CHAPTER TWO

Meteorites: Fragments of Asteroids

What the…we've come out of hyperspace into a meteor shower. Some kind of asteroid collision. It's not on any of the charts.

Han Solo in *Star Wars: A New Hope*

Asteroids in History

In Chap. 1, we discussed the difference between meteors, meteoroids, and meteorites to be certain we are all speaking the same language. The study of asteroids also has its own evolving language. The name *asteroid* was given to these small bodies by William Herschel in 1802 in the first scientific paper on the newly discovered objects. (1 Ceres and 2 Pallas) "…resemble small stars so much as hardly to be distinguished from them. From this, their asteroidal appearance, if I may use that expression, I shall take my own name, and call them Asteroids…"

Gradually, as more asteroids were discovered astronomers began to realize that they were simply bodies of subplanetary mass and size which, in their minds' eyes gave asteroids a minor status among the Solar System's much more massive planets. By the late nineteenth century many astronomers referred to them as *planetoids* implying they were small and insignificant compared to the major planets. The final blow came when textbooks on astronomy began to refer to them as *minor planets*. After all, no telescope on Earth could resolve them into even a tiny disk. They remained star-like, even as they had been when seen by Herschel in the then largest telescope in the world (his own 48-in. reflector). Not until the 1970s did astronomers begin to realize the importance of the asteroids. These minor planets, small in stature and faint of light, would soon become giants in the struggle to understand the origin of the Solar System. A refreshing new name was finally given to them. They are *asteroid parent bodies* and their "children" are meteorites. Fragments of these parent bodies have been bombarding Earth and the other planets by the millions over the past 4.56 billion years. Hidden within these rocks from space are the clues we seek to the origin of our Solar System. It is indeed ironic that meteorites tell us more about the early Solar System than all the telescopic studies of the planets put together since the discovery of the asteroids.

Asteroids and the asteroid belt are still misunderstood by many people, particularly film makers. For example, in the movie *The Empire Strikes Back* the Millennium Falcon spacecraft encounters an "asteroid storm."

The Falcon turns into the asteroid storm and as the ship completes its turn, asteroids start coming straight at the cockpit windows. A large asteroid tumbles away from the Falcon's path at top speed. Several smaller asteroids crash into the big one, creating small explosions on its surface… The droid, Threepio, calmly calculates the possibility of successfully navigating an asteroid field as approximately three thousand, seven hundred and twenty to one.

This, of course, is fantasy. Today, thousands of asteroids are known to occupy the main asteroid belt in a zone two AU wide between the orbits of Mars and Jupiter. If you were in the main belt you would never encounter, much less have a collision with, an asteroid in your lifetime. Too much space, two few asteroids. One collision on a time scale of millions of years might be possible but never an "asteroid storm."

Main Asteroid Belt

It was Galileo's contemporary, Johannes Kepler, who first noticed the curious gap between the orbits of Mars and Jupiter. It was conspicuous because the orbits of the terrestrial planets Mercury, Venus, Earth, and Mars are remarkably symmetrical with respect to their mean distance from the Sun. As we proceed outward from the Sun, we notice that the distances between the planets increase in an orderly geometric progression. They increase in mean distance by 0.321 AU for each planet: Mercury at 0.387 AU; Venus at 0.723 AU; Earth at 1.000 AU; Mars at 1.524 AU. If we maintain this progression of distance the next planet would have a mean distance from the Sun of about 2.8 AU. No major planet occupies this position. The next planet outward from the Sun is Jupiter at 5.2 AU, clearly twice the distance if this geometric progression were to be maintained. Kepler was aware of this and was convinced that it was real. There must be an unknown planet at the 2.8 AU gap. Kepler derived an empirical relationship between a planet's mean distance from the Sun and its period of revolution: $P^2 = d^3$ where d is the planet's mean distance from the Sun in terms of Earth's mean distance in astronomical units (AU) and P is the planet's orbital period in terms of Earth's period. With this "Harmonic Law," Kepler could calculate a planet's mean distance by simply observing its period of revolution around the Sun.

The Harmonic Law along with the Law of Areas and the Ellipse Law was among the first scientific laws to emerge from the western world. Kepler himself did not know why the three laws worked. He could only trust them to what he considered to be a "divine plan" operating in the Solar System. In 1596, with only metaphysical reasons to back him, he strongly suggested that there *must* be an undiscovered planet orbiting between Mars and Jupiter. He would not live to see its discovery.

Asteroids and the Titius-Bode Rule

Over a century later, in 1766, the German astronomer Titius von Wittenburg discovered a geometrical tool that showed the spacing of the planets to be a mathematical progression. Table 2.1 shows the way it works. The progression is obtained by listing the numbers 0, 3, 6, 12, 24 48, 96, 192, 384, 768. Each of these numbers is obtained by doubling the preceding one and then adding 4 to each number. The sum is then divided by 10. The numbers obtained give the approximate distances from the Sun in terms of Earth's distance, the astronomical unit (AU).

The director of the Berlin Observatory, Johann Bode, was impressed with the rule, so much so that he used it to convince other European astronomers that there must be a planet between Mars and Jupiter. The climax came when William Herschel discovered Uranus by accident on March 13, 1781. Observations of the motions of Uranus showed conclusively that the Titius-Bode

Table 2.1. The Titius-Bode rule which describes the spacing of the planets as a mathematical progression

Titius' progression	Planet	Actual distance (AU)
(0 + 4)/10 = 0.4	Mercury	0.387
(3 + 4)/10 = 0.7	Venus	0.723
(6 + 4)/10 = 1.0	Earth	1.000
(12 + 4)/10 = 1.6	Mars	1.524
(24 + 4)/10 = 2.8	Missing planet	2.77 (1 Ceres)
(48 + 4)/10 = 5.2	Jupiter	5.203
(96 + 4)/10 = 10.0	Saturn	9.539
(192 + 4)/10 = 19.6	Uranus	19.18
(384 + 4)/10 = 38.8	Neptune	30.06
(768 + 4)/10 = 77.2	Pluto	39.4

Rule worked, at least out to Uranus, 1.5 billion mi from the Sun. The Rule showed that there should be a planet at 19.6 AU. Uranus' mean distance was measured at 19.18 AU, good enough to raise European astronomers' confidence level. It seemed they now had a rule for finding planets beyond Uranus if they existed. The next planet beyond Uranus (Neptune) according to the Titius-Bode rule should have a mean distance from the Sun of 38.8 AU. In October 1848, astronomers discovered Neptune, not by the Titius-Bode rule but by gravitational perturbations upon Uranus by an unknown planet beyond Uranus. The Titius-Bode rule fails completely for Neptune and Pluto.

Discovery of the First Asteroids

After Uranus was discovered other astronomers, their interest renewed, took up the search for the elusive planet that had to exist between Mars and Jupiter. In Palermo, on the island of Sicily, where the most southerly European Observatory had been completed a decade earlier, Giuseppe Piazzi had been working on a new star chart which could be used to search for the presumed planet. On the night of December 31, 1800, he spotted an 8th magnitude star near the ecliptic in the constellation Taurus. This star was not on the charts he had been revising. He positioned the star on the new chart and awaited the following night. The next night the star had moved again relative to the stationary background stars. Over the next several weeks, he plotted the motion of the star through the constellation Taurus. On February 11, 1801, Piazzi became ill and was forced to end the observations. Fearful of losing the object, he contacted Bode at the Berlin Observatory and reluctantly made his observations known. Understandably, Piazzi wanted to keep the observations a secret until he had an opportunity to plot the section of the orbit he had observed. It wasn't until late spring that he finally disclosed the positional data he had acquired, first to Bode in Berlin (May 31) and then to J. J. Lalande at the Paris Observatory (June 11). In this interim and without confirmation from the other observatories, Piazzi named the new "planet" 1 Ceres, the Roman Goddess of agriculture. By this time, the new "planet" had changed its position and it could not be located at either of these observatories. No matter how diligently these European astronomers searched the skies, the new "planet" 1 Ceres was promptly lost.

But the story of the first asteroid to be discovered does not end there. Several observatories searched for it with no luck. Then Europe's most distinguished mathematician, Karl Gauss, joined the search. Gauss was able to calculate an orbit from the original data Piazzi had acquired up to February 11, 1801. From this data, he pinpointed its location. On January 1, 1802, exactly 1 year after of the initial discovery, 1 Ceres was rediscovered and never lost again. (Figure 2.1)

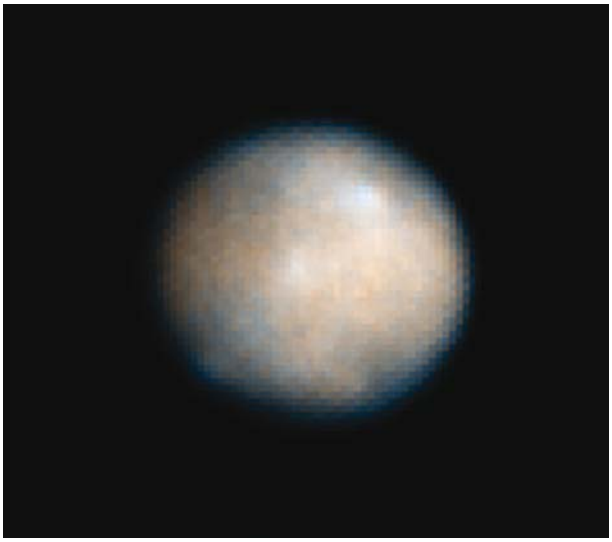

Figure 2.1. False color image of 1 Ceres taken on January 24, 2004, by the Hubble Space Telescope. Courtesy of NASA, ESA, J. Parker (Southwest Research Institute), P. Thomas (Cornell University), L. McFadden (University of Maryland), and M. Mutchler and Z. Levay (STScl).

The recovery of 1 Ceres was the beginning of a series of discoveries made over the next 7 years that culminated in the discovery of three additional asteroids: 2 Pallas, 3 Juno, and 4 Vesta. It became apparent that the space between Mars and Jupiter was not the home of a single planet but of several "minor planets," each with its own orbital characteristics which placed them in a zone called the *asteroid belt*. The vast majority of asteroids are found in the main belt between 2 AU and 4 AU from the Sun. The discovery of new asteroids after the first four had to wait 38 more years. Finally, the wait was over when, in 1845, a German amateur astronomer announced the discovery of the fifth asteroid, Astraea. The discovery prompted a renewal of the asteroid race but by this time (early nineteenth century) a new technology had appeared that was destined to change everything—astronomical photography. Before the invention of photography, both amateur and professional astronomers had only their eyes glued to the eyepiece of a telescope to help them make their discoveries. But this dependency on the human eye at the telescope was short-lived. By the mid-nineteenth century, dry plate photography was rapidly taking over and long time exposures on film were capable of picking up asteroid images hundreds of times fainter than the human eye alone could detect. By the close of the nineteenth century over 300 asteroids were known. By the mid-twentieth century, over 4,000 asteroids had been located and their orbits determined. There seemed to be no end to these little worlds. The minor planets ruled supreme. Now, there are over 30,000 known.

The last quarter of the twentieth century saw the most extraordinary advance in astronomical imaging in the history of observational astronomy. The development of charge coupled devices (CCDs) with sensitivities hundreds of times that of the fastest films rapidly engulfed the study of asteroids. Asteroid astronomy has become digital. Now, automated electronic telescopes nightly comb the skies for these chunks of rock. And amateur astronomers are not far behind. Today, they have equipped themselves with large aperture commercially made telescopes with sensitive CCD electronics that only professional observatories had possessed just a decade or two earlier. With relatively large amateur telescopes equipped with digital electronics, images of asteroids to the 16th magnitude or fainter have become possible. Amateurs have significantly added to the discovery rate. If this continues, in only 3 or 4 years there will be a doubling of known asteroids.

Cataloging and Naming New Asteroids

After the end of World War II, the International Astronomical Union (IAU) established the Minor Planet Center where observational data from amateur and professional astronomers world-wide could be sent for analysis. Each month huge volumes of data pour into this data bank located at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. Here, data on new discoveries of comets and asteroids are processed. The first step is to feed the data from the new discovery into computers to see if there is a match with known or suspected comets or asteroids. If the object appears to be a new asteroid, a temporary provisional designation is given the object. The object must have been observed over at least two consecutive nights to be eligible for this temporary designation. The provisional number is a combination of the year and month of discovery. The position of the provisional asteroid must now be compared with known asteroid positions (or other provisional asteroids) through at least one opposition of the object in question. If no link can be made with other provisional asteroids, then further observations are made, from which an orbit is computed. At this time, the asteroid could be followed through several more months to refine the orbit and search for other links with provisional asteroids. Finding no further links at this time, it is highly probable the object is indeed a new asteroid. Once astronomers have reached this certainty, the asteroid is given its final designation—a number preceding its name that denotes the numerical order of discovery and finally a name. Thus, 1 Ceres, the first asteroid discovered would be given the number 1 and the name, 1 Ceres. Other asteroids follow 1 Ceres in numerical order. Naming the newly discovered asteroid is a much simpler process. The finder has the privilege of providing the name. When asteroids were first found they were given female names from classical Greek and Roman mythology. At the time, astronomers had no idea that these names would quickly be depleted as the number of asteroid discoveries climbed rapidly through the nineteenth century. It is no surprise that this privilege soon led to some rather inappropriate names—from rock stars to historical characters of rather dubious distinction. Finally, in 1982, the IAU formed the Small Bodies Names Committee whose purpose was to examine each name and judge its suitability for publication.

From Asteroid Belt to Earth

It is generally accepted among planetary astronomers that asteroids are parent bodies of the meteorites. That meteorites are fragments of asteroids has yet to be proven but is provisionally accepted as a working hypothesis. What is questioned is how meteorites manage to make it to Earth. There are three zones in the Solar System where asteroids are known to reside. The best known is the *main belt* which occupies a zone between 2 AU and 4 AU from the Sun. It is a zone of considerable stability. Most of the main belt asteroids have been there in near circular orbits about the Sun since their formation 4.56 billion years ago. By 1866, a sufficient number of asteroids had been discovered in this region to establish the reality of the zone, but something was amiss. In that year, the American astronomer Daniel Kirkwood pointed out that the Belt was not as uniform as first thought. There seemed to be gaps in the belt in which few or no asteroids were found. Figure 2.2 shows the distribution of asteroids within the belt. The gaps are obvious, but what was causing them? Kirkwood and other astronomers knew that Jupiter's gravitational force was probably responsible for initially herding the asteroids into the main belt. But more importantly, he recognized that some of the asteroids near or within the gaps had unstable orbits. Kirkwood calculated the orbital period of the gap positions and found that the periods were related to Jupiter's orbital period, that is, the asteroids in the gap positions have orbital periods that were simple fractions of Jupiter's period. For example, an asteroid at 3.28 AU has a period of 5.94 years which is exactly half of Jupiter's orbital period of 11.88 years. Thus, every 2 years Jupiter

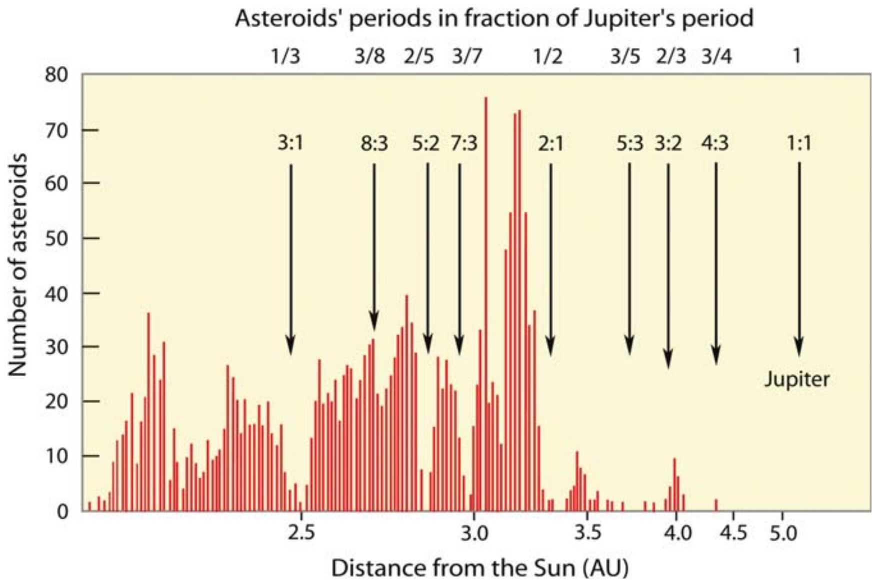

Figure 2.2. A plot of asteroid distance versus orbital period shows obvious gaps in the asteroid belt produced by Jupiter's gravitational perturbations. These are known as the Kirkwood gaps.

and that asteroid will experience a close encounter. This gravitational link is called *resonance*. Any asteroid whose period is a simple fraction of Jupiter's period will experience gravitational perturbations much more often than the other asteroids in stable orbits. The result of these perturbations is that within a few million years the orbital eccentricities of these perturbed asteroids will gradually increase, accelerating them along elliptical orbits and carrying them across the belt, raising the probability of collision with other main belt asteroids. Such collisions may be the mechanism that sends fragments across the asteroid belt toward Earth and the terrestrial planets. If they survive passage through the main belt they may eventually establish elliptical orbits among the inner planets.

Near-Earth Objects

Near-Earth Objects or NEOs are those asteroids that have escaped the confines of the main belt. They roam freely among the planets of the inner Solar System in which Earth is the largest target. Asteroid 433 Eros was the first discovered to have left the main belt and crossed the orbit of Mars. Eros comes within 13 million miles of Earth's orbit. In March 1932, another Mars-crossing asteroid was discovered with a perihelion of 1.08 AU. It was given the name *1221 Amor*. It became the prototype Mars-crosser with a perihelion between 1.0 AU and 1.3 AU. About a month later, another near-Earth asteroid was found but this time with a perihelion inside Earth's orbit. This asteroid was moving very swiftly when discovered, indicating its nearness to Earth. 1862 Apollo was designated the prototype Apollo asteroid having perihelia well inside Earth's orbit. Further observations showed that Apollo actually passed inside the orbit of Venus. Collectively, they were given the name *Earth-crossing* asteroids. Both Amors and Apollos still maintain their ties with the main belt, having their aphelia within the confines of the main belt. Inevitably, in 1975, another asteroid was discovered that had entirely broken its ties with the asteroid belt. Its mean distance lay entirely within the Earth's orbit. This asteroid, 2062 Aten, became the prototype for *Aten* asteroids.

Trojan Asteroids

There is one last asteroid group that we should include in this brief survey. The very dark bodies in this group share a mutual orbit with Jupiter. There are actually two separate groups found 60 degrees east and west of Jupiter (Figure 2.3). Discovery of the first *Trojan* asteroid was made by the German astronomer Maximilian Wolf in 1906. It was not a complete surprise that such asteroid clusters existed. The French mathematician Joseph Lagrange in 1772 showed that as many as five such clusters could exist "attached" to Jupiter's orbit. However, of the five *Lagrangian* points, only two (L_4 and L_5) are stable. The Trojan asteroids are at the 1:1 resonance point where small asteroids can remain stable for an extended period. The largest Trojan asteroid is 624 Hector which measures ~190 by 95 mi (300 by 150 km). The total population, averaging 9 mi (14 km) or less in diameter, may number in the thousands and are comparable to the smaller asteroids in the main belt.

An Important Job for Dedicated Amateur Astronomers

Today we know of 800 or more Near-Earth asteroids. There must be many others awaiting discovery. Here is a wonderful research opportunity in which amateur astronomers can become involved and make an important contribution. The situation is that there are too many asteroids

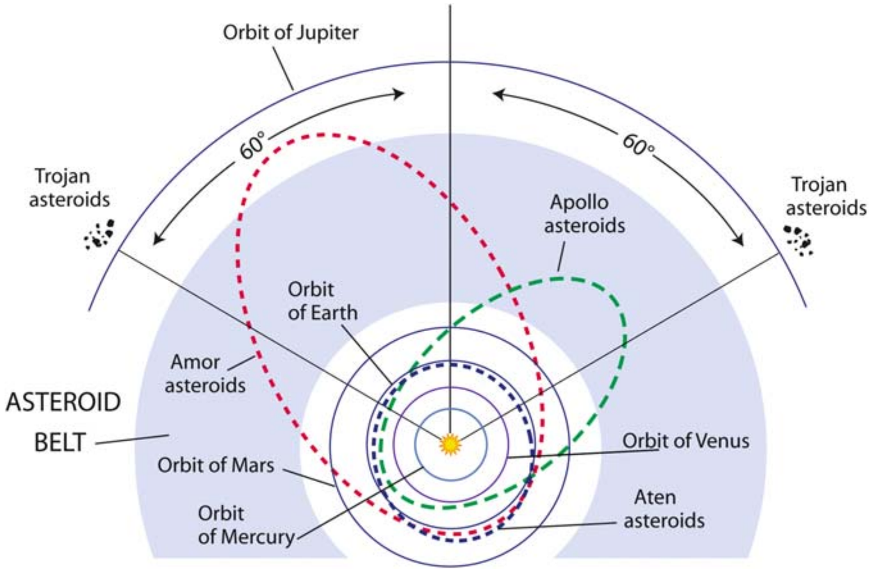

Figure 2.3. Typical orbits of Apollo, Amor, and Aten asteroids, all of which cross Earth's orbit. They are collectively termed Near-Earth asteroids. Trojan asteroids occupy very stable positions 60 degrees east and west of Jupiter's position.

and not enough observers. We saw that there are currently over 30,000 asteroids known, the vast majority from the main belt. In addition, there may be as many as 1,000 or more NEOs. All of these asteroids are affected by gravitational perturbations from Jupiter and Saturn that, in only a few years, will have changed their orbits sufficiently so that they become lost. (Remember the first asteroid to be discovered, 1 Ceres, was lost within months of its discovery, not to be found again for another year.)

Astronomers involved in the surveys (five currently operating—see below) report their NEO discoveries to the Smithsonian Astrophysical Observatory's Minor Planet Center located at Harvard University, Cambridge, Massachusetts. These observations are posted to a Website called the NEO Confirmation Page. Once an object is designated an NEO, it must be continually tracked to assure that it not be lost. There is always some uncertainty in their orbits that only increase in time. They need to be observed on a regular basis. There are too many newly discovered NEOs that require follow-up observations. Here is where the dedicated amateur astronomer can help. Amateur astronomers play a critical role by relocating and further tracking each new NEO discovery. These observations help refine the object's orbital data and assure that the asteroid will not be lost in the future.

The Five Major NEO Surveys

MIT Lincoln Lab and Air Force LINEAR project in Socorro, New Mexico
University of Arizona Spacewatch Survey, Steward Observatory, Tucson, Arizona
Lowell Observatory LONEOS at Flagstaff, Arizona
Jet Propulsion Laboratory, NASA and Air Force NEAT program in Hawaii
Catalina Sky Survey in Tucson, Arizona

Comparing Asteroids with Meteorites

Virtually all astronomers believe that meteorites are pieces of asteroids although they have never sampled an asteroid directly. We know that meteorite collections world-wide must contain pieces of at least 135 separate asteroids. These probably do not include all of the asteroid types. About 85% of all meteorites that have made it to Earth are ordinary chondrites. This tells us that the meteorites in our collections are probably biased toward the ordinary chondrites. What we need is to find a way to compare the mineralogy of meteorites in the laboratory to the mineralogy of asteroid parent bodies in the asteroid belt. Simply said, but not so simply done; however, there is a way. The Galileo spacecraft had near encounters with the asteroids 951 Gaspra and 243 Ida, both probably related to ordinary chondrites. Their surfaces appeared to be covered with blankets of loose rocky material that rested on a consolidated layer of bedrock. This material accumulated after countless millions of years of repeated impacts by small meteoroids. This surface is called a *regolith*. It is a major surface covering much of the Moon as well as the surfaces of main belt asteroids. Much of the material has experienced a history of fragmentation and compaction during countless episodes of cratering. During collisions, angular rocks were broken into smaller rocks and then cemented into a hard rocky material called a regolith *breccia*. Some regolith breccias from carbonaceous chondrites and ordinary chondrite meteorites have actually made it to Earth intact.

The surface regolith material on the smallest scale is a mixture of fragmented and compressed rock made of tiny mineral grains. Sunlight reaching the surface of an asteroid is either absorbed, transmitted through or reflected by these grains. The ratio of incident light to reflected light is called the *albedo* which is defined as the reflective efficiency of the tiny grains. The reflectivity depends upon how each mineral responds to the visible and infrared spectrum. As sunlight passes through the mineral grains, the grains absorb specific wavelengths and reflect back a solar spectrum minus the absorbed wavelengths. The mineral crystals on the surface do not produce sharply defined absorption lines like we see on the Sun; rather, we see a composite of broad dark bands composed of several minerals making up the surface spectra. These are sorted out by comparing the spectra with laboratory reflectance spectra of purified minerals.

Only a few minerals produce prominent infrared absorption features measured by a reflectance spectrophotometer. Fortunately, these are the very minerals that are found in chondritic meteorites. Figure 2.4 shows reflectance spectra of the three primary chondritic minerals: pyroxene, olivine, and iron (metal). Using reflectance spectra, a classification of asteroids was worked out. Table 2.2 summarizes the important asteroid compositional types, relating them to their albedos, meteorite association, and their approximate location in the asteroid belt. The table is arranged in order of decreasing albedo but it is also arranged in order of increasing distance from the Sun. For example, type E asteroids are close to the inner belt and also to the Sun. They are chemically related to meteorites called *aubrites*. Type V is related to the asteroid 4 Vesta. It is a differentiated asteroid that has undergone numerous collisions in its history. We will return to 4 Vesta shortly.

Type S asteroids are believed to be related to *ordinary chondrites*, the most commonly found meteorites on Earth. They are located between the middle and inner asteroid belt. Type M asteroids are found in the central belt and may be related to the iron-bearing E chondrites and the iron meteorites. Type D are Jupiter's Trojan asteroids found on the L_4 and L_5 Lagrangian points some 60° on either side of Jupiter and beyond the extreme outer edge of the main belt. They are very dark and metallic. Type C carbonaceous asteroids are most abundantly found in the main belt and may be related to the CM2 carbonaceous chondrite meteorites.

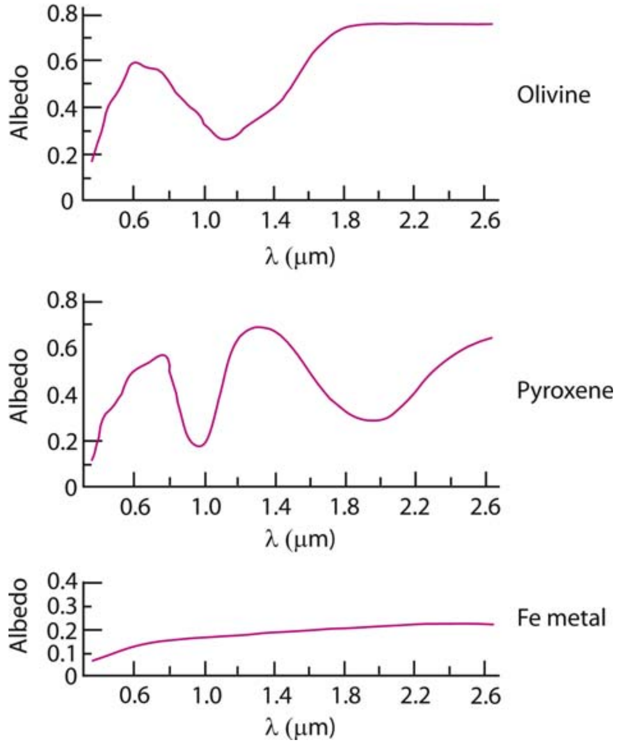

Figure 2.4. Reflectance spectra of the three primary minerals in chondritic meteorites.

After asteroid reflectance spectra are made, the next step is to select meteorites in the laboratory that have similar reflectance spectra for comparison. Most asteroids are covered with a regolith of broken fragments with fine-grained minerals cementing them. To make asteroid/meteorite comparisons the surface characteristics of both must closely match. This simulation is best done by grinding the meteorite to a fine crystalline powder to make the optical qualities as similar as possible. Figure 2.5 shows a few of these comparisons. Here, reflectance is plotted against the visible and infrared wavelength. The lines show laboratory reflectance spectra of five common

Table 2.2. Classification of asteroids arranged in order of decreasing albedo

Type	Albedo (%)	Associated meteorite	Location
E	25–60	Aubrites	Inner belt
A	13–40	Pallasites, olivine-rich	Main belt (?)
V	40	Eucrites, basaltic	Middle main belt, 4 Vesta and fragments
S	10–23	OC (?), mesosiderites	Middle to inner belt
Q/R	Like S	Possibly unweathered OC, with variable olivine/pyroxene	Middle to inner belt
M	7–20	E-chondrites, irons	Central belt
P	2–7	Like M, lower albedo	Outer belt
D	2–5	Trojans	Extreme outer belt, Jupiter L_4, L_5 points
C	3–7	CM carbonaceous chondrites	Middle belt, 3.0 AU
B/F/G	4–9	C subtypes	Inner to outer belt

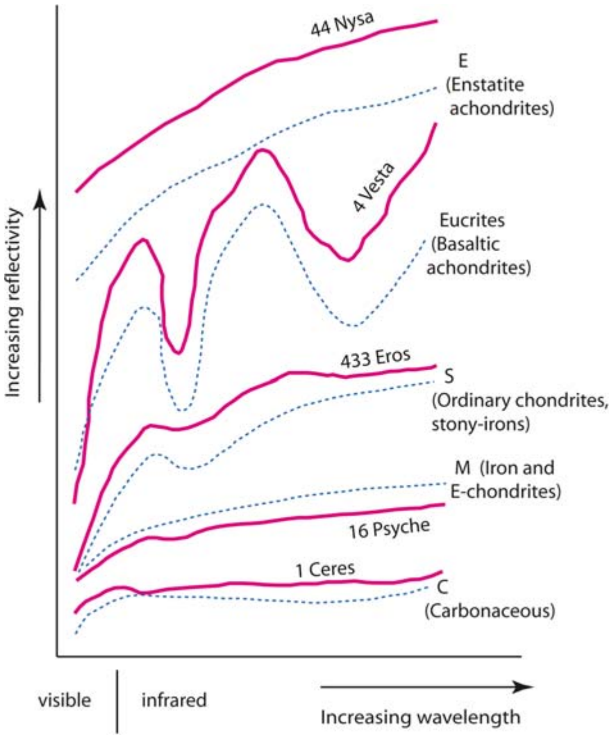

Figure 2.5. A comparison of a few selected asteroid and meteorite reflectance spectra from the visible spectrum to the infrared and differing in mineralogy. These are compared to asteroid reflectance spectra of surface minerals made with telescopes from Earth.

meteorites. The solid lines show asteroid reflectance spectra. The comparison shows a close match between the asteroid surfaces and the mineralogy of the powdered meteorites. In particular, the spectrum of 433 Eros closely matched an L4 ordinary chondrite, as did the spectrum of the Apollo asteroid 1685 Toro (not shown).

C-type carbonaceous asteroids are the most abundant of the asteroids found in the main belt. They are dark bodies with albedos between 3% and 7%, only half the albedo of the Moon. More than half of the C-type asteroids show signs of combined water.

The S-type asteroids are the second largest group in the main belt. They probably represent the closest match to the ordinary chondrites. Here a conundrum arises. On Earth the ordinary chondrites outnumber all other meteorite types by a large margin. Yet only about 16% of the S-type asteroids studied have chondritic compositions. The disparity between the carbonaceous chondrites, rare on Earth but plentiful in the asteroid belt, and the ordinary chondrites, common on Earth but relatively rare in the asteroid belt, seems to be telling us that ordinary chondrites probably came from one or at most a few asteroid parent bodies. The large numbers of chondrites reaching Earth are apparently not indicative of large numbers in space. Thus, it does not seem that we can rely upon our meteorite collections to tell us the true ratios of asteroid types.

4 Vesta

In 1970, T.B. McCord and his coworkers at the Institute of Geophysics and Planetology, University of Hawaii, made astronomical history when they were the first to recognize similar characteristics between the spectra of 4 Vesta and a specific meteorite type. They compared the reflection spectra of the Nuevo Laredo achondrite with the reflection spectra of 4 Vesta. Nuevo Laredo is a member of the HED clan of achondrites, specifically, a eucrite. It was the first successful effort to relate an asteroid to a specific meteorite type.

4 Vesta was a good choice for the analysis in that it is one of the largest asteroids known at 330 mi (530 km) in diameter and it is occasionally bright enough to be seen with the unaided eye. Amateur telescopes easily show it as a 5th magnitude star-like object moving slowly among the stars. 4 Vesta rotates on its axis with a period of 5.3 h. As it rotates, its spectrum constantly changes. This can only mean that it is not a homogeneous body, but a heterogeneous one. Its surface composition constantly changes in time as it rotates. In some areas, the asteroid shows a surface that is primarily eucritic, meaning that it is basaltic in composition. The eucritic crust is interpreted as areas where lava flows had erupted from beneath the surface and spread over the landscape. Some of the surface has been impacted by other asteroids forming impact craters. These craters pass through the thin eucritic crust to an intrusive layer in 4 Vesta's upper mantle. This is composed of a plutonic layer with a diogenitic composition. (HED stands for Howardite–Eucrite–Diogenite, related basaltic meteorites believed to originate on 4 Vesta.) The deepest layers exposed on 4 Vesta may be composed of olivine-rich material (Figure 2.6).

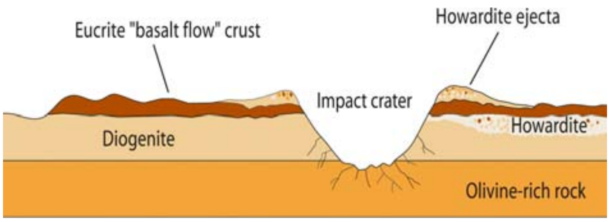

Figure 2.6. Diagram of asteroid 4 Vesta showing surface structure and interior cross section of the crust and upper mantle.

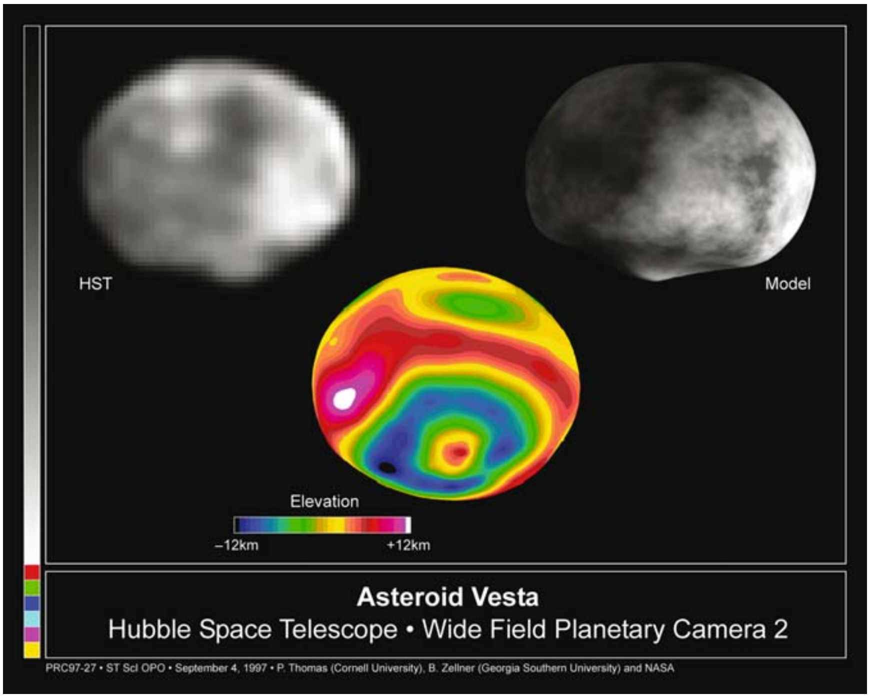

Figure 2.7. Hubble Space Telescope images of 4 Vesta revealing surface features including a huge impact basin 456 km in diameter and nearly 13 km deep. Photo taken September 4, 1997. Courtesy NASA, Ben Zellner (Georgia Southern University), and Peter Thomas (Cornell University.)

In 1997, the Hubble Space Telescope photographed a series of images that revealed a huge impact basin near Vesta's south pole measuring 283 mi (456 km) wide that covered more than 75% of one side (Figure 2.7). The impactor was about 18 mi (30 km) in diameter and struck Vesta at a speed of 3.0 mi/s (4.8 km/s) leaving behind a crater 7.9 mi (12.8 km) deep. Although huge chunks of Vesta were undoubtedly expelled, the impact was not energetic or massive enough to disrupt Vesta but countless meteorite-sized fragments must have been blasted into space. It was estimated that about 1% of the material that makes up Vesta must have been excavated at the time of impact. Further Hubble images showed a knob-like structure near the South Pole of the asteroid which has been interpreted as an impact basin almost as large as Vesta itself! As the resolution increased in time, a central uplift or rebound peak was revealed, similar to rebound peaks centrally located inside impact craters on the Moon. It is probable that the formation of this impact basin is responsible for the origin of the HED achondrite meteorites.

1 Ceres

Earlier we reviewed the story of the discovery of 1 Ceres, the largest asteroid in the main belt. 1 Ceres is a member of the C-type asteroids (as is Pallas, the second asteroid discovered). It is a nearly spherical body about 584 mi (940 km) in diameter and is among the most primitive asteroids known. It is very dark, having an albedo of only about 5%. A broad absorption band in its spectrum at 3.0 μm indicates the presence of water-bearing clay minerals or phyllosilicates. 1 Ceres is most closely compared to members of the carbonaceous chondrite groups, especially the CI and CM chondrites that have suffered severe aqueous alteration.

In 2006, the International Astronomical Union (IAU) reclassified 1 Ceres as a dwarf planet. So the largest asteroid is now the smallest dwarf planet, one of three. The others are Eris and Pluto.

Asteroid Close Encounters

We have seen how difficult it is to observe main belt asteroids even with the largest Earth-based telescopes. And even under the best of conditions the Hubble Space Telescope could only image the largest asteroids as small, nearly featureless disks. But that was about to change. On October 29, 1991, the Galileo spacecraft making its way to Jupiter encountered the S-type main belt asteroid 951 Gaspra. Images were obtained from a distance of 3,190 mi (5,150 km). It was immediately obvious that Gaspra was a relatively small irregular fragment splintered off a much larger asteroid (Figure 2.8). It measured 11.3 × 5.5 × 6.5 mi (18.2 × 8.9 × 10.5 km). Gaspra showed a surprising lack of large impact craters, most appearing almost erased from the landscape. This sheared-off fragment apparently exposed a fresh surface with few if any large impact craters. Two years later while still on its journey to Jupiter, the Galileo spacecraft again made history when it encountered a much larger asteroid. It passed by 243 Ida from a distance of only 6,790 mi (10,950 km) (Figure 2.9). This was another S-type asteroid. In contrast to Gaspra, Ida was heavily

Figure 2.8. Galileo spacecraft image of asteroid 951 Gaspra, the first asteroid image made from space. Galileo spacecraft image made October 29, 1991. Courtesy of NASA.

Figure 2.9. Galileo spacecraft image of asteroid 243 Ida taken August 28, 1993, from a distance of 10,950 km. Ida is an S-type weathered asteroid. Newly discovered satellite, Dactyl, on far right is only 1.5 km in diameter and 48 km from Ida's surface. Courtesy of NASA.

cratered. It was also a fragment of a much larger parent body, and measured 37.1 mi (59.8 km) in length. During Ida's flyby, an astonishing discovery was made. A small moon 1 mi (1.5 km) in diameter was orbiting Ida at a distance of only 30 mi (48 km) from the surface. This little satellite, now called Dactyl, was the first moon discovered orbiting around an asteroid.

Both Gaspra and Ida with its moon show S-type spectral characteristics different from the ordinary chondrites measured in the laboratory. Studying the surface spectral characteristics strongly suggest that the optical characteristics of the surface minerals of S-type asteroids have been altered due to *space weathering*.

253 Mathilde

On February 17, 1996, asteroids once again made the news when the NEAR (Near Earth Asteroid Rendezvous) spacecraft was launched. The first two asteroid encounters were brief opportunities which took a back seat to the primary Galileo/Jupiter mission. The primary mission was to be the near-Earth asteroid 433 Eros. But this asteroid mission had a secondary target, the asteroid 253 Mathilde. On June 27, 1997, the NEAR spacecraft passed to within 751 mi (1,212 km) of Mathilde. This asteroid was discovered over a century ago, but it wasn't until 1995 that ground-based observations showed Mathilde to be a C-type asteroid with an albedo of only 4%, the brightness of charcoal, half the albedo of the dark mare on the Moon. This low albedo strongly suggested that Mathilde was a fragment of a CM carbonaceous chondrite. Further density studies gave Mathilde a bulk density of only 1.3 g/cm^3, half the bulk density of a typical CM chondrite. This could only mean that Mathilde has a rubble pile internal structure.

There are two models that could describe the interior of a chondritic asteroid parent body. The original body is accreted as it orbits in the protoplanetary disk. The result is a homogeneous body with its mineral components evenly distributed throughout the interior. Internal heating by the short-lived radioisotope ^{26}Al provides the energy to heat the interior from the deep core of the body to the near surface. Thermal metamorphism slowly heats the interior to a petrographic type 6 at the core. The heat makes its way through the body, slowly converting various regions of the interior to different petrographic types from type 6 to type 3. The result is a layered structure something like an onion's interior, thus, the *onion shell model*. Sometime early in its history after the onion shell had formed, the asteroid parent body was catastrophically disrupted by impact with another asteroid. The impact broke the body into myriads of smaller fragments, but in this case the impact was not strong enough to scatter the pieces. Instead, mutual gravity between the pieces reassembled the rubble pile into a mixture of petrographic types (Figure 2.10).

Today, Mathilde is heavily scarred with two enormous impact craters, one in deep shadow (Figure 2.11). The other sits on top of the asteroid when viewed nearly edge on. The surface is smooth and remarkably uniform, suggesting a homogeneity that probably runs through the entire body. Mathilde is a very ancient, primitive world.

433 Eros

Unlike the asteroids explored above, 433 Eros does not reside in the main asteroid belt. It is a Near Earth Asteroid that has its aphelion well inside the asteroid belt but its perihelion just inside Earth's orbit. Figure 2.12 shows the path taken by the NEAR spacecraft on its extraordinary mission to Eros. The NEAR EARTH ASTEROID RENDEZVOUS mission was launched on February 17, 1996, and after a brief encounter with Mathilde received a gravity assist as it encountered Earth on January 23, 1998. NEAR was scheduled to arrive at Eros on December 23, 1998, but within 3 days of the arrival a malfunction of its main engines caused orbit insertion to be aborted. The burn had

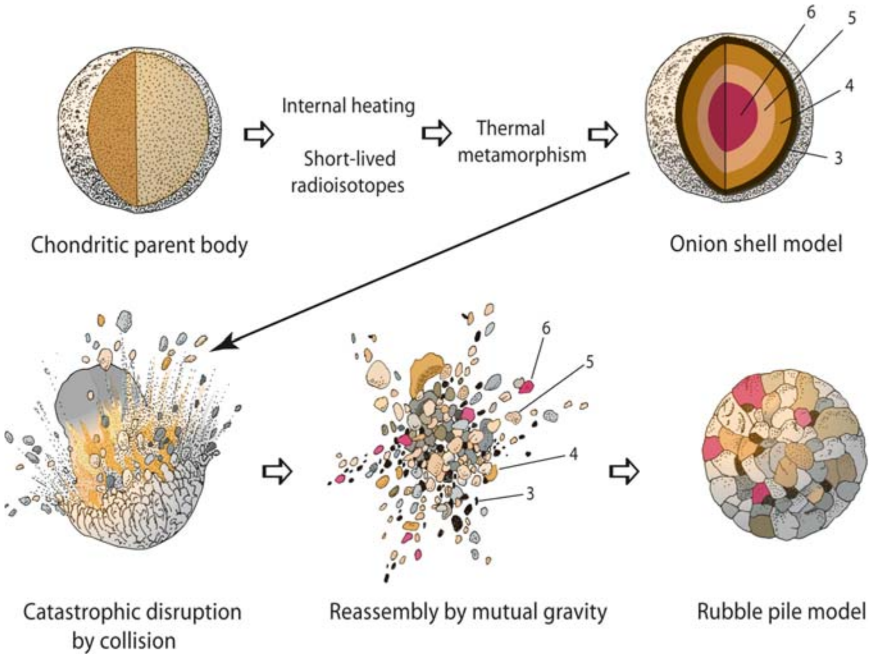

Figure 2.10. Onion shell versus rubble pile models of a chondritic asteroid parent body.

Figure 2.11. Asteroid 253 Mathilde photographed June 27, 1997, by the NEAR spacecraft on its way to asteroid 433 Eros. Mathilde has an albedo (reflectivity) of only 4%, fainter than charcoal and half the brightness of Earth's moon. Courtesy of NASA.

stopped after less than 2 seconds. Mission operators had lost contact with the spacecraft. NEAR was tumbling in space with no guidance. After a grueling period of 27 hours contact was finally reestablished but the opportunity to rendezvous and orbit around Eros on December 23, 1998, as planned, was no longer possible. If nothing else happened to control and redirect the spacecraft, NEAR would coast by Eros on the 23rd of December at a distance of 2,378 mi (3,827 km). The spectacular saga of NEAR's eventual rendezvous and orbit around Eros beginning on Valentine's Day, February 14, 2000, is an extraordinary story. It is dramatically presented in the book Asteroid Rendezvous—NEAR Shoemaker's Adventures at Eros, published by Cambridge University Press, 2002.

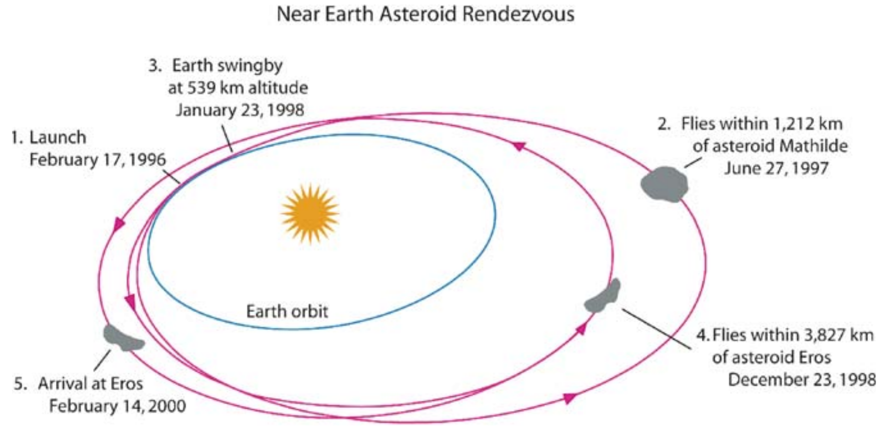

Figure 2.12. Trajectory of the NEAR spacecraft to 433 Eros. Courtesy of the Applied Physics Laboratory, Johns Hopkins University, and NASA.

The year 2000 will be remembered by planetary astronomers and meteoriticists throughout the world as the year NEAR orbited 433 Eros. This was the first opportunity to study a near-Earth S-type asteroid for a full year. Among the many instruments carried by the NEAR spacecraft was a near-infrared spectrometer (NIS) designed to scan the surface and measure the spectrum of sunlight reflecting off Eros at wavelengths between 0.8 and 2.7 μm. The goal was to determine the composition, distribution and abundance of surface minerals. For 3 months after initial orbit insertion, the NIS instrument took over 200,000 reflectance spectra of Eros'surface. The spectra confirmed the presence of olivine and pyroxene on the surface. Moreover, the ratio of olivine to pyroxene was similar to that found in ordinary chondrite meteorites. The stage was set.

On May 13, 2000, the NIS instrument unexpectedly failed, but fortunately not before 90% of the surface had been scanned. NEAR had provided strong evidence that Eros was indeed a fragment of a larger asteroid parent body, and that body was an L4 ordinary chondrite.

Hayabusa

Formerly called MUSES-C, the Hayabusa (the name means falcon) mission is in many ways similar to the Eros mission except that it was designed to bring back samples from a small near-Earth asteroid named 25143 Itokawa. The Hayabusa spacecraft employs new technology designed to use, for the first time in space, an ion propulsion engine. This engine ionizes and accelerates the propellant gas, xenon, and then electrically emits these accelerated particles into space.

Until now, only the extraterrestrial material gathered during the Apollo Moon missions has been used for Earth-side analysis. Overall chemical compositions of the Moon and planets can be determined from Earth-based telescopes and compared with meteorite samples scattered across the Earth's surface. But the Moon and planets have evolved over time, changing due to thermal processing of the Solar System's earliest parent bodies. Thus, the Moon and other planetary bodies cannot provide us with a pristine record of the early Solar System. Asteroids, however, are thought to be small enough to have preserved the physical state of the early Solar System. Soil and rock samples from a small asteroid like Itokawa can give us important clues about the raw materials that made up asteroid parent bodies in their formative years 4.56 billion years ago.

Hayabusa was launched on May 9, 2003, and rendezvoused with Itokawa in mid-September 2005. Hayabusa first surveyed the asteroid's surface from a distance of about 12 mi (20 km) and then moved in for a much closer look. The spacecraft studied Itokawa's numerous physical parameters such as its composition, color, density, shape, and topography. Then, on November 4, 2005, Hayabusa attempted to land on Itokawa but was unable to complete the maneuver. At the second landing, the spacecraft was programmed to fire tiny projectiles at the surface and then collect the resulting spray in its "collection horn." The second attempt failed, but on November 19 Hayabusa set down on the surface. It lifted off without taking a sample; however, there is a high probability that on a later attempt some of the dust from the surface made its way into Hayabusa's sampling chamber which is now sealed for the journey home.

Hayabusa was not specifically designed to land on Itokawa but only to touch the asteroid's surface with its sampling tool. Though not part of the original mission plan, Hayabusa was indeed able to land on the asteroid's surface, remaining there for about 30 minutes. before resuming flight. This is the first time a spacecraft has landed and taken off from a solar system body other than the Moon (Figures. 2.13–2.15).

Itokawa has been shown to be a chondritic rubble pile that has never undergone differentiation into core and mantle. Instead, for millions of years, it has suffered countless impacts from the rocks still scattered everywhere on its surface. Amazingly, Itokawa has no impact craters, only a rocky boulder-ridden surface. Near the "Muses Sea" where smooth terrain interrupts the otherwise rocky surface, the first successful historic touchdowns were made.

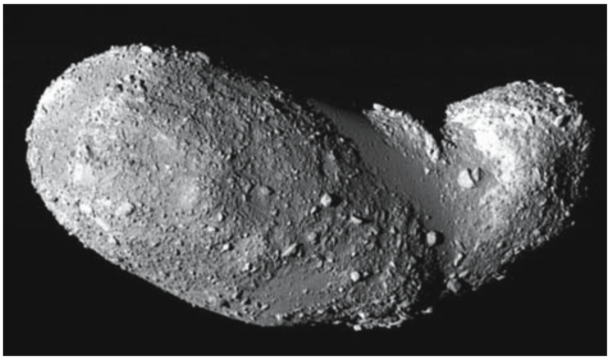

Figure 2.13. The asteroid Itokawa photographed by the Hayabusa spacecraft on October 23, 2005, from a distance of 4.9 km. Some areas on the surface are very smooth and ill-defined, notably the area known as the Muses Sea near the center of the asteroid. Researchers believe this is the result of vibrations caused by impacts on a "rubble-pile" (loosely consolidated) asteroid. Copyright ISAS/JAXA.

Figure 2.14. Itokawa seen from its north pole on November 1, 2005. The longest axis is 535 m and the other axes are 294 and 209 m. Itokawa appears to be composed of two or three individual segments reassembled after multiple impacts. Copyright ISAS/JAXA.

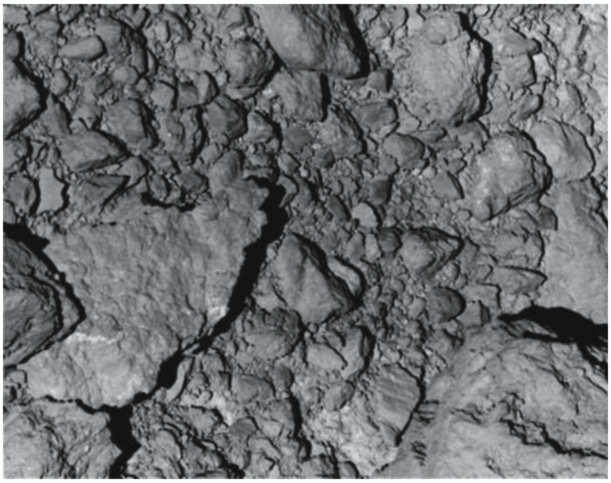

Figure 2.15. Rocks broken by countless impacts lie scattered on the surface of Itokawa, seen from a distance of 0.11 km. Taken on November 12, 2005. Copyright ISAS/JAXA.

The Dawn Mission to 4 Vesta and 1 Ceres

The Dawn mission to 4 Vesta and 1 Ceres was cancelled due to cost overruns and technical problems. But the human drive to understand our origins is a drive that cannot easily be controlled, much less denied. On March 26, 2006, NASA senior management officials announced to the world that the Dawn Mission had been reinstated. "We revisited a number of technical and financial challenges and the work being done to address them. Our review determined the project team has made substantive progress on many of this mission's technical issues. And in the end, we have confidence the mission will succeed." (NASA Associate Administrator Rex Geveden, chairman of the review panel.)

The mission was named because it was designed to explore and study objects dating from the dawn of the Solar System 4.56 billion years ago. The mission's objectives are to send a spacecraft to asteroids 4 Vesta and 1 Ceres, among the largest asteroids orbiting the Sun between Mars and Jupiter. Of the thousands of asteroids orbiting in the main belt, asteroid 1 Ceres is the largest at 584 mi (940 km) in diameter, while 4 Vesta ranks 4th at 330 mi (530 km) in diameter. The two asteroids are quite different from each other. 1 Ceres is the most primitive. It contains both water and organic compounds much like carbonaceous chondrite meteorites and it may harbor clues to the origin of life. 4 Vesta is much more evolved than 1 Ceres and is one of the few asteroids we know of that may be differentiated into core, mantle, and crust much like Earth and Mars.

Dawn launched on September 27, 2007. It will reach Mars in early 2009 where it will gravity assist to send the spacecraft into the asteroid belt. Dawn will reach the belt in October 2011 and will spend ~6 months orbiting 4 Vesta, conducting science along the way. Then it will leave 4 Vesta and travel to 1 Ceres arriving there in August 2015. This is the first time that a single spacecraft has been designed to travel to two different worlds in succession, orbiting each in turn. Each will be thoroughly photographed and maps made with an infra-red mapping spectrometer to determine their precise chemical and mineral composition.

Manned Missions

Now that NASA is talking about returning to the Moon by 2020, there is also discussion about a plan to send a manned mission to an asteroid using the same Orion capsule and Ares rocket that will be used for lunar missions. The obstacles to such a venture are great, of course, but solving them and many more will be a necessary part of any future long-term space explorations by humans. For many years, there has been tremendous interest in asteroids and speculation about the feasibility of mining them for the raw materials necessary to make space colonization a reality. Until that day comes, we will have to continue to wait for the asteroids to come to us as meteorites, as they have been doing since Earth was young.

References and Useful Web Sites

Books

Beatty JK, Petersen CC, Chaikin A. *The New Solar System, Fourth edition*. Sky Publishing Company; 1999.
Cunningham CJ. *Introduction to Asteroids*. Willmann-Bell; 1988.
Bell J, Mitton J (editors). *Asteroid Rendezvous NEAR Shoemaker's Adventures* at Eros. Cambridge University Press; 2002.
Lewis JS. *Rain of Iron and Ice*. Helix Books; 1996.

Web sites

Small Bodies Data Archives, University of Maryland College Park—http://pdssbn.astro.umd.edu
Lunar and Planetary Science links to asteroid information—http://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html

http://www.springer.com/978-1-84800-156-5

Field Guide to Meteors and Meteorites
Norton, O.R.; Chitwood, L.
2008, XV, 287 p., Softcover
ISBN: 978-1-84800-156-5