, all poorly characterized, but with diameters on the order of 20 km.

Neptune's chaotic satellite system, dominated by a giant retrograde moon, NI Triton, defies easy description, and Pluto, with one large satellite (PI Charon) and several tiny companions, holds only remote interest.

Patrolling the outer Solar System are thousands of dirty-ice bodies, the Centaurs. From Jupiter on out to Neptune, these bodies pursue generally unstable, short-lived orbits subject to severe perturbation by, and impacts with, the Jovian planets. Because they exist, they must be a naturally renewable resource, possible recruited from populations farther from the Sun. The largest Centaurs are huge (10199 Chariklo has a diameter of about 260 km), carrying a mass of volatiles comparable to the entire mass of volatiles in the Asteroid Belt. Present estimates of the Centaur population suggest 40,000-50,000 bodies with diameters greater than 1 km. Several Centaurs display cometary activity, and are entitled to bear both asteroid and comet designations. There is evidence that Saturn's moon SIX Phoebe (with its diameter of about 220 km) may be a captured Centaur. Close-up imaging data on Phoebe from the *Cassini* spacecraft in 2004 plus tracking data provide a mass estimate of 8.3×10^{21} g and a density of 1.64 g/cm^3, a number that is characteristic of "dirty snowball" cometary bodies with cosmic proportions of ice and rock.

From about the middle of the Asteroid Belt at 2.8 AU from the Sun out to Jupiter the abundance of water in asteroids is high: individual objects with interiors of comet-like composition, dominantly water ice and other frozen volatiles, may be common. The Centaurs represent a compositional class in which the members have generally not experienced severe surface heating and loss of volatiles. It is unfortunate that the asteroids most accessible to Earth, the Aten NEAs, are the driest group known. This fact encourages us to seek out exploitation targets that are not only nearby, but also made of the right stuff.

Logistics of Asteroid Mining – and Beyond

Several studies of the logistics of retrieval of asteroidal material for use in space and on Earth have been published, out of which a few of the most cogent conclusions are outlined in **Table X.2**. The central theme of these studies has been the establishment of a permanent, self-sustaining human presence in space, deriving all necessary resources from accessible Solar System bodies and powered by the Sun. A few critical technologies are required to set the process of human expansion into space in motion. The first of these required technologies is the direct use of asteroidal water for propulsion, such as in Solar Thermal Propulsion and in electrical propulsion systems that use water as the working fluid. The second is the fabrication of aerobrakes to permit aerocapture of returning asteroid payloads into the Earth-Moon system.

Table X.2 Logistics of Sustained Asteroid Mining

1. Use of space-derived propellants is essential
2. Direct use of water as propellant is highly desirable: Solar Thermal Propulsion
3. Spectral characterization must be required before launch to any asteroid
4. High importance of targeting C-cadre asteroids for their content of volatiles
5. Large logistical advantages of transporting only useful (processed) materials
6. Need for one-step fully automated processing (magnetic or volatility)
7. Large safety and reliability incentives to avoid drilling, blasting, and crushing
8. Target asteroid must be large enough for regolith development and ice retention
9. Missions should be based in HEEO for ease of departure and return
10. Development of space-derived aerobrakes needed for aerocapture upon Earth return
11. Multiple HEEO-asteroid round trips are highly desirable
12. Target markets are propellants in LEO and HEEO, metals and station-keeping propellants in GEO, and radiation shielding wherever humans travel
13. All possible human consumables can and should be derived from asteroids
14. Multiple-trip scenarios with aerocapture and water-based propulsion can deliver mass payback ratios of 100:1or better

A third critical technology is the development of propulsion systems that use the bulk (unprocessed) material of the asteroids as reaction mass for de-spinning the asteroid, diverting it in its orbital motion, or returning asteroidal resources to near-Earth space.

On the asteroids themselves, water extraction and purification by automated equipment is essential. Added capabilities would arise from the production of hydrogen and oxygen for chemical rocket propulsion, but this step is not an essential prerequisite for development.

The sequential expansion of access to ever more remote and ever more massive reservoirs of resources begins with Earth launch, extends first to the Near Earth Asteroids and the moons of Mars, then to the Asteroid Belt, then to the Jovian Lagrange point populations of Trojan asteroids and the outer moons of Jupiter, then to the Saturn system and the Centaurs, then to the Uranus and Neptune systems, then to the plutinos and the Kuiper Belt. Each step here will take many decades to play out, assuring that we will not progress very far along this road before new, superior technologies emerge to make our expansion easier and faster.

The next step along our path beyond these relatively closely-spaced stepping stones is the development of interstellar travel. It seems likely that fusion propulsion, whenever it is mastered, would be required to make that giant step. There is an eternal truth about controlled fusion: it is always about 30 years off. I suspect that this is an eternal truth because it has been true since I was an undergraduate. Present wisdom says we will reach the point of commercially viable fusion reactors in “mid-century”, which I take to be 2040 to 2060. Yes, that day may arrive within 30 years—or maybe it will remain eternally true. Much of the uncertainty about the time scale may be resolved by the ITER (International Thermonuclear Experimental Reactor) program, currently under construction in France, and still years away from operation. You may follow the progress of ITER at: http://www.iter.org/. When (and if) fusion reactors become a practical reality, the demand for fusion fuels will become the dominant energy issue facing human civilization. In space, fusion propulsion would enable enormous increases in our ability to travel at high speeds and to move vast masses of material. The atmospheres of the Jovian planets contain quantities of the desirable fusion fuels deuterium and helium-3 sufficient for all conceivable human needs. Access to these resource-rich environments requires the ability to operate deep in a planetary gravity well and to escape from it: since Jupiter and Saturn’s gravitational potentials are excessive, Uranus and Neptune emerge as the more promising targets if some form of high-thrust nuclear propulsion (NTP or fusion) is available.

Our present concerns about exhausting resources should be viewed in the context of our exponentially growing knowledge of the Solar System in which we live. We also must acknowledge the dawning of a new era of low-cost access to space through competitive private launch services, which makes space travel much more accessible to commercial and private travelers. Our present zero-sum game of competition for ever-dwindling terrestrial resources need not be the model for our future. Instead, we may choose a limitless future by turning to the vast ocean of energy and resources that lies around us.

Our journey into that ocean begins with the Near-Earth Asteroids.

Appendix A
Detailed Taxonomy of Meteorites

This Appendix contains a much more detailed description of the known classes of meteorites. The order of treatment, as in Chapter III, begins with the "primitive" meteorites, the chondrites, which are the meteorites that have not undergone melting and separation into layers of different density and composition. We then treat the differentiated meteorite classes, beginning with the achondrite stones, then the stony-irons, and concluding with the irons.

Chondrites

The meteorite types that are most volatile-rich, and hence closest to the Sun in elemental composition, are the *carbonaceous chondrites*. The common features shared by all carbonaceous groups are 1) a high content of carbon and organic material, 2) a generally high level of oxidation of the mineral phases, illustrated by the low to vanishing proportion of metallic iron and the high abundance of iron oxides. The usual taxonomy of carbonaceous (C) chondrites includes eight groups, each named after the type example of that group: CI (after Ivuna), CM (after Mighei), CV (Vigarano), CO (Ornans), CK (Karoonda), CB (Bencubbin), CR (Renazzo) and the CH group (H here means exceptionally high total Fe and Fe metal content). Of these, CI is the "most primitive" (most volatile-rich; most similar to the Sun in elemental composition), with CM next in order. The C chondrites clearly span a considerable range of properties, mineralogy, and presumably different parent bodies. Some rare or unique C chondrites remain unassociated with any defined group.

Far more abundant in our collections, and far more uniform in mineralogy, are the chondrites that are dominantly composed of a mixture of olivine, pyroxene, troilite, plagioclase, and metal. Because of their abundance, they are collectively referred to as *ordinary chondrites*. There are significant differences in Fe metal content and FeO content between the different ordinary chondrites groups, but they are formally distinguished by their total iron abundance (i. e., their bulk Fe:Si ratio). All the ordinary chondrites groups have somewhat lower Fe:Si than the C chondrites. The ordinary chondrites group with the highest Fe:Si ratio is called the high-iron (H) group, and there is also a low-iron (L) group. Subsequent to the discovery of this distinction a third group with even lower total Fe was identified and named the low-low-iron

(LL) group. The H and L chondrites are the two most common groups of meteorites, with the LL chondrites several times less abundant. Grady's *Catalog of Meteorites* lists 6902 H chondrites, 6213 L chondrites, and 1044 LL chondrites. In addition, there is an apparently significant cluster of three other meteorites called the K (Kakangari) chondrites, which are closely similar to the L chondrites in Fe:Si but distinctly lower in oxidized iron content. They are sufficiently rare to make the epithet "ordinary" seem forced and inappropriate.

The remainder of the chondrites are highly reduced, containing less, and sometimes far less, than 1% FeO. They therefore are essentially devoid of olivine, with the pyroxene phase consisting of very pure enstatite. For this reason, they are called the *enstatite (E) chondrites*. The E chondrites consist of two distinct groups with different total iron contents, the EH and EL groups. The EH group has an Fe:Si ratio as high as that found in the CI chondrites (about 30% metal), whereas the EL group has a total Fe content of about 23%, similar to that of the L chondrites. The LL chondrites contain only 20% total Fe.

Figure A.1 displays the major compositional trends in the chondrites in a format of % "reduced" iron (Fe in Fe metal plus FeS) vs % Fe in Fe oxides in bulk meteorite material. Contours of constant total iron content have a slope of -1; lines for 28%, 23%, and 20% total iron are shown. The highly reduced and very iron-rich E chondrites are shown on the left side of the diagram, cleanly resolved into two groups, EH and EL. The H, L, and LL chondrite regions of the diagram are outlined, as are the regions occupied by the CV and CO chondrites and the CM and CI chondrites. The rare R chondrites are also included.

In addition to these chemical groups, chondrites can be characterized by their degree of internal recrystallization and equilibration. That re-equilibration may reflect temperature during long-term storage inside parent bodies or peak temperatures reached during later re-heating. The CI chondrites show least evidence of such thermal alteration, and are assigned a petrological grade of 1. The scale runs from 1 to 6, with a petrological grade of 7 denoting a high degree of crystallization with peak temperatures little short of incipient melting (some meteoriticists recognize individual stones of petrologic grade 7; some do not). The easiest measure of the petrologic grade is the degree of recrystallization (devitrification) of the glassy chondrules.

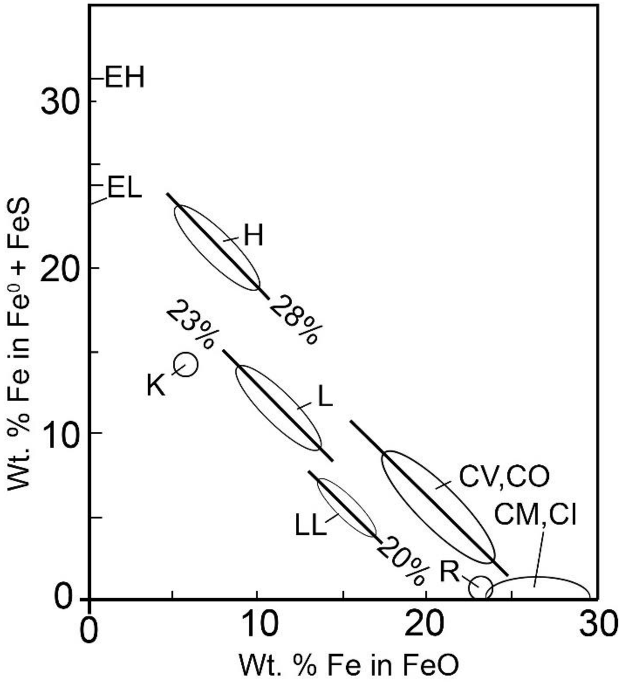


Figure A.1 Compositional Trends in Chondrites. A Urey-Craig plot of the abundance of reduced (metal plus FeS) iron vs. oxidized iron in chondrites. Diagonal lines of slope -1 correspond to constant total iron content; H denotes the High-iron chondrites, L is the Low-iron, and LL is the Low-Low iron group. The CI, CM, CV and CO chondrites and the compositionally similar (nearly metal-free) R chondrites cluster together; the strongly reduced E chondrites lie close to 0% FeO (typically < 0.03%).

Credit: Deep Space Industries – John S. Lewis

Table A.1 lists all known chondrite falls through June, 2012.

Table A.1 Observed Falls of Chondritic Meteorites

Source: http://www.lpi.usra.edu/meteor/metbull.php?code=57165

Grade:	**1**	**2**	**3**	**4**	**5**	**6**	**Total**	**% of all falls (1100)**
C	5	19	14	2	0	0	40	3.7%
EH			3	3	2		8	0.7
EL						8	8	0.7
H				59	170	80	309	28.1
L			10	20	78	264	372	33.8
LL			13	25	1	42	81	7.4
All chondrites	5	19	40	109	251	394	818	74.4*

* Many unanalyzed stones are also chondrites, and many others are known to be chondrites but have not been studied in sufficient detail to assign them to specific groups. The true percentage of chondrites among all falls is probably close to 90%.

Carbonaceous Chondrites

The carbonaceous (C) chondrites are of great interest because of their high content of non-biogenic organic material. They have the lowest density and highest porosity of all meteorites; many contain abundant water in the form of –OH silicates, interlayer and adsorbed water on phyllosilicates, and hydrated salts, all of which can be released as vapor by heating to moderate temperatures. They are also physically weak, making them highly vulnerable to aerodynamic destruction during entry. Because of this weakness, many carbonaceous chondrites stones are tiny, on the order of 1 to 10 grams. Each stone is loosely bound together by organic matter and water-soluble salts, making them extremely susceptible to destruction during atmospheric entry, to contamination, and to weathering. Many carbonaceous chondrites are observed falls, known only from small pieces recovered from hard ice in Antarctica or on high-latitude lakes in winter.

There are eight recognized compositional families of C chondrites and a number of unique individuals that cannot be assigned to groups. The C chondrites may originate on as many as 15 different parent asteroids. The highly eclectic nature of C chondrites suggests that carbonaceous asteroids are very common in the NEA population. **Table A.2** lists all known falls of carbonaceous chondrites. In addition, 12 CH chondrites are known, all finds, and 26 additional CRs are among the finds.

Table A.2 Observed Falls of Carbonaceous Chondrites

Source: http://www.lpi.usra.edu/meteor/metbull.php?code=57165

Class	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
CI	5						5
CM		15					15
CV			7				7
CO			6				6
CK				2			2
CB							1
CH							0
CR		2					2
C unclassified		4	1				5
All Cs:	5	19	14	2	0	0	40

CI Chondrites

As the most primitive and most volatile-rich meteorites, the CI chondrites are all assigned petrologic grade 1, implying that alteration was driven by water, not by high heat. This group is small, consisting of five observed falls, Orgueil, Tonk, Alais, Ivuna, and Revelstoke, and two tiny and relatively poorly characterized Antarctic finds. The type example, and source of the CI designation, is Ivuna.

These meteorites are distinguished by their very high content of organic matter and water. The organic matter, chiefly insoluble and involatile tarry or kerogen-like polymers, pervades these meteorites and coats its mineral grains. This material probably predates the formation of asteroids, having been made by surface-catalyzed reactions on fine grains dispersed in a low-density gas of grossly solar composition, either in the Interstellar Medium or in the original Solar Nebula from which the Solar System formed. The polymeric organic matter is accompanied by water-soluble and volatile organic compounds, including hydrocarbons, carboxylic acids, aldehydes, ketones, alcohols, amino acids, and organic bases.

The CI1s also contain white veins of oxysalts including carbonates, sulfates, and phosphates, many of them bearing easily extracted water of hydration, and found as well-formed crystals diagnostic of slow crystallization from solution in liquid water.

Among the dominant minerals in the CI1s are magnetite (Fe_3O_4) and a variety of hydroxyl silicates with layered, mica-like structures (phyllosilicates), which also can accommodate water molecules between the silicate sheets. The usual ferromagnesian minerals, olivine and pyroxene, are virtually absent except for small, heavily weathered grains. Water attack on both of these minerals causes a process called "serpentinization" , the wholesale oxidation and hydration of these relatively high-temperature minerals to form serpentine [$(Mg,Fe)_6Si_4O_{10}(OH)_8$] and other phyllosilicates. Measured water abundances in CI1s run as high as 22%, but there are also water adsorption sites that are unfilled in fresh falls, apparently due to the loss of very loosely-bound water in space before falling on Earth. Both the phyllosilicates and the veins of water-soluble salts such as gypsum ($CaSO_4{\cdot}2H_2O$) and epsomite ($MgSO_4{\cdot}7H_2O$) attest to the former presence of liquid water and hence to temperatures high enough to melt ice. It is clear from the mineralogy that the minerals in the CI1s have experienced the highest degree of oxidation encountered in meteorites.

Magnetite's formula ($Fe_3O_4 = Fe_2O_3{\cdot}FeO$) illustrates the abundant presence of Fe^{3+}, ferric iron, in stark contrast to the general behavior of iron in meteorites, which exclusively favors Fe^{2+} (ferrous iron) and Fe^{o} (metallic iron). The chemistry of sulfur also bears strong evidence of oxidation. Small amounts of FeS and other sulfides are present, along with elemental sulfur, organic sulfur compounds, and the sulfates in the white veins. At isotopic equilibrium, the sulfur in the sulfates would be much heavier (a high ^{36}S:^{32}S ratio) than either S or FeS; but in the CI1s the sulfate is isotopically far lighter than the S in either elemental sulfur or sulfides. The only way to account for the observed pattern is to invoke kinetic isotope fractionation during unidirectional oxidation of sulfide to make sulfur and sulfate. Laboratory simulations show that this oxidation process requires the presence of a strong oxidizing agent such as oxygen or hydrogen peroxide in liquid water, and must have taken place at a temperature near $0^{o}C$.

The apparent paradox presented by the pervasive coexistence of highly reduced and highly oxidized materials can be resolved by attributing the origin of these two components (organics and oxysalts) to two different environments, and requiring that temperatures experienced by the mixture were never high enough to permit chemical and isotopic equilibration. The organic polymer is certainly older than the oxidized minerals, and the chemical and isotopic evidence can be satisfied by having the oxidation process occur in an asteroidal parent body where cold water was stable and an oxidizing agent was present. The water-soluble organics may in large part be derived from attack by liquid water and oxidizing solutes on the more reactive parts of the older polymer. The question of what source of oxidizing agents was available is especially interesting. A source of oxygen or HOOH from solar UV photolysis of water vapor would require a bound water-bearing atmosphere on the parent body, but all reasonable parent asteroids are far too small to allow retention of an atmosphere and far too cold to have water vapor or liquid water present near its surface. Surface water is not an option for asteroids: liquid water would boil away instantly, even at the freezing point, and be lost into space. Radiolysis of water in the interior of the asteroid by beta and gamma radiation from radioactive decay events may provide an adequate source of oxidizing agents, providing that they can be dissolved and concentrated in aqueous solution. The hydrogen made by radiolysis of water would rapidly diffuse to the surface of the asteroid, where it would instantly be lost from the asteroid's feeble gravitational field.

There are interesting parallels between the sulfur chemistry of Jupiter's innermost Galilean satellite, Io, and the chemistry we see in the CIs. Io (aside from presenting an almost insurmountable problem of pronunciation to scientists and press alike) presents a challenge in explaining the source of the oxidizing agent that made the elemental sulfur and sulfur oxides seen on its surface and in its volcanic emissions.

CI1 material is rare and precious, inhibiting researchers (and museum curators) from carrying out or approving extensive experiments on their release of volatiles upon heating. Yet such research, done on a small scale, has produced fascinating evidence regarding release of water and other volatiles. It is clear from these experiments that even brief heating to 50°C would result in irreversible loss of many volatiles that we observe in them. Even at depths of only 1 or 2 mm inside the fusion crust on CI stones, these volatiles are still present.

CM Chondrites

There are 14 known falls of CM chondrites, including the recent (2012) fall of the Sutter's Mill meteorite in California. An aerial explosion equivalent to several kilotons of TNT dropped 75 recovered stones, the largest of which was an impressive 205 grams. The total number of known CM chondrites, about 100, shows that finds greatly outnumber falls, a direct consequence of their higher crushing strength and superior resistance to weathering compared to CI1 stones.

The type example of the CMs is Mighei, which fell in 1889 in the Ukraine. The CMs, like the CIs, are very dark in color due to tarry organic polymers and magnetite, have a low density because of the absence of free metal, and are highly porous. CMs contain, on average, about half as much water as CI1s. Since CMs are very slightly altered, they are assigned a petrologic grade of 2, so that they are labeled as CM2. Chondrules, though sparse, are present throughout. Both phyllosilicates and magnetite are common. The survival of some chondrules, and the absence of veins of water-deposited oxysalts, attest to the lower degree of water alteration.

Small white inclusions (called calcium-aluminum inclusions, or *CAIs*) are clearly visible in the black matrix. The CAIs, which have diameters of a few millimeters, are characterized by high concentrations of Ca, Al, and Ti. They contain distinctive minerals such as corundum (Al_2O_3), perovskite ($CaTiO_3$), and spinel ($MgAl_2O_4$). Both silicon and iron are severely depleted in the CAIs.

Figure A.2 This is an organics-rich CM sample from the massive Murchison fall.

Credit: Aerolite Meteorites LLC

All the minerals present in the CAIs are *refractory*, meaning that they have very low vapor pressures. They are concentrates of highly refractory minerals that have survived at temperatures so high that virtually everything else remained as vapor: they have the composition of heat-shield (aerobrake) material, or of the refractory bricks made for use in high-temperature chemical and mineral processors. Research on the CAIs in the Allende meteorite below supports the idea that these particles were early high-temperature condensate from a very hot gas, not evaporation residues from extreme re-heating of typical chondritic solids, and hence that they are very ancient.

CV Chondrites

The CV chondrites derive their name from the type example, Vigarano, which fell in 1910 in Italy. Roughly 60 independent CVs are known, seven of which are observed falls. These meteorites, which show no evidence of alteration by either liquid water or heat, are assigned petrologic grade 3. The most massive CV3 fall, and for that reason the most-studied, was the Allende meteorite, which dropped a large number of stones in northern Mexico in 1969.

Figure A.3 An example of a CV carbonaceous chondrite with prominent chondrules.
Credit Aerolite Meteorites LLC

The differences between the CV3 chondrites and the CI1 and CM2 chondrites are profound. The CV3s contain far less carbon and only a trace of water, with a high abundance of large, un-weathered chondrules. Aside from the presence of magnetite, the major-element mineralogy is closer to that of ordinary chondrites than that of CI1s and CM2s. The dominant mineral in the fine-grained matrix is fayalite-rich (high FeO) olivine, in contrast to the chondrules, which are much more magnesian (forsterite-rich) and frequently contain FeS (troilite). White salt veins are wholly absent, and CAIs are large and abundant.

The CAIs in the CV3 chondrite Allende contain tiny diamonds with anomalous ^{13}C:^{12}C ratios that require an origin outside the Solar System in a distinctly different isotopic reservoir, such as the remnants of a supernova explosion. Many of the larger CAIs display distinct layering from deposition of a changing suite of minerals on their surfaces during cooling.

CO Chondrites

The type example of this group is the Ornans chondrite from France, an observed fall from 1868. CO chondrites exhibit a number of similarities to the CVs and to the CK chondrite group discussed below. All belong to petrologic grade 3, reflecting absence of both alteration by water (as in CI and CM chondrites) and thermal recrystallization, as in the large majority of chondrites. Thus they are all designated CO3 chondrites. Six CO falls are known, out of 46 members. The ratios of finds to falls for COs and CVs are both about 8:1, reflecting the similar physical strengths for the two groups.

The water content of CO3s is quite small, and tiny flakes or particles of metal are present. Aside from the presence of magnetite, most of the minerals of the CO3s are far less oxidized than those of either the CI1 or CM2 groups. The meteorite matrix contains a densely packed array of small chondrules. Many small CAIs are also present. The chemical and mineralogical similarities between the CV3 and CO3 chondrites make it plausible, but far from certain, that they may originate from the same asteroid.

CK Chondrites

The type example of the CK group is Karoonda. It and Kobe are the only two observed falls, out of roughly 200 individual stones known. Based on geographical distribution and chemical similarities, it is likely that those 200 stones originated in only 20 events. The proportion of falls to finds is similar to that seen in the CV3s and CO3s, suggesting a similar strength. Like CV3s and CO3s, the CK chondrites contain CAIs and abundant chondrules. Large CAIs are found in some but not all individuals. Also similar is the presence of magnetite, a small amount of metal, and a rather FeO-rich olivine. Significant NiO resides in the olivine, an indicator of rather oxidizing conditions. Some of the CK stones exhibit clear evidence of thermal metamorphism, but none show evidence of the action of water. Individual stones are ranked as CK3 to CK6, although most are classified as CK4.

The oxygen abundance systematics link CK with CO and CV meteorites and with the high-temperature minerals in the CMs. Some CK stones exhibit evidence of strong mechanical shock.

CR Chondrites

The CR chondrites are those that resemble the type meteorite, Renazzo. Only two CRs were observed to fall, Renazzo and Al Rais. The total number of known CRs is about 15. These are quite primitive meteorites, most individuals being assigned petrologic grade 2. They contain water-bearing phyllosilicates and magnetite, coexisting with up to several weight percent of metal and FeS. The metal is found both in the black matrix and in the large and abundant chondrules. Some of these chondrules are coated with metal and FeS, earning them the name "armored chondrules". This feature sets the CRs apart from all other C chondrite groups except the CBs, described below

Genetic connections between the CR chondrites and the CH and CB groups have been suggested, leading some researchers to refer to them collectively as the "CR clan".

CH Chondrites

The type meteorite of this group is an Antarctic meteorite from the Allan Hills search area, named ALH 85085. Since this name defies abbreviation in the usual fashion, the name of this group has been chosen to reflect the high metal content of its members: CH is a mnemonic for "Carbonaceous High-Iron". Other members of the group include Acfer 214, Acfer 366, SaU 290 and 8 others, all finds, and all with equally unprepossessing names. The CH chondrites fall into petrologic grades 2 and 3. Their chemical and petrological similarity to the CR and CB chondrites has already been remarked.

The most striking feature of their chemistry is the presence of 15% of metallic iron-nickel. Most of the chondrules in them are broken, and the CAIs are quite small. They also contain some phyllosilicates in coexistence with the metal.

CB Chondrites

The minimum requirement for defining a meteorite group is that it must have at least five members. The CB chondrites just meet this criterion. The type example is Bencubbin, a meteorite found in Australia in 1930. One fall, Gujba, is known in this group.

The chemistry of the CB chondrites is unique: they contain as much as 50% Fe-Ni metal. They also contain low-FeO silicates and have, like the CR chondrites, armored chondrules. Some CBs contain CAIs. Genetic relationship to the CRs is quite plausible, but whether they are siblings from the same parent body, or cousins from asteroids with closely similar histories, remains to be discovered.

C Oddities

We include here both ungrouped meteorites and outliers of recognized groups. One prospective future group, presently consisting of three members, is the Coolidge "grouplet", Coolidge, Sahara 00177, and

Loongana 001. These objects share a high ratio of matrix to chondrules and a general enrichment of refractory elements.

Certain of the unabashedly carbonaceous meteorites appear to be heated and partially outgassed CI1 and CM2 meteorites. These include Belgica 7904, Yamato 82162, Yamato 86720, Dhofar 225, and Dhofar 735. These meteorites contain few and generally small CAIs, are depleted in Fe and S relative to CI1s, and have distinctive oxygen isotope ratios.

Some stones, such as Sahara 00182 and NWA 1152, appear to be borderline cases between the CR3 and CV3 groups. They may be thought of as mixtures, cousins, or transitional representatives in a continuum that spans both groups and thus unites them into a single group.

Finally we encounter Tagish Lake, which fell in 2000 in northern British Columbia, near the border of the Yukon Territory, landing on the ice of Tagish Lake in winter. This meteorite contains two distinct lithologies, one containing carbonate and the other carbonate-free. Tagish Lake contains nano-scale diamonds and refractory grains of interstellar (presolar) origin, and has the lowest density seen in meteorites. The reflection spectrum is strikingly similar to that of the outer Belt asteroid 773 Irmintraud, which is a D-class asteroid with an orbital semimajor axis of 2.858 AU, suggestive of a "super-carbonaceous" source. Of course the fact that Tagish Lake struck Earth requires that it arrived here on an Earth-crossing orbit. How did a piece of a D asteroid get into an NEA orbit? It happens that 773 Irmintraud orbits close to a Kirkwood gap in the Belt, a narrow zone of highly unstable orbits in which bodies receive repeated mutually reinforcing perturbations from Jupiter, leading to a dramatic increase in the eccentricity of the orbit.

Tagish Lake is a C2 chondrite of uncertain affinities to other chondrite classes. More than 500 pieces of this fall were found, totaling over 10 kilograms. The largest stone was about 2.3 kilograms. Best estimates of its entry behavior place its entry mass at 56 tonnes, of which about 0.02% survived to be recovered as meteorites.

No other meteorite similar to Tagish Lake has ever been reported.

Ordinary Chondrites

As we saw in Table III.2, the large majority of all meteorites are stones, the large majority of stones are chondrites, and the large majority of chondrites belong to three groups that contain the same basic minerals, but in different proportions. For convenience, these three groups are collectively referred to as ordinary chondrites ("OCs"), although that phrase has no taxonomic significance. The major distinction between these groups is in their total iron content, which, since we refer all abundances to silicon as the standard, means that their Fe:Si ratios are significantly different.

One of the first generalizations about meteorites linked the density and chemical distinctions between ordinary chondrites to different degrees of oxidation. Thus progressive oxidation leads to 1) a progressive removal of Fe from the metal, causing an increase in the proportions of Ni, Co and other solutes in the remaining metal; 2) addition of FeO to the olivine and pyroxene, and 3) an increase in the ratio of 2+ ions to silicon, manifested as an increasing ratio of olivine to pyroxene. These generalizations, known as Prior's Rules, were found by Harold C. Urey and Harmon Craig to fail to account for the differences between the two most abundant chondrite groups, the H (high-iron) and L (low-iron) groups. Later a third important ordinary chondrite group, the LL chondrites, was discovered. These groups differ in total iron (Fe:Si), and therefore could not possibly be explained by the Prior scheme, in which elemental ratios of lithophile elements were conserved. However, *within* each ordinary chondrite group the Fe:Si ratio is nearly constant, and Prior's rules apply quite well.

The mineralogy of the ordinary chondrites is refreshingly simple after facing the complexities of the carbonaceous chondrites with their soluble salts and refractory inclusions. The essential minerals are two iron-nickel alloys, kamacite (alpha iron, <6%Ni), taenite (gamma iron, >6% Ni), troilite (FeS), olivine, pyroxene, and plagioclase feldspar. The pyroxene may exsolve a Ca-rich phase (clinopyroxene, which crystallizes in the monoclinic system) from the dominant ferromagnesian phase (orthopyroxene, with orthorhombic structure). The usual clinopyroxene is diopside [$CaMgSi_2O_6$].

The major-element composition of the metal grains in ordinary chondrites varies systematically from group to group. The group with the highest formation temperature, the H group, is the least oxidized, and therefore has suffered the least loss of Fe into FeO-bearing silicates. The concentration of Ni in H-group metal is therefore the lowest of the three groups. Co, which, like Ni, is less electropositive and harder to oxidize than iron, follows the behavior of Ni quite closely. The Ni and Co contents of H group metal are typically 8.5 to 11.0 % Ni and 0.3 to 0.55 % Co.

In the L group, the ranges are 11 to 18% Ni and 0.6 to 0.9 % Co. In the more oxidized (iron-poor) LL chondrites, Ni ranges from 20 to 70% and Co from about 1.1 to 4 %. **Figure A.4** shows the trajectory followed by the metal composition during cooling from 1540 K (the onset of Fe-Ni metal condensation) to the point of disappearance of the last Fe metal at about 490 K. The first metal condensate has an elevated Ni content because Ni is more refractory than Fe. Below about1400 K both metals are completely condensed and the Fe:Ni ratio in the metal is given by the cosmic elemental abundance ratio. Below about 900 K the effects of Fe removal from the metal by oxidation to FeO begin to be visible. At 680 K FeS begins to form by reaction of metallic iron with H_2S, a temperature far too high for Ni to form sulfides. FeS formation is essentially complete below 600 K, but accelerating oxidation of Fe to FeO causes the Ni content of the metal phase to increase up to the endpoint for metal oxidation, near 490 K. The residual metal is extremely Ni-rich. Beyond this point, Ni enters into sulfides such as pentlandite. All ordinary chondrites contain FeS and FeO-bearing silicates.

The sequence of oxidation from about 1400 K down to the disappearance of native metal at about 490 K leads to sequential enrichment of cobalt as well as nickel in the residual metal. **Figure A.5** shows the enrichment trends for Ni and Co in the metal phase of ordinary chondrites.

Metal particles in chondrites are frequently associated with troilite and chromite, and cohenite [$(Fe,Ni)_3C$] and schreibersite [$(Fe,Ni)_3P$] are sometimes seen as small inclusions in the metal. Tiny particles of elemental copper are also found associated with the iron-nickel metal phase.

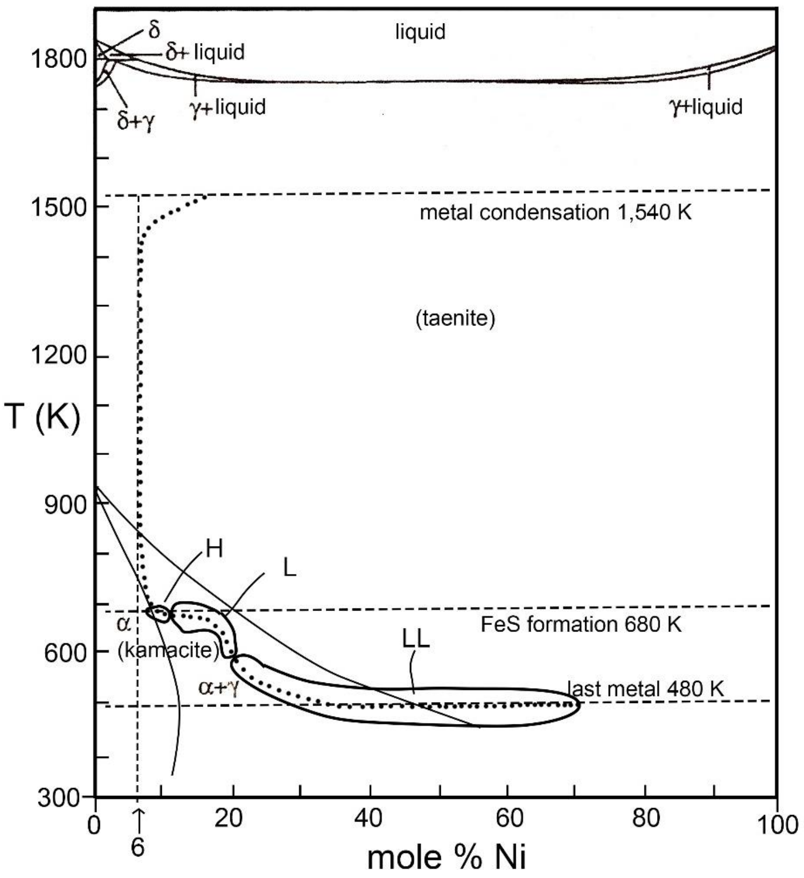


Figure A.4 Compositional Variation of Chondrite Metals. The sequence of reactions of metal with gas for solar composition material from the condensation temperature of metal down to the point of disappearance of the last metal at 490 K is shown by the dotted line on this Fe-Ni phase diagram. The curves originating at 930 K and 0% Ni are the phase boundaries of the two-phase alpha-plus-gamma region. The observed composition ranges of the metal grains in ordinary chondrites are marked with H, L, and LL respectively.

Credit: Deep Space Industries – John S. Lewis

Many minor elements are carried within these mineral phases, although a few do segregate as separate minor and accessory minerals. Chromium often appears as minor amounts of the spinel-structure mineral chromite ($FeCr_2O_4$). Titanium may occur as ilmenite ($FeTiO_3$). The phosphate mineral apatite [$Ca_5(PO_4)_3(OH, Cl, F)$] also appears with variable proportions of OH, Cl and F. Merrillite [$(Ca,Mg)_3(PO_4)_2$] , farringtonite [$Mg_3(PO_4)_2$], and stanfieldite [$Ca_4(Mg,Fe)_5(PO_4)_6$] have also been reported. Orthoclase feldspar ($KAlSi_3O_8$) is also sometimes found as a separate phase, where its solubility limit in plagioclase is exceeded.

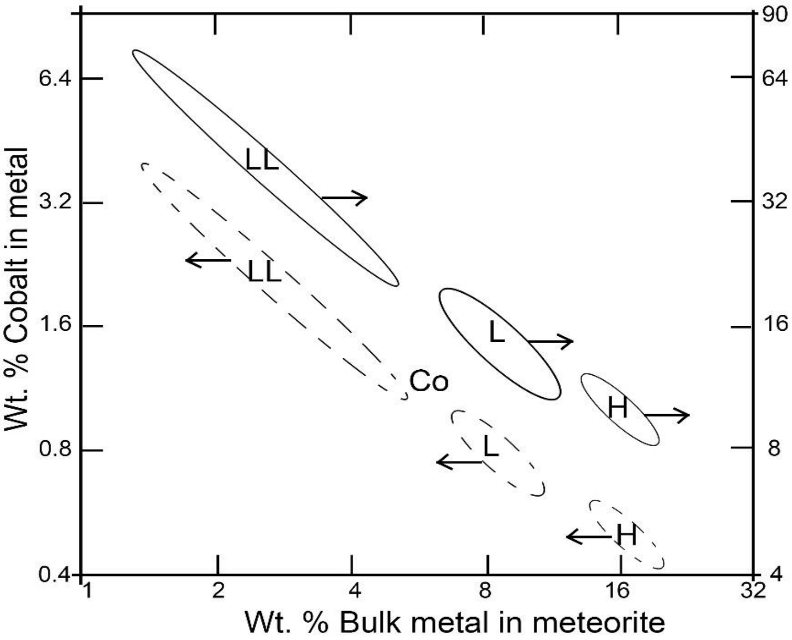


Figure A.5 Cobalt and Nickel Enrichment in Ordinary Chondrite Metal. The nickel and cobalt concentrations in ordinary chondrites are compared and correlated with the weight percent of total metal: the dashed line (left-hand scale) gives the Co content; the right hand scale and solid lines give the Ni content.

Credit: Deep Space Industries – John S. Lewis

The lowest petrologic grades of ordinary chondrites (the L3 and LL3 stones) also contain traces of phyllosilicates in their matrix.

H Chondrites

The metal phase in the high-iron ordinary chondrites is iron-rich. The total weight % Fe in the metal plus troilite ranges from 18 to 23%. The metal contains the highest proportion of Fe and the lowest proportion of Ni found among the ordinary chondrites, making the alpha (low-Ni) phase kamacite the dominant crystal form of metal. In the higher metamorphic grades of H chondrites (especially grade 6) reheating and quenching have nearly homogenized the metal, giving it a micro-crystalline structure called *plessite*.

Abundances of the minor elements in the metal phases of ordinary chondrites are a composite of several effects: the higher degree of oxidation of metal that coexists with high-FeO silicates; the differential solubility of the minor and trace elements in kamacite vs. taenite; the increasing proportion of taenite relative to kamacite due to oxidative

Figure A.6 This 2.5 gram H chondrite was collected in Burkina Faso.

Credit: Amethyst Galleries, Inc.

removal of iron from the metals; the effect of formation temperature on element abundances due to differences in the elements' volatility; and the formation temperature of the metal phase (which may reflect the temperature gradient in the early Solar System, causing low T to correlate with high oxidation). The H chondrite metal contains, not surprisingly, the lowest Ni and Co content of the ordinary chondrite metals. They also have the lowest Au:Ni ratio, reflecting the fact that gold, which is even more strongly siderophilic than nickel, is also far more volatile. The H chondrite metal contains a lower concentration of almost every interesting solute, from gold (because of its volatility) to the platinum-group metals (because of their dilution by the high proportion of metallic Fe).

L Chondrites

Aside from the systematic differences in total Fe content, degree of oxidation of iron, and the Ni and Co contents of the metal phase explained above, there is only one other feature requiring comment. This is the existence of a small proportion (about 3 to 5%) of L-group stones of petrologic grade 3. These contain traces of minerals familiar in C chondrites, such as phyllosilicates. If, as seems reasonable, the L chondrites of all petrologic grades originated on a single asteroidal

Figure A.7 This 1.6 gram L chondrite was collected near Jalu, Libya.

Credit: Amethyst Galleries, Inc.

parent body, then the L3 chondrites are prime candidate for near-surface origin. The admixture of C-type material may simply be evidence of contamination by carbonaceous asteroid debris from impact events. Whether the trace of water now observed in these meteorites is of terrestrial origin through adsorption or exchange, or is of pre-entry origin, the existence of phyllosilicates with active water absorption sites essentially guarantees that the parent material once carried traces of native water.

We have already discussed the metal phase of L chondrites in our overview of chondrites.

LL Chondrites

The LL chondrites, by far the least common of the ordinary chondrite groups, have both the lowest formation temperatures of the ordinary chondrites and the highest degree of oxidation. The LL population contains about 15% of LL3 objects, consistent with an origin farther from the Sun than the other ordinary chondrites. Iron-rich olivine (~30 mole % fayalite) coexists with troilite, metal, low-Ca pyroxene, feldspar, chromite, and phosphates. Chondrules are large, ~1 mm in diameter.

Some LL3 chondrites (Krymka, NWA 3099) contain inclusions that appear to be fragments of carbonaceous chondrites plus abundant

Figure A.8 This 1.6 gram LL chondrite was found near Bensour, Morocco.
Credit: Amethyst Galleries, Inc.

troilite, iron-rich olivine, and graphite. The chondrules in many LL3s are shattered. Several LL3 chondrites contain water with elevated D:H ratios, demonstrating a non-terrestrial source. The isotopic heterogeneity of the volatile elements in LL3s suggests very limited reheating and isotope exchange. The chemical trends in the LL chondrites associate the sequence from LL4 to LL7 with successive oxidation.

The metal in LL chondrites, although small in quantity (no more than 3%), is exceptionally rich in siderophile solutes. Several LL chondrites contain taenite particles with Co:Ni ratios greater than 1. One rare kamacite sample from the LL6 Jelica has a Co:Ni ratio of 2 (the cosmic abundance ratio is more like 0.05) with a Co content of 9.55%. We shall return to the topic of Co- and Ni- rich metals when we review iron meteorites.

R Chondrites

The R-group chondrites, often referred to as Rumurutiites after their type example, consist of about 30 stones, of which Rumuruti itself was the only witnessed fall. Most specimens are from African desert sites or Antarctica. The R chondrites have similarities to but are distinct from the ordinary and carbonaceous chondrites. As non-carbonaceous chondrites, the designation “ordinary chondrite” is assumed by default, even though “extraordinary chondrite” would be a better fit.

R chondrites contain fewer chondrules but more xenoliths (foreign rocks fragments) than the ordinary chondrites, suggesting an origin in an impact-shattered asteroid surface layer. In keeping with a regolith origin, they also contain high concentrations of implanted solar wind gases. CAIs are also present. The extremely low metal content of the R chondrites reflects their high degree of oxidation: their total Fe content places then at the extreme low end of the C chondrite spectrum, roughly on a par with H chondrites (See **Figure A.1**). Olivine in R chondrites is high, 37 to 40 mole % fayalite. The sulfides are highly oxidized, with troilite generally absent, and with residual sulfides rich in copper, like those in C chondrites. Even Ni sulfides are oxidized, leading to a high NiO content in the olivine. Fayalite-rich olivine is accompanied by ferrosilite-rich orthopyroxene; the sulfides pyrrhotite, pentlandite, chalcopyrite ($FeCuS_2$), pyrite (FeS_2); graphite; chromite; the (water-bearing) amphibole tremolite [$Ca_2Mg_5Si_8O_{22}(OH)_2$]; traces of magnetite; ilmenite; and particles of metallic copper. The residual Fe-Ni metal is best described as awaruite, with a composition of 67 to 75 mole % Ni, similar to the metal composition in the most extreme LL chondrites and irons.

Enstatite Chondrites

The enstatite (E) chondrites are distinguished by their extreme state of chemical reduction. So extreme were their conditions of origin that many elements depart from their traditional geochemical classification, and many rare or unique minerals abound. As we have seen, the extreme degree of reduction means a very low FeO content, favoring orthopyroxene of enstatite composition, and ensuring that there will not be a sufficient supply of 2+ cations for conversion of pyroxene into olivine. One of the many striking chemical oddities of the E chondrites is that elemental silicon is found dissolved in the metal phase.

The total population of known E chondrites is about 200, of which 16 are observed falls. The E chondrites are divided into two groups on the basis of their total iron content (Fe:Si ratio), called the EH and EL groups, which are different enough to suggest different parent bodies.

EH Chondrites

The known EH chondrites span petrologic grades 3, 4 and 5. All have abundant small (0.2 mm) chondrules; all have low abundances of refractories. The mineralogy of the E chondrites in general is far removed from normal terrestrial experience because of the exceptional degree of chemical reduction. The Ni-poor (kamacite) metal phase contains 2.5-3% elemental Si. The South Oman stone contains 3.9% Si and 6.7% Ni in its kamacite. The silicide mineral perryite is found in several stones, including Kota-Kota, Sahara 97072(EH3), and Horse Creek, with a composition of 81%Ni, 12.4% Si, 4% Fe, and 3.5%P. Translated into a formula, this composition corresponds roughly to $(Ni,Fe)_2(Si,P)$, but with the (Si,P) slightly deficient (~8 metal atoms per 3 nonmetal atoms).

Some individuals contain igneous graphite in impact melt breccias; not exsolved from Fe metal. There is an astonishing variety of very unusual sulfide minerals, many unknown from terrestrial experience and never found in ordinary chondrites: oldhamite CaS, niningerite (Mg,Fe)S, ferroan alabandite(Mn,Fe)S, titaniferous troilite, manganiferous daubreelite ($FeCr_2S_4$) (a thiospinel), caswellsilverite ($NaCrS_2$), and djerfisherite $K_6Na(Fe,Cu,Ni)_{24}S_{26}Cl$. Of the cations in these sulfides, Ca, Mg, Ti, Cr, Mn, Na and K, normally all unambiguous lithophiles, are the most striking evidence of a very low state of oxidation.

The lowest metamorphic grade (EH3) individuals contain abundant carbon and a variety of volatile hydrocarbons. The Abee EH3 stone contains impact melt with 0.42% C, 0.01% shock-produced diamond, and traces of methane, ethane, ethylene, acetylene, and benzene (for a total content of gaseous hydrocarbons of 0.3 ppm). The involatile organic polymer has a very low D:H ratio and a very low ^{13}C:^{12}C, unlike the graphite.

EL Chondrites

The low-iron enstatite chondrites range from petrologic grade 3 to 6, favoring 6. The chondrules in the EL chondrites are typically several times larger in diameter (about 1 mm) than those in the EH chondrites. The metal grains are also larger, and most individuals show textures characteristic of recrystallization. The rare sulfide mineral alabandite (MnS) is present; unlike the EHs there are no alkali sulfides. The ELs also contain the unusual mineral sinoite, Si_2N_2O, whose formula makes sense if written $Si_3N_4 \cdot SiO_2$: it is an interlayer compound of silica and silicon nitride.

The dominant mineral, enstatite, is usually reported to contain 0.4 to 4% ferrosilite ($FeSiO_3$); however, electron microprobe analyses of the orthopyroxene phase have often been contaminated by the presence of tiny blebs of kamacite and troilite, leading to an overestimate of the Fe content of the silicate. The most careful analyses, with active discrimination against Fe contamination, find 0.02-0.04 mole % $FeSiO_3$.

Even so, it might be more cautious to quote a range of 0.01-0.04% for the ferrosilite component, far below the range found in silicates on Earth, Mars, or the Moon. This extreme degree of reduction is mirrored by the presence of up to 1% Si in the kamacite phase. Comparison to the EH chondrites, with up to 4% Si in the metal, and with smaller enstatite particles (more vulnerable to contamination by foreign iron), suggests that the true uncontaminated ferrosilite abundance in the EHs may be even lower than in the ELs.

K Chondrites

The type example of the K chondrites is Kakangari. There are three known K chondrites, all of petrologic type K3. They contain armored chondrules and abundant troilite, with metal abundances around 15 % by weight, similar to H chondrites. They have high proportions of fine-grained matrix, ranging up to over 75% of the total volume, a trait reminiscent of C chondrites. The olivine contains only 2.2 mole% fayalite and the enstatite contains 4.4% ferrosilite, intermediate between the E and H chondrite groups. Their oxygen isotope ratios distinguish them from all other chondrite groups. For these reasons, it appears certain that the K chondrites are a distinct and independent group which, despite the smallness of their number, justifies treating them as samples of a separate parent asteroid.

Achondrites

Of the three main categories of igneous meteorites, achondrites are those that represent the essentially metal-free silicaceous differentiates analogous to terrestrial crustal and mantle rocks. The much-denser core-forming metal-rich meteorites, the irons, and the intermediate-density stony irons complete the list of complementary differentiates.

The silicate and metal phases in these differentiated meteorites, like the undifferentiated chondrites, span a wide range of oxidation states. In particular, there is a carbon-rich class of achondrites called the ureilites, a suite of three related groups of more ordinary composition embracing the *howardites, eucrites*, and *diogenites*, collectively referred to as the *HED* achondrites, and a strongly reduced group, predictably very rich in enstatite, called the enstatite achondrites. Again, as with the chondrites, there are some individuals and grouplets which defy classification and probably represent different but poorly sampled parent bodies.

Ureilites

The ureilites, named after the type example Novi Urei, are represented by about 100 stones, many recovered from the deserts of North-West Africa. They contain up to about 3% carbon, largely as graphite and tiny (few micrometers in diameter) black diamonds. They also bear soluble organic materials, including a suite of amino acids. They are dominated by olivine and pyroxene (about 97% of their total mass) and essentially devoid of feldspar. The ureilites have suffered severe collisions, lending them a brecciated structure of re-bonded rock fragments. Some individuals are composed of re-accumulated fragments of a single uniform composition (a monomict breccia) and some contain fragments of two or more different types of parental material (polymict breccia).

Particles of metal have exceptionally low Ni contents, lending credence to the idea that the metal was formed as a result of shock heating of the mixture of FeO-bearing silicates and graphite. The metal is accompanied by sulfides and Fe_3C. There is a general positive correlation between the FeO content of the silicates and the graphite content from stone to stone, strongly suggesting that reheating has caused reduction of FeO even to the point of exhaustion of graphite. The graphite-free extremes have the highest metal content, the lowest FeO content, and even free silica, SiO_2, which is a product of the reduction of ferrosilite. Typically the FeO content is higher in grain interiors than in their rims.

Olivine and pyroxene grain sizes less than 1 mm are most common; however, some ureilites contain pyroxene grains with sizes up to 2 cm mixed very unevenly with the more common small-grained material.

The observed general depletion of chalcophiles suggests that the ureilite parent body underwent early core formation, with separation of a dense, fluid Fe-FeS eutectic melt.

There are reports in passing in the literature claiming that ureilite material is attracted by a magnet. Presumably these are the individuals that have experienced the greatest degree of FeO reduction to metal.

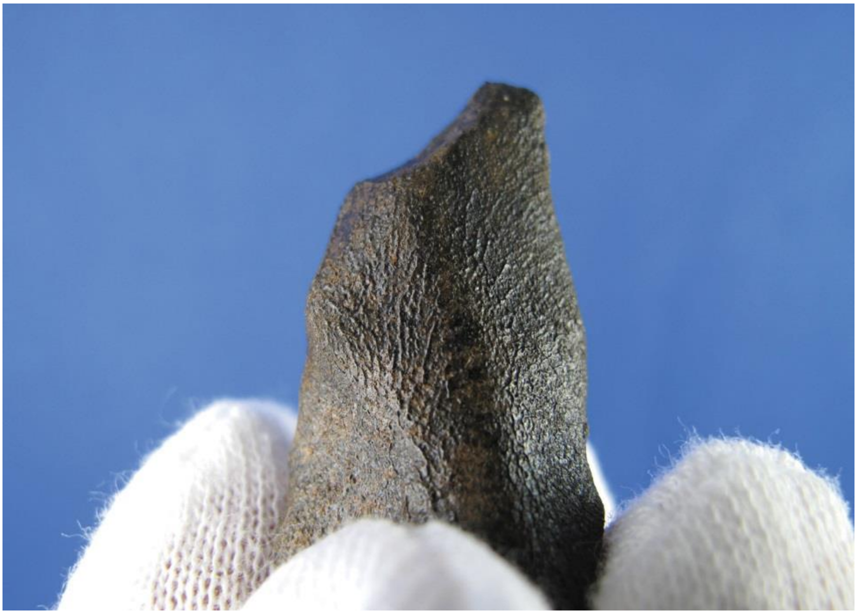


Figure A.9 A basaltic eucrite has reflection spectra similar to that of the main Belt asteroid 4 Vesta.

Credit: Aerolite Meteorites LLC

Howardite-Eucrite-Diogenite (HED) complex

When we surveyed the chondritic meteorites we devoted relatively little attention to the three most common ("ordinary") chondrites, the H, L and LL groups, simply because they bore such a close similarity in mineralogy. Similarly, the three dominant classes of achondrites, which together account for about 60% of all achondrites, are mineralogically similar to one another and may be treated as a single topic. The dominant minerals in these three achondrite groups are pyroxene, feldspar, and some olivine, the minerals that make up basaltic rocks on Earth, leading to the term "basaltic achondrites" for them. The HED meteorite share the common characteristic that they are differentiated silicate rocks with very low, and often undetectable, metal and sulfide contents. The reflection spectra of HED meteorites are closely similar to that of the asteroid 4 Vesta and its family of small collision fragments.

Monica Grady's *Catalog of Meteorites* reports 93 howardites, 94 diogenites, and 200 eucrites, numbers which include multiple stones that apparently were parts of the same fall events. The number of distinct falls may be as low as about half these numbers.

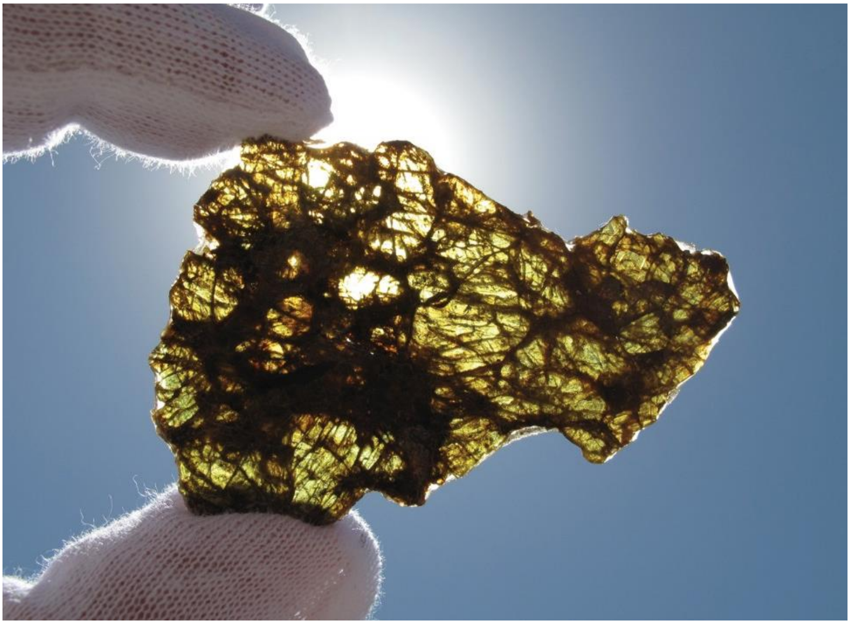


Figure A.10 A thin section of a diogenite meteorite.

Credit: Aerolite Meteorites LLC

The diogenites are distinguished by a low proportion of calcium (a Ca/Mg atomic ratio of 0.02 to 0.04, compared to about 0.05 in ordinary chondrites) and a Fe/(Fe+Mg) ratio of about 0.25 to 0.30. They are dominantly composed of pyroxene with minor plagioclase feldspar and olivine. Crystal sizes in diogenites are larger than in the eucrites and howardites, implying slower cooling and prolonged crystallization, and therefore greater depth of burial in their parent asteroid.

At the opposite extreme are the eucrites, which have so high a plagioclase content that the Ca/Mg ratio is about 1. The Fe/(Fe+Mg) is very high, around 0.6, even higher than most C chondrites and proving a high degree of oxidation. The dominant minerals are a low-calcium, high-iron pyroxene called pigeonite and a very Ca-rich plagioclase of approximate anorthite ($CaAl_2Si_2O_8$) composition. The textures of eucrites range from consolidated regolith breccia to cumulates that appear to have formed in deep-interior magma chambers. Some eucrites are mixtures of eucritic with a few percent diogenite material (a “polymict breccia”) transitional to the howardites.

Figure A.11 A representative sample of howardite from the HED complex.

Credit: Aerolite Meteorites LLC

The howardites can be reasonably understood as mixtures of eucrite and diogenite materials. In texture, they are a polymict breccia containing easily recognizable fragments of both of these rock types. A conventional dividing line between brecciated eucrites and howardites has been set at 10% diogenite. There is considerable compositional range among the howardites, with compositions of individual stones lying closely along a mixing line between eucrite and diogenite compositions.

There is good reason to describe the eucrites and diogenites as complementary differentiates from the same parent body, with the howardites representing the mixing of both kinds of material as a consequence of violent impact events that shattered the parent asteroid to sufficient depth to excavate diogenite material and deposit it on the surface. The parent material was highly oxidized, as attested by the high FeO content of the pyroxene. The only large asteroid with the spectrum of basaltic achondrites is 4 Vesta. The higher-energy ejecta from impacts escaped from Vesta and gave rise to the small Vesta-family (V-class) asteroids.

Enstatite Achondrites (Aubrites)

The type example is Aubres from France. As the name implies, the enstatite achondrites are highly reduced, similar in oxidation state to the enstatite chondrites, but with severe depletion of metal. The $FeSiO_3$ mole fraction in the enstatite is typically 0.0x% (meaning a few hundredths of 1% Ferrosilite), although analytical difficulties tend to overestimate the FeO content because of microprobe beam spread inadvertently picking up traces of Fe and FeS. The trace of remaining metal is kamacite with about 5.4 to 6.7% Ni content, generally with about 1.5 to 2.4% elemental silicon. The nitride mineral carlsbergite (CrN) is present in minor amounts; oldhamite (CaS) with embedded and apparently exsolved osbornite (TiN) is also present.

Several enstatite achondrites (QUE 94204; NWA 2526; Itqiy) look like partially melted and differentiated enstatite chondrites. The unique Happy Canyon stone is about 85% orthopyroxene of enstatite composition (0.4% ferrosilite reported), with 5 to 10% plagioclase and about 5% of the calcium-bearing pyroxene diopside. The bulk composition suggests a genetic relationship to E6 chondrites; the texture suggests it is a cumulate from a melt. There are no chondrules present. This stone appears to be transitional between unmelted chondrites and thoroughly differentiated achondrites.

The NEA 3103 Eger has a reflection spectrum compatible with aubrite composition.

Angrites

This small class of achondrites, named after the type example Angra dos Reis, has only 12 known members. Particular interest attaches to this class because they are differentiated basaltic meteorites of exceptional age, 4.556 billion years (Ga). Vesicles (bubbles) are often found in them (the angrite SAH 99555 has a vesicle 2.5 cm in diameter). The angrites are characterized by a high FeO content and an apparent absence of metallic Fe-Ni. The dominant mineral, clinopyroxene, has a very unusual composition in that it is exceptionally rich in both Al and Ti. Normally Al_2O_3 and Ti_2O_3 are excluded efficiently from pyroxenes because the 3+ ions of Al and Ti do not substitute well for either the 2+ (Ca, Mg, Fe) or 4+ (Si) ions in clinopyroxene [$(Ca,Mg,Fe)SiO_3$]. A common clinopyroxene is diopside [$CaMgSi_2O_6$]. However, the solubilities of aluminum and titanium oxides are significant at high melt temperatures and in pyroxenes that crystallize first from the melt during cooling, in the mineral fassaite, [$Ca(Mg,Fe,Al)(Si,Al)_2O_6$], in which two Al^{3+} ions substitute for a $M^{2+}Si^{4+}$ pair. Fassaite is also known as a component of the calcium-aluminum refractory inclusions in the CM and related meteorites. The weight of evidence is that the angrites began crystallizing at high temperatures in an oxidized (FeO-rich) melt generally similar to basaltic composition. Slow cooling would have permitted the Al and Ti oxides to exsolve from the clinopyroxene, but this clearly did not happen. The coexisting olivine is also unusually Ca-rich, another indicator of high crystallization temperatures. It is likely that they formed very early in Solar System history from melted CV or CO chondritic material that cooled quickly, probably because of a shallow depth of burial, and possibly as a surface melt or flow.

The spectrum of angrites has been tentatively linked to the asteroids 289 Nenetta or 3819 Robinson in the Belt; a similarity to the planet Mercury has also been suggested.

Brachinites

The brachinites (frequently misnamed brachin<u>a</u>ites) are named after the type example Brachina, found in South Australia in 1974. About 30 independent falls are known. These meteorites are dominated by olivine, sometimes with up to 10% plagioclase, 6% clinopyroxene, 3% troilite, and about 0.5 to 3% each of chromite [$FeCr_2O_4$] and orthopyroxene. Traces of metal and phosphates are also present. The olivine is quite oxidized, with about 35 mole% fayalite.

The clinopyroxene contains about 10 to 15% ferrosilite and about 46% of the Ca endmember, wollastonite [$CaSiO_3$]. The phosphate phases include chlorapatite [$Ca_5(PO_4)_3Cl$] and merrilite [$(Ca,Mg,Fe)_3(PO_4)_2$]. The composition and mineralogy are suggestive of highly oxidized chondrites, but chondrules are absent. Brachinites are often called "primitive" achondrites.

Lodranites

Lodranites, named after the type example which fell in Lodhran, Pakistan in 1868, are also called primitive achondrites. Some meteoriticists have compared them to ureilite achondrites because of their composition, which is dominated by orthopyroxene and olivine. Sodium-rich (~75% albite) plagioclase, diopside, and troilite are present in minor amounts, and metal is depleted, suggesting heating of an oxidized chondritic parent body to a temperature above the Fe-FeS eutectic, followed by partial loss of the dense metal-metal sulfide melt.

Chromite, schreibersite [Fe_3P], phosphates, and chromium-bearing diopside are all present in minor amounts. Traces of graphite are sometimes found. The degree of oxidation is much less than seen in the brachinites: olivine contains about 5 to 15% fayalite, and the orthopyroxene contains about 5 to15% ferrosilite. The metal grains are kamacite with only about 3 to 7% Ni.

Acapulcoites

This group of at least 12 members is named after the type example, which fell at Acapulco, Mexico in 1976. Aside from the absence of chondrules, the meteorite resembles a chondrite, earning it a place as another type of primitive achondrite. The minerals in the acapulcoites, in decreasing order of prominence, include olivine, orthopyroxene, plagioclase, kamacite, and troilite. The texture is fine-grained, diagnostic of rapid cooling. The acapulcoite NWA 725 shows an abundance of chondrules, emphasizing that these stones occupy a borderland between chondrites and thoroughly melted and differentiated achondrites. They are roughly equally similar to H and E chondrites, with oxygen isotope systematics different from both, but closely similar to the lodranites. Many lines of evidence suggest that the lodranites and acapulcoites shared a common parent asteroid.

Stony Irons

The stony-iron meteorites are, as the name accurately suggests, mixtures of roughly equal amounts of metal and silicates. Only a few hundred stony-irons are known, divided almost evenly between pallasites and mesosiderites. The dominant minerals are olivine, kamacite, and taenite. There is a structural distinction between the two groups of stony irons: the pallasites have a continuous matrix of metal, within which large chunks of olivine are trapped; the mesosiderites contain chunks of both metal and silicates, without any continuous metal matrix. The mesosiderites have undergone fragmentation (brecciation) and reaccumulation. Graphite, the iron sulfide troilite, the iron carbide cohenite, and the iron phosphide schreibersite all accompany the metal, as in iron meteorites. Accessory minerals include daubréelite.

Mesosiderites

Of the nearly 200 mesosiderites known, only seven were observed to fall. Their enhanced frequency among finds is due to their distinctive high density and good resistance to weathering. Because of their strength, a disproportionate number of massive mesosiderites are known, with one individual (Vaca Muerta) accounting for several tons of material.

The metal is millimeter- or smaller-sized particles with an intergrowth of kamacite and taenite, intermingled with chunks of silicates which are made of ortho- and clinopyroxene, anorthite (Ca-rich; 92% An and 8%Ab) feldspar, and sparse olivine, a mix reminiscent of the diogenites and eucrites discussed above. The pyroxenes have a high ferrosilite content (33 to 43%) and pyrrhotite is sometimes found rather than troilite, both demonstrating a rather oxidized state. Chromite is present in accessory amounts, as are free silica (tridymite) and the phosphate merrillite. Free silica and olivine do not constitute a stable assemblage, and cannot coexist at equilibrium. Zircon (ZrO_2) is present in trace amounts in Vaca Muerta. Ilmenite ($FeTiO_3$) and both baddeleyite and rutile (TiO_2) are found in some rocky xenoliths in the same meteorite. Daubréelite ($FeCr_2S_4$) is found in association with, and exsolved from, troilite in the Estherville mesosiderite.

The bulk composition suggests a re-accretion of impact-generated core and crust materials, discriminating effectively against mantle (olivine-rich) materials. Conditions of origin of the mesosiderites were similar to those of the HED achondrites, although chemical differences suggest that they do not originate from the same parent body.

Pallasites

The reader should be warned in advance that the pallasites have nothing whatsoever to do with the asteroid 2 Pallas, but were named in recognition of the German scientist Peter Pallas, who studied the first known meteorite of this class, Krasnoyarsk.

At present, over 60 pallasites are known, including four observed falls. Because of their strength and resistance to corrosion, large individuals can survive atmospheric entry and many thousands of years of exposure to the elements. Several pallasites have masses over 1000 kg.

The requisite properties that define a pallasite are its metallic matrix and the presence of large cm-sized olivine crystals embedded in the metal. The olivine crystals are of such size and clarity that many qualify as gemstones (peridot). Within each meteorite the oxidation state (fayalite content) of the olivine is strikingly uniform; over the pallasites group the olivine contains from about 10 to 20% fayalite. Some of the olivine grains contain 4 to 5% P_2O_5, a remarkably high phosphate content for olivine. Minor amounts of pyroxene coexist with olivine, and chromite is often found.

The metal is mostly kamacite with minor taenite. The detailed composition of the metal matches well with the type III iron meteorites described below. Troilite and the phosphide schreibersite are commonly associated with, and often entirely inside, the metal.

Several phosphates, including stanfieldite [$Ca_4(Mg,Fe)_5(PO_4)_6$], farringtonite [$Mg_3(PO_4)_2$], whitlockite [$(Ca,Mg,Fe)_3(PO_4)_2$], and merrillite [$(Ca,Mg)_3(PO_4)_2$] are also known to be widespread minor constituents. Coexistence of phosphide and phosphates defines the degree of oxidation of the pallasites parent asteroid.

Several pallasites, including Eagle Station, have established metallographic affinities to the Type IIF irons (see below), and two others, Yamato 8451 and Vermillion, are distinguished by elevated orthopyroxene contents and fine-octahedrite metal structure.

Winonaites

This group of about 25 individuals is named after the type example, the Winona meteorite from Arizona. Their composition is intermediate between that of the H and E chondrites, but they have recrystallized to the point that no chondrules remain. The oxygen isotope signature of their silicates matches that of the IAB irons (see below). The texture shows extensive thermal metamorphism due to heating to the point of incipient melting. Winona itself contains olivine, enstatite, and plagioclase as the principal silicate phases, with minor diopside, chromite, and apatite. The metal is accompanied by troilite, graphite, alabandite [$(Mn,Fe)S$] and daubréelite [$FeCr_2S_4$]. The Hammada al Hamra 193 winonaite stone is unique in containing amphibole minerals. Both apatite and amphibole are water-bearing minerals that can also accommodate halides, usually Cl or F, in their structure.

Irons

Iron meteorites display three major structural categories; hexahedrites, octahedrites, and ataxites. All three are igneous products overwhelmingly composed of iron-nickel alloys, natural stainless steel, although inclusions of graphite, troilite, schreibersite and cohenite are common. Despite accounting for only a few percent of observed falls, irons are highly resistant to weathering, have very distinctive high density, and account for a much higher fraction of finds: they make up about 86% of the total mass of meteorite material in our collections.

Their extreme physical strength (to about 3.5 kilobars) also means that they are very resistant to breakup during atmospheric entry: they undoubtedly are even rarer among entering meteorites than among the observed falls. Their strength also accounts for the occurrence of iron meteorites of very high mass, reaching a record of about 60 tonnes for the Hoba iron of Namibia. Several others have masses greater than 20 tonnes.

Hexahedrites

The hexahedrite irons consist almost entirely of cubic alpha- Fe, containing 5.3 to 5.8% Ni. The complex and striking kamacite-taenite intergrowth pattern seen on polished and etched octahedrite irons is absent, although one often sees the faint parallel systems of striations caused by mechanical shock, the Neumann lines.

All iron meteorites are also subdivided by chemical criteria into distinct groups. The elements used to determine these chemical groupings are gallium, germanium, and iridium. Hexahedrite irons, because of their very low nickel content, are easily resolved from other metal types by chemical criteria alone. John Wasson and his coworkers at UCLA have analyzed hundreds of iron meteorites and pioneered in the discovery and definition of their chemical composition classes. A summary of the composition classes is shown in **Figure A.12**.

Because the chemical groups are independent of the structural groups, it is possible for different members of a chemical group to belong to different structural groups. For example, the IIAB irons range from octahedrites to hexahedrites in structure, but show a similarity and continuity of their chemical properties. The IIA irons, with 5.3 to 5.7% Ni, have Ga and Ge concentrations similar to those of the IIB octahedrites, but with up to 60 parts per million (ppm) of iridium, about 100 times as high as in the IIB irons, reflecting preferential partitioning of Ir into kamacite.

The only other hexahedrites group is the IIG irons, which are made of kamacite with large and abundant schreibersite crystals. Their phosphorus content is about 2%, the highest found in any class of meteorite, with a sulfur content that is unusually low, only 0.2%. There are only six IIG meteorites known. The IIG irons have low iridium and high gold concentrations. It is reasonable to associate the IIAB irons with a relatively sulfur-rich complementary differentiate and the IIG irons with a phosphorus-rich phase from which the IIAB irons

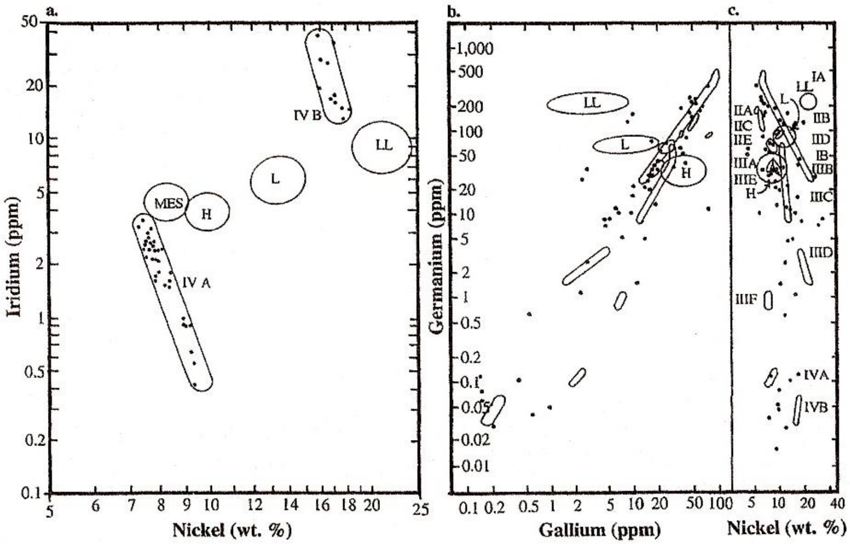


Figure A.12 Compositional Families of Irons. The variations of the gallium, germanium, and iridium concentrations in irons and ordinary chondrite metal are correlated with the nickel content. Note the vast range of concentrations.

Credit: Deep Space Industries – John S. Lewis

separated via liquid immiscibility, placing the source of both groups on the same parent body.

Octahedrites

The octahedrites irons, which range from 5.7 to 11.5% nickel, show widely divergent crystal intergrowth textures after cutting, polishing, and etching with acid. Some of the chemical groups, notably IB and IIICD, span a continuous range from octahedrite to ataxite nickel contents and structures.

The Ga-Ge groups found among the octahedrites correspond in complex ways to their structural classifications. It appears to be impossible to produce all these composition groups from only four or five parent bodies: it may be necessary to derive the octahedrite irons from a dozen or more different asteroids.

IA: Medium and coarse octahedrites, 6.4-8.7% Ni, 55-100 ppm Ga, 190-520 ppm Ge, 0.6-5.5 ppm Ir, Ge-Ni correlation negative

IB: Ataxites and medium octahedrites, 8.7-25% Ni, 11-55 ppm Ga, 25-190 ppm Ge, 0.3-2 ppm Ir, Ge-Ni correlation negative

IIB: Coarsest octahedrites, 5.7-6.4% Ni, 446-59 pm Ga, 107-183 ppm Ge, 0.01-0.5 ppm Ir, Ge-Ni correlation negative

IIC: Plessitic octahedrites, 9.3-11.5% Ni, 37-39 ppm Ga, 88-114 ppm Ge, 4-11 ppm Ir, Ge-Ni correlation positive

IID: Fine to medium octahedrites, 9.8-11.3%Ni, 70-83 ppm Ga, 82-98 ppm Ge, 3.5-18 ppm Ir, Ge-Ni correlation positive

IIE: octahedrites of various coarseness, 7.5-9.7% Ni, 21-28 ppm Ga, 60-75 ppm Ge, 1-8 ppm Ir, Ge-Ni correlation absent

IIIAB: Medium octahedrite 7.1-10.5% Ni, 16-23 ppm Ga, 27-47 ppm Ge, 0.01-19 ppm Ir

IIICD: Ataxites to fine octahedrites, 10-23% Ni, 1.5-27 ppm Ga, 1.4-70 ppm Ge, 0.02-0.55 ppm Ir

IIIE: Coarse octahedrites, 8.2-9.0% Ni, 17-19 ppm Ga, 3-37 ppm Ge, 0.05-6 ppm Ir, Ge-Ni correlation absent

IIIF: Medium to coarse octahedrites, 6.8-7.8% Ni,6.3-7.2 ppm Ga, 0.7-1.1 ppm Ge, 1.3-7.9 ppm Ir, Ge-Ni correlation absent

IVA: Fine octahedrites, 7.4-9.4% Ni, 1.6-2.4 ppm Ga, 0.09-0.14 ppm Ge, 0.4-4 ppm Ir, Ge-Ni correlation positive

Figure A.13 A 3.4 kg iron octahedrite was recovered in Nantan County, Guanxi, China.

Credit: Amethyst Galleries, Inc.

Ataxites

The word “ataxite” connotes absence of visible structure, specifically the Widmanstätten figures characteristic of octahedrite irons. The term has been used for two unrelated types of irons, those that have so high a nickel content that kamacite is absent and those with more normal (octahedrites-like) nickel contents that have been reheated and often worked by blacksmiths. In the older literature the low-nickel individuals are called “Ni-poor ataxites”, but current usage generally reserves the ataxite group designation for nickel-rich irons which owe their structure to nature.

The IB group contains both ataxites and medium octahedrites as members. Silicate inclusions are large and numerous, essentially basaltic in composition, dominated by orthopyroxene, olivine, and calcium-rich (anorthitic) plagioclase feldspar. The pyroxene contains about 4 to 9% of the ferrosilite component and the olivine has a fayalite content of about 5.6 mole %. The texture is described as “primitive”, meaning that evidence of melting and differentiation is absent. The nickel content in the metal ranges up to 25%. The gallium content ranges from 11 to 55 ppm and the germanium content from 25 to 190 ppm, correlating negatively with nickel. The iridium content is only 0.3 to 2.0 ppm.

Some IIICD irons are ataxites containing up to 24% nickel. The gallium content is about 1.5 ppm and the germanium content is about the same. The iridium content is an astonishingly small 0.052 ppm. Examples include Freda and Wedderburn.

The IVB group irons are ataxites containing from 16 to 26 % nickel, accompanied by 13 to 38 ppm of iridium, a very high level of platinum-group metal concentration. Gallium ranges from 0.17 to 0.27 ppm, and germanium from 0.03 to 0.07 ppm, correlating positively with Ni within the group. They are clearly products of melting and differentiation.

Ungrouped Iron Meteorites

This is actually quite a large collection of over 100 meteorites (about 15% of the total number of irons) which do not fit into any of the larger classes above, and which come from as many as 50 distinct parent bodies.

Among these oddities, the Butler iron is especially noteworthy. Butler contains an astonishing 0.2% germanium, several times higher than in any other iron. The gallium concentration is also quite high, at 87 ppm.

Although Butler displays the Widmanstätten pattern characteristic of octahedrites, it has a nickel content of 16%, placing it at the borderline of the composition range of ataxites, and a cobalt content of 1.4%.

Primitive Iron Meteorites

The IAB and IIE iron groups, as well as certain rare ungrouped irons, contain abundant silicates and have textures that do not suggest melting and differentiation into planetary cores. The IAB irons are structurally diverse, including hexahedrite, octahedrite, and ataxite members, although they constitute a coherent chemical group. Their abundant silicate inclusions include two pyroxenes, olivine, plagioclase, chromite, and various phosphates. Graphite, troilite and daubréelite accompany the metal phase. Numerous variants and outliers of the central IAB group are known. An origin related to the winonaite achondrites (above) is widely suspected.

The rare IIE irons, of which only 21 members are known, contain abundant H-chondrite material and bear an oxygen isotope signature consistent with this chondrite group. It is usually supposed that the IIE irons were formed by near-surface melting on an asteroid of H-group composition, presumably triggered by a violent impact. The asteroid 6 Hebe has been suggested as the source of both groups.

Physical Properties of Irons

The densities of iron meteorites generally are little influenced by the inclusions of sulfides, silicates, phosphides, and carbides in them. They do, however, show a correlation of density with nickel content. Hexahedrite irons generally have densities close to 7.5 g/cm^3; nickel-rich ataxites run close to 8.0 g/cm^3.

The crushing and shear strengths of irons are generally close to 3.5 kilobars, similar to industrial stainless steel. At normal temperatures, meteoritic iron is significantly malleable, deforming under stress without fracturing.

The spectrum of meteorite iron is rather bland, devoid of distinctive absorption bands, with a visual albedo usually close to 0.15. In the absence of size and albedo data on an asteroid, the spectrum of a metallic body cannot be confidently distinguished from that of a far darker carbonaceous body or a far brighter enstatite body.

Appendix B - Meteorite Minerals of Resource Interest

Category Mineral Name	Mineral Formula	Notes
Free Metals		
Kamacite	Fe,Ni; <6% Ni (alpha-iron)	I, O
Taenite	Fe,Ni; >6% Ni (gamma-iron)	I, O
(Plessite)	Intergrowth of kamacite and taenite	I
Copper	Cu	C
Nonmetal Elements		
Sulfur	S_8	C
Graphite	C	I
Diamond	C	I, U
Sulfides		
Troilite	FeS	I, O
Pyrrhotite	$Fe_{1-x}S$	C
Pyrite	FeS_2	C
Pentlandite	$(Fe,Ni)_9S_8$	C
Chalcopyrite	$CuFeS_2C$	
Brezinaite	Cr_3S_4	I
Daubreelite	$FeCr_2S_4$	I
Caswellsilverite	$NaCrS_2$	E
Alabandite	$(Mn,Fe)S$	E
Gentnerite	$Cu_8Fe_3Cr_{11}S_{18}$	I
Djerfisherite	$K_3CuFe_{12}S_{14}$	E
Molybdenite	MoS_2	R
Niningerite	$(Mg,Fe)S$	E
Oldhamite	CaS	E
Sphalerite	$(Zn,Fe)S$	E
Carbides, Phosphides, Nitrides, Silicides etc.		
Cohenite	$(Fe,Ni)_3C$	I
Perryite	$(Ni,Fe)_5(Si,P)_2$	E
Suessite	Fe_3Si	E
Schreibersite	$Fe,Ni)_3P$	I
Carsbergite	CrN	E
Osbornite	TiN	E
Roaldite	$(Fe,Ni)_4N$	E
Sinoite	Si_2N_2O	E
Oxides		
Corundum	Al_2O_3	R
Perovskite	$CaTiO_3$	R
Hibonite	$CaAl_{12}O_{19}$	R
Hematite, maghemite	Fe_2O_3	C

Magnetite		Fe_3O_4	C
Spinel solid solutions			
	Spinel	$MgAl_2O_4$	R
	Hercynite	$(Fe,Mg)Al_2O_4$	R
	Chromite	$FeCr_2O_4$	R
Quartz, tridymite		SiO_2	E
Rutile		TiO_2	I, M
Baddeleyite		ZrO_2	O
Ilmenite		$FeTiO_3$	O
Pyrophanite		$MnTiO_3$	O

Oxysalts

Whewillite		$CaC_2O_4.H_2O$	C
Calcite, aragonite		$CaCO_3$	C
Dolomite		$CaMg(CO_3)_2$	C
Magnesite		$(Mg,Fe)CO_3$	C
Gypsum		$CaSO_4 \cdot 2H_2O$	C
Epsomite		$MgSO_4 \cdot 7H_2O$	C
Bloedite		$Na_2Mg(SO_4)_2$	C
Farringtonite		$Mg_3(PO_4)_2$	C
Stanfieldite		$Ca_4(Mg,Fe)_5(PO_4)_6$	C
Merrillite		$(Ca,Mg)_3(PO_4)_2$	C
Sarcopside, graftonite		$(Fe,Mn)_3(PO_4)_2$	C
Brianite		$CaNa_2Mg(PO_4)_2$	C
Panethite		$(Ca,Na_2)(Mg,Fe)_2(PO_4)_2$	C
Buchwaldite		$NaCaPO_4$	C
Apatite		$Ca_5(PO_4)_3(OH,F)$	C
Chlorapatite		$Ca_5(PO_4)_3Cl$	C

Halides

Lawrencite		$FeCl_2$	I

Silicates

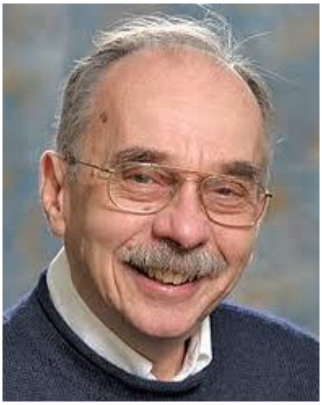
Olivine s. s.		$(Mg,Fe)_2SiO_4$	O
	Forsterite	Mg_2SiO_4	
	Fayalite	Fe_2SiO_4	
Orthopyroxene s.s.		$(Mg,Fe)SiO_3$	O
	Enstatite	$MgSiO_3$	
	Ferrosilite	$FeSiO_3$	
Clinopyroxene s. s.		$(Ca,Mg,Fe)SiO_3$	O
	Wollastonite	$CaSiO_3$	
Augite		$Mg(Fe,Ca)(SiO_3)_2$	O
Diopside		$CaMg(SiO_3)_2$	R
Hedenbergite		$CaFe(SiO_3)_2$	
Pigeonite		$(Fe,Mg,Ca)SiO_3$	
Feldspar s. s.			
	Plagioclase		
	Anorthite	$CaAl_2Si_2O_8$	O

	Albite	$NaAlSi_3O_8$	O
	Orthoclase	$KAlSi_3O_8$	O
Melilite s. s.			R
	Åkermanite	$Ca_2MgSi_2O_7$	
	Gehlenite	$Ca_2Al_2SiO_7$	
Roedderite		$(K,Na)_2Mg_5Si_{12}O_{30}$	E
Krinovite		$NaMg_2CrSi_3O_{10}$	E
Ureyite		$NaCrSi_2O_6$	I
Zircon		$ZrSiO_4$	A
Hydroxyl Silicates			
Serpentine		$(Mg,Fe)_6Si_4O_{10}(OH)_8$	C
Chamosite		$Fe_6Mg_3[(Si_4O_{10})(OH)_8]_2$	C
Kaersutite		$Ca_2(Na,K)(Mg,Fe)_4TiSi_6Al_2O_{22}(F,OH)_2$	C
Muscovite		$(K,Na,Ca)_2Al_4(Si_6Al_2O_{20})(OH,F)_4$	C
Montmorillonite		$Al_4Mg_6(Si,Al)_{16}O_{40}(OH)_8$	C
Sodalite		$Na_8Al_6Si_6O_{24}(Cl,OH,F)_2$	C
Richterite		$Na_2CaMg_5Si_8O_{22}(F)_2$	I, E

Notes

A = achondrites, C = carbonaceous chondrites, E = enstatite meteorites, I = irons, M = mesosiderites, O = ordinary chondrites, R = refractory inclusions in C chondrites

About the Author



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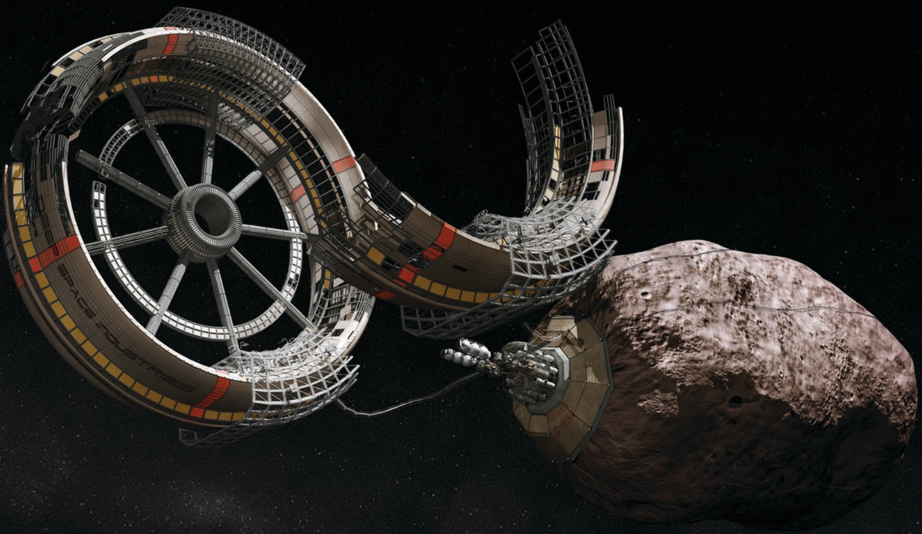
Dr. Lewis has been a member or Chairman of numerous NASA and NAS advisory committees, ranging from Solar System exploration strategies to planetary quarantine to interstellar communication. He has also advised the European Space Agency and lectured at Centers of the Chinese Academy of Science.

He has appeared in many special programs for the Discovery Network (US, Canada, UK), the German *Welt der Wunder* series, the Science Fiction Network, and the History Channel, as well as serving as an expert commentator on Chinese civil space launches on China Central Television (2004-present).



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Geoff Notkin
Science writer and host
of TV's *Meteorite Men*
and *STEM Journals*

Dr. John S. Lewis is a globally acclaimed expert on asteroid resources with more than 150 technical papers on space science and space engineering. In addition to writing college textbooks on planetary science, he is the author of *Rain of Iron and Ice* and *Mining the Sky. He is Professor* Emeritus of Planetary Science at the Lunar and Planetary Laboratory of The University of Arizona.

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