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Origin and history of the Solar System

1.1 Preamble

As early astronomers recognized, the planets are orbiting the Sun on paths that are nearly circular and coplanar, with motions in the same sense as the Sun's rotation, making it difficult to avoid the conclusion that the formation of the Sun led directly to its planetary system. A comparison of the planets (Table 1.1) shows that the Earth belongs to an inner group of four, which are much smaller and denser than the outer four giant planets. For this reason the inner four are referred to as the terrestrial (Earth-like) planets. The outer four large planets are gaseous, at least in their visible outer regions, but they have solid satellites with very varied external appearances and a wide range of mean densities, all much lower than those of the terrestrial planets. The asteroids, which are found between the two groups of planets, are believed to be remaining examples of planetesimals, the pre-planetary bodies from which the terrestrial planets formed. Meteorites are samples of asteroids that have arrived on the Earth, by a mechanism discussed in Section 1.9, and so provide direct evidence of the overall compositions of the terrestrial planets.

We probably learn more about the formation of planets from their differences than from their similarities. Several features of the Earth distinguish it from all other bodies in the Solar System and require special explanations.

(i) The Earth is the only planet with abundant surface water, both liquid and solid.
(ii) It is also the only planet with an atmosphere rich in oxygen.
(iii) It appears to be the only planet with extensive areas of acid, silica-rich rocks, such as granite, which are characteristic of the Earth's crust in continental areas.
(iv) It is usually regarded as the only planet with a bimodal distribution of surface elevations (Fig. 9.4), marking the division into continental and oceanic areas, although it is possible that Mars has weak evidence of a similar crustal structure (Section 1.14).
(v) The Earth is the only terrestrial planet with a strong magnetic field. In this respect it resembles the giant planets (Table 24.2).
(vi) Perhaps the existence of a large moon should be added to the list of features that make the Earth unique, at least among the terrestrial planets. The origin and history of the Moon are the subjects of rival ideas. Sections 1.15 and 8.6 address this problem.

The first four of these features are related and water provides the connecting link. It is necessary for the plant life that has produced the atmospheric oxygen. It is also essential to the tectonic process that leads to acid volcanism (Section 2.12). The acid rocks that form the basis of the continents are lighter than the underlying mantle and 'float' higher in the gravitational (isostatic) balance of the Earth's crust (Section 9.3), causing the bimodal distribution of surface elevations.

Meteorites are especially important to our understanding of the early history of the Solar

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Table 1.1 Planetary parameters

n Planet	Orbit radius[a] (AU) (r_n/r_3)	Rotation period (days)	Tilt of equator to orbit (degrees)	Mass (Earth masses)	Radius[b] (Earth radii)	Mean density (kg m^{-3})	Decompressed density (kg m^{-3})	Number of known satellites
1 Mercury	0.387	59	2.0	0.055 28	0.3830	5427	5017	0
2 Venus	0.723	243.02	177.3	0.814 999	0.9499	5204	3868	0
3 Earth	1	0.997 2697	23.45	1	1	5515	3995	1
Moon				0.012 3000	0.2728	3345	3269	
Earth + Moon				1.012 3000			3945	
4 Mars	1.524	1.026	25.2	0.107 4468	0.5321	3933	3697	2
[5] Asteroids	~2.8					3700[c]	3700	
6 Jupiter	5.2013	0.413	3.1	317.89	10.973	1327	largely	62
7 Saturn	9.538	0.444	26.7	95.18	9.140	688	gaseous	35
8 Uranus	19.18	0.718	97.9	14.54	3.98	1272		27
9 Neptune	30.06	0.671	30.2	17.15	3.86	1640		13
10 Pluto	39.52	6.387	117.6	0.0022	~0.18	2080	~2000	3

[a] Semi-major axis of orbital ellipse
[b] Radius of a sphere of equal volume (for surface at 1 atmosphere pressure for outer planets)
[c] Average of observed falls

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System (Sections 1.7 to 1.11) and its composition (Sections 2.2 to 2.5). Most of them are fragments of asteroids. They are samples of small bodies with relatively simple histories that have remained virtually unaltered since the Solar System was formed. Collisions in the asteroidal belt projected these fragments into orbits that evolved, initially by the Yarkovsky effect (Section 1.9) and then by orbital resonances with Jupiter, into Earth-crossing paths, providing us with samples that are more representative of the total chemistry of the terrestrial planets than is the Earth's crust. For a broad review of their importance to our understanding of early Solar System history see Wasson (1985).

Our estimate of the age of the Solar System is derived from measurements of isotopes produced in meteorites by radioactive decay (Section 4.3). It is clear that most of them have a common age, 4.57×10^9 years. The evidence that this dates the formation of the whole Solar System is less direct because we do not find on the Earth any rocks that have survived that long unaltered. However, by obtaining an estimate of the average isotopic composition of the Earth as a whole we can plot it as a single data point on the isochron (equal-time line) of meteorite lead isotopes (Fig. 4.1) and see that it fits reasonably well.

1.2 Planetary orbits: the Titius–Bode law

For many years theories of the origin of the Solar System were based on rather little hard evidence. Motions of the planets were well observed and orbital radii were seen to follow a regular, if approximate, pattern. This regularity was represented by an equation known as the Titius–Bode law or sometimes simply as Bode's law. As originally proposed this law gave the orbital radius of the kth planet (counted outwards) as

$$r_k = a + b \times 2^k, \tag{1.1}$$

a and b being constants. Modern discussions favour a power law but still refer to it as the Titius–Bode law,

$$r_k = r_0\, p^k. \tag{1.2}$$

Although we now have much more information about the planets, this relationship is still central to our understanding of the Solar System.

The choice of value of p in Eq. (1.2) depends on how the planets are counted. The wide gap between Mars and Jupiter led to the search for a 'missing' planet in the region now recognized to be occupied only by numerous asteroids. We no longer suppose that the asteroids were ever parts of one or two planets, and cannot logically fit the Titius–Bode law to the whole set of planets. Attempts to do this (the broken line in Fig. 1.1) are only of historical interest and we should fit Eq. (1.2) to the two groups of planets separately (the solid lines in the figure). Pluto must not be considered with the outer group as it is identified with the pre-planetary fragments (Kuiper belt objects, Section 1.13) that have escaped accretion into the regular planets. But, in spite of these difficulties, the approximate geometrical progression of orbital radii is clear and obviously has a fundamental cause. As evidence of the generality of the Titius–Bode law, we note that the orbital radii of the major satellites of the giant planets also fit Eq. (1.2). The fit is particularly good for the satellites of Jupiter (Io, Europa, Ganymede, Callisto) which give $p = 1.64 \pm 0.03$, in the same range as for the planetary fit. Bode's law is an interesting example of scale invariance, which is seen in many physical phenomena. It is an apparently universal law, independent of the scale of the orbits and of the masses of planets or satellites.

Theories to explain the Titius–Bode law abound, as discussed in a historical review by Nieto (1972). There are two basic approaches, appealing to regularities in the scale of turbulence in the solar nebula or to the competition between gravitational attractions of aggregating bodies in the gradient of the solar gravity field. The vortex theories were pioneered by Laplace and more recently by R. P. von Weizsäcker. They were given a focus by White (1972), who argued that the nebular cloud was sufficiently tenuous to have negligible viscosity, so that vorticity was conserved. With this assumption, White's theory leads to jet streams spaced radially from the Sun in the manner of Eq. (1.2). Prentice (1986, 1989)

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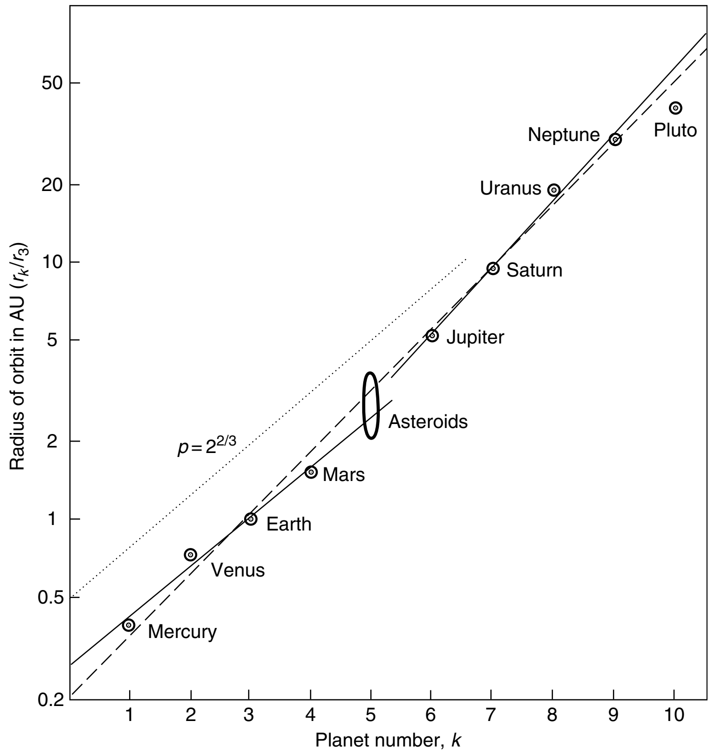

FIGURE 1.1 Radii of planetary orbits fitted to the Titius–Bode law (Eq. 1.2). Solid lines are independent fits to the terrestrial planets ($p = 1.56$) and the four giant planets ($p = 1.82$). The broken line is a fit to all planets except Pluto, allowing for a missing fifth (asteroidal) planet ($p = 1.73$). The dotted line indicates a gradient for $p = 2^{2/3} = 1.59$, which would apply if all orbital periods of neighbouring planets differed by a factor of 2 (Kepler's third law – Eq. (B.23) in Appendix B).

pointed out that the turbulence would have been highly supersonic, and developed a theory of planetary accretion on that basis. White's point about the low viscosity draws attention to the need for a mechanism to damp the turbulence. In Section 4.6 we argue that that the only plausible one is electromagnetic and could not have operated until the arrival of highly radioactive supernova debris ionized the nebular material and made it sufficiently conducting for hydromagnetic damping to occur.

There can be little doubt that mutual gravitational attraction of planetesimals had a role in planetary accretion, at least in its late stage, and there are several variants of the gravitational interpretation of Bode's law. The simple observation, that the parameter p in Eq. (1.2) is very close to $2^{2/3} = 1.587$, invites close scrutiny. By Kepler's third law (Eq. B23 in Appendix B), this ratio of orbital radii corresponds to orbital periods with 2:1 ratios. It is the simplest of the resonances that have been intensively studied in connection with asteroids, but, in that case, interaction with Jupiter is of interest rather than mutual interactions between small bodies. Attempts to explain Bode's law in terms of gravitational interactions appeal to the fact that orbital speeds of planetesimals decreased as $a^{-1/2}$ with distance, a, from the Sun. Mutual interactions extended over ranges that increased systematically with a by virtue of the decreasing differential speeds. An unambiguous theory of Bode's law eludes us, but the evidence for universal validity of Eq. (1.2) is compelling. We apply it as an empirical rule in discussing the early history of the Moon in Section 8.6.

1.3 Axial rotations

The rotations of the planets differ greatly from one another in both speed and axial orientation

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(Table 1.1). Rotation in the sense of the orbital motion predominates, but Uranus, whose axis is almost in the orbital plane, and Venus, whose very slow rotation is retrograde, are exceptions. The conventional explanation for the variation in axial alignment is the same statistical one as is offered for the scatter of orbital radii about a regular pattern (Fig. 1.1), that is, it depends on the infall of planetesimals on independent, but reasonably close orbits. Precisely how they collided determined the rotations of the composite bodies.

The terrestrial planets and Pluto are rotating slowly compared with both the giant planets and the asteroids. In the cases of Mercury, Venus, the Earth and Pluto, the slower rotations are due to the dissipation of rotational energy by tidal friction (discussed in Section 8.3). The rotation of Mercury is believed to be tidally locked to its elliptical orbit about the Sun. The tide raised in Pluto by its satellite, Charon, has stopped it rotating relative to Charon, to which it presents a fixed face, as does the Moon to the Earth for the same reason. Venus must have been slowed by friction of the solar tide, but that does not explain the retrograde sense of its rotation, which must therefore be a consequence of the accretion process. Mars is too far from the Sun and its present satellites are too small for tidal friction to have had a noticeable effect on it and, unless it once had a large, close satellite that spiralled in and merged with the planet (as suggested for Mercury and Venus in Section 1.15), the slow rotation is what it was left with after the arrival of the last planetesimal. The near coincidences of the rotational speeds and axial alignments (obliquities) of Mars and the Earth are fortuitous. The early rotation of the Earth was certainly much faster and the obliquity of Mars is subject to variation by gravitational interactions, especially with Jupiter.

The rotation of Uranus, with its axis close to the orbital plane, gives a clue to the mechanism of planetary accretion. The silicate and iron content could not reasonably be sufficient to account for the rotational angular momentum, even if it arrived as a tangentially incident planetesimal. We therefore suppose that Uranus accreted from volatile-rich planetesimals that had formed in independent solar orbits. Direct accretion from gas could not have caused the axial misalignment if dissipation of turbulence in the nebula and collapse to a disc preceded planetary formation. This would have confined the motion of the gas more or less to the plane of the disc, from which random accretion of very large numbers of molecules could not have resulted in a planetary rotational axis close to the plane. The planetesimals would have been composed of ices that could condense out of the nebula, and not hydrogen or helium, which could have accreted only on a planet that was large enough to hold them gravitationally. In the case of Jupiter, for which hydrogen and helium represent a much larger proportion of the total mass, the axial misalignment is very slight.

1.4 Distribution of angular momentum

Using Kepler's third law (Eq. B.23, Appendix B) we can write the orbital angular velocity of the kth planet,

$$\omega_k = (GM_S/r_k^3)^{1/2}, \tag{1.3}$$

in terms of its orbital radius r_k, the mass of the Sun, $M_S = 1.989 \times 10^{30}$ kg and the gravitational constant, G. This allows us to write the orbital angular momentum in a convenient form,

$$a_k = m_k r_k^2 \omega_k = (GM_S)^{1/2} m_k r_k^{1/2}, \tag{1.4}$$

for calculation of the total orbital angular momentum of the Solar System from Table 1.1,

$$\sum a_k = (GM_S)^{1/2} \sum m_k r_k^{1/2} = 3.137 \times 10^{43}\ \mathrm{kg\ m^2 s^{-1}}, \tag{1.5}$$

Jupiter accounts for more than 60% of this total.

The angular momenta of planetary rotations are very much smaller than the orbital angular momenta. The rotational angular momentum of the Earth, $5.860 \times 10^{33}\,\mathrm{kg\,m^2\,s^{-1}}$, is 2.2 parts in 10^7 of its orbital angular momentum, $2.662 \times 10^{40}\,\mathrm{kg\,m^2\,s^{-1}}$. We can compare Eq. (1.5) with the rotational angular momentum of the Sun, which has 99.866% of the total mass of the Solar System

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(assuming that we know about it all). The surface of the Sun is rotating faster in equatorial regions than at the poles and, although there is no direct observation to indicate how the interior is rotating, observations of the modes of free oscillation (helioseismology) are consistent with coherent rotation, so it suffices for the present purpose to assume rigid body rotation with the angular speed taken as representative by Allen (1973), $\omega_S = 2.865 \times 10^{-6}\,\mathrm{rad\,s^{-1}}$. The rigid body moment of inertia can be obtained by integrating the density profile of the Sun (Problem 1.3, Appendix J), which has a strong concentration of mass towards the centre. Allen's (1973) value is $5.7 \times 10^{46}\,\mathrm{kg\ m^2}$. With the above value of ω_S, this gives the angular momentum

$$(I\omega)_S = 1.63 \times 10^{41}\,\mathrm{kg\,m^2\,s^{-1}}. \tag{1.6}$$

Thus the Sun has only a small fraction (0.5%) of the angular momentum of the Solar System, which is dominated by the planetary orbits (Eq. 1.5), although the planets have little more than 0.1% of the mass.

The slow solar rotation can be explained by an outward transfer of angular momentum in the nebula which surrounded the Sun when it was still young. Alfvén (1954) argued that this occurred because a strong solar magnetic field (rotating with the Sun) dragged with it the ionized gases of the nebula and an intense solar wind. His suggestion fits well with other observations, especially the magnetizations of meteorites (Section 1.11). Early in the development of the Solar System the Sun is believed to have passed through a stage reached at the present time by a number of young stars (several hundred in our Galaxy), of which T-Tauri is the representative example. They are very active, with strong stellar winds and magnetic fields several orders of magnitude more intense than that of the Sun at present. We suppose that the meteorites were forming when the Sun was at its T-Tauri stage and so were magnetized by its strong field.

The angular momentum transfer by Alfvén's magnetic centrifuge mechanism could have contributed to chemical fractionation in the Solar System. It is only the plasma of charged particles that would be affected by the motion of the magnetic field. Once solid particles began to form, they and any un-ionized gas molecules would have been coupled to the field only by viscous drag of the surrounding plasma. The early condensing, generally less volatile materials would therefore have become relatively more concentrated in the inner part of the Solar System, with most of the volatiles centrifuged to the outer regions.

1.5 Satellites

The giant planets have numerous satellites (Table 1.1), but the terrestrial planets have only three between them and, of these, the Earth's Moon is outstandingly the largest. The other two, Phobos and Deimos, are small, irregularly shaped close satellites of Mars that give the impression of being captured asteroids. The larger one, Phobos, is so close that it orbits Mars three times per day (the Martian and Earth days are almost equal). It has a dark surface, with a reflection spectrum similar to those of many asteroids and to a class of meteorite, the carbonaceous chondrites (Section 2.4). The closeness of the orbit means that Phobos raises an appreciable tide in Mars, in spite of being so small. This makes capture a plausible hypothesis, because it allows the orbit to evolve by tidal friction. Deimos is even smaller and is more remote from Mars, making capture unlikely, although it, too, looks asteroidal.

As well as having many satellites, the giant planets all have rings of fine particles that are most clearly observed around Saturn. In the case of Jupiter, it is apparent that most or all of the small, outer satellites are captured asteroids. Their orbits are tightly clustered in two distinct groups, one prograde at about 11.5×10^6 km from Jupiter and the other retrograde at about 23×10^6 km. These are the orbits predicted by capture theory. The larger satellites of Jupiter are much closer and, as we mention in Section 1.2, follow the Titius–Bode law. The case for satellite capture by the other giant planets is not as clear, but Neptune's Triton has a retrograde orbit and Nereid a very elliptical one, making capture, or some other vigorous interaction,

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perhaps with Pluto, appear likely. All the other satellites are presumed to have formed with their parent planets in the same manner as the planets were formed around the Sun. As with the planets, there is a wide range of properties.

Surfaces of the satellites of the giant planets are very different from one another. Extrapolating from our observations of the Moon, we might have expected Voyager images to show ancient, cratered surfaces everywhere. Instead, several satellites show evidence of internal activity and even active volcanism. This is most striking on Jupiter's closest large satellite, Io, where it is attributed to the generation of internal heat by tidal friction (Peale *et al.*, 1979); eccentricity of the close orbit ($e = 0.0043$) is maintained by resonances with other satellites, causing a strong radial tide. Neptune's Triton is another example, and Enceladus, a satellite of Saturn, shows evidence of 'cryovolcanism' of its light ices.

The densities of the satellites of the giant planets are mostly less than $2000\,\mathrm{kg\,m^{-3}}$, much lower than the densities of terrestrial planets, indicating compositions rich in ices (condensed volatiles such as H_2O, CH_4). The exceptions are Jupiter's innermost two large satellites, Io ($\rho = 3530\,\mathrm{kg\,m^{-3}}$) and Europa ($\rho = 3014\,\mathrm{kg\,m^{-3}}$), which evidently have larger silicate components (and perhaps even small metallic cores). Europa is a case of particular interest. While its surface is permanently frozen hard, a suggestion that it has a liquid ocean at modest depth arises from its influence on Jupiter's magnetic field (Kivelson *et al.*, 2000). Its orbit is within Jupiter's magnetosphere and it is a source of induced fields driven by variations in the planetary field. A saline ocean would have a sufficiently high electrical conductivity to explain this effect, but the glacial cover would not do so because ice would be almost salt-free and a poor conductor. But, of course, the observations indicate only the presence of a conductor and not its composition.

Satellites are a normal feature of the Solar System, as evidenced by their large numbers for the giant planets. Pluto has a large satellite (Charon), as well as two smaller ones, and the asteroid Ida is seen to have a satellite (Dactyl). We need a special explanation for their fewness in the inner Solar System and this is provided by tidal friction (see Chapter 8, especially Section 8.6, and the comment on the early history of the Moon in Section 1.15).

1.6 Asteroids

The small bodies with orbits concentrated between Mars and Jupiter are sometimes referred to as minor planets, but we prefer to reserve the word planets for the eight large bodies. The word asteroid is the normal scientific term. A few of them have elliptical orbits extending as far as the Earth and are referred to as near Earth asteroids (NEAs) or, sometimes, as the Apollo group of asteroids. They are of particular interest because they are the best observed and because meteorites are NEAs intercepted by the Earth. They may not be totally representative of the larger asteroidal population, and it is possible that some are residual cores of comets. More than 10 000 asteroids have been identified and new discoveries occur at a rate of about one per day. The total number must be very much larger because the population is biased towards small bodies, but only the larger ones are seen. Except for recent collision fragments, the lower size limit is probably set by the Poynting–Robertson and Yarkovsky effects (Section 1.9).

Orbits of the asteroids do not form an uninterrupted continuum but have gaps, known as Kirkwood gaps after their discoverer. The gaps are swept clear of asteroids by resonant gravitational interactions with Jupiter. The 3:1 resonance, for an asteroid with an orbital period 1/3 of the orbital period of Jupiter, has attracted particular attention. A calculation by Wisdom (1983) showed that, for an asteroid in this situation, the Jupiter interaction rapidly increased the eccentricity of the orbit, and Wetherill (1985) argued that this process maintained a flux of fresh asteroidal material in the vicinity of the Earth. The idea is that collisions in the main asteroidal belt project fragments into this and other gaps, so that their orbits evolve until interrupted by gravitational encounters with Mars, the Earth, or perhaps even Venus. They may then be deflected into orbits that evolve

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more slowly and from which they may be captured by one of these planets.

Collisions in the main asteroidal belt could not be violent enough to project fragments directly into Earth-crossing orbits. The resonant interaction with Jupiter is necessary for maintenance of the population of NEAs against losses by capture, orbital evolution out of range or, in the case of very small bodies, space erosion. However, it is not a sufficient explanation. Bottke *et al.* (2005) pointed out that direct injection of fragments into resonant orbits is too rare to explain the population of NEAs and would produce them only at infrequent intervals. They appealed to the Yarkovsky effect, which brings collision fragments into resonance more slowly, as explained in Section 1.9.

1.7 Meteorites: falls, finds and orbits

Meteorites are iron and stone bodies that arrive on the Earth in small numbers, on elliptical orbits that extend from the main asteroidal belt. Observed falls (firefalls or bolides) are signalled by fiery trails through the atmosphere. A few meteorite falls have been observed in sufficient detail to allow reliable calculations of their preterrestrial orbits. This requires timed photographs of the trails from several well separated points. The first clear example was the chondritic meteorite, Pribram, that fell in Czechoslovakia in 1959 and this is one of the five with orbits plotted in Fig. 1.2. Similar orbits are obtained for the larger number of photographed bolides from which there are no recovered meteorites and, more qualitatively, from eyewitness reports of bolides associated with recovered meteorites. An interesting statistical consequence arises from the orbits of meteoritic bodies: falls occur twice as frequently between noon and 6 pm local time as between 6 am and noon, when the opportunity for observation is similar (Wetherill, 1968). This requires the bodies to be overtaking the Earth in orbit when intercepted. It is statistical confirmation, with much larger numbers, of the conclusion from direct observations of bolides that the meteorite bodies are orbiting the Sun in the same sense as the planets, but on elliptical paths extending much farther out than the Earth. This means that when they reach the Earth they have higher orbital velocities. They are asteroidal collision fragments projected into Earth-crossing orbits by the mechanism discussed in Section 1.9.

It is important to distinguish meteorites from meteors, the briefly luminous trails in the upper atmosphere. Most meteors are produced by small particles, called meteoroids, that never get near to the ground. Although a few meteoroids are probably of meteoritic origin, most are small, friable particles of low density, identified as debris from comets. Like comets (Section 1.13), they approach the Earth from all directions. They are not confined to the plane of the Solar System, or to the direction of its rotation, as are the meteoritic bodies.

There are over 1000 specimens of meteorites that were seen to fall, but they are outnumbered by finds, that is bodies that are obviously meteoritic but were not seen to fall. The world collection of finds increased dramatically with the discovery in Antarctica of many thousand meteorites on areas of bare ice. Many of them could have been moved considerable distances by glacial motion of the ice sheet; cosmic ray exposure measurements (Section 1.8) show them to have been on or in the ice for thousands of years. However, the circumstances of the Antarctic finds ensure that they cannot be confused with terrestrial rocks. For this reason they have become important in identifying unusual types of meteorite and in estimating the relative abundances of the different kinds.

There are various classes of meteorite, all composed of stony material and iron, that is, the materials believed to comprise the mantles and cores of the terrestrial planets. Iron meteorites are normally 100% metal, but the stony meteorites commonly contain some iron, in some cases sufficient to classify them as stony-irons. Many stony meteorites contain small rounded inclusions, called chondrules, several millimetres in size, that are chemically distinct from the surrounding material. These meteorites are termed chondrites. Chondrules resemble droplets and, although they probably formed as direct

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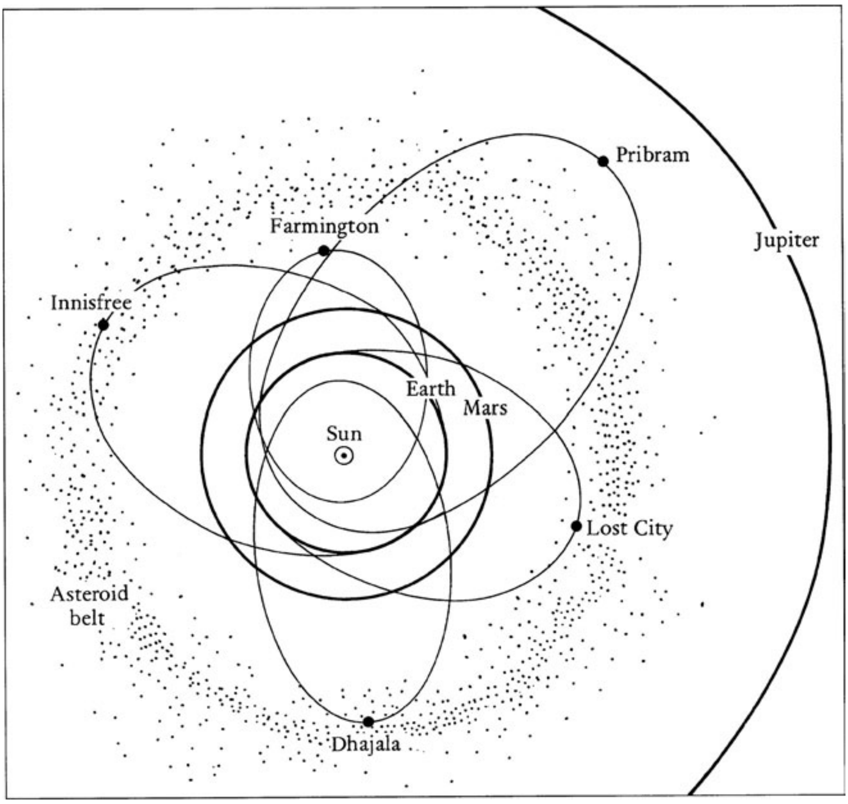

FIGURE 1.2 The calculated orbits of five recovered meteorites identify them with the asteroidal belt. The orbits are drawn to scale, but their orientations are chosen for clarity of illustration. Reproduced by permission from McSween (1999).

condensations of solid from vapours in the solar nebula, they were subjected to subsequent transient heating and even melting. They are uniquely meteoritic, with no equivalent in terrestrial rocks. Chondrites have escaped strong heating and metamorphism that would have converted them to crystal structures similar to terrestrial rocks. Carbonaceous chondrites are a special class, being the meteorite type that is apparently closest to the original accumulation of particles and dust in the solar nebula. As the name implies, they are rich in carbon compounds, which have mostly been lost by the more processed bodies. They also contain refractory inclusions rich in calcium and aluminium (CAIs), that are distinct from chondrules but of similar sizes and appear to have condensed in the solar nebula even earlier than the chondrules. Achondrites are stony meteorites without chondrules that exhibit post-formation metamorphism and differentiation. They have little iron content and are fully crystalline like terrestrial rocks.

The grains and dust in the early solar nebula are believed to have been similar in composition to the carbonaceous chondrites, in which the iron occurs as oxides, especially magnetite, Fe_3O_4. The other meteorite types evolved from this mix. The abundance of carbon allows the suggestion (Section 2.2) that meteoritic iron (and the core material of the terrestrial planets) originated in reactions, similar to that in a blast furnace, triggered by collisional heating. Then the processed material accreted into larger bodies that included metallic iron. The iron

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meteorites are collision fragments of bodies that had developed sufficiently towards the formation of planets for gravitational separation of iron cores. They have large crystal sizes, evidence of slow cooling and burial in bodies several kilometres in size (Section 1.10).

1.8 Cosmic ray exposures of meteorites and the evidence of asteroidal collisions

Cosmic rays penetrate only the outer 1 m or so of each independent body, so that each asteroidal fragmentation event exposes fresh material to cosmic ray bombardment. Extremely energetic cosmic ray protons cause violent disruption (spallation) of the atomic nuclei in exposed meteorites. A representative example of nuclear spallation is

$$^{56}\mathrm{Fe} + {}^{1}\mathrm{H} \rightarrow {}^{36}\mathrm{Cl} + {}^{3}\mathrm{H} + 2\,{}^{4}\mathrm{He} + {}^{3}\mathrm{He} + 3\,{}^{1}\mathrm{H} + 4\mathrm{n}. \tag{1.7}$$

Many products arise from numerous similar reactions. When a meteorite arrives on the Earth and is protected by the atmosphere from further exposure, it has accumulated cosmogenic (cosmic ray produced) nuclides from which the duration of its exposure can be determined. Nuclides, with half lives much shorter than the duration of cosmic ray exposure (^{39}Ar, ^{14}C, ^{36}Cl), are maintained in equilibrium concentrations during the exposure but decay after arrival. Their residual concentrations provide a measure of the time that has elapsed since a meteorite arrived on the Earth. This is sometimes referred to as a terrestrial age. Added to the exposure duration it dates the fragmentation event, referred to as the cosmic ray exposure age. Of course these ‘ages’ must not be confused with the age as normally understood, which is the solidification age of original formation, a subject of Chapters 3 and 4.

With correction for terrestrial age, or from measurements on observed falls, uncertainties in cosmic ray intensities and partial shielding of samples by burial in a large meteorite can be allowed for by comparing concentrations of two cosmogenic nuclides, one stable and the other short lived. The concentration of the short lived species is a measure of the rate of production. By selecting pairs of nuclides whose production cross-sections have similar dependences on cosmic ray energy we have two isobaric pairs (^{3}H–^{3}He and ^{36}Cl–^{36}Ar) and two isotopic pairs (^{38}Ar–^{39}Ar and ^{44}K–^{41}K) as species of greatest interest. The first three of these pairs, being gases, also avoid the problem of initial composition that arises in the case of non-volatile spallation products. Then, in terms of the measured concentrations S, R of the stable and radioactive nuclides and their production cross sections σ_S, σ_R determined from laboratory data, the cosmic ray exposure age of a meteorite is given by

$$t = \frac{S}{R}\frac{\sigma_R}{\sigma_S}\frac{t_{1/2}}{\ln 2}, \tag{1.8}$$

where $t_{1/2}$ is the half-life of the active nuclide, which is assumed to be short compared with t. In the cases of the isobaric pairs the stable nuclides are produced by decay of the active ones as well as directly, so that the equation becomes

$$t = \frac{S}{R}\frac{\sigma_R}{\sigma_S + \sigma_R}\frac{t_{1/2}}{\ln 2} \tag{1.9}$$

(Problem 3.2, Appendix J).

Most of the reliable exposure ages for stony meteorites are grouped around 4×10^6 and 23×10^6 years, but others cover the range from 2.8×10^6 to 100×10^6 years with obvious groupings of different types. Some of the lower estimates are probably invalidated by diffusion losses because the same meteorites have small potassium–argon solidification ages. Iron meteorites have generally had much greater exposures, up to a maximum of 2200×10^6 years with groupings at 630×10^6 and 900×10^6 years but not at 23×10^6 years (Anders, 1964). On this time scale variability of the cosmic ray flux can be recognized (Pearce and Russell, 1990), requiring a correction to age estimates. There is a wide scatter and, in some cases, imperfect agreement between different measurements, but there are no coincidences of exposure ages for irons and stones. It is evident that the meteorites are

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