Physical Processes in the Solar System

An introduction to the physics of asteroids, comets, moons and planets

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Chapter 6

Asteroids

6.1 Overview

The **asteroids** (or **minor planets**) make up a large family of small bodies, most of which orbit the Sun between the paths of Mars and Jupiter. They range in size from a maximum diameter of about 1000 km on down to diameters of a kilometer or less, and there are probably many, many objects in the **asteroid belt** quite a lot smaller still. The orbits of most asteroids lie more or less in the ecliptic plane with the planets, and most of these orbits are no more elongated and off-centred than that of Mercury. Studies of the way asteroids reflect light of various colours suggest that they are composed of minerals similar to those found in several common classes of meteorites, and most meteorites are almost certainly samples of some asteroids. We believe that some asteroids have undergone rather little chemical or physical change since the era when the planets of the solar system formed, and thus these small objects (together with the comets) contain important clues about the process of planet formation. In fact, they seem to be essentially a group of primordial planetesimals that never succeeded in accumulating to form a major planet.

6.2 Discovery

In the 1770's, Johann Bode (1747–1826) discovered and popularized an empirical "law" of planetary orbits (also found earlier by J. D. Titius, and now known as the **Titius-Bode law**). This law describes approximately the spacing of the orbits of the known planets, and predicts that there should be a planet between Mars and Jupiter at about 2.8 AU from the Sun. The Titius-Bode law led to the suspicion that there might be a planet there that had not yet been discovered. The discovery of the planet Uranus by William Herschel (1738–1822) in 1781 made it clear that new planets could indeed be found. In 1800, Franz von Zach, Director of the Ducal Observatory at Gotha, in Germany, began to organize a systematic search for the missing planet. However, on January 1, 1801, before serious work had begun on von Zach's programme, an object not shown on star charts was found by the Sicilian astronomer Giuseppe Piazzi (1749–1826) at Palermo. He observed the new "star" on the following nights and within three nights was sure that it moved. At first Piazzi thought he had discovered a new comet. He measured its position relative to the background stars as often as possible until early February 1801, when he fell seriously ill.

At the end of January, Piazzi had written to report his new "comet" to other astronomers, including Bode at Berlin. The report created some stir among the Germans, and von Zach even speculated that the new object might be the missing planet. However, the letters travelled slowly enough to Northern Europe that by the time the German astronomers heard of Piazzi's discovery, the new body was too close to the Sun to observe. In fact, by summer, Bode and Piazzi realized that it was lost—the methods of calculating orbits in use at the time were simply too crude to yield a useful orbit from position measurements spread over only a few degrees of sky.

The situation was saved by the brilliant young German mathematician Karl Friedrich Gauss (1777–1855), who read about the new object in the newspaper. He put aside his other work and set to devising a better method of determining an orbit from limited observations. By November of 1801 he was successful, and on December 31 von Zach recovered the body almost exactly where Gauss had predicted that it would be. Gauss won such fame from this work that in 1807, at the age of only 30, he was appointed the director of the Göttingen Observatory, where he remained for the rest of his life. The orbit calculated by Gauss clearly showed that the new body follows a nearly circular orbit at 2.8 AU from the Sun, rather than a cometary orbit, and it was generally agreed that the missing planet predicted by the Titius-Bode law had been found. Following Piazzi's proposal, the new planet was named Ceres, for the patron goddess of Sicily.

Since the "missing" planet had now been found, it came as a great surprise when, in March 1802, Wilhelm Olbers (1758–1840), a busy Bremen physician and an active amateur astronomer, discovered a *second* small planet near Ceres, about as bright as Ceres, moving in an orbit of about the same size as that of Ceres, but rather strongly inclined to the ecliptic. The new body, soon named Pallas, naturally fueled searches for other similar objects, and in 1804 Juno was discovered, followed in 1807 by Vesta. And so the gap in the spacing of the planets between Mars and Jupiter was filled, but in a completely unexpected way: by four tiny planets, rather than one large one. Because of their star-like appearances (they are so small that they show no detectable disks when viewed through a telescope), they soon were called asteroids (from Greek *aster*, star).

No more new minor planets in the zone between Mars and Jupiter were found until 1845, but after that fainter asteroids were found with increasing frequency until more than 300 were known by 1891. In that year, the German astronomer Max Wolf (1863–1932) at Heidelberg first used long time exposure photography to find asteroids; on a photograph taken with a telescope that faithfully follows the fixed stars, the stars appear as dots but slowly moving asteroids make small dashes which are readily noticed. This technique is so powerful that by now many thousands of asteroids have been detected; more than 2×10^4 have computed orbits.

6.3 Orbits

For most of the two centuries that asteroids have been known, interest has centred on discovering them and determining their orbits. Only since about 1960 has a major effort been made to understand their physical nature.

When an asteroid is discovered and then frequently observed for some weeks or months as it moves through the sky, an orbit may be computed from which future positions can be predicted. Once the asteroid has a securely known orbit, so that it can be found again, it is officially recognized as a known asteroid, and is given a serial number, and a name chosen by the discoverer. Thus the full designation of an asteroid would be a name like 1 Ceres, 2 Pallas, 3 Juno, or 324 Bamberga. With many thousands of asteroids already named, you can imagine that finding a "suitable" name not already in use can be a challenge.

The physical and orbital characteristics of some of the largest asteroids (mostly with diameters of 200 km or more) as well as of a number of smaller but individually interesting bodies are listed in Table 6.1. In this table, two or more numbers in the "diameter" column indicate that the asteroid is known to be non-spherical; the numbers give approximate diameters measured along the main axes of the body. The columns describing orbital characteristics should be familiar from earlier chapters; the last two columns (albedo and spectral class) will be described later in this chapter.

Most asteroids are found to have orbits with semi-major axes of between 2.2 and 3.5 AU. These orbits are normally somewhat elliptical (not quite circular), with eccentricities e of the order of 0.1 or 0.2. All asteroids circle the Sun in the same sense as the planets, and their orbits lie in planes that are mildly inclined to the plane of the ecliptic, usually by no more than $15°$ or $20°$. (Recall the description of elliptical orbits in Section 1.3.) The asteroid orbits are a little more eccentric than those of most planets, which have orbital eccentricities of 0.1 or less, except for Mercury with 0.21 and Pluto with 0.25. The orbits of asteroids are also somewhat more varied in inclination than those of most planets, all of which have orbit planes within $4°$ of the ecliptic, again except for Mercury (at $7°$) and Pluto (at $17°$). However, the eccentricities and inclinations of asteroids are much smaller than those of the comets. The great majority of asteroids are thus located in a wide belt that starts somewhat outside the orbit of Mars ($a = 1.5$ AU), but does not reach as far as the orbit of Jupiter ($a = 5.2$ AU). Because of the inclinations of the asteroid orbits, this belt also extends to roughly 1 AU above and below the ecliptic plane.

An overview of the orbital characteristics of several thousand numbered asteroids is shown in Figure 6.1, which plots for each of about 5000 numbered asteroids the orbital semi-major axis a and the orbital eccentricity e. Each asteroid is represented by a dot in the figure; you can clearly see the inner and outer edges of the main asteroid belt at about 2.2 AU and 3.2 AU, and the relatively small number of asteroids with orbital eccentricity of more than 0.2.

Within the asteroid belt, a remarkable feature of the orbits is that certain values of the semi-major axis seem to be virtually forbidden. This phenomenon is visible in Figure 6.1 in the obvious existence of lightly populated vertical bands in the swarm of points at a values of 2.5, 2.8, 2.9, and 3.3 AU. The tendency to avoid certain orbit sizes (or periods) is still more clearly seen in Figure 6.2, which plots the total number of numbered asteroids having orbital periods P within small intervals. Definite gaps in this histogram are clearly visible, for example around periods of 3.95, 4.75, and 5.1 yr. These "forbidden" orbits are found to correspond to orbital periods that are in resonance with Jupiter, which means that an asteroid in such an orbit would pass closest to Jupiter at the same place(s) in many successive orbits. For example, if the orbital period of Jupiter (11.86 yr) is exactly three times longer than

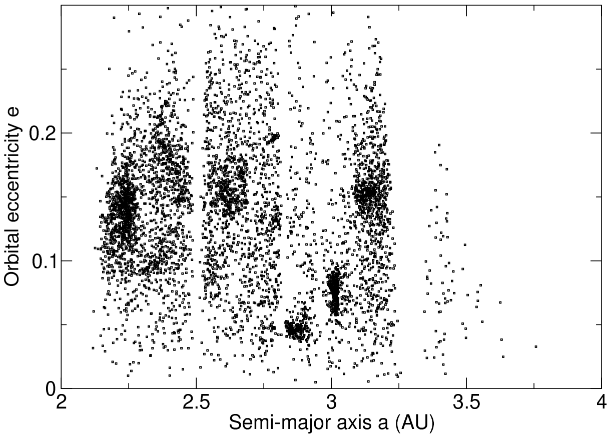

Figure 6.1: This diagram summarizes orbital properties of about 5000 numbered asteroids. Each point represents the orbit of a single asteroid; its horizontal position gives the semi-major axis a, while the orbital eccentricity e is plotted vertically. A position in the upper part of the diagram thus indicates an asteroid with a rather eccentric orbit. The Kirkwood gaps are visible as narrow vertical regions with few points. (Figure based on data made available by Dr Andrea Milani.)

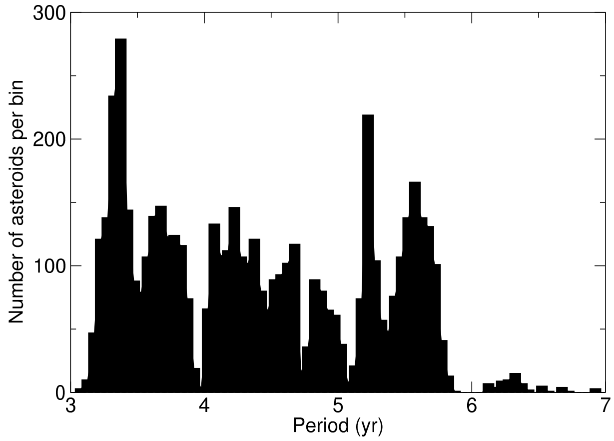

Figure 6.2: A histogram showing the numbers of asteroids having various orbital periods. The Kirkwood gaps at the 2:1, 3:1, 5:2 and 7:3 resonances with Jupiter (respectively at 5.93, 3.95, 4.74 and 5.08 yr) are quite obvious in the figure. (Figure based on data made available by Dr Andrea Milani.)

that of an asteroid (which thus has a period of 3.95 yr, one of the gaps noted above), Jupiter and the asteroid will always pass close to one another at two points on opposite sides of Jupiter's (and the asteroid's) orbit. Such repeated close encounters at the same points in the orbit will eventually result in Jupiter being able to change substantially the orbit of the asteroid by its extra gravitational effect on the asteroid at the positions of close encounter.

Exercise Sketch the orbital motions of Jupiter and of an asteroid having an orbital period one-third that of Jupiter over two Jupiter years (24 earth years) and find the points in the two orbits where the two bodies repeatedly pass one another.

The "forbidden" orbits are known as the **Kirkwood gaps** after their discoverer; they occur for orbits having period ratios P(Jupiter) : P(asteroid) with Jupiter of 2:1, 3:1, 4:1, 5:2, 5:3, and 7:3. Note that the Kirkwood gaps are forbidden values of period of revolution (or of semi-major axis), not of distance from the Sun; a map of actual asteroid positions at any moment shows no gaps at all. A very strange situation occurs for a period ratios of 3:2, 4:3 and 7:2, however, where there are actually accumulations of asteroids!

Astronomers who study orbital motions have begun to understand the logic of where Kirkwood gaps appear and where they do not. In the gaps, the effect of the resonance with the orbital period of Jupiter is to change the orbit parameters (eccentricity and semi-major axis) of the asteroid steadily in an unpredictable direction, so that these orbits become chaotic. The orbits of asteroids in these resonances become more and more eccentric, and they may end by crossing the orbit of Mars. In such a planet-crossing orbit, the asteroid is likely to be ejected from the solar system or to impact the Sun or a planet. In contrast, the resonances where asteroids are still present seem to be where the perturbing effect of Jupiter is to make orbit parameters vary up and down around some average values. In the long term the orbits of these asteroids are not changed substantially, and so these orbits remain populated.

A number of asteroid families (**Hirayama families**) have been identified. These are groups of between roughly 10 and 80 asteroids that have almost identical orbits. The asteroids of a given family are not actually particularly close to one another in space; they are spread along their common orbital track in much the same way that comet debris spreads out along the cometary orbit. What they have in common is nearly identical values of a, e, and i. A few of the most populous families show up on Figure 6.1 as clusters of points, for example the Themis family at $a = 3.14$, $e = 0.15$, Eos at $a = 3.01$, $e = 0.08$, and Koronis at $a = 2.88$, $e = 0.04$. Perhaps as many as half of all asteroids are members of one of roughly 100 Hirayama families that have been identified; some 10% belong to the three largest families. Some of these families are very probably made up of the debris from a single asteroid disrupted by a violent collision with

Table 6.1: Orbital and physical characteristics of some interesting asteroids.

Number & Name		Diameter (km)	Distance from Sun (semi-major axis, AU)	Orbital period (yr)	Orbital eccentricity e	Orbital inclination (°)	Albedo	Spectral class
Near-Earth asteroids								
2062	Aten	1.0	0.966	0.95	0.200	19.3		S
433	Eros	$30 \times 19 \times 7$	1.46	1.76	0.219	10.8	0.18	S
1862	Apollo	1.6	1.47	1.78	0.549	8.9		Q
1866	Sisyphus	10	1.89	1.893				
Main Belt asteroids								
4	Vesta	$566 \times 531 \times 437$	2.36	3.63	0.090	7.1	0.38	U
13	Egeria	215	2.58	4.13	0.121	16.3	0.099	C
15	Eunomia	270	2.64	4.30	0.143	13.3	0.19	S
3	Juno	267	2.67	4.36	0.255	13.0	0.22	S
324	Bamberga	240	2.68	4.39	0.285	13.3	0.057	C
45	Eugenia	215	2.72	4.49	0.115	6.1	0.048	C
1	Ceres	959×907	2.77	4.60	0.077	10.6	0.10	C
2	Pallas	$570 \times 525 \times 482$	2.77	4.61	0.233	34.8	0.14	U
16	Psyche	265	2.92	4.99	0.138	3.1	0.10	M
704	Interamnia	335	3.06	5.36	0.153	17.3	0.064	C
451	Patientia	230	3.06	5.36	0.068	15.2	0.073	C
52	Europa	280	3.10	5.45	0.109	7.5	0.057	C
48	Doris	225	3.11	5.49	0.064	6.7	0.064	C
24	Themis	230	3.13	5.55	0.159	1.2		C
10	Hygeia	430	3.14	5.57	0.118	3.8	0.075	C
31	Euphrosyne	250	3.15	5.61	0.228	26.3	0.070	C
511	Davida	$417 \times 333 \times 292$	3.18	5.67	0.172	15.9	0.053	C
Asteroids beyond the Main Belt								
65	Cybele	245	3.43	6.35	0.110	3.6	0.057	C
87	Sylvia	270	3.48	6.51	0.093	10.9	0.040	C
153	Hilda	175	3.97	7.91			0.060	P
279	Thule	135	4.29	8.90			0.060	D
Trojan asteroids								
624	Hektor	150×300	5.20	11.86			0.02	D
Centaurs								
944	Hidalgo	50	5.86	14.19	0.66	42.4		
2060	Chiron	220	13.65	50.43	0.383	6.9	0.08?	C
5145	Pholus		20.30	91.43	0.572	24.7		
Trans-neptunian objects								
	1992 QB1		44.01	292.0	0.071	2.2		

Sources: R. P. Binzel, T. Gehrels & M. S. Matthews (eds.) 1989, *Asteroids II* (Tucson: Univ. of Arizona Press), Parts II &VI; and C. T. Kowal 1996, *Asteroids: Their Nature and Utilization* (New York: John Wiley & Sons)

another asteroid. Since the ejection velocity of most debris from a violent collision is typically in the range of 0.1 to 1 $\mathrm{km\,s^{-1}}$ (relative to the centre of mass of the colliding bodies), and this is small compared to orbital speeds of around 18 $\mathrm{km\,s^{-1}}$, the fragments continue to follow almost the same orbit that the parent body did, gradually spreading around the orbit.

Not all asteroids are found in the main asteroid belt, however. A small number have orbital semi-major axes that are near one AU. These near-Earth asteroids, although relatively rare, are of particular interest to us because they may be able to collide with Earth (recall Sec. 5.2). Such asteroids are usually assigned to one of three families on the basis of orbit size. The Aten group have semi-major axes a of less than 1.00 AU, and thus orbit the Sun more quickly than the Earth does. The Apollo group have Earth-crossing orbits with $a > 1.00$ AU. Still further out, the Earth-approaching Amor asteroids move in orbits which do not at present cross that of Earth, but which have perihelion distances from the Sun of less than 1.3 AU. These three groups of objects are usually lumped together and called **near-Earth asteroids (NEA's)**. Roughly 200 such bodies are now known, and it is estimated that about 700 Apollo asteroids have diameters greater than 1 km. The probability of a collision between Earth and one of these bodies within the next 1000 years is about 0.4%. They are probably the source bodies for many of the meteorites that fall to Earth.

A little further out, not far outside the orbit of Mars, the small Hungaria group orbits between 1.8 and 2.0 AU, substantially closer to the Sun than the inner edge of the main belt at about 2.2 AU.

Beyond the main asteroid belt, which ends at about 3.2 AU, we have the Cybele family at about 3.4 AU, the Hildas at 4 AU, and the **Trojan** asteroids, which revolve around the Sun in orbits of $a \approx 5.2$ AU, essentially the same as the orbit of Jupiter. The Trojans occupy particularly interesting orbits; they are found in two clusters on Jupiter's orbit, equidistant from the Sun and from Jupiter. One group is about 5 AU ahead of Jupiter on its path, and the other is about 5 AU behind. These orbits are two of the so-called **Lagrange points**, after the great French mathematician Joseph-Louis Lagrange (1736–1813), who in 1772, more than one century before the discovery in 1906 of the first Trojan asteroid, showed that bodies in these particular positions relative to Jupiter would be kept gently in position by the gravitational "shepherding" of the planet.

A few really remote small bodies have been found in recent years orbiting among the outer planets. It is not clear whether these objects are physically more similar to the main belt asteroids or to the nuclei of comets, but with one exception they show no cometary outgassing, so we can conveniently look at them along with the asteroids. These bodies have much more distinctive orbits than the main belt asteroids, both in their much larger distances from the Sun and in their much larger eccentricities. Three are listed in Table 6.1. 944 Hidalgo travels from a perihelion at 2 AU, inside the inner edge of the main asteroid belt, out to 9.7 AU, just beyond the orbit of Saturn. Its highly inclined orbit resembles that of a short-period comet, but it shows no cometary activity. 2060 Chiron, farther out, ranges from 8.5 AU from the Sun, somewhat inside Saturn's orbit, out to 18.9 AU, near the orbit of Uranus, in an orbit not far out of the plane of the ecliptic. For ten years after its discovery, Chiron looked like a normal asteroid, but in 1988 it was observed to flare up in brightness, and the next year it showed a faint coma, like a comet. Unlike objects in the main belt, bodies at such large distances from the Sun may well contain considerable amounts of ice, so they may be physically closely related to comet nuclei even if they show no comas.

Finally, recall the bodies discovered in the Kuiper belt (Sec. 4.5). The objects so far discovered in this broad region outside the orbit of Neptune are typically of order 200 km or more in diameter (smaller bodies are mostly still too faint to be detected from the Earth). They are thus very similar to the larger asteroids in size, although they are very probably made of a mixture of ice and rock, like comet nuclei. Like the asteroids, most Kuiper belt objects orbit the Sun in orbits that are mildly eccentric and moderately inclined. In many ways, the Kuiper belt appears to be a second asteroid belt beyond the region of the giant planets. Because it is so much more difficult to detect and especially to study Kuiper belt objects, we still know rather little about this outer family of small bodies. The first object discovered in the Kuiper belt, 1992 QB1, is included in Table 6.1. The few large "asteroids" like Chiron and Pholus that are found among the giant planets could well be bodies brought in from the Kuiper belt by the perturbing action of Neptune, as described later in Chapter 7.

6.4 Physical nature of asteroids

Asteroids are mostly so small that it is very difficult to obtain accurate measurements of size or mass for them by the kinds of direct methods useful for large planets. Hence a variety of indirect techniques are employed. As only one asteroid has ever been landed upon, and only a few have been observed close up by spacecraft, much of what we know about them still comes from Earth-based observations.

Sizes

Even the largest asteroids are somewhat less than one second of arc in diameter as seen from Earth, an thus are not seen as disks in a telescope, but simply as fuzzy points of light. Direct measurements of diameter are therefore difficult and inaccurate except for rare measurements from space probes. However, several methods provide asteroid diameters indirectly. The simplest method is to assume a reflectivity (the fraction of light reflected is usually called the **albedo**) for an asteroid (one might reasonably guess from comparison with terrestrial rocks that perhaps 10 or 20% of the light is reflected), and then to use the measured brightness at a known distance from the Sun and Earth to calculate the size the asteroid must have to reflect as much light as it does. Clearly a (spherical) asteroid with a diameter of 100 km and a projected surface area of $\pi D^2/4 = 7850$ km^2 will reflect roughly 10,000 times more light, and be about 10,000 times brighter, than an asteroid of only 1 km diameter with a projected surface area of 0.8 km^2; even if the albedos are not known exactly, the enormous difference in reflecting surface between large and small asteroids allows one to derive a rough size for an asteroid as soon as its orbit is determined and its brightness is measured. The biggest source of uncertainty in measuring sizes by this method is the assumed albedo. Terrestrial rocks actually vary in reflectivity from around 3% (coal) to 50% (limestone); if we assume a corresponding range in asteroid albedos, the derived asteroid diameters are uncertain by a factor of more than three!

The situation can be greatly improved if the albedo can be measured. There are several methods for doing this. One is to recognize that the fraction of the sunlight that falls onto an asteroid but is *not* reflected must be absorbed. This warms the asteroid up to a temperature at which the heat radiation from the surface just balances the heating from absorbed sunlight. Now if the asteroid has a high albedo, and reflects most sunlight so that little warming takes place, it will be *cooler* than another darker asteroid at the same distance from the Sun, which reflects less light and absorbs more. The darker asteroid will have a higher surface temperature than the lighter asteroid, in order to radiate away the larger amount of absorbed heat. Now an important difference between the incoming sunlight and the radiated heat is due to the fact that the asteroid surface is far cooler than the surface of the Sun. Because the Sun's surface is at about 6000 K, most of the heat it radiates comes out between about 2,000 and 20,000 Å (0.2–2.0 μm), essentially in the (visible) band of wavelengths to which the eye is sensitive. The *reflected* light from an asteroid will therefore also be in this wavelength range. In contrast, an asteroid normally has a surface temperature of less than 200 K, and hence emits mainly in the wavelengths band between 6 and 100 μm, in the infrared. Thus a measurement of an asteroid's brightness in visible light measures the amount of reflected light, while an infra-red brightness measurement determines the amount of absorbed and re-radiated energy. A highly reflective asteroid will be brighter in reflected light than in re-radiated light, while a dark asteroid will be brighter in the infra-red than in visible light. Calculating the ratio of these two brightnesses allows us to determine an asteroid's albedo, and then to use the observed infrared brightness to deduce a reasonably accurate (±10%) diameter. The idea is illustrated in Figure 6.3.

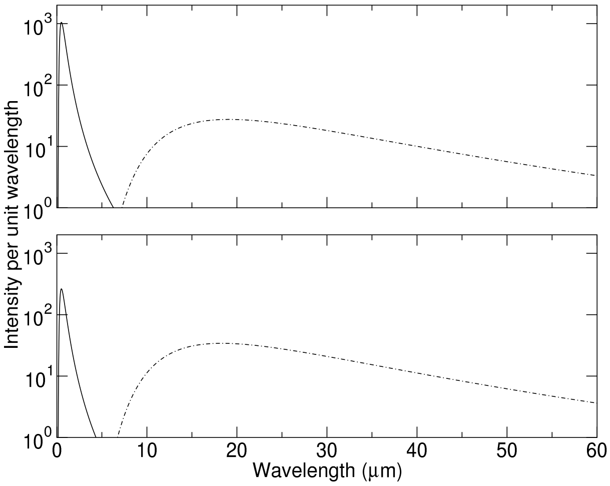

Figure 6.3: This figure shows approximately the reflected visible light (solid lines) and the infra-red heat radiation (dot-dash lines) for two asteroids at 3 AU from the Sun. The asteroid of the upper panel has (visual) albedo $A = 0.20$, and the lower has $A = 0.05$. Notice, first, that the reflected visible light and the radiated IR light virtually do not overlap, so it is easy to identify which is reflected light and which is thermal radiation. Then notice that the ratio of visible to infra-red radiation (the ratio of the areas under the two curves in the panel) is higher for the more reflective asteroid of the upper panel than is for the less reflective body in the lower panel. By comparing the *relative* amounts of visible and infra-red light from an asteroid, you can deduce its albedo.

A much more accurate method of measuring asteroid sizes takes advantage of the fact that an asteroid will occasionally pass in front of a star and eclipse it. If the event has been predicted, astronomers can set up portable telescopes along the path of the asteroid's shadow on Earth, and measure the time and duration of the eclipse. (Amateur astronomers have been of great help to professionals in a number of such campaigns.) From several such observations of the same event (called an occultation), one can easily calculate how large the asteroid's shadow is on the Earth while it eclipses the star. The eclipsed star is so far away that all the light rays from it striking the asteroid are parallel, and the asteroid's shadow is a cylinder with the same diameter as the asteroid. Thus, knowing the shadow diameter gives directly the asteroid size. This technique has yielded quite accurate (±10 km) diame-

Figure 6.4: The asteroid 951 Gaspra was imaged from a distance of 5300 km by the Galileo space probe in 1991. It is about 19 x 12 x 11 km in size. The smallest features visible in the image are about 100 m across, about the size of a football field. Some 600 small craters are visible in images of this body. The very irregular shape of the asteroid suggests that it may be a piece of a larger asteroid fragmented by a violent collision. (Courtesy of NASA.)

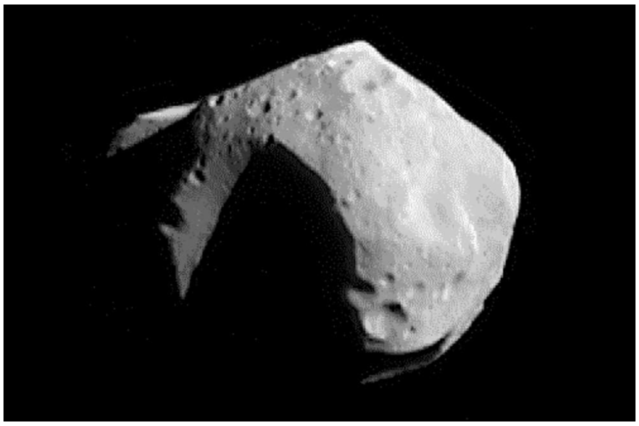

Figure 6.5: The asteroid 253 Mathilde, which is 56 km across its largest dimension, was observed by the NEAR spacecraft in 1997. This view, from about 2400 km away, clearly shows a huge crater comparable in size to the asteroid itself. The asteroid is almost black, reflecting only about 3% of the sunlight striking it, in contrast to Ida and Gaspra, which are about as reflective as gray rock. (Courtesy of NASA.)

ters for a few of the larger asteroids. The largest, Ceres, has had not only its diameter but its shape measured by this method. Due to its rather rapid rotation (one rotation every 9 hours), it has the shape of a slightly flattened sphere (like the Earth), with an equatorial diameter of 959 ± 5 km and a polar diameter of 907 ± 9 km.

Sizes have been determined by one method or another for a large number of main belt asteroids by now. Estimated sizes are available for almost all the asteroids listed in Table 6.1. Ceres is by far the largest. The next two largest in size are Pallas and Vesta, with diameters of a little over 500 km. More than 10 asteroids have diameters exceeding about 250 km. As one goes down in size, the number of asteroids increases rapidly. About 100 are larger than 150 km in diameter; almost 1000 exceed 40 km. And there are certainly hundreds or thousands of bodies more than 100 km in diameter in the Kuiper Belt.

At still smaller sizes, there must be many thousands of asteroids, but such small bodies are very faint and hard to study, and only a small fraction have known orbits. However, on the basis of the number of asteroids found in surveys, it is possible to estimate their total numbers, at least of those with sufficiently large diameters (of the order of hundreds of m) to be detected. There are probably around 40,000 bodies in the asteroid belt with diameters of 1 km or more, and perhaps one million bodies if we count everything more than 100 m across. (Note that such a statistic, to be meaningful, must specify the lower size limit of objects included in the count!) Although this seems to be an enormous number of objects, the volume of space occupied by the asteroid belt is huge, and the typical separation between asteroids with diameters of 100 m or more is of the order of 3 million km. The familiar image from the movies of a space ship maneuvering madly to avoid one asteroid after another is certainly not appropriate for the solar system's asteroid belt!

Three asteroids have been viewed from distances of only a few thousand km by passing space probes, and a fourth has been studied in detail by its own orbiter. The asteroids Gaspra (in 1991) and Ida (in 1993) were imaged by the Galileo spacecraft during its long trip to the Jupiter system. Ida and its tiny moon Dactyl are seen in Figure 1.5. Gaspra is shown in Figure 6.4. Asteroid Mathilde (Figure 6.5) was observed by the NEAR (Near Earth Asteroid Rendezvous) space probe in 1997 (now called the NEAR-Shoemaker mission). The NEAR probe then went into orbit around Eros (Figure 6.6), from which it has sent back an enormous amount of fascinating information, finally *landing* (Figure 6.7) on the asteroidal surface at the end of the mission!

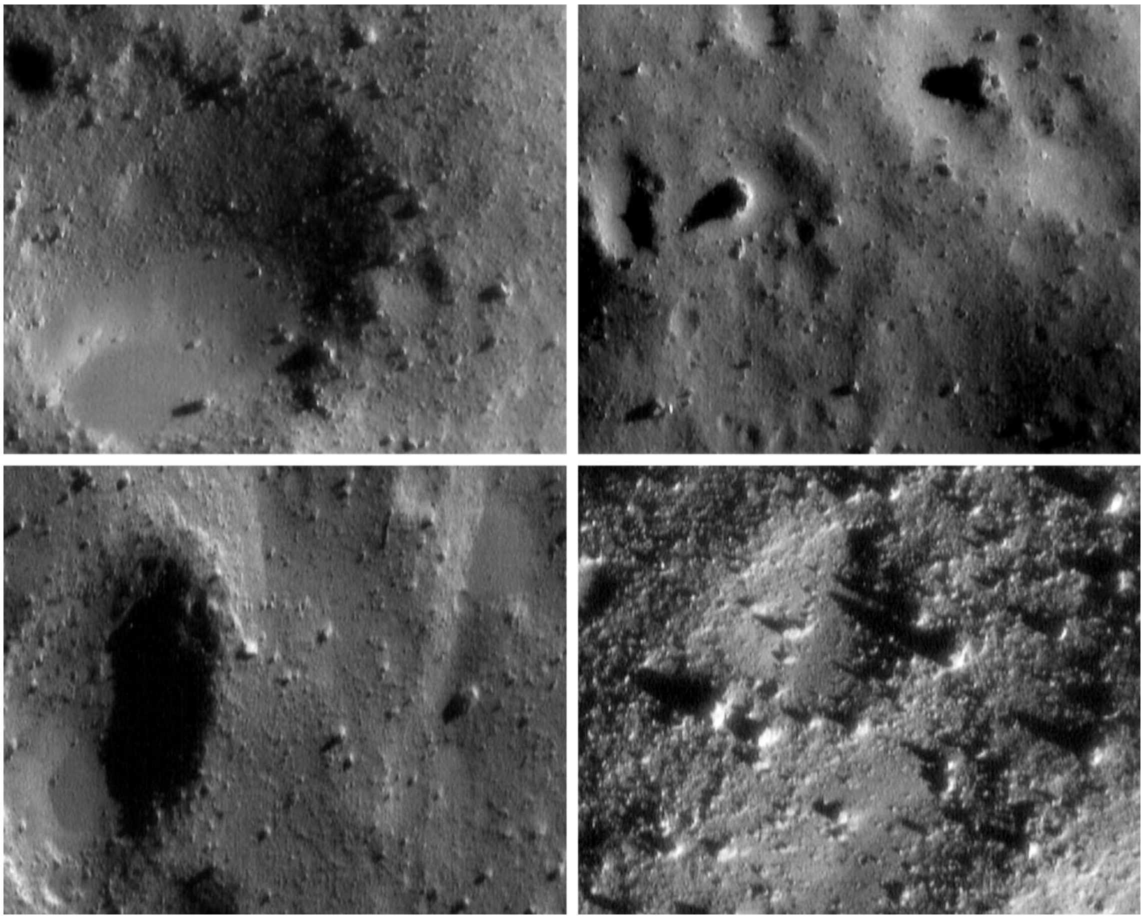

Figure 6.7: Four views of the surface of asteroid 433 Eros taken during the last few days of the mission before the NEAR spacecraft settled in to land on the surface of the asteroid. The top images were taken from about 12 km above Eros, and show regions about 500 m across; the two lower images are from about 5 km up and show regions about 250 m across. The surface of Eros is dotted with small craters and covered with boulders. (Courtesy of NASA.)

Spins and Shapes

Careful observations of the brightness of most asteroids show changes in brightness that repeat regularly with periods that are usually between about six hours and 2 days. This effect is caused by rotation, combined with non-spherical shapes and/or perhaps non-uniform surface reflectivity (darker and light regions). Variations in reflectivity or colour over the surface ("spots") probably dominate the brightness changes for the largest asteroids (with diameters of $\sim$ 300 km or more), which are massive enough that their own gravities force them to be roughly spherical. The much more common smaller asteroids are often markedly non-spherical. Ida (Figure 1.5), Gaspra (Figure 6.4), and Eros (Figure 6.6) all have longest dimensions roughly twice as large as their smaller dimensions. The small near-Earth asteroid 4179 Toutatis has been imaged by radar, and it is found that it has a shape like a peanut, smaller around the waist and larger at both ends. As such a small irregular body spins, usually around an axis roughly perpendicular to the longest dimension, the light it reflects towards Earth varies strongly as we see the asteroid broadside on and then end on.

Such close-up views are not possible for most asteroids. However, we can still obtain information about the shapes of asteroids that we see only as points of light by studying closely the light variations. As an asteroid and the Earth move around their respective orbits, we are able to observe how the light reflected from the spinning asteroid varies when seen from various directions. At one moment, we might be looking at the asteroid (let's assume that it is elongated like Eros, and rotating around an axis perpendicular to its long dimension) from its equatorial plane. We would then observe large variations in the brightness of reflected sunlight as we see first the full length of the asteroid and then its smaller end-on profile. At another time,

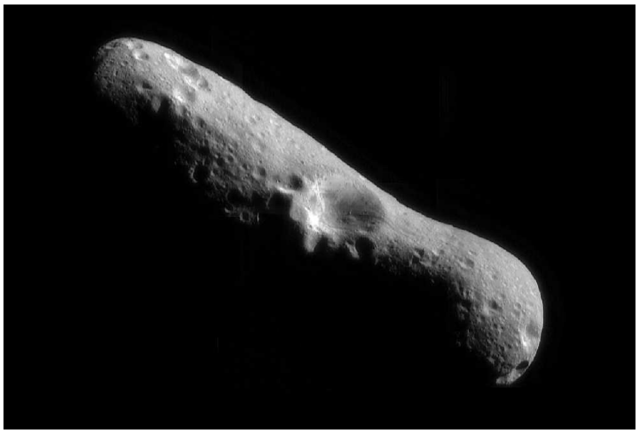

Figure 6.6: The asteroid 433 Eros, viewed in a mosaic of images obtained by the NEAR spacecraft shortly after going into orbit around the asteroid in February 2000, from a distance of about 300 km. The many high resolution images sent back to Earth from NEAR will help space scientists to understand the details of Eros' history. Notice how remarkably non-spherical this small body is (the longest dimension is about 30 km), and that the largest visible crater is more than 15% of the asteroid's length in diameter! (Courtesy of NASA.)

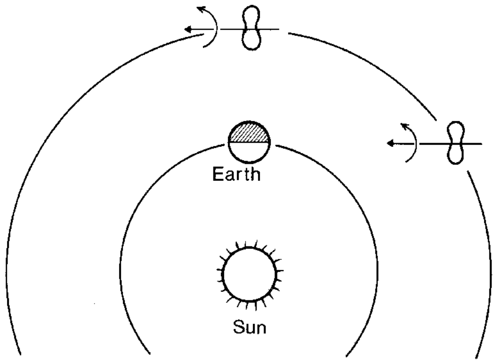

Figure 6.8: This sketch shows an elongated asteroid (like Gaspra or Eros) that is rotating around an axis perpendicular to its long axis, as seen from the Earth at two different places in its orbit. At one location, its rotation is seen from the side, and the apparent area and brightness of the asteroid vary considerably as it is seen first end on and then side on. In the other position, its rotation is seen from along its rotation axis, and although its orientation on the sky changes, its projected surface does not, so that its brightness variations are quite small.

we could be looking roughly along the rotation axis; in this case, we would hardly see any variations. These possibilities are sketched in Figure 6.8. By observing a particular asteroid a number of times from various directions, it is possible to deduce – very approximately! – its overall shape and the direction in space of its rotation axis. The bodies in Table 6.1 for which the diameters are given as three numbers are mostly bodies for which observations of light variations have allowed astronomers to infer shapes. Other techniques (such as occultations, use of radar, and "speckle interferometry") provide valuable additional information. It appears that the very bizarre shapes seen in the images of asteroids are typical enough of the great majority of small asteroids which have never been seen from close up.

Masses and densities

The masses of the three largest asteroids, Ceres, Pallas, and Vesta, have been determined observing the tiny attractive effects these bodies have via gravity on smaller asteroids in similar orbits, and on each other. The attractive forces of even these largest asteroids on other bodies are so small that the effects to be observed require extraordinarily precise position determinations, and the deduced masses still differ somewhat from one investigation to another. Table 6.2 lists masses that have been determined in this way, as well as three others that have been observed from nearby spacecraft. The masses given for Ceres and Vesta are probably still uncertain by about 10%, and that of Pallas by 20%. Ida's mass is derived from observations of its moon Dactyl, and is accurate to about 15%; Mathilde was weighed by observing the deflection of the NEAR space probe and is uncertain by about 4%. The mass of Eros was measured with enormous precision (±0.05%) by the NEAR craft, which orbited the asteroid for months before actually landing on it on 12 February 2001.

Both mass and mean radius are well enough known for the large asteroids Ceres, Pallas and Vesta to obtain approximate mean densities, which provide valuable clues about the overall chemical composition of these small bodies. The density of Ceres is significantly lower than the density of almost any kind of terrestrial rock, but similar to the densities of carbonaceous chondrite meteorites. The densities of Pallas and Vesta are considerably larger; their densities are comparable to the densities of ordinary (not carbonaceous) chondrites, or to the typical densities of achondritic meteorites or those of stony-irons (see Table 5.3). It seems probable that Ceres is made of material similar to that in carbonaceous chondrites, while Pallas may be related to ordinary chondrites. Vesta is clearly related to a family of igneous (differentiated) meteorites.

As we have seen, spacecraft passed quite close to the asteroids Ida and Mathilde, and actually orbited

Table 6.2: Masses, mean radii and mean densities of some asteroids

	Name	Mass (kg)	Mean diameter (km)	Mean density (kg m^{-3})
1	Ceres	9.54×10^{20}	933	2230
2	Pallas	2.4×10^{20}	524	3200
4	Vesta	2.8×10^{20}	508	3900
243	Ida	4.2×10^{16}	31	2600
253	Mathilde	1.03×10^{17}	53	1300
433	Eros	6.687×10^{15}	16.8	2670
	All others	3×10^{20}		

Sources: Viateau, B. & Rapaport, M. 1998, *Astr. Ap.* 334, 729; Yeomans, D. et al. 1997, *Science* 278, 2106; Yeomans et al. 2000, *Science* 289, 2085.

Eros. Those close encounters changed the probe orbits enough to allow determination of the masses of these small bodies, and since the detailed shapes were also observed, volumes and mean densities could be computed. The densities of Ida and of Eros are typical of carbonaceous chondrites or terrestrial rock, so from this information we would suspect that they are parent bodies of such meteorites. However, they are not nearly as dark as carbonaceous meteorites. Mathilde's density turned out, to everyone's great surprise, to be only 1300 ± 200 kg m^{-3}, less than half the density of any normal rock. Mathilde is probably a loose aggregate of boulders, with much empty space inside between rocks; even if Mathilde's boulders have the relatively low density of carbonaceous chondrites, which is consistent with the nearly black colour of the asteroid, some additional effect such as internal voids must be lowering the both densities still further. This discovery makes it seem likely that densities of other small asteroids are probably lower than the densities of the rocks of which they are composed. (Of course, for asteroids near the outer edge of the asteroid belt, a significant mineral could be water ice, with its density of about 900 kg m^{-3}, but this is not possible for the asteroids observed up to now from space probes, because they are too close to the Sun and hence too warm.)

If we estimate the total mass of all the smaller asteroids by assuming a reasonable typical density, it turns out (see Table 6.2) that Ceres contains about half the mass of the asteroid belt, and that the total mass of all the asteroids only adds up to about 1/40th of the mass of the Earth's Moon.

Chemical and mineral composition

To understand the nature and history of asteroids, we need to know not only about their orbits, sizes, shapes, and masses, but also about their chemical and mineral compositions. These compositions are the result of the processes that formed and altered them, and thus contain extremely valuable clues about these processes. How can we learn something about the minerals present in an asteroid?

The first broad hint about asteroid chemistry comes from the fact that asteroids are mostly quite dark (they have relatively small albedos); furthermore, among the larger asteroids there seem to be some, like Mathilde, that are almost black, like coal or soot (albedos of 3 or 4%), while others, such as Gaspra and Ida, are merely dark, like dark grey rocks (albedos of 10 to 20%), and a few are actually rather bright, like limestone (albedos approaching 50%). This fact strongly suggests that there are at least two or three kinds of asteroids that probably have rather different minerals and chemistry.

Further differences among asteroids can be found when we look into how well they reflect various colours – that is, we measure the brightness at several wavelengths. This has been done for more than a thousand asteroids using a photometer (a device that measures the brightness of light, like the light meter in a camera). In the simplest version of this kind of measurement, the brightness of the asteroid is measured through three standard coloured glass filters, which pass yellow, blue, and near ultraviolet light. When the brightness of the asteroid as measured through the three filters is compared, we obtain information about the colour of the asteroid. For example, a grey-coloured asteroid would reflect all three colours about the same, and so would have the same brightness as measured through all three filters. On the other hand, and asteroid that has a reddish colour, like some sandstones – or bricks – reflects more yellow than blue light, so the brightness as measured through the yellow filter would be brighter than measured thorough the blue filter. Notice that since this type of measurement relies on *ratios* (for example the ratio of brightness through the blue filter to the brightness through the yellow filter), it does not depend on whether the asteroid is bright or faint, large or small, or near or far.

Using both albedo measurements and this sort of colour measurement, we find that the asteroids group into several large, more-or-less distinct classes. Each of the larger classes is found to have albedo and colour that is characteristic of a family of meteorites. It was natural to guess that the similarity of albedo and colour of each large class of asteroids to the characteristics of one type of meteorite hints that the asteroids of that class are actually similar in mineral composition to

Table 6.3: Asteroid types, meteorite analogues, and mineral identifications

Type	Number	Albedo	Meteorite analogue	Possible mineral identifications
A	4	high	olivine-rich achondrites, pallasites (stony-irons)	olivine, olivine-metal
B, C, F, G	6, 88, 13, 5	low	CI and CM carbonaceous chondrites	hydrated silicates, carbon, organic materials
D, P	26, 23	low	organic-rich CI and CM carbonaceous chondrites?	carbon- and organic-rich silicates?
E	8	high	aubrites (enstatite-rich achondrites)	enstatite or other iron-free silicates
M	21	middle	irons, perhaps also enstatite chondrites	iron-nickel, perhaps metal and enstatite
Q	1	high	ordinary (not carbonaceous) chondrites	olivine, pyroxene, and metal
R	1	high	pyroxene-olivine achondrites	pyroxene and olivine
S	144	middle	pallasites, olivine-rich stony-irons, ureilites (olivine-rich achondrites), CV and CO carbonaceous chondrites	combinations of metal, olivine, and pyroxene
T	4	low		similar to types P and D?
V	1	high	basaltic achondrites	pyroxene and/or feldspar

Source: M. J. Gaffey, J. F. Bell & D. P. Cruikshank 1989, in *Asteroids II*, ed. R. P Binzel, T. Gehrels & M. S. Matthews (Tucson: Univ. of Arizona Press), p. 98.

the corresponding meteorites, and the asteroid classes have been named accordingly. Thus, asteroids that are nearly black but reflect all colours about equally well (or poorly), and are similar to the carbonaceous chondrites (recall Table 5.3), were placed in the C class. The more reflective asteroids with A values of 0.1 or 0.2 break into two distinct groups, one with colour similar to iron meteorites which were called M asteroids, and a redder group with colours like those of some stony-iron meteorites, thus labelled S asteroids. A few really reflective, neutral coloured asteroids are similar in colour and reflectivity to the enstatite meteorites and have been assigned to the E class. The strong similarities found between meteorites and asteroids supports the idea that most meteorites are derived from asteroids.

However, colour measurements using only three filters are not sufficient to discriminate among the large number of meteorite types described in the previous chapter, or, one assumes, among a similarly large number of kinds of asteroids. Thus asteroid scientists have developed still more powerful methods of observation that yield more information. One of the main ways this has been done is to measure brightness of a larger number of colours at both visible and infrared wavelengths. Substantial differences in brightness observed in the infrared are found among various meteorites – and among the asteroids. With more colours, more asteroid classes are identified, and in recent years the classification system has grown to include more than a dozen different types. For reference, the main classes in use are summarized in Table 6.3. The various types have been tentatively identified both with specific classes of meteorites that have similar reflectance properties, and with the kinds of minerals that can lead to the various colour properties observed. From the table, you can see that some classes (S, C, M, D, P, etc.) have a large number of members, while others (Q, R, V, etc.) have few or even only one known representative. (Of course, the numbers in this table are large for types of asteroids that are found near the Earth than for types far out in the solar system.) These are the asteroid types used to describe individual asteroids in Table 6.1.

The natural next step after measuring the brightness of an asteroid at several wavelengths is to measure the brightness of reflected or emitted radiation at many wavelengths – that is, to observe the spectrum of the body. From the ground, this is most practical in the visible and near infrared, between about 0.3 μm and 2.5 μm, where the reflected sunlight is relatively bright (see Figure 6.3) and the Earth's atmosphere does not present too much absorption. Asteroid (and mineral) spectra in this wavelength region are found to contain a lot of information about the chemical and mineral nature of the material(s) observed.

Unlike gases, solids do not show sharp spectral emission lines (Figure 2.3) or absorption lines (Figure 3.7).

Instead, mineral – especially iron-rich ones – show broad regions of relatively poor reflectivity whose position and width in the spectrum allow one to identify with reasonable certainty particular mineral species (such as olivine or pyroxene), and to determine which metal (iron, magnesium, etc.) is the main one present in the mineral. The way in which reflectivity varies with wavelength is shown for several common minerals in Figure 6.9. Clearly each of the minerals shown exhibits a distinctive signature in its reflection (or reflectivity) spectrum.

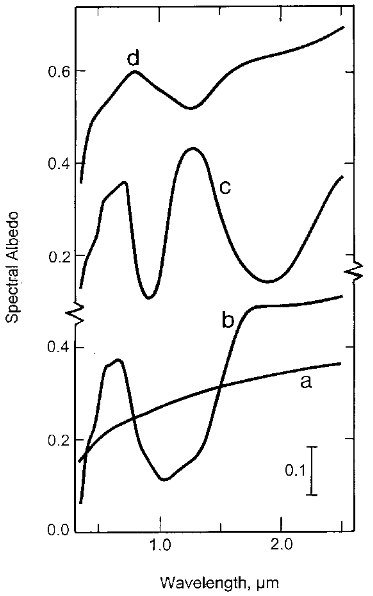

Figure 6.9: Reflectivity spectra of common silicate minerals and iron. From bottom to top they are (a) metallic nickel-iron, (b) olivine, (c) pyroxene, and (d) plagioclase feldspar (anorthite). Notice that the vertical scale makes a sudden change about half-way up the figure. (Adapted from M. J. Gaffey, J. F. Bell, and D. P. Cruikshank 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels and M. S. Matthews (Tucson, AZ: Univ. of Arizona Press), p. 101.)

Several important kinds of absorption patterns are found in the reflectivity spectra of the kinds of substances that seem to be common in asteroids. First, there are opaque, very poorly reflecting materials. These include various forms of carbon such as graphite, various tarry organic materials, and the iron oxide magnetite (Fe_3O_4). All are black – that is, they reflect almost no light of any colour; they simply have albedos that are very low (around 0.03) throughout the visible and near infrared spectrum. Next, there are the abundant metals, such as iron, perhaps mixed (alloyed) with nickel. These metals have no distinctive features in their reflection spectra, but rather show a moderate reflectivity (of order 0.30) that rises steadily towards longer wavelengths, from the near ultraviolet into the infrared. Sunlight reflected from a metal is more depleted in blue light than in red, and so the reflected light has a somewhat reddish colour (Figure 6.9 (a)).

Another type of spectrum is the family of silicate minerals containing iron. The two most prominent families in asteroids are the olivine series $(Mg_2,Fe_2)SiO_4$ and the pyroxenes $(Mg,Fe)SiO_3$. The olivines (Figure 6.9 (b)) show a single deep absorption between 0.7 and 1.5 μm (and the strong peak of reflectivity between 0.5 and 0.7 μm is responsible for the pronounced green colour of this mineral). The pyroxenes have a pair of regions of poor reflectivity, one around 1 μm and the other centred near 1.9 μm (Figure 6.9 (c)). The shape and width of an observed absorption near 1 μm, and the presence or absence of the 1.9 μm depression, are key indicators of the relative importance of these two mineral families. The plagioclase feldspars ($NaAlSi_3O_8$ – $CaAl_2Si_2O_8$), which normally contain trace amounts of iron, show a weak, broad absorption near 1.2 μm (Figure 6.9 (d)).

A final spectral family of importance in asteroids is that of water and ice. H_2O molecules can be present as ice, or H_2O or OH can be bound into hydrated minerals such as serpentine, $(Fe,Mg)_3Si_2O_5(OH)_4$, which can be formed by reaction of pyroxenes with water. Substances containing water or OH will typically show fairly narrow absorption bands at 1.4 and 1.9 μm, and also between 2.9 – 3.3 μm.

The spectrum of reflected sunlight has now been observed for several hundred of the brighter – larger and/or nearer – asteroids (this is not yet practical for the fainter ones). In these spectra we immediately see many of the same regions of poor reflectivity as are found in the albedo spectra of laboratory mineral samples and meteorites. Several examples of asteroid reflectivity spectra are shown in Figure 6.10. It is obvious that some of the same features seen in Figure 6.9 are present in the the spectra of these asteroids, and it is thus possible to identify one or more major minerals present at the surfaces of these small bodies. In a few cases, spectra have been obtained from several directions as the asteroid rotates, and it is possible to deduce which are the dominant minerals on various sides of a single body. The results of such investigations are summarized for a number of asteroids in Table 6.4. It is from such studies that the mineral identifications in Table 6.3 have been derived.

Note that the detailed investigations, which require fairly bright asteroids to be possible, are very incomplete both in not sampling asteroids of less than about 20 km diameter, and not sampling well the darker asteroids, particularly in the outer asteroid belt. Never-

Table 6.4: Mineral nature of asteroid surfaces

Asteroid (type)	Surface minerals and probable nature
1 Ceres (G)	Iron-poor phyllosilicates containing water molecules, magnetite or opaque carbonaceous material. Produced by aqueous (water) alteration of CI/CM material.
2 Pallas (B)	Similar to Ceres.
4 Vesta (V)	Strong pyroxene absorption, weaker plagioclase. Surface is mostly similar to certain basaltic achondrites, with regions of feldspar-poor basalt. The surface of Vesta is the nearly intact crust of a differentiated planetesimal.
8 Flora (S)	Metal, olivine, and some pyroxene present, and quite variable over the surface. The present surface might be the core-mantle boundary of a differentiated asteroid that has lost its crust.
15 Eunomia (S)	Metal and olivine, with some pyroxene. This asteroid is quite elongated, and may expose the interior of a differentiated body from core-mantle boundary to crust.
16 Psyche (M)	No Mg or Fe-rich silicates; surface dominated by metals. Psyche reveals the iron-rich core of a differentiated body.
44 Nysa (E)	Highly reflective surface is apparently iron-poor enstatite. The surface is the crust or exposed mantle of a differentiated body similar to the enstatite chondrites.
113 Amalthea (S)	Olivine with some pyroxene and metal. This might be the lowest part of the mantle of a very differentiated parent object.
349 Dembowska (R)	Spectrum shows strong pyroxene absorption and some evidence of olivine, but no metal. Dembowska's surface is probably the iron-poor silicate residue in the upper mantle of an incompletely differentiated body.
354 Eleonora (S)	Olivine and metal. Perhaps the core-mantle boundary layer of a completely differentiated parent object.
446 Aeternitas (A)	Essentially pure olivine, the mantle of a strongly differentiated parent object.
1866 Apollo (Q)	Olivine and pyroxene, indistinguishable from the spectrum of an ordinary chondrite. Apollo is the only known probable source of this common meteorite type.

Source: M. J. Gaffey, J. F. Bell & D. P. Cruikshank 1989, in *Asteroids II*, ed. R. P Binzel, T. Gehrels & M. S. Matthews (Tucson: Univ. of Arizona Press), p. 98.

theless, spectral studies like those discussed in Table 6.4 reveal that asteroids, like meteorites, range from almost unaltered primitive solar nebula material similar to the carbonaceous chondrites, to highly differentiated, thermally processed bodies analogous to the igneous meteorites.

Many of the same spectral features are seen in meteorites. In fact, the spectra of some asteroids and some meteorites match extremely well, as shown in Figure 6.11. The strong olivine-pyroxene absorption is clearly visible in Vesta, while the increase in reflectivity of iron is obvious in the spectrum of Amantis.

One of the very puzzling points that emerged from the study of the minerals on the current surfaces of asteroids is the realization that the meteorites held in collections on Earth show very important differences from the asteroids. Although plausible asteroidal sources have been identified for essentially all meteorite classes, the relative proportions of various kinds of known meteorites are *very* different from the proportions of various types of asteroids. The worst problem concerns the ordinary chondrites. Only a *single body*, the tiny Earth-crossing asteroid Apollo, is known to have reflection characteristics closely similar to those of the ordinary chondrites, although these are by far the most common type of meteorite seen to fall. At the other extreme, the very common S asteroids display spectra that match roughly those of the rather rare stony-iron meteorites. One possible resolution of this dilemma is that the surface spectra of the S asteroids is somehow altered by exposure to cosmic rays or impacts with other asteroids (this effect is called space weathering) so that the spectra of such bodies are not really representative of their composition. This idea has received strong support both from the low densities measured for the S asteroids Ida and Eros, and from the x-ray and γ-ray experiments on board the NEAR orbiter, which observed essentially chondritic ratios of major chemical elements for Eros. Thus it appears that the S asteroids, in spite of have spectra reminiscent of stony-iron meteorites, may be the parent bodies of ordinary chondrites. (Note that the conclusions of Table 6.4 were drawn at a

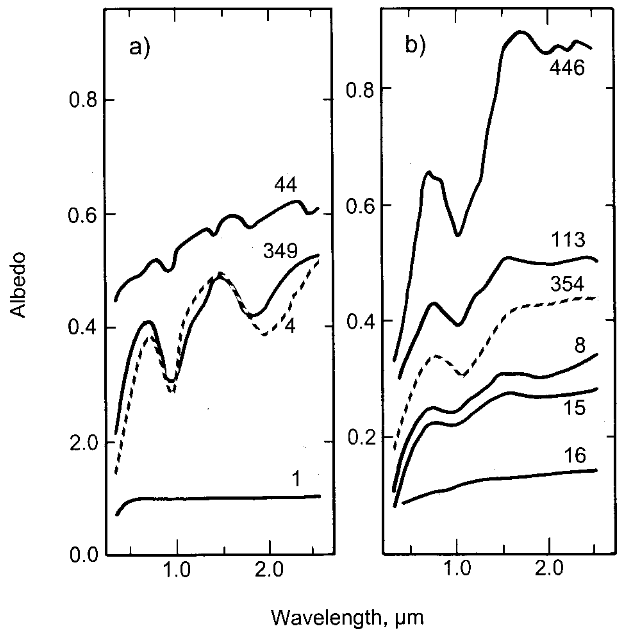

Figure 6.10: Reflectivity spectra of several bright asteroids, labeled by asteroid number. A plausible interpretation of these spectra is described in Table 6.4. (Adapted from M. J. Gaffey, J. F. Bell, and D. P. Cruikshank 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels and M. S. Matthews (Tucson, AZ: Univ. of Arizona Press), Figs. 3 and 4.)

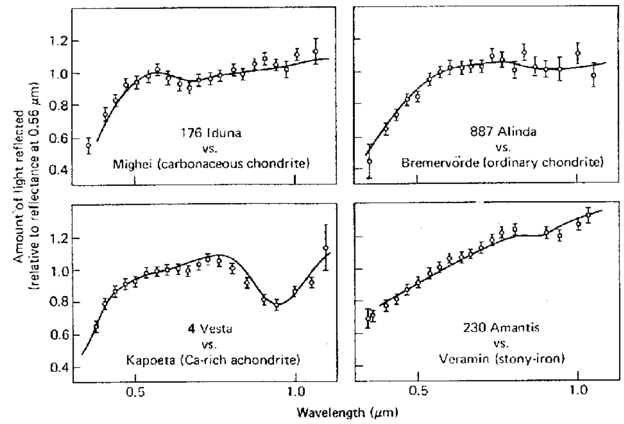

Figure 6.11: These four panels compare the fraction of light reflected by individual asteroids at a number of wavelengths (colours) between about 3500 Å (in the near ultraviolet) and 1.1 μm (in the near infrared), shown as points with error bars, to the reflectivity of powdered meteorite rock samples, shown as solid curves. The two upper curves show asteroids similar to carbonaceous and ordinary chondrites; both have very low reflectivity (albedo). The lower left panel shows the strong pyroxene absorption band near 0.9 μm in Vesta and a basaltic achondrite. The lower right panel shows the relatively poor blue reflectivity of a stony-iron meteorite and an S asteroid. (Source: C. R. Chapman 1976, Geochim. Cosmochim. Acta, 40, 701.)

time when it still seemed that S asteroids are stony-iron rather than ordinary chondrites.)

Another problem occurs for the achondrites. Basalt-rich achondrites are about 100 times commoner among meteorite falls than olivine-rich achondrites, but among the asteroids that may be the sources of these meteorites, the A types (olivine-rich surfaces) are roughly four times as common as the V types (basalt surfaces). Where are all the olivine achondrites?

It appears that the meteorites that fall to Earth at any one time (almost all those currently available have fallen within the past 1 Myr) are dominated by source bodies which sample the main asteroid belt very unevenly. Thus, although almost all meteorites certainly come from the asteroids, they may provide a rather non-representative sample of the larger bodies.

The numerous classes of asteroids, which are essentially distinguished by having different spectra, can be grouped into a small number of **superclasses** on the basis of broadly common history concerning the extent of heating during their formation. The dark, organic and carbon-rich asteroids of classes of types C, D, P and Q, which are related to carbonaceous and ordinary chondrites, we may call **primitive** meteorites. These objects, like the carbonaceous chondrites, appear to be almost unaltered from the small fragments that originally accreted to form planetesimals; they may have been strongly heated, but they never melted. The asteroids whose minerals have been altered by liquid water (types B, F, G and T) may be called **metamorphic**. These asteroids seems to have been mildly heated, enough to melt water ice and form hydrated minerals, but not enough to differentiate rock and metal. (The least processed meteorites in our possession, the carbonaceous chondrites, probably come from this group of asteroids.) Finally, many asteroids seem to have been differentiated by partial or complete melting of their rocky minerals (types A, E, M, R, S and V), so we call these bodies **igneous** asteroids (but recall that the membership of the S asteroids in this class is now very questionable).

When the number of members of each superclass is plotted for various orbital semi-major axis bins, it is found that the relative proportions of the three superclasses change dramatically with increasing distance from the Sun, as shown in Figure 6.12. Near the inner edge of the asteroid belt around 2 AU, almost all the asteroids are igneous (this is reflected in the large number of igneous asteroids described in Table 6.4). By

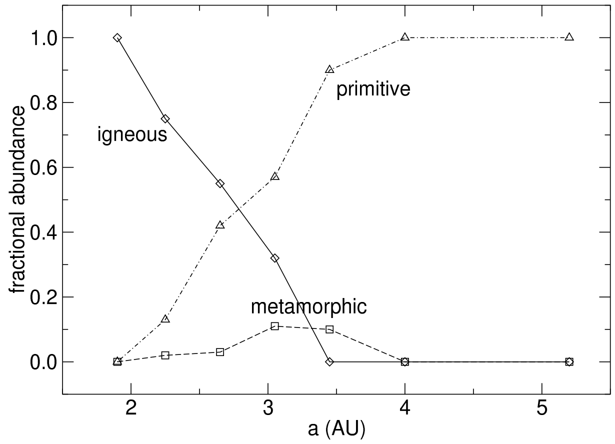

Figure 6.12: Variation of the relative numbers of the three asteroid superclasses with distance from the Sun. Igneous asteroids (squares) diminish rapidly in numbers with increasing a and are no longer present beyond 3.5 AU. Metamorphic asteroids (circles) are a minor type around 3 – 3.5 AU. Primitive asteroids (diamonds), minor in the inner asteroid belt, dominate beyond about 3 AU. (Data from J. F. Bell et al. 1989, in *Asteroids II*, ed. R. P. Binzel et al. [Tucson: Univ. of Arizona Press], p. 921.)

3.5 AU from the Sun, such asteroids have completely disappeared. The metamorphic asteroids, always rare, are concentrated around 3 AU. The primitive asteroids rise rapidly in importance with increasing a values, until beyond 3.5 AU where they completely dominate the composition of the asteroid belt. Thus the degree of alteration experienced by an asteroid is very closely connected with its distance from the Sun. This dramatic change in asteroid mineral properties with distance from the Sun may be a very important clue about the origin and history of the asteroid belt.

Exercise: A small space probe is put into orbit around an asteroid. Because of budget limitations, the probe is only able to send back black-and-white visual images of the asteroid. In addition, from the radio signals the size and orientation of the probe's orbit around the asteroid can be determined. Can anything be deduced about the chemical composition or internal structure of the asteroid from such data?

6.5 Origin and evolution of asteroids

It was natural in the past to imagine that the asteroids are remnants of an exploded planet, since they are small, they occupy similar orbits in a region of the solar system where the Bode-Titius "law" predicts a planet, and many meteorites (long thought to be possibly asteroid fragments) seem to have come from a geologically differentiated planet. In recent years, this theory has been discarded. In the first place, the *total* mass of the present asteroid belt is more than 100 times smaller than that of any of the terrestrial planets (see Table 6.2), and no source of energy is known which would be able to disrupt a terrestrial-sized planet. Furthermore, it is clear that none of the minerals found even in the igneous meteorites requires high pressure (such as would be found in the deep interior of a full-size terrestrial planet) for formation. Finally, we now can imagine some plausible ways of heating bodies too small to have been much heated internally by gravitational energy during accretion or by the kind of long-lived radioactivity that powers geological activity in the Earth: quick heating might have been produced, for example, by short-lived (and now extinct) radioactivities, or by induction heating due to interaction with an early, powerful solar wind carrying a magnetic field.

Instead, it has seemed more reasonable recently to observe that the asteroid belt as it now exists is rather reminiscent of the planetesimal stage of development of the solar system, with swarms of small bodies that collide from time to time, sometimes sticking together by gravity and sometimes disrupting one another. Thus, much effort has recently been given to understanding the asteroid belt as a natural part of the process that built all the planets. Furthermore, the asteroid belt is probably also the best remaining source of clues about conditions in the inner solar nebula at the time of planet formation, and so study of its origins should shed much light on the more general problem of formation of the planets.

To follow this line of thought, we must try to see, first, how a structure like the asteroid belt might have been formed, and why it should have failed to produce a planet. Then we have to look at processes that have affected the belt since it was created to try to find out to what extent it really is a fossilized relic of early solar system history, and what kinds of important changes may have taken place since that time, both in the orbital organization of the asteroid belt, and in the asteroids themselves.

Formation

According to the view of the development of planets discussed in Chapter 4, the accretion disk of the solar nebula that surrounded the forming Sun contained much matter that solidified as dust grains. These dust grains apparently accumulated by collisions into larger and larger bodies until eventually they formed planetesimals with sizes that we estimate may have been of the order of a km across. We now look in more detail at what may have happened next. As we do so, we will discover a great many parts of the picture which are still very unclear or even contradictory. This is a field of solar system research that is still very much under construction.

A first major uncertainty, as we pick up the story of the newly formed small bodies in the region of the asteroid belt, is that it is unclear just how large a mass of solid material was deposited there. Was there only a few times the total mass of the present asteroid belt bodies, say around 10^{22} kg, of the order of 10% of the mass of the Earth's Moon? Or was the mass in this region at one time perhaps 10^3 times larger than that, comparable to the mass of the Earth? The history of the solar system is not well enough understood to be at all certain on this point. If we look at the amount of mass that ended up in planets both in the inner and the outer solar system, we realize that the asteroid belt is at present particularly deficient in mass. Closer to the Sun, enough solid matter was available to form the massive planets Venus and Earth. However, going outwards, there is already a shortage of mass apparent in the fact that Mars has so much less mass than its two big inner neighbors, even though it had a bigger swath of orbital space than they did from which to accumulate material. In the (present) asteroid belt the shortage of mass is several powers of ten more severe than at the distance of Mars. And then we come to Jupiter, and suddenly there is a lot of mass again. On this argument, we would perhaps expect that originally the asteroid belt had far more mass than today. On the other hand, it may be that the original solar nebula had a pronounced ring structure, with a large gap in the asteroid belt.

We do have some constraints derived from calculations carried out to try out various possible initial conditions and see where they lead. It is found that at a minimum at least several times the mass of the present asteroid belt should have been present; without this much, the accretion of a single body as large as Ceres would have taken the age of the solar system or longer. At the other extreme, a mass many hundreds of times larger than the present total mass of asteroids would have quickly led to the **runaway growth** of a single planet-sized body like Mars or the Earth. If such a body once formed, where is it now? We have already discounted the possibility that it was somehow disrupted. On balance, it seems preferable to assume that the original mass of the asteroid belt was only a few times more than the present mass.

We believe that in the early stages of the solar nebula, the orbital motions of newly formed planetesimals around the Sun were in nearly circular orbits of very small eccentricity and inclination. That is, at each distance from the Sun, all the planetesimals had nearly the same speed. They thus had very small speeds relative to one another; when they collided, their relative speeds were usually less than 1 km s^{-1}. This is certainly no longer the case in the asteroid belt. At some point in the early history of the solar system, *something* substantially changed the speeds of most asteroids, to such an extent that now collisions occur at speeds of roughly 5 km s^{-1}. While relative speeds were small, collisions mostly resulted in coalescence and the gradual construction of larger and larger planetesimals. Today, with the much larger relative speeds found at each distance from the Sun, collisions occur at such high speed that the impact fragments are not left bound to either asteroid. Collisions mostly lead to material fragmenting and splashing off into space. The current collisions are mostly destructive rather than constructive. If the relative speeds had remained small, eventually practically all the planetesimals *would* have been swept up by the largest one. (This is what is meant by runaway growth.) What stopped the gradual sweeping up of small bodies by the largest ones, and left the asteroid belt as a big collection of small bodies rather than as a single small planet, was most probably the change from relative speeds of hundreds of m s^{-1} to relative speeds of several km s^{-1}.

We do not know precisely what caused the great increase in eccentricities and inclinations of the orbits of the asteroids, but it is usually supposed that it was due to Jupiter. This seems likely because, first, the fact that the only asteroid belt in the interior of the solar system is directly adjacent to Jupiter is a strong hint; secondly, the existence of the Kirkwood gaps shows directly the powerful influence that Jupiter can have on asteroid orbits; and finally, a very powerful perturber is needed to stir up the asteroid orbits to their present level of disorder.

However, this hypothesis still leaves a number of questions to answer. First, we need to be reasonably sure that Jupiter was able to form quickly enough out of the planetesimals at its distance from the Sun that it was already able to influence the orbits of the planetesimals in the asteroid belt as they began to to accumulate into larger and larger bodies. It is not clear yet that this was the case; calculations of the formation of the planets are still on very shaky ground because we know so little about the start-up conditions, and because the processes were so very complex.

Let's suppose that Jupiter did form quickly enough to have a major influence on the development of the asteroid belt. Two main ways have been suggested for the giant planet to affect the asteroids. First, as the planets formed there must have been a number of rather large bodies (even the size of small planets such as Mars) orbiting the Sun that had not yet been swept up into the present planets or ejected from the solar system. By near collisions, Jupiter could have altered the orbits of such bodies to send them sweeping through the asteroid belt. As these objects passed back and forth through the asteroids, near collisions with planetesimals there would have altered the planetesimal orbits, increasing inclinations and eccentricities. The main weakness with this idea is that a number of fairly large bodies (Mars-sized) are required. It is not at all clear that enough bodies that big would have been available, and one wonders what has become of them since – where are they now? Perhaps they too ended up being incorporated into Jupiter (or Earth) or being expelled, but it is surprising that none are left.

The second way in which Jupiter might have greatly altered orbits in the asteroid belt is if the giant planet itself has not always been at the same distance from the Sun as at present, but had a changeable orbit size early in its history, perhaps from tidal effects produced by the solar nebula or due to Saturn. In this case, the period resonance which today cause the Kirkwood gap would have affected asteroids with many different orbit sizes as Jupiter's orbit changed, perhaps again with the effect of greatly increasing inclinations and eccentricities among the forming asteroids. (This effect is known as **resonance sweeping**.)

In any case, it seems plausible that it was the increase in orbital disorder, and the consequent rise in collision speeds, that changed the situation in the asteroid belt from one of the larger bodies gradually sweeping up and incorporating the smaller ones, to a situation in which most collisions led to fragmentation and destruction. It is the increase in orbital speeds that probably prevented Ceres from becoming essentially the only body in the asteroid belt. The fact that most collisions are destructive has kept the asteroid belt full of small bodies, and even today infrequent collisions between the larger asteroids are gradually reducing their sizes and contributing orbiting debris to the asteroid belt.

However, there are observational features of the asteroid belt that indicate that the degree of orbital disorder introduced by Jupiter was not so extensive that the entire region of the belt became mixed. The observation that igneous and primitive asteroids each dominate a part of the belt (see Figure 6.12) clearly shows that the asteroid belt has never been completely mixed, since we are pretty sure – from meteorite ages, for example – that the heating of some asteroids occurred very close in time to the period of formation of these objects.

Thus, our overall picture of the early evolution of the asteroid belt is roughly the following. We guess that the belt started off as a huge swarm of small planetesimals, containing at least several times as much mass as the present asteroid belt, in which initially small relative velocities made it possible for collisions to lead to gradual growth of a few large bodies by accumulation of many smaller ones. This process was probably only part way to producing a single final asteroid when Jupiter pumped up the orbital eccentricities enough to change collisions from occurring at hundreds of m s^{-1} to occurring at several km s^{-1}. This ushered in the era of destructive collisions, and the asteroids have mostly been slowly decreasing in size since this time, breaking down into smaller and smaller fragments as they collide with one another.

Heating

The condensation process that deposited solids in the central plane of the solar system certainly deposited a mixture of chemical elements that depended on distance from the Sun, as already discussed in Chapter 4. Near the Sun, only the most refractory elements and compounds froze out as solids; this would probably have included metallic iron, oxides of magnesium and silicon, and oxides of a number of less abundant elements such as Ti, Al, and Ca. Further out, the more volatile metals such as Na, K and Fe condense in oxide form, and still further out carbon compounds, then water ice, and finally even CO_2 and perhaps NH_3 and CH_4 freeze out. Thus, the chemical composition of the dust grains that gradually accumulated to form planetesimals would have varied rather strongly with distance from the Sun (and also somewhat with time). Even within the region that was to become the asteroid belt, a fairly strong composition variation would have been found.

Now from the fact that many meteorites clearly solidified from molten rock or metal, while others seem never to have been much heated at all, and from the igneous minerals detected in some, but not all, asteroids by spectroscopy, it is clear that some asteroids were heated strongly enough to melt iron and sometimes rock, while others were only mildly heated, just enough to incorporate water into mineral structure. From the variation of asteroid superclasses with distance from the Sun (Figure 6.12), it appears that this heating must have depended quite strongly on distance from the Sun, diminishing rapidly with increasing distance. However, the strong overlap of the igneous, metamorphic, and primitive superclasses between about 2 and 3 AU also suggests that the heating mechanism, whatever it was, was not simply dependent on distance from the Sun, but depended as well on something else. At a particular distance from the Sun, some asteroids were strongly heated, while others were hardly affected. What was it that heated some, but not most, of the asteroids?

One obvious possibility is the heat energy released by gravity as the various planetesimals collide and stick together, as discussed in several previous chapters. Small bodies are accelerated towards a larger object that they collide with and that sweeps them up, and as they strike the surface of the larger object their speed of infall is converted instantly into heat energy. Some of this heat is radiated back into space, but often much will be deposited into the crust of the larger body, and as more material is swept up, this heat is trapped in the interior of the growing object.

For objects as large as the terrestrial planets, this is a powerful source of internal heating, as we will see in Chapter 9. However, the total heat per kilogram released by accumulation increases with the mass of the larger body, and although it is very important for terrestrial planets, it is only capable of heating a body as large as Vesta, the largest differentiated asteroid, by some 50 K. This is not a large enough heat release to be a significant means of melting asteroids.

Another possible heat source is radioactivity, the spontaneous splitting of unstable atomic nuclei. The basic idea of this process has been discussed in Chapter 2. In a **radioactive decay**, the nucleus of an atom spontaneously breaks into two (or more) pieces because of an imbalance between the number of protons and the number of neutrons in the nucleus. Some of the nuclear reactions that occur in stars, as described in Chapter 3, involve the spontaneous decay of nuclei that are produced during these reactions, for example by expelling a positron (e^+) particle, and changing from one element to another. Other examples were found when we looked at dating meteorites by using radioactive atoms, in Chapter 5. When an atomic nucleus decays, one of the effects is that a large amount of energy is released along with the fragments, in the form of gamma rays, high speed electrons or positrons, or as kinetic energy of the separating fragments. Usually some millions of electron volts of energy are released from each decay, as compared to the few electron volts released when two atoms combine chemically. Radioactive decay is thus potentially a source of energy that can release millions of time more energy from a given mass than is available from chemical reactions involving the same amount of matter; this is why fission reactors have come into use for generating electricity.

Radioactive nuclei, like other nuclei, are produced in the nuclear furnaces of stars. Such radioactive nuclei display a huge variety in the average time it takes for half the nuclei in a particular sample to decay into something else; this time is known as the **half-life** of that type of nucleus, and is a definite time for each kind of radioactive nucleus. Some nuclei decay within microseconds of the instant that they are created, while others take thousands or even billions of years. Radioactive nuclei with very short half-lives will hardly escape the place where they are formed before falling apart. Other, longer-lived isotopes will be able to travel far from their places of origin before decaying. We therefore expect that the atomic nuclei that found their way into the solar nebula would include hardly any isotopes that decay with much shorter half-lives than the time that elapsed between the last supernova explosion to blast into the interstellar cloud from which the Sun formed, and the collapse of that cloud to form the solar system. On the other hand, isotopes with half-lives longer than this interval would be incorporated into the solar nebula, and many of these would certainly end up as trace elements in the solids that froze out of this cloud to become planetesimals. When such radioactive nuclei end up incorporated into planets or asteroids, where they finally undergo radioactive decay, they provide a potential source of heat.

However, only the relatively slowly decaying nuclei are left by this time. Because they decay very slowly, during millions or even billions of years, and also because they make up only a tiny fraction of the total number of nuclei, such radioactive nuclei are quite weak heaters except in bodies large enough that the heat takes even longer to leak out than it does to be released. In bodies the size of the Earth, the time it takes for heat released by radioactivity (or heat released by gravity as the planet accumulates) to leak out of the planet is billions of years, and for these objects even very slowly released radioactive energy is a powerful heat source. An example is provided by the element potassium (symbol K), which has $Z = 19$ protons in each atomic nucleus. In the Earth's crust at present, 93.26% of naturally occurring potassium has 20 neutrons and an atomic mass number $A = 39$, while 6.73% has 22 neutrons and $A = 41$. Both ^{39}K and ^{41}K are stable. However, about 0.01% of naturally occurring potassium is ^{40}K, which is naturally radioactive. ^{40}K can decay either by converting a proton into a neutron, a positive electron, and a neutrino and thus becoming an argon nucleus,

$$^{40}\mathrm{K} \to {}^{40}\mathrm{Ar} + \mathrm{e}^+ + \nu,$$

or it can convert a neutron into a proton to become a calcium nucleus,

$$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + \mathrm{e}^- + \overline{\nu}.$$

In both decay modes little more than 1 MeV is released per event. As it takes about 1.3×10^9 years for half the ^{40}K atoms initially present in an asteroid to decay, this process can provide an important source of heat inside planets over a geologically long time. Other isotopes that provide substantial heat to the solid bodies of the solar system at present are ^{232}Th (thorium) and ^{238}U (uranium), both of which also have half-lives measured in billions of years.

However, asteroids are far smaller than the big terrestrial planets, and so the time required for heat to leak out to the surface and be radiated into space is much smaller. For these small bodies, the slowly released radioactive energy of the main current radioactive heat sources can raise the internal temperature by only a couple of hundred degrees. This is not enough to melt anything much more refractory than water ice. Furthermore, the radioactive ages of igneous meteorites show that the asteroids were heated very shortly after the formation of the solar system, not much later in its history.

But we have not yet excluded all possible radioactive heat sources. In our study of meteorites, we found evidence that the last polluting supernova before the collapse of the solar nebula may have occurred less than a million years before that collapse – perhaps the collapse was even caused by that last explosion. If the supernova created an important number of radioactive nuclei with half-lives so short that they have long since disappeared, but long enough to have still been present in the solar nebula, such nuclei could perhaps have been an important heat source. Because they would heat the asteroid quickly and briefly, such nuclei might overcome the problem of rapid heat leakage from small bodies by releasing their heat even more quickly than it could escape. They would also have done their heating right at the beginning of the solar system, as the meteorite ages demand. We need to look for hints of the brief presence of such short-lived isotopes.

One radioactive nucleus that might have functioned in this way is ^{26}Al. This isotope decays to ^{26}Mg by emission of a positron and a neutrino, with a half-life of 726,000 yr. It appears to be produced in significant amounts in supernovae, and there is evidence from excess ^{26}Mg in the refractory inclusions of oxides and silicates of Ti, Al, and Ca found mainly in CV meteorites (see Chapter 5) that a high enough percentage of ^{26}Al was once present in these grains to completely melt a body of this composition if it was at least some km in diameter. However, there is no evidence that the km-size bodies of this composition were ever present in the solar system – the grains that were once enriched in ^{26}Al are all very small. Furthermore, this excess ^{26}Al is only known to have been present in some unusual grains in one particular kind of meteorite; there is no clear evidence that excess ^{26}Al was more widely distributed in the solar system. Thus it not clear whether this short-lived radioactivity was an important heat source in any asteroids. However, the increasing number of meteorite sites which have yielded evidence of a number of short-lived radioactivities has encouraged many researchers to favour this explanation of the rapid initial heating of some asteroids.

Yet another possible heat source that may have melted some of the early asteroids is due to the interaction of the growing asteroids with the outflowing solar wind from the growing Sun. As the Sun settled down to become first a T Tauri star (Chapter 4) and then a main sequence star, it probably went through a phase of producing a very strong stellar wind, as we now observe in many current T Tauri stars. This T Tauri wind would probably have included a weak magnetic field. Because of this magnetic field, as the wind flowed past forming planets and asteroids, electrical currents would have been induced in the solid bodies by the effect known as "electromagnetic induction". These electrical currents could have heated the interiors of bodies that were sufficiently strongly affected.

Evolution

We now come back to the main thread of our effort to understand the evolution of asteroids. From the discussion above, we expect that the composition of the planetesimals in the present asteroid belt initially varied with distance from the Sun. Planetesimals were probably made of fairly refractory compounds near the orbit of Mars, but the further out one looked, the more volatile material such as water ice and various compounds of carbon would have been incorporated into these small bodies. These planetesimals collided with one another and so gradually become asteroids, also with composition that varied systematically with distance from the Sun. In the inner belt, we probably would have found asteroids with composition similar to that of the enstatite (EH and EL) chondrites, with Mg in the form of pyroxenes but iron still in metallic (unoxidized) form. Somewhat farther out, the composition could have been appropriate for ordinary (H, L, LL) chondrites, with both Mg and Fe in oxidized form in silicates. Beyond that, the planetesimals could have had a composition like the CO and CV chondrites, with fully oxidized metals and small amounts of water and carbon compounds. Still farther out we would have found the asteroid sources of the most primitive meteorites, the CI and CM carbonaceous chondrites. At even greater distance from the Sun, in a region not sampled by the meteorites in our collections, we imagine that the planetesimals had a composition still more primitive and rich in organic compounds. If we had any meteorites of this material, we might call them ultra-carbonaceous.

As we have seen, some – but not all – of the asteroids formed from this material were heated. Some of the enstatite-rich bodies melted to produced rock like the enstatite-rich achondrite meteorites. Asteroids with composition like the ordinary chondrites melted to produce the minerals found in the igneous meteorites. Farther out in the forming asteroid belt, some bodies were heated enough to incorporate water into their mineral structures and produce serpentine, but not enough to melt any of the metal or rocks. Still farther out, little heating of importance occurred.

The strong heating of some asteroids in the inner belt led to such high temperatures (around 1600 K) that the metallic iron in these bodies, probably present initially in the form of small grains like those found in chondritic meteorites, melted. This melting led to the separation of some asteroids into layers of different density. Because iron is much denser than the surrounding rock, the iron sank towards the centre of the asteroid under the pull of gravity, while the less dense rock tended to float above the iron, like oil on top of vinegar in a salad dressing. This separation occurred whether the temperature rose high enough to completely melt the rock or not; the liquid iron could have flowed downward through cracks and fissures in solid (but somewhat flexible) rock, or if the rock melted, the liquid rock floated on top of the liquid iron core. A thin veneer of particularly low density material, similar to terrestrial basalts, could have been separated – again by buoyancy – from the main layer of olivine-rich rock and formed the surface of such fully melted bodies. Thus the heating episode led to some asteroids developing a structure with a metallic core (mainly iron but including minor elements with an affinity for iron, such as nickel), a thick middle layer (a mantle) of dense rock with an olivine-rich composition, and perhaps a thin surface crust of basalt. Probably the boundary between one layer and the next was not sharp, but formed a thick zone of mixed composition. As the heat source that had stimulated the melting waned, the asteroids froze, rapidly at the surface and more slowly in the interiors. The larger bodies, with greater distances for heat to travel before it could radiate away into space, and a larger mass of interior material to radiate heat away through each square meter of surface area, cooled more slowly than the smaller objects.

During the same period when the heating and melting of some asteroids was happening, collisions continued to occur. As we have seen above, at first these collisions involved rather low speeds, and mostly led to smaller bodies growing by coalescence. This process gradually led to one dominant asteroid, Ceres. However, before the collisions had allowed Ceres to sweep up all its competitors, something (probably Jupiter)

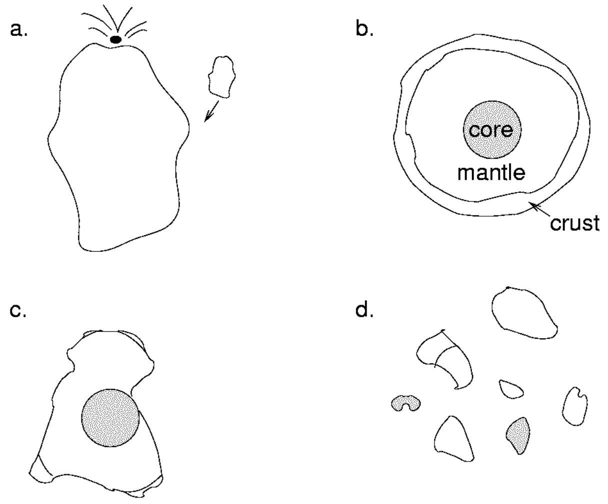

Figure 6.13: An asteroid forms by accretion of planetesimals. As it originally develops (a) it may be uniform throughout, with approximately the chemical composition of ordinary or carbonaceous chondrites, depending on where in the solar system it forms. As a result of strong internal heating (b), which did not occur in all asteroids, it may develop a layered structure, with a core of composition similar to an iron meteorite, a thin region around the core where iron is mixed with overlying rocky layer, as in stony iron meteorites, a mantle of rock similar to ordinary chondrites or achondrites (depending on how hot it got) and perhaps a basalt-rich crust. Further violent collisions (c) may disrupt the asteroid enough to reveal one or more of the inner layers, and perhaps eventually (d) fragment it entirely into an asteroid family.

increased the inclinations and eccentricities of asteroid orbits to the point that most collisions became destructive rather than constructive. Further impacts between asteroids led to blasting off pieces rather than continued growth of even the largest bodies. A few asteroids such as Vesta avoided really destructive collisions (although even Vesta has a large impact crater near one pole), but most asteroids were at least shattered and many were broken into smaller pieces that continued in separate orbits as members of one of the asteroid families. This evolution is sketched in Figure 6.5.

This era of destruction would have blasted the rocky shells off some of the asteroids that had developed a structure with a metallic core surrounded by a rock mantle. Because rock is considerably weaker than iron, many of the rock mantles were probably shattered into big boulders and ejected by successive collisions from the layered asteroids. The stronger iron cores would have been more resistant to disruption and probably mostly remained largely intact. As a result, it appears that iron cores make up a relatively high proportion of the large inner-belt asteroids, the ones that can easily be studied from the Earth, while their rocky mantles have become small, hard-to-detect bodies. Selective destruction of rocky bodies may be the reason that the population of larger, well-studied asteroids of the main belt appears to differ greatly from the proportions of different types of chemical composition found among meteorites, although we should not forget that the study of Eros suggests that asteroid spectra may not be infallible guides to asteroid chemistry.

Many of the smallest fragments of collisions have gradually been lost to the asteroid belt. This could occur, for example, through interaction between sunlight and small (mm- or cm-size) objects, which experience the flood of photons from the Sun as a kind of fluid through which they must move in their orbits around the Sun. The drag from sunlight is strong enough to have caused such small particles to spiral into the Sun in a time less than the age of the solar system. This and related effects may have reduced the mass of the asteroid belt by a factor of several since it was formed.

As we discussed in Chapter 5, delivery of a small fraction of the asteroids and fragments from the main belt to Earth-crossing orbits, and eventually to the Earth's surface as meteorites, probably occurs through a series of interactions. Initially, we think that asteroids suffered collisions among themselves, knocking off pieces a few km or smaller across. These spinning fragments found their orbits changing slowly as a result of the very weak force of re-radiated heat, which is more strongly emitted on the evening side than the morning side. Some of these pieces eventually came to have orbital periods near one of the unstable resonances with Jupiter's or Saturn's period, and soon their orbits were perturbed to more and more eccentric form. Some of these are eventually shifted into orbits so eccentric that they cross the orbit of Mars or even Earth. The largest fragments are seen by us as Apollo, Aten or Amor asteroids. Some near-Earth asteroids and many smaller fragments eventually collide with Earth or the Sun; many others are ejected from the solar system by close misses. The amount of time a near-Earth asteroid or meteoroid can spend in an Earth-crossing orbit before it is swept up by the Earth or ejected from the solar system is only a few million years.

We thus have a provisional picture of how asteroids have formed and developed, and how they are may be related to the various kinds of meteorites that we have in collections here on Earth. This picture still leaves many points unclear, and will certainly change significantly during the coming years, but much of it is undoubtedly already basically correct.

6.6 Mathematical aspects

Orbital properties

Exercise: Radar observations have revealed that the small near-Earth asteroid 1999 KW4 is has a satellite (i. e., this is a binary system). The larger body in the system has a diameter of about 1.2 km. Assuming that the density of the larger asteroid is about 2 kg m^{-3}, estimate its mass. The small body orbits around the larger with a period of about 16 hours. Assume that the orbit of the smaller body around the larger is circular, and use the orbital period to estimate the semi-major axis of the orbit. (You may be surprised at how small it is.)

Exercise: At one point the NEAR–Shoemaker space probe orbiting the asteroid 433 Eros was in a circular orbit with radius 200 km. The mass of Eros is about 7.2×10^{15} kg. How long did the probe take to orbit Eros once?

Reflection and radiation from an asteroid

As we have discussed above, the size and albedo of an asteroid may be estimated if the radiation coming from it can be measured in both the visible part of the spectrum and in the infrared. Let's see more exactly how that works, making whatever approximations we need to in order to get a reasonably simple result.

Consider a spherical asteroid of radius R at a distance r from the Sun. You know from the images you have looked at that most asteroids are really not spherical, so this is a fairly rough approximation. Consider R as a typical dimension of a real asteroid. Now the flux $f_\odot$ of solar energy (the amount of energy falling on a square meter each second, in W m^{-2}) at r is

$$f_\odot(r) = L_\odot/(4\pi r^2), \tag{6.1}$$

where $L_\odot$ is the luminosity of the Sun. Let's assume (again an approximation; see Figure 6.10) that the average albedo in visible light has the value $A_{\rm v}$. The total energy reflected from the projected surface πR^2 of the asteroid per second, which we may think of as the asteroid's visible "reflected luminosity" $\ell_{\rm ref}$, is

$$\ell_{\rm ref} = A_{\rm v} f_\odot(r)\pi R^2, \tag{6.2}$$

while the energy absorbed per second, and then reradiated as long wavelength infrared thermal radiation (see Figure 6.3), which we think of as the asteroid's "thermal luminosity" $\ell_{\rm th}$ is

$$\ell_{\rm th} = (1 - A_{\rm v}) f_\odot(r)\pi R^2. \tag{6.3}$$

The visible sunlight is not reflected uniformly into all directions. If you are between the asteroid and the Sun, you will see the fully illuminated asteroid, like the full Moon, and the flux of reflected light from the asteroid will be relatively large. If you are looking at the asteroid from the side, as you see the first or third quarter Moon, only half of the asteroid will appear lit, so it will appear fainter than when you see only the lit side. In addition, reflection tends to be more efficient when light is returned back towards the direction from which it comes, while the efficiency for reflecting in other directions is less; this effect will also make the asteroid less bright when viewed from a direction in which it appears only partly illuminated. The extreme case is when you view the asteroid from the side facing away from the Sun: you do not see any reflected light at all. Thus we need to describe or approximate the way in which reflected light is distributed in angle around the line joining the Sun and the asteroid. We use a very simple approximation: we assume that the asteroid is in opposition to the Earth (we are on the line joining the Sun and the asteroid), and that the reflected sunlight is reflected uniformly but only into half of the full 4π steradians of possible directions. On the Earth we are at a distance $r_\oplus$ from the Sun, and so our distance d at opposition from the asteroid is $d = r - r_\oplus$. Since we assume that the asteroid's luminosity ℓref is reflected uniformly into 2π steradians, the flux we will detect at Earth is approximately

$$f_{\rm ref} \approx \ell_{\rm ref}/(2\pi d^2) = A_{\rm v} f_\odot R^2/(2d^2). \qquad (6.4)$$

From this expression you can easily see that the brightness of the reflected light from an asteroid increases as R^2, so the difference in brightness between an asteroid of $R = 1$ km and that of an asteroid having $R = 100$ km, both at opposition and at the same distance from Earth, is a factor of the order of 10^4. This is why a simple brightness measurement allows us to estimate the size of an asteroid at a known distance from Earth, even if $A_{\rm v}$ is fairly uncertain.

Similarly, the re-radiated sunlight, which is emitted from the asteroid as long wavelength infrared radiation, is not emitted uniformly into all directions. If the asteroid always keeps one face pointed towards the Sun (if it is spinning, its rotation axis would need to be aligned with the Sun-asteroid line), only one side will be heated, and even that will not be heated uniformly, any more than the equatorial and polar regions on Earth are heated equally intensely by the Sun. We nevertheless assume, as a rough approximation (which will allow us to follow the basic reasoning that we use in this problem), that the asteroid is spinning fairly quickly in such a way that it is heated on all sides, and assume that the thermal radiation is also emitted uniformly in all directions. Then the flux of thermal infrared radiation received at Earth is

$$f_{\rm th} \approx \ell_{\rm th}/(4\pi d^2) = (1 - A_{\rm v}) f_\odot R^2/(4d^2). \qquad (6.5)$$

Now if we *measure* both the reflected flux $f_{\rm ref}$ and the thermal flux $f_{\rm th}$ that reach the Earth, and then take the ratio of these two measurements, most of the factors in each of the expressions above cancel out and we find

$$f_{\rm v}/f_{\rm th} \approx \frac{A_{\rm v}/2}{(1 - A_{\rm v})/4} = 2A_{\rm v}/(1 - A_{\rm v}), \qquad (6.6)$$

which can easily be solved for $A_{\rm v}$.

Once $A_{\rm v}$ has been determined, either of the two flux expressions can be inverted to allow determination of R, again showing that a brightness measurement allows an estimate of the asteroid size to be made. (Note that in practice we cannot measure the whole visible and whole infrared fluxes; we measure brightnesses at one or two wavelengths in each spectral region and use these to estimate the total fluxes that are needed.)

Exercise Verify the equation above, solve it for $A_{\rm v}$, and find an even simpler expression valid when $A_{\rm v}$ is much smaller than 1.

Exercise Solve the equations above to determine R, expressing the result as a function of r, d, $L_\odot$, and the two measured fluxes $f_{\rm v}$ and $f_{\rm th}$.

Internal heat sources

The pressures and densities found inside asteroids are almost independent of the internal temperature of the asteroid, provided that it is not too hot inside. That is, for typical asteroid internal pressures the equation of state is essentially $\rho =$ constant, independent of p and T. This holds as long as p satisfies $p \leq 10^{10}$ Pa (10^5 atm) and T satisfies $T \leq 1 \times 10^5$ K, both of which are certainly valid inside asteroids.

However, the internal temperature of an asteroid or planet can be quite important even if it does not significantly affect the internal density. If the temperature is high, rock will deform slowly even under rather low pressure. A still higher temperature can cause part or all of the interior of a body to melt, allowing separation of an iron core from the silicate component. Temperatures near melting in the interior of an asteroid or planet can lead to occurrence of surface volcanic activity, and to slow internal convective motions (circulation of material like that observed in thick soup on the stove just before it boils). The mantle of the Earth is believed to flow – very slowly – in this way. Thus, even if the hydrostatic equilibrium in an asteroid is not affected much by a high internal temperature, it is still of considerable interest to study the resulting effects.

Table 6.5: Heat released by radioactive decay of elements important in heating planets.

Isotope	Half-life $t_{1/2}$ (10^9 yr)	Isotope fraction x	Element abundance C	Heating rate (isotope) ($\mathrm{J\,yr^{-1}\,kg^{-1}}$)	Heating rate (chondrite) ($\mathrm{J\,yr^{-1}\,kg^{-1}}$)
^{40}K	1.25	0.00011	5.60×10^{-4}	9.20×10^{2}	5.7×10^{-5}
^{87}Rb	50.0	0.293	2.20×10^{-6}	5.44×10^{-1}	3.51×10^{-7}
^{232}Th	13.9	1.00	2.9×10^{-8}	8.37×10^{2}	2.4×10^{-5}
^{235}U	0.71	0.0072	8.2×10^{-9}	1.80×10^{4}	1.1×10^{-6}
^{238}U	4.50	0.993	8.2×10^{-9}	2.97×10^{3}	2.4×10^{-5}

Sources: G.H.A. Cole 1984, *Physics of Planetary Interiors* (Bristol: Adam Hilger Ltd.), Table 5.1. *CRC Handbook of Chemistry and Physics, 1982–83 Ed.* (Boca Raton, Fla: CRC Press, Inc.), B-255. J.T. Wasson 1985, *Meteorites* (New York: W.H. Freeman and Co.), Appendix D.

Several internal energy sources have been identified that could be important in most asteroid or planetary-sized bodies. The first of these is the gravitational energy released in forming the body from planetesimals or diffuse matter. The gravitational energy released in forming a body by accretion (or required to completely disrupt it) has already been calculated for a body of constant density in Chapter 4 (Equation 4.3); recall that the result is

$$E_{\mathrm{g}} = -\frac{3}{5}\frac{GM^2}{R}. \tag{6.7}$$

Now in fact, not all this energy will actually be available to heat the forming asteroid. The infall of new material onto an accreting body will heat the surface of the body, using the freshly released gravitational energy. If accretion is very slow, and the infalling bodies are small, much of this energy will be radiated away into space as it is released rather than being stored inside the forming object. Only if accretion is fairly rapid, or the impacting objects large, will most of the energy released by gravity be retained in the interior of the body as internal energy. On the other hand, the loss by radiation of some of the energy released by infall will be partly compensated by the fact that collisions will usually occur with velocities somewhat larger than the escape velocity of the accreting body. Thus it is not unreasonable to use Equation 4.3 to estimate the heat energy available from gravitational energy release.

A quite different heat source is due to the natural radioactivity of a few unstable isotopes that are present in a solar or CI carbonaceous chondrite mixture of refractory chemical elements. These elements are individually rather powerful energy sources, but all are present only in minute amounts in the original mixture of elements (although geochemical processes have concentrated some of them into particular ore bodies in the terrestrial crust). The principal radioactive energy sources of greatest importance in the context of planetary heating are listed in Table 6.5. For each radioactive isotope (an isotope is a nucleus of a particular chemical element which also has a definite number of neutrons), the table lists the half-life $t_{1/2}$ of that isotope, the fraction x of the element that normally occurs *at present* in the form of the radioactive isotope in question, the fractional concentration C (by weight) of all isotopes together of the element in a carbonaceous chondrite, the energy release (heating rate) in Joules per yr per kg of the isotope in question, and the heating rate in Joules per yr per kg of carbonaceous chondrite.

Most of the heat energy supplied by radioactivity in geological circumstances today comes from ^{40}K, ^{232}Th, and ^{238}U; the total is about $1.1 \times 10^{-4}\ \mathrm{J\,yr^{-1}}$ for each kg of carbonaceous chondrite-like matter. This value was higher in the past because abundances of the radioactive isotopes were higher; the abundance of ^{40}K was about 12 times larger 4.5×10^9 years ago than it is now, the abundance of ^{238}U was 83 times larger then than now, and the abundance of ^{238}U was 2.0 times larger than now (note that the half-life of ^{238}U almost exactly equals the age of the solar system). When the solar system formed, the total radioactive heating rate would have been about $8.5 \times 10^{-4}\ \mathrm{J\,yr^{-1}\,kg^{-1}}$, almost ten times higher than at present, mainly due to the large abundance then of ^{40}K.

Specific Heat

An important effect of energy release inside an asteroid or planet by any of the mechanisms just discussed is to raise the internal temperature. To assess the significance of this effect we must know how much a given energy input to a unit mass of material raises the temperature: that is, we must know the specific heat $C_{\rm v} = dU/dT$, where U is the (thermal) internal energy.

The simplest system in which to study the dependence of U on T is an ideal gas of monatomic molecules (for example a noble gas such as Ne or Ar). It is well known that in such a gas, the specific heat depends on how energy is added to the gas. If heat is added at *constant volume*, so that the gas does not use any of the added energy doing work on its surroundings, the specific heat of a monatomic gas is $3R_{\rm g}/2$ per mole, where $R_{\rm g}$ is the gas constant, or $3k/2$ per atom, where k is Boltzmann's constant (see Equation 2.8). If heat is added at *constant pressure*, so that the gas can do work on its surroundings, the specific heat of a monatomic gas is increased by roughly half again, and has the value $C_{\rm p} = 5R_{\rm g}/2$ per mole, or $5k/2$ per atom.

The specific heat may also depend on atomic structure. This is immediately clear when you recall that the specific heat at constant volume of a diatomic gas such as N_2 is $5R_{\rm g}/2$ per mole, or $5k/2$ per molecule ($5k/4$ per atom) at room temperature. Thus we can expect specific heats of different substances to vary from one to another.

Table 6.6: Specific heat at constant volume for various substances.

Substance	$c_{\rm v}$ (J K^{-1} kg^{-1})	$\mu m_{\rm u} c_{\rm v}$ (J K^{-1} atom^{-1})	$\frac{\mu m_{\rm u} c_{\rm v}}{k}$
Argon (Ar)	3.12×10^2	2.07×10^{-23}	1.50
Hydrogen (H_2)	1.04×10^4	3.45×10^{-23}	2.50
Nitrogen (N_2)	7.42×10^2	3.45×10^{-23}	2.50
Water (H_2O)	4.19×10^3	4.18×10^{-23}	3.03
Ice (H_2O)	2.1×10^3	2.1×10^{-23}	1.5
Mercury (Hg)	1.38×10^2	4.60×10^{-23}	3.33
Iron (Fe)	4.6×10^2	4.3×10^{-23}	3.1
Basalt (typical rock)	8.4×10^2	3×10^{-23}	2

Table 6.6 lists a few representative specific heats for several substances. These are given as specific heats at constant volume per kg ($c_{\rm v}$) and per atom in solids and liquids, and per molecule in gases ($c_{\rm v}\mu m_{\rm u}$). Notice that although the specific heats per kg vary by almost a factor of 100 between H_2 and Hg, the specific heats per molecule or atom of the substances in the table are all between $1.5k$ (A) and $3.3k$ (Hg), regardless of the molecular weight of the substance, and regardless of whether it is solid, liquid or gas. In fact, this behaviour is quite general, and specific heats differ strongly from about $3k$ per atom only at temperatures near absolute zero, where they fall below this value. For reconnaissance purposes, or when one is in ignorance of the true specific heat, $c_{\rm v} \approx 3k/(\mu m_{\rm u})$ per atom is usually a reasonable estimate for any solid or liquid if the temperature is well above $T = 0$ K, while for gases a good estimate is $c_{\rm v} \approx 3k/(2\mu m_{\rm u})$ per atom for monatomic gases, or $c_{\rm v} \approx 5k/(2\mu m_{\rm u})$ per molecule for diatomic ones.

Exercise: By equating the available gravitational energy to the change in internal energy, show that the maximum average temperature increase that could be achieved in an accreting rocky body of mass M and radius R, composed of atoms having a typical molecular weight μ, as a result of release of gravitational energy is approximately

$$\Delta T \approx \left(\frac{m_{\rm u} G}{5k}\right)\left(\frac{\mu M}{R}\right). \tag{6.8}$$

Evaluate this expression for an asteroid with a radius of 200 km and a mean density of 3500 kg m^{-3}that is made of atoms with a typical molecular weight of about 35. Could gravitational energy contribute in a significant way to heating this forming asteroid?

Heat transfer by conduction

If the interior of an asteroid or planet is hot, the heat will gradually leak to the surface and be radiated into space. There are three general ways in which heat may leak from one place to another inside a hot object. These are conduction (the effect by which the outside of a metal pot becomes hot when you pour hot water into the pot), radiation (the means by which the direct radiation of the Sun warms your skin on a cool, sunny day), and convection (when heat is transferred physically from one place to another by boiling motions in which hot blobs of liquid move to cool regions, exchanging places with cooler blobs, as above a hot room radiator). In fact, in an object like an asteroid which is not too hot inside (say $T < 1000$ K), so that the rock is much too solid to slowly flow as it probably does inside the Earth, only conduction is important.

Conduction is described by an equation known as the heat flow equation. Imagine a slab of material of thickness dx, with temperature $T(x)$ on one side and temperature $T(x+dx) = T(x)+dT$ on the other. Then the heat energy flowing across the slab from the hot side to the cool side, per unit time, is

$$\frac{\Delta Q}{\Delta t} = -k_c A \frac{dT}{dx}, \tag{6.9}$$

where A is the area of the slab. The amount of heat flowing across a *unit* area per unit time, $q = \Delta Q/A\Delta t$, is often called the **heat flux**. The quantity k_c may be measured empirically and is known as the **thermal**

conductivity of the material in the slab (the usual symbol for this quantity is k, but we use k_c here to avoid confusion with Boltzmann's constant, also called k). Thermal conductivities of some common materials are listed in Table 6.7.

Table 6.7: Thermal conductivities of common substances.

Substance	k_c ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Air	2.5×10^{-2}
Water	6.7×10^{-1}
Ice	2
Iron	8.0×10^{1}
Copper	4.0×10^{2}
Sheet insulation (e.g. corkboard)	4×10^{-2}
Limestone (typical rock)	2
Granite (typical rock)	3

Source: *CRC Handbook of Chemistry and Physics*, 1982–83 edition (Boca Raton, Fla: CRC Press Inc.), Sec E.

It may be seen that conductivities range over about four orders of magnitude. For rocky material such as might be found in the mantle of an asteroid or planet an appropriate value is probably around $2\ \mathrm{W\,m^{-1}\,K^{-1}}$; for an iron core the conductivity is about 40 times larger.

Heat loss from asteroids

The internal temperature of an object such as an asteroid that has – or had – a significant internal heat source is the result of a competition between internal heat production and the rate at which the heat leaks out into space. A familiar form of this competition occurs when you get into bed on a cold night – the heat production of your body (roughly 25 W) keeps you warm all night if you have thick covers over you, which insure slow heat loss, but if you try to sleep under just a sheet the heat loss rate is high enough that your heat production does not keep you at a comfortably warm temperature.

When we look at how the competition between heat production and heat loss determines internal temperature in asteroidal or planetary bodies, we find two extreme cases where the result is fairly easy to calculate. At one extreme, consider a body which has a brief but intense heating episode (from heat released by accretion, for example, or a short-lived radioactivity) which quickly dies away. In this case, once the heat source has run down or switched off, the heated object slowly cools back towards equilibrium with its surroundings: its internal temperature gradually approaches that of the surroundings (typically the internal temperature approaches the surface temperature set by solar heating of the surface). The other extreme is the case where the heated object has a heat source which does not change substantially during the characteristic time required for the body to lose most of its internal energy once the internal heating switches off. This is the case for small bodies heated by long-lived radioactive heat sources such as ^{238}U. In this case the asteroid settles into an equilibrium in which the heat production internally essentially balances the heat loss to the surroundings. Situations intermediate between these two also occur, of course, but are more difficult to evaluate.

Let us first estimate the **cooling time scale** for a solid body of radius R from an initial hot state, assuming that there are no continuing internal heat sources. (This is also an estimate of the time required for the body to come into approximate equilibrium with a very slowly changing internal heat source.) Suppose the internal temperature T is much higher than the surface temperature, so that $dT/dx \sim T/R$. If the material has specific heat $c_{\rm v}$ per kg, the total internal energy is roughly $U \sim 4\pi R^3 \rho c_{\rm v} T/3$. The total heat flow out of the body is of order

$$\begin{aligned} \frac{\Delta Q}{\Delta t} &\sim -k_c 4\pi R^2 (T/R) \\ &\sim -4\pi R k_c T \end{aligned} \tag{6.10}$$

and so the characteristic time for cooling (i.e., the time required for heat flow to carry to the surface – or redistribute – most of the initial heat content) is

$$\begin{aligned} \tau &\sim -\frac{U}{(\Delta Q/\Delta t)} \\ &\sim (R^2/3)(\rho c_{\rm v}/k_c) \end{aligned} \tag{6.11}$$

The quantity $\kappa = k_c/\rho c_{\rm v}$ is often called the thermal diffusivity, and for rocky planetary material it has a size of roughly $1 \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$. Then Equation (6.11) shows that the characteristic time to cool an initially hot rocky body is of order

$$\tau_{\rm yr} \sim 1 \times 10^4\ R_{\rm km}^2 \tag{6.12}$$

where $R_{\rm km}$ is the size in km and $\tau_{\rm yr}$ is measured in years. A body as small an asteroid ($R_{\rm km} < 500$ km) would lose any initial internal energy in a time short compared to the age of the solar system, but a body as large as any inner planet ($R > 2400$ km) should still be hot inside if it was initially formed hot, even without any radioactive internal energy sources!

Exercise How does the estimated cooling time scale change if the surface temperature of the body is $T_{\rm s}$ rather than being taken to be essentially zero as in the discussion above?

Now consider the opposite limit, in which a body has an internal heat source that changes slowly compared to the time in which most of the current internal energy can leak out. In this case the heat production in the interior gradually (in about the characteristic cooling time) settles into an equilibrium with the heat loss, and the internal temperature of the body comes to a steady state that changes only as the internal heat sources change. We will look at this case through the example of Ceres. The basic idea is that the asteroid reaches an equilibrium in which the rate of heat release in the centre approximately balances the loss of heat through leakage to the surface. Ceres is small enough ($R =$ 470 km) that its cooling time scale is less than the age of the solar system, and so this approximation may be roughly valid. Let's see what temperature would result from this equilibrium. The surface temperature $T_{\rm s}$ of Ceres, set by solar heating, is about 200 K (see Section 4.4). As a rough approximation, assume that the temperature drop from centre (at temperature $T_{\rm c}$) to surface occurs roughly uniformly over the radius of the asteroid, so that the temperature gradient is

$$dT/dx \approx (T_{\rm c} - T_{\rm s})/R. \tag{6.13}$$

The surface area of Ceres is $A = 4\pi R^2$, so the heat loss to the surface (Equation 6.9) is approximately

$$\frac{\Delta Q}{\Delta t} \approx (4\pi R^2) k_c (T_{\rm c} - T_{\rm s})/R. \tag{6.14}$$

Assume a heat production typical of a carbonaceous chondrite, about $L \sim 4 \times 10^{-12}$ W kg^{-1}, and a mass $M \approx 9.5 \times 10^{20}$ kg. We now equate the total heat production rate LM with the rate at which heat is lost from the surface, and solve the resulting equation for $T_{\rm c}$, which leads to

$$T_{\rm c} \approx T_{\rm s} + ML/(4\pi k_c R). \tag{6.15}$$

With the values appropriate to Ceres, we find $T_{\rm c} \approx 520$ K. As long as the internal radioactive heat production does not change greatly, Ceres will maintain a central temperature of about 500 K, which drops steadily with distance from the centre towards the surface, reaching about 200 K at the surface.

Note that reradiation of incident sunlight, which provides roughly 10^2 W m^{-2}, is much larger than the internal heat leakage rate, about 2×10^{-3} W m^{-2}, and so the surface temperature of Ceres is not altered significantly by the leakage of internal heat.

Exercise Confirm the internal heat leakage rate given above for Ceres, and estimate the increase in surface temperature caused by the leakage of internal heat to the surface.

Exercise Apply the reasoning above to estimate the present surface and central temperatures of the asteroid 511 Davida, assuming equilibrium (see Table 6.1).

6.7 References

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6.8 Review questions

6.1 Why are certain orbital periods apparently not allowed for asteroids?

6.2 How can the dimensions and masses of any asteroids be determined?

6.3 Could the asteroids of the main belt have been created by the disruption of a large terrestrial planet originally formed between Mars and Jupiter?

6.4 What information do we have about the chemical composition of asteroids?

6.5 How do we know that some asteroids have been differentiated into a structure with a metallic core and a rocky mantle? How could this differentiation have occurred?

6.6 What evidence shows that some meteorites originate in asteroids of the main belt? How are such meteorites transported to Earth?

6.7 Where and how did most most meteorites originate? What evidence helps us to answer this question?

6.8 What information do we have to estimate the fraction of various types of meteorite that occur in the region from which these meteorites originate? How is this information altered by the process of recovering meteorites on Earth?

6.9 Is it possible to identify specific source bodies for particular meteorites? If so, how?

6.10 What kinds of bodies in the current solar system are capable of catastrophic impact with the Earth? How do they get into orbits which can lead to Earth impact?

6.9 Problems

6.1 Two asteroids orbit the Sun in virtually identical orbits. One has a radius of 40 km and a density of 3300 kg m^{-3}. The other has a radius of only 100 m, and the same density. Because of a tiny initial difference in speed, the larger asteroid eventually comes close enough to the small one to capture it gravitationally, and the small asteroid crashes into the large one. (a) With what velocity does the small body hit the larger one? (b) Assume that all the energy released in the impact is retained in the immediate neighborhood of the impact, in an amount of matter equal to twice the mass of the smaller asteroid. Making reasonable assumptions about the specific heat of asteroidal material, how much would the temperature of the heated matter rise?

6.2 Assume that Jupiter and an asteroid are moving in circular, coplanar orbits, and that the ratio of orbital periods if $P(\text{Jupiter}) : P(\text{asteroid}) = 5 : 3$. (a) Sketch the two orbits to scale. (b) Show that the time from one close approach and the next of the two bodies is equal to xP_{Jupiter} and also equal to $(1+x)P(\text{asteroid})$, where x is some number. (c) Calculate how long an interval of time elapses between one close approach of the asteroid to Jupiter and the next. Give the result in Jupiter revolutions and in years, (d) On your sketch, show the places in the two orbits where the giant planet and the asteroid (repeatedly) pass closest to one another.

6.3 On Earth, a vigorous person can jump vertically to a height of roughly 0.3 meter (i.e. raise her centre of mass by that much). Suppose an astronaut tries to launch herself into a hyperbolic (escape) orbit from a small asteroid of mean density $\rho = 3000\ \mathrm{kg\,m^{-3}}$, radius R, and mass $M = 4\pi\rho R^3/3$. From how large an asteroid could the astronaut escape? Make your assumptions and reasoning clear.

6.4 Consider an asteroid in a circular orbit around the Sun at 2.8 AU. (a) What is its velocity? (b) Suppose it were slowed down enough to drop into an elliptical orbit with an aphelion of 2.8 AU and perihelion of 1.0 AU. What would its velocity at aphelion then be? (c) Calculate the change in the kinetic energy per kg of the asteroid for this orbit change, at aphelion. (d) Calculate the mass of the asteroid and the gravitational binding energy per kg, for an asteroid of density $\rho = 3000$ kg m^{-3} and radius $R = 10$ km. (e) Calculate the number of atoms per kg, assuming a composition of $(MgFe)SiO_4$. (f) Calculate the crystal binding energy per kg, assuming that it is of order $E_{\rm b} \sim 3nkT_{\rm b}$, where n is the number of atoms per kg and $T_{\rm b}$ is the boiling point of the rock, roughly about 3000 K (note that this estimate ignores latent heats). (g) Is it likely that an asteroid could be shifted from the circular orbit into the elliptical one as a result of a collision without being completely fragmented or vaporized?

6.5 With what rotation period would Ceres have to rotate so that the rotational velocity of material at the equator of the asteroid would just be equal to the speed of a small body orbiting just above the surface? Could Ceres rotate with a period any shorter than this? Explain your conclusion.

6.6 Assume that the asteroid belt extends between 2.2 and 3.2 AU, and extends to 0.5 AU above and below the ecliptic. (a) If we estimate that there are about 10^6 asteroids of $R > 0.1$ km within this volume of space, what is the average space density of such asteroids (in asteroids per km^3), and an estimate of their typical separation (in km and in AU)? (b) When Voyager 1 passed through the asteroid belt, it had a speed of about 22 km s^{-1}, and its trajectory (which was confined essentially to the plane of the ecliptic) made approximately a

45° angle with the radius vector to the Sun. Ignoring the motion of the asteroids, use the space density calculated above to estimate (c) the probability P(100) of passing within 100 km of an asteroid of $R > 0.1$ km, and (d) the distance of closest approach to an asteroid of $R > 0.1$ km (that is, find the distance at which the probability of interaction at that distance would be about 1 for Voyager 1's track through the asteroid belt). (e) From a closest approach to an asteroid of $R \sim 10$ km equal to the distance estimated in (b), how large an angle would the asteroid subtend from Voyager? Would Voyager have been able to send back a detailed photo of this asteroid if the smallest detail its cameras could detect was about $3''$ across on the sky?

6.7 Suppose you discover an asteroid. You decide to observe it intensely, and you name it after your childhood pet, Gloop. You find that Gloop is in opposition (directly opposite the Sun as seen from Earth) every 1.25 years. (a) Assuming that Earth has a circular orbit, how far from the Sun is Gloop, what is its orbital period and what is the shape of its orbit? How far from the Earth is Gloop at opposition? (b) You also measure the total visible and near infrared light reflected from Gloop at opposition, finding a flux of about 1.0×10^{-13} W m^{-2}. Similarly, the total flux of heat radiation received from Gloop at infrared wavelengths longer than about 5 μm is 1.0×10^{-12} W m^{-2}. Assume for simplicity that Gloop rotates rapidly, and that it reflects light uniformly into 2π steradians and reradiates heat uniformly into 4π steradians. What are the albedo and radius of Gloop?

6.8 Consider an asteroid with an iron core ($\rho_c = 8000$ kg m^{-3}) covered by a thin silicate mantle ($\rho_m = 3400$ kg m^{-3}) with a thickness of 20% of the radius R of the asteroid. Assume that the internal temperature $T_i = 600$ K is constant throughout the core because of the high thermal conductivity of iron. Take the thermal energy of the core to be $3kT_i$ per atom, and assume that the thermal conductivity of the silicate mantle is about $k_c = 2$ W m^{-2} (K m^{-1})$^{-1}$. Ignore the heat capacity of the mantle. If the surface of the asteroid has a temperature of $T_s = 200$ K, find the value of the radius R for which the cooling rate is about 1 K per 10^6 yr. (You are estimating the size of the asteroid which could be the parent of an iron meteorite).

6.9 Consider an asteroid that forms by accretion in a very short time and that traps in its interior almost all the heat released by gravity during the formation. The resulting asteroid has uniform density $\rho = 3000$ kg m^{-3} and constant chemical composition throughout. Assume that the internal energy per atom is given by $E_{th} = 3kT$, that the mean molecular mass is $\overline{m} = 25m_u$, and that the melting point of iron is $T_{melt} = 1800$ K. Assume also that the accreting matter starts with $T_0 = 200$ K before accretion. (a) Suppose that the accretion occurs in a time short compared to the time required for heat to be transported away from the level at which it is deposited. Derive an expression for the temperature as a function of radius, $T(r)$, inside the asteroid of radius R. How large must the R grow for the local temperature to exceed the melting point anywhere? (b) Now make a different assumption, namely that mixing is effective enough that as the body accretes, the whole interior stays at about the same (increasing) temperature $\overline{T}(R)$. How large must R be in this case in order for enough heat to be supplied to melt the entire object? (c) Does it appear that accretion heating is a plausible mechanism for explaining how asteroids can differentiate?

6.10 Suppose that the asteroid 52 Europa is chemically homogeneous throughout, and that the radioactive heat sources are uniformly distributed through the asteroid's volume. Let the heat energy released per unit mass per unit time due to radioactive decay be E. From Table 6.5 the value at present of E for carbonaceous chondrite-like matter is about 1.1×10^{-4} J kg^{-1} yr^{-1} $= 3.5 \times 10^{-12}$ J kg^{-1} s^{-1}. Now suppose that E changes so slowly that the asteroid has been able to reach a state of equilibrium in which the total heat produced inside a radius r is just balanced by the heat carried out of that volume by thermal conduction. (a) For an arbitrary value of r, write down the expression for L_r, the total radioactive energy release per second inside of r. Write down a corresponding expression for the total energy flux carried outward by conduction at r; this expression will involve dT/dr. The condition of equilibrium is that these two expressions are equal. (b) Assuming that E and the conductivity k_c are independent of r, integrate the resulting equilibrium equation to get an equation relating $T(r) - T_c$ to r, where T_c is the central temperature $T(0)$. (c) Assume that $T(R)$ is known to be about 200 K, that E has the value above, and that k_c is about 2 W m^{-1} K^{-1}. Solve for the value of T_c. Graph the resulting temperature profile $T(r)$.