Meteorites and the origin of the solar system

STEPHEN G. BRUSH

University of Maryland, College Park, MD 20742, USA (e-mail: brush@ipst.umd.edu)

Abstract: During the past two centuries, theories of the origin of the solar system have been strongly influenced by observations and theories about meteorites. I review this history up to about 1985.

During the 19th century the hypothesis that planets formed by accretion of small solid particles ('the meteoritic hypothesis') competed with the alternative 'nebular hypothesis' of Laplace, based on condensation from a hot gas. At the beginning of the 20th century Chamberlin and Moulton revived the meteoritic hypothesis as the 'planetesimal hypothesis' and joined it to the assumption that the solar system evolved from the encounter of the Sun with a passing star. Later, the encounter hypothesis was rejected and the planetesimal hypothesis was incorporated into new versions of the nebular hypothesis. In the 1950s, meteorites provided essential data for the establishment by Patterson and others of the presently accepted 4500 Ma age of the Earth and the solar system. Analysis of the Allende meteorite, which fell in 1969, inspired the 'supernova trigger' theory of the origin of the solar system, and furnished useful constraints on theories of planetary formation developed by Urey, Ringwood, Anders and others. Many of these theories assumed condensation from a homogeneous hot gas, an assumption that was challenged by astrophysical calculations.

The meteoritic–planetesimal theory of planet formation was developed in Russia by Schmidt and later by Safronov. Wetherill, in the United States, established it as the preferred theory for formation of terrestrial planets.

The old idea that the planets were formed by aggregation of meteorites (Chladni 1794, p. 58) was revived in the mid-19th century as a result of proposals by the German physicist and physiologist Julius Robert von Mayer (1814–1878) in (1848), and the Scottish physicist John James Waterston (1811–1883) in (1853), that the Sun's heat might be maintained by an influx of meteoritic matter. At the same time astronomers who discussed Immanuel Kant's cosmogony (1755) distinguished it from the French mathematician and theoretical astronomer Pierre Simon Laplace's (1749–1827) 'nebular hypothesis'(1796); they noted that the former postulated the initial state to be a cold, possibly dusty or particulate cloud, whereas the latter assumed it to be a hot gas (Huxley 1869, p. xlvi). Gaseous and meteoritic origins of the solar system were often opposed, but could also be combined: the British physicist James Clerk Maxwell's (1831–1879) proof (1859) of the particulate nature of Saturn's rings suggested that the rings spun off from Laplace's nebula would condense to small solid particles before agglomerating to form larger objects. Similarly, the idea that the asteroids discovered in the region between Mars and Jupiter represent material condensed from a Laplacean ring that failed to collect into a single planet, rather than the remnants of an exploded planet, encouraged the idea that planets form from solid particles such as meteorites rather than directly from gas (Kirkwood 1869).

The American philosopher and mathematician Chauncey Wright (1830–1875) advocated a meteoric theory, motivated perhaps in part by his dislike of the English philosopher Herbert Spencer's (1820–1903) cosmic evolutionary theory, which was tied to the nebular hypothesis. He estimated that enough material to form an Earth-size planet could be collected in 20 billion years, or rather – since the size of the collecting body itself must have been smaller in the past – perhaps 60 billion years (Wright 1864, p. 28). (In this article I use the word 'billion' to mean a thousand million, in agreement with current British custom.)

The 'meteoritic hypothesis' is often associated with a theory of the English astrophysicist Sir Joseph Norman Lockyer (1836–1920), described by one biographer as 'one of the most comprehensive schemes of inorganic evolution ever devised' (Dingle 1973, p. 441). Lockyer attributed to the British mathematician and physicist Peter Guthrie Tait (1831–1901) (Tait 1869, 1871) the suggestion that nebulae

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are associated with meteorites rather than masses of gas, and to the French astronomer Hervé Faye (1814–1902) the view 'that the solar nebula may have [as] probably consisted of a cloud of stones as a mass of gas' (Lockyer 1887, p. 150). The Scottish mathematician and physicist Lord Kelvin (1824–1907) (Kelvin 1871) also endorsed Tait's idea; the best source is Lockyer's book (Lockyer 1890).

But Lockyer's own hypothesis dealt primarily with stars, nebulae and comets; he never applied it in any detail to the formation of the solar system. He did not intend his theory to compete with Laplace's nebular hypothesis but rather to complement it by explaining how the nebula was originally formed (Lockyer 1877, p. 414).

The English astronomer Richard Proctor (1837–1888) was an influential advocate in the late 19th century of the meteoritic theory of the formation of planets (Proctor 1870). He suggested that the history of the solar system was a combination of cooling and solidification processes, as in the nebular hypothesis, and accretion of meteoric matter (Proctor 1874, pp. 9–11). Postulating simultaneous growth of all the planets, he eliminated 'what had always seemed to me the greatest difficulty of the nebular hypothesis' – that Neptune must have been formed millions of ages before Uranus, and so on, yet the appearances of the planets we can observe do not indicate any great differences in ages. Moreover, we now think that all the planets are made of the same elements, which favours a common meteoric origin, whereas Laplace's theory implies different constituents for different planets. The strongest argument for his own theory, Proctor asserted, is that it relies on processes we still see going on, and which work in only one direction, and so we can trace it back into the distant past, whereas 'contraction may alternate with expansion, according to the changing condition of a forming system' (Proctor 1870, p. 13).

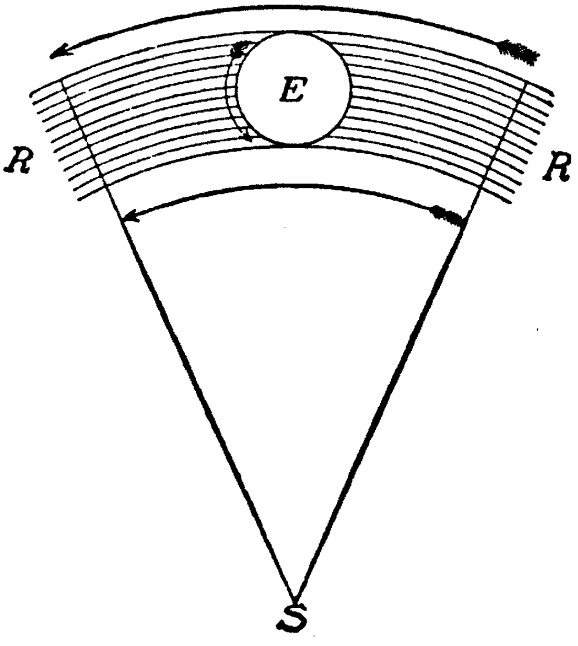

Fig. 1. Chamberlin's illustration of the explanation of direct rotation on the Nebular Hypothesis. 'RR represents a ring of gas moving as a unit and hence the outer portion the faster. If converted into a spheroid, E, centrally located, the rotation is forward, as shown by the arrow' (Chamberlin 1916, p. 91).

To appreciate the major objection to the meteoritic theory in the 19th century we must recall that all the planets have 'direct' rotation: they spin around their own axes (insofar as it was possible to detect their rotation) in the same direction as they revolve around the Sun. The nebular hypothesis explains this fact by assuming that the original nebula rotates as if it were a solid disk, so that the linear speed of material at any distance from the centre of the nebula (eventually to become the Sun) is proportional to that distance. When material from neighbouring circular orbits in the nebula combine, the material from the more distant orbit will be moving faster, and the resulting body will have direct rotation (Fig. 1). But if the planets are formed by the aggregation of solid particles that move in separate orbits, each governed by Kepler's Third Law, then the particles from the more distant orbit will have a *smaller* linear speed and the resulting body will have retrograde rotation (Fig. 2). Hence, the meteoritic hypothesis appears to be unable to account for the direct rotations of planets in the solar system.

Proctor did not present a quantitative derivation of planetary properties from his theory. He asserted that 'the effect of multiplied collisions would necessarily be to eliminate orbits of exaggerated eccentricity, and to form systems traveling nearly on the mean plane of the aggregate motions, and with a direct motion' (quoted in Mather & Mason 1939, pp. 547–548). While pointing out that Laplace's mass could not be expected to rotate as a whole – the postulate from which direct rotation of the planets could be deduced – Proctor did not explain from his own theory how the planets came to have their present rotations.

Several astronomers pointed out that that the meteoritic hypothesis incorrectly predicted retrograde rotation of planets (Kirkwood 1864; Faye 1885; Gore 1893 and others). Hinrichs (1864),

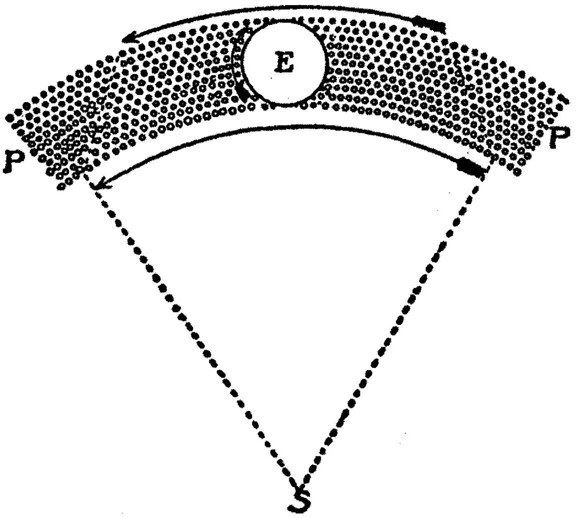

Fig. 2. Chamberlin's illustration of the rotation produced by combining particles moving in adjacent circular orbits, with linear speeds decreasing with distance from the Sun according to Kepler's Third Law: 'PP represents a belt of planetesimals revolving concentrically about the center, S. If these collect about the central point of the belt into a spheroid, E, by the enlargement of the inner orbits or the reduction of the outer ones, the concentric arrangement remaining, the rotation will be retrograde, as shown by the arrow' (Chamberlin 1916, p. 92).

Kirkwood (1864) and Faye (1884) proposed hypothetical mechanisms by which direct rotation could be achieved. Nevertheless, this was a major obstacle to the adoption of the meteoritic hypothesis in the 19th century.

Evidence from the Earth's chemical composition

If the Earth was formed from meteorites, it should have the same chemical composition as they do. Chemical analysis of meteorites in the 19th century indicated that they consist mainly of iron and rock (Marvin 2006). Since the English natural philosopher William Gilbert's (1544–1603) pioneering work on the Earth's magnetism at the end of the 16th century, it had often been suggested that the Earth, like a lodestone, contains a substantial portion of iron under a rocky crust; but knowledge of the Earth's internal composition was only qualitative and indirect.

A notable step forward was the German seismologist Emil Wiechert's (1861–1928) (1896) development of a quantitative model for the Earth's internal structure, assuming an iron core surrounded by a thick stony shell; the core radius and the densities of core and shell were determined so as to fit all available data. Both are solid, in accordance with Lord Kelvin's theory that the Earth is as rigid as steel (Brush 1996). Unlike earlier models, which were based on a continuous increase in density from surface to centre, Wiechert attributed both physical and chemical significance to his two-part Earth model and argued that the mantle–core boundary corresponds to a discontinuous change from stone to iron as well as a jump in density.

Wiechert (1897) pointed out that the density of the inside of the Earth must be substantially greater than that of the crustal materials; the average density of the Earth is about 5.6 times that of water, while that of rocks near the surface is only about 3. Supposing (in accordance with 19th-century ideas) that the molecules in a solid are already very close together at low pressures, Wiechert argued that density cannot be increased very much by compression; hence, the density difference must be ascribed to a difference in chemical composition rather than merely to pressure. As only the metals are known to have densities greater than 5.6, it seemed likely that the Earth has a metallic core.

Using data from geodetic measurements, precession and nutation, Wiechert found that the radius of the core is about 5000 km; the thickness of the shell is thus about 1400 km. The density of the core is 8.2, that of the rocky shell is 3.2. As the density of iron is 7.8 under ordinary conditions, Wiechert proposed that the core is mostly composed of iron, slightly compressed.

Chamberlin's planetesimal hypothesis

According to the nebular hypothesis, the Earth was formed as a hot molten ball from the primordial gaseous nebula; it gradually cooled down while solidifying. Lord Kelvin estimated the time required for this cooling process and found it to be a few tens of millions of years, a result that contradicted geological evidence including much longer periods. As it also contradicted the English naturalist Charles Robert Darwin's (1809–1882) suggestions about the time periods available for organic evolution, Kelvin's calculation of the age of the Earth played an important role in the late 19th century debate about the validity of Darwin's theory (Brush 1967; Burchfield 1990). While many geologists tried to accommodate their theories about the Earth's past to Kelvin's restrictive timescale, the American geologist Thomas Chrowder Chamberlin (1843–1928) (Fig. 3) responded by attacking the nebular hypothesis and rejecting the physical basis of Kelvin's

Fig. 3. T.C. Chamberlin (1843–1928), American geologist who proposed the planetisimal theory of the origin of the solar system.

calculations. Kelvin had assumed not only that the Earth had condensed from a hot gas, but also that there was no internal source of energy to replace the heat radiated into space (this was before the discovery of radioactivity).

Chamberlin, a specialist in North American glacial geology, doubted the assumption of some scientists that the early Earth had a hot dense atmosphere rich in carbon dioxide. The temporal variations of this atmosphere were frequently invoked by climatologists to explain major climatic changes and glaciation. But Chamberlin (1897) realized that this idea was contradicted by the kinetic theory of gases, which predicted that a hot dense atmosphere would have been quickly dissipated into space, rather than being locked up in mineral deposits on the Earth's surface. If the primeval Earth was molten, its temperature must have been at least 4000 °C; but if the temperature was higher than 3000 °C, most of the gas molecules in the atmosphere would have exceeded the gravitational escape velocity. The same objection would apply with even greater force to the earlier stage of the nebular hypothesis, the supposed gaseous rings from which the Earth and other planets condensed; only by assuming that such a ring rapidly cooled and crystallized into small solid particles would one avoid the conclusion that its material would have been dissipated into space (see also Chamberlin 1916, chapter 1).

Another objection to the nebular hypothesis was its failure to explain the slow rotation of the Sun. The hypothesis implied that as the nebula cooled and contracted it would continue to rotate faster and faster (according to the Law of Conservation of Angular Momentum), so that rings that were to condense into planets had been spun off; the remaining proto-Sun would be rotating rapidly around its own axis. This criticism had been made in the 19th century, but Chamberlin's colleague the American astronomer Forest Ray Moulton (1872–1952) reinforced it with precise calculations (Chamberlin & Moulton 1900).

As an alternative to the unsatisfactory nebular hypothesis Chamberlin proposed to revive what he called 'the meteoroidal hypothesis'. But as he began to read the literature on cosmogony, Chamberlin encountered the argument mentioned above; that planets formed by aggregation of solid particles would be expected to have retrograde rotation.

Chamberlin detected a fallacy in the argument: it was based on the assumption that the particles move in circular orbits so that in an encounter of two particles, the outer one will be moving more slowly. But, in reality, collisions occur only if and when the orbits of the two particles intersect, and this implies that at least one of them moves in an ellipse. The geologist, applying Kepler's Second Law, noticed a point that seemed to have escaped the attention of the astronomers who had previously written on this subject: the orbits are likely to intersect at a place where the aphelion of the inner corresponds to the perihelion of the outer orbit; at this place, the outer body will move faster than the inner one. Hence, the rotation of the body formed by combining them will be direct, not retrograde. Although this is not true for all collisions, it is valid for most and, hence, Chamberlin's conclusion is statistically correct (Giuli 1968*a*, 1968*b*; Harris 1977; and letter quoted by Brush 1996, vol. 3, p. 33).

Chamberlin was able, with the help of his colleague Moulton, to give a quantitative refutation of the nebular hypothesis and to revive the meteoritic hypothesis in its place. He called the latter the 'planetesimal hypothesis' because he argued that all the planets had been formed by the aggregation of infinitesimal planets. He was also able to refute Lord Kelvin's estimate of the age of the Earth; if the Earth were formed by the aggregation of *cold* planetesimals, it would have converted gravitational to thermal energy and thereby *warmed up* to its present temperature rather than *cooling down* from an initial hot state. Soon afterwards the research of the Polish–French physicist Marie Curie (1867–1934) and her colleagues revealed another reason why Kelvin's 'cooling-down' model was wrong: he did not realize that radioactive minerals in the Earth's crust release enough heat to counteract the heat lost by radiation into space.

Chamberlin and Moulton went even further by rejecting the assumption that the solar system had been formed by the same process that created the Sun. Instead, he argued that the Sun had been formed originally without any planets; then it suffered an encounter with another star, which sucked gaseous material out of it through the action of gravitational tidal forces. This gas first condensed to planetesimals, which later aggregated to form planets (Chamberlin 1905, 1916; Chamberlin & Salisbury 1906; Chamberlin & Moulton 1909). The theory was favourably received by many American and a few British astronomers during the next few years (Brush 1996, vol. 3, pp. 60–65).

Jeffreys' critique of the planetesimal hypothesis

The 'encounter' or 'tidal' theory of the origin of the solar system – without the planetesimal hypothesis – was later advocated by the English mathematician and physicist Sir James Jeans (1877–1946) and the English astronomer and mathematician Harold Jeffreys (1891–1989). Jeffreys (1916, 1917, 1918) argued that high-velocity collisions among the planetesimals would vaporize them so quickly that the material would remain gaseous until it collected into planets. Chamberlin & Moulton had assumed that nearly all collisions will be 'overtakes', with low relative velocity, but Jeffreys argued that perturbations due to the planetary nuclei would change the orbits so much that after about 100 000 years the planetesimals would be moving in all directions. He therefore proposed to return to the 19th century assumption that the Earth was originally a hot fluid ball and has been cooling down ever since. In his influential treatise *The Earth* he gave a more detailed critique of the planetesimal hypothesis and tried to refute Chamberlin's argument that a hot fluid Earth could not have retained water vapour and atmospheric gases (Jeffreys 1924, pp. 250–256).

The encounter theory of the origin of the solar system – in either the Chamberlin–Moulton or the Jeans–Jeffreys version – was widely accepted by astronomers in the 1920s and 1930s, even though it was never worked out in sufficient detail to provide a convincing explanation of the quantitative properties of the Sun and planets. Astronomers abandoned the planetesimal hypothesis on the strength of Jeffreys' critique; geologists remained loyal to that hypothesis through the 1930s, although did not always accept Chamberlin's inference that the Earth had remained cold and mostly solid throughout its history. The only significant criticism was a paper by the American geologist Harry Fielding Reid (1859–1944) (Reid 1924), who estimated the effect of the accretion of planetesimals by a planetary or satellite nucleus and found that it was much too small to account for satellite orbits. A leading American astronomer, Henry Norris Russell (1877–1957), told Moulton in private correspondence that the Jeffreys–Reid objections should be taken seriously even if they were not conclusive; he agreed with Jeffreys that planetesimals would collide with each other so frequently that they would be smashed to dust (although not to separate gas molecules as Jeffreys thought). The result would be a medium of particles moving in circular orbits, which would reduce the expected forward rotation of the planets (Russell 1925, 1926).

Revival of the nebular hypothesis along with the planetesimal hypothesis

The tidal–encounter theory was rejected by astronomers as a result of devastating criticism by H.N. Russell and others in the late 1930s. A new version of the nebular hypothesis emerged in the 1940s – one in which Chamberlin's planetesimal hypothesis played a prominent role. This was in part because of calculations by the Swedish astronomer Bertil Lindblad (1895–1965) (Lindblad 1934, 1935). He showed that partly inelastic collisions between particles initially moving with different speeds in eccentric orbits with different inclinations will tend to make all the particles move at similar velocities in circular orbits lying in a flat ring. Collisions between the particles would then occur with small relative velocities, thereby avoiding Jeffreys's argument that collisions would vapourize the particles. Lindblad suggested that a cold particle immersed in a hot gas would tend to grow by condensing the gas on its surface. The Dutch theoretical physicist, and Reader of Theoretical Physics at Oxford, Dirk ter Haar (1919–2002) elaborated this idea by using the Becker–Döring kinetic theory of the formation of drops in a saturated vapour and reinforced Lindblad's proposal that solid particles could grow initially by non-gravitational forces (Haar 1944, 1948).

Jeffreys himself began to reconsider his objection to the planetesimal hypothesis and suggested that the vapour pressure of solids at very low temperatures might be below the pressure in the surrounding medium, so that condensation would outweigh the vaporizing effect of collisions (Jeffreys 1944). The American physicist Alfred Locke Parson published an estimate of the vapour pressure of iron that indicated that condensation would be favoured in interstellar space (Parson 1944, 1945), and Jeffreys (1948) admitted that his original objection had thereby been answered. But in 1969 he raised a new objection: the expected recondensation 'makes the eccentricities of the orbits harder to understand than ever' (Jeffreys 1974, p. 105).

The American astronomer Fred Lawrence Whipple (1906–2004) proposed another mechanism for the aggregation of dust particles to form meteorites and larger bodies. He argued that radiation pressure acting on particles in a dust cloud would tend to push them together; each of a pair of nearby particles would shield the other from the radiation, leaving an effective attraction (Whipple 1942/1946). He proposed condensation of dust particles originally as a means of star formation from the dark clouds currently attracting the attention of astronomers, but also used it as an initial stage in the formation of planetary systems (Whipple 1948*a*, *b*).

The Swedish plasma physicist Hannes Alfvén (1908–1995) incorporated the idea of planetesimal accretion into his own theory of the origin of the solar system, adding another important concept that removed a well-known objection to the Nebular Hypothesis, the too-slow rotation of the Sun. He showed that an ionized gas surrounding a rotating magnetized sphere will acquire rotation and thereby slow down the rotation of the sphere (Alfvén 1942). In his own more elaborate theory of the origin of the solar system, Alfvén (1946, 1954) proposed that the early Sun had a strong magnetic field, and that its radiation ionized a cloud of dust and gas, which then trapped the magnetic field lines and acquired most of the Sun's original angular momentum. This mechanism of 'magnetic braking' was later adopted by other theorists who rejected the rest of Alfvén's theory.

The post-Second World War revival of the nebular hypothesis in the West was based originally on an article by the German physicist and philosopher Baron Carl Friedrich von Weizsäcker (Weizsäcker 1944). He postulated a gaseous envelope surrounding the Sun and associated with its formation. Whereas Laplace had assumed, rather implausibly, that the gaseous nebula wold rotate like a rigid solid, Weizsäcker pointed out that there would be a tendency towards differential rotation with faster motion inside and slower outside, as in Kepler orbits. But friction between adjacent streams would tend to equalize their speeds by accelerating the outer stream and decelerating the inner one. This creates an instability, causing the outer stream to move further out and the inner stream to move inward, resulting in turbulent convection currents and eventually the formation of a pattern of vortex motions. Weizsäcker assumed that the best place to accumulate particles into planets would be the regions where adjacent vortices come into contact producing violent turbulence.

Weizsäcker's theory was initially greeted with enthusiasm, especially in the United States. In the Netherlands, ter Haar (Haar 1948) adopted it as a basis for further work, incorporating his own mechanism for condensing dust particles. But subsequent work on turbulence theory indicated that the regular pattern of vortices postulated by Weizsäcker could not occur, but must instead be replaced by a range of eddy sizes. Although his original theory was abandoned, it stimulated work by others such as the Dutch astronomer Gerard Peter Kuiper (1905–1973) and American chemist Harold Clayton Urey (1893–1981). Kuiper (1951) assumed that large gaseous protoplanets would form from the nebula by gravitational collapse ('Jeans instability'), while Urey (1951) postulated instead that numerous smaller objects of asteroidal and lunar size were first formed and later accumulated into planets. Modified versions of both theories survived in later decades, with gaseous protoplanets seen as the origin of the major planets (Jupiter, Saturn, Uranus and Neptune) and accumulations of smaller solid particles as the origin of the terrestrial planets (Mercury, Venus, Earth and Mars).

Urey had won the 1934 Nobel Prize in Chemistry for his role in the discovery of deuterium; after the Second World War he taught at the University of Chicago, and later at the University of California, San Diego. He was responsible for influencing many bright chemists and physicists to undertake research in planetary science (Brush 1996, vol. 3, p. 144).

Meteorites and the age of the Earth (see also de Laeter 2006)

As mentioned above, Lord Kelvin's estimate of the age of the Earth, based on the nebular hypothesis and the assumption that the Earth has gradually cooled down from a hot molten state, gave results inconsistent with geological evidence. One of the advantages of Chamberlin's planetesimal hypothesis was that it assumed instead a cold early Earth, whose temperature gradually *rose* to its present value. This was consistent with the inferences drawn from the discovery around 1900 of radioactivity in rocks at the Earth's surface. Radioactive decay of radium and other elements could produce enough heat to compensate for the heat lost by radiation into space. Moreover, quantitative analysis of the decay of radium to other elements, producing helium gas, allowed estimates of the age of those rocks, giving results ranging from 40 to 2400 Ma by 1906 (Brush 1996, vol. 2, pp. 68–69). The British geologist Arthur Holmes (1890–1965) led a concerted effort over the next few decades to estimate the age of the Earth by radiometric dating, using more and more sophisticated techniques (Lewis 2000; Lewis & Knell 2001). By the 1930s this effort produced estimates of about 3000 Ma, creating a dilemma for cosmologists as the age of the entire universe based on its estimated rate of expansion was less than 2000 Ma (Brush 2001).

In the 1930s it was understood that different isotopes of lead were produced as the end products of radioactive decay starting from different isotopes of uranium and thorium, producing helium as a byproduct. If one could assume: (1) that all the helium present in a rock has been generated by such decays; and (2) that none of it has been lost, one could estimate the age of the rock – that is, the time since it was solidified and started to retain helium – from the amounts of helium, lead, and uranium present. But research at that time indicated that while assumption (1) is valid, (2) probably is not. Thus, the helium method gives only the *minimum* age of the rock, usually a value significantly less than those found by other methods.

The Austrian chemist Friedrich Adolf Paneth (1887–1958) and his co-workers obtained much greater ages for meteorites – as much as 7600 Ma – using the helium method (Arrol *et al.* 1942). For a time it was thought that these meteorites must have been formed before the solar system itself. But Carl August Bauer pointed out that, in addition to the recognized problem of helium leakage, meteorites are subject to bombardment by cosmic rays, which can produce helium and thus make the meteorite appear older than it really is (Bauer 1947, 1948). As cosmic rays produce the isotope ^{3}He in a measurable proportion to ^{4}He, while the decay of uranium and thorium to lead produces only ^{4}He, it was possible to correct for this effect. Revised estimates of ages of meteorites then no longer exceeded 4600 Ma (Singer 1954, 1957).

A method based on quantitative measurements of the abundances of the isotopes of lead was developed by the American physicist Alfred Otto Carl Nier (1911–1994) in the late 1930s. He found that the stable isotopes of lead (204, 206, 207, 208) do not occur in the same proportions in all rocks. If one knew the relative abundances of these four isotopes at some initial time ('primeval abundances') one could compare the amounts of the two isotopes (206 and 207) generated at different rates by the decay of uranium (isotopes 238 and 235, respectively) after a certain time *t*. This is called the 'radiogenic component' of the isotope. If the primeval abundances could be estimated, then from the current relative abundances of the lead isotopes one could determine the amount of time elapsed. Nier and his colleagues assumed that the closest approximation to primeval lead would be a rock that has the highest proportion of ^{204}Pb, as all of that isotope is primeval. Using a galena from Ivigtut, Greenland for this purpose, they found that a mineral sample called Huran Claim Monazite gave an age of 2570 Ma (Nier *et al.* 1941).

In 1946 Holmes and the Polish-Austrian physicist Friedrich Georg Houtermans (1903–1966) independently pointed out that Nier's method could be extended to give not only the ages of particular rocks but the age of the Earth itself. They showed that a group of samples solidified at the same time but with different admixtures of primeval and radiogenic lead should have different abundances of the two isotopes ^{206}Pb and ^{207}Pb relative to ^{204}Pb, but if one plots the amount of the 207 isotope against the amounts of the 206 isotope one should get a straight line. Houtermans called this line an 'isochrone' as it displays the variation in isotopic composition for rocks formed from varying amounts of uranium and thorium at the same time. From the slope and intercept of the line, together with an estimate of the primeval abundances of the lead isotopes, one can calculate the time when the Earth was formed with those abundances (Brush 1982; Dalrymple 1984, 1983).

When Holmes and Houtermans applied this method to the data available in 1946, they found the Earth's age to be 2900 ± 300 Ma. Holmes (1947*a*, *b*) soon revised this value to 3350 Ma.

Although some scientists pointed out that the available data did not exclude a value for the age of the Earth as high as 5000 Ma, the Holmes–Houtermans value of 3000–3400 Ma was generally accepted until 1953. In that year a group of scientists at the University of Chicago and the California Institute of Technology reported that the abundances of the radiogenic lead isotopes in some meteoritic material were significantly lower than the figures previously considered 'primeval' in estimating the age of the Earth. It seemed reasonable to suppose that this material was much less affected by chemical differentiation processes than minerals found in the Earth's crust, so that these values were the most appropriate ones to use for the abundances at the time of formation of the Earth. Results based on these date were announced in September 1953 by the American geochemist Clair Cameron Patterson (1922–1995) (Fig. 4) (Patterson *et al.* 1953; Brown 1957). The minimum age of the Earth is 'about 4.5 billion years and is probably somewhat older'. Houtermans (1953) published a similar result based on the same data soon afterwards: 4500 ± 300 Ma.

By 1956 Patterson thought that enough data were available to clinch the argument for the 4500 Ma age. The meteorites used in the calculation had been found to have the same age by three independent radiometric methods, with the known limits of accuracy of each method: lead/uranium, potassium/argon and strontium/rubidium. The most accurate method, based on the ^{207}Pb/^{206}Pb ratio, gave an age of 4550 ± 70 Ma. Several terrestrial minerals were found to contain lead isotope ratios that fell on the same 4550 Ma isochrone as do the meteorites. Patterson concluded that the age of the Earth is the same as that of the meteorites: 'we should now admit that the age of the Earth is known as accurately and with about as much

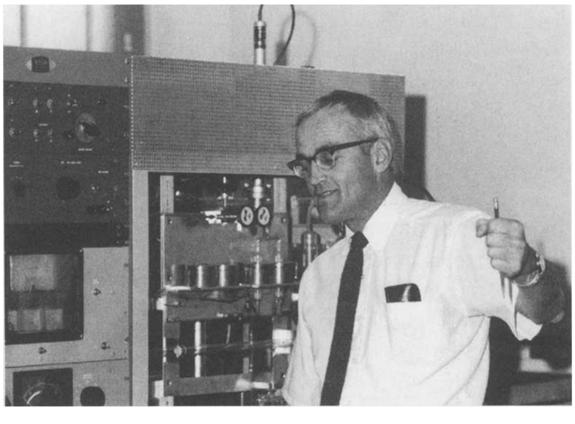

Fig. 4. Clair C. Patterson (1922–1995), American geochemist, leader of the group that first determined the currently accepted value for the age of the Earth. (Photograph courtesy of C.C. Patterson.)

confidence as the concentration of aluminum is known in the Westerly, Rhode Island granite' (Patterson 1956, p. 230; see also de Laeter 2006).

The major objection to Patterson's result was that many meteorites did not seem to contain enough uranium to account for the radiogenic lead. But even if those meteorites were excluded, further research produced enough other cases to convince the skeptics that at least *some* meteorites are about 4500 Ma old. One could still doubt whether the Earth is as old as those metorites, but the overwhelming majority of Earth scientists accepted this conclusion by the 1970s, especially after the analysis of lunar rocks showed that the Moon is also about 4600 Ma old (for additional references see Brush 1996, vol. 2, pp. 78–85).

Isotopic anomalies and the supernova trigger

The establishment of the 4.5 billion year age of the Earth was the beginning of a period of lively speculation and controversy about the origin of the solar system, in which meteorite research played an important role. The most striking new feature of the three decades 1956–1985 was the role played by isotopic anomalies. Although these anomalies have little bearing on most of the traditional problems of planet and satellite formation, they were believed to offer important clues to the initial stages of formation and contraction of the solar nebula as related to nuclear processes in the Sun and other stars. The best-known example is the 'supernova trigger' hypothesis, based in part on the excess ^{26}Mg found in the Allende meteorite that fell in February 1969; the earlier history and recent demise of this hypothesis are not so well known. (The words 'excess' and 'anomalous' refer to deviations from the average abundances in the solar system.)

Starting with the discovery of excess ^{129}Xe in the Richardton meteorite by the American geophysicist John H. Reynolds (1923–2000) in 1960, theorists reasoned that a short-lived isotope (in this case ^{129}I) must have been synthesized in a supernova, ejected into the interstellar medium and incorporated into a meteorite parent body that cooled down enough to retain xenon gas, all within a period of only about a few Ma. Because a supernova explosion also produces a shock wave that might compress rarefied gas-dust clouds to densities high enough for them to become unstable against gravitational collapse, the isotopic anomalies might indicate that a supernova *caused* the solar system to form. Although the idea of a supernova trigger for *star* formation had been discussed by the Estonian astrophysicist Ernst Julius Öpik (1893–1985) (Öpik 1953), the first explicit mention of this mechanism for the origin of the solar system apparently in a paper by the American astrophysicist William Alfred Fowler, American astronomer Jesse Leonard Greenstein and the English astrophysicist Fred Hoyle (Fowler *et al.* 1961). But they discounted it, and it remained for Alastair Graham Walter Cameron (Fig. 5) to argue in its favour in 1962.

Of the many isotopic anomalies, the most intriguing was the possible excess of ^{26}Mg, considered as the decay product of ^{26}Al. J.R. Simonton and his colleagues had discovered in 1954 that the latter nuclide has a previously unknown ground state that decays by positron emission to ^{26}Mg with a half-life of less than 1 Ma (later found to be about 720 000 years). Harold Urey (1952) proposed that ^{26}Al in the early solar system could have been a source of heat to melt meteorites, but then rejected this mechanism because it would have also melted

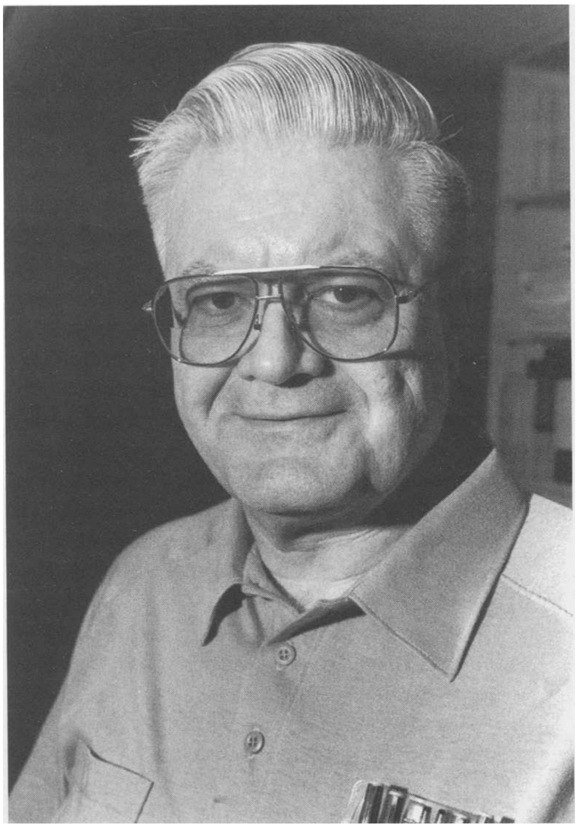

Fig. 5. Alastair G.W. Cameron, Canadian–American astronomer who proposed several theories of the origin of the solar system. (Photograph courtesy of A.G.W. Cameron.)

the Moon (contrary to his belief at that time about the cold early Moon). The idea was revived and extended by the Latvian-American chemist Edward Anders' group at Chicago (see footnote 3 in Brush 1996, vol. 3, p. 120). Because of its short half-life the ^{26}Al must have been produced fairly recently on a cosmic timescale, perhaps by proton irradiation of magnesium. Everyone at that time assumed that the time interval between collapse of the presolar nebula and formation of meteorites must have been much more than a million years.

The Allende meteorite, contributed significantly more to our understanding of the solar system than the lunar samples obtained by the *Apollo 11* mission later that year. Analysis of its calcium–aluminium-rich inclusions led directly to the revival of the supernova trigger theory; it also provided important data for the high-temperature condensation theory discussed in the following section.

In 1970 W.B. Clark and his colleagues reported a 4–6% excess of ^{26}Mg in the meteorites Bruderheim and Khor Temiki. But David Schramm, Fouad Tera and geophysicist Gerald Joseph Wasserburg (Schramm *et al.* 1970) could find no anomalies in several samples including the ones analysed by Clarke's group. Schramm (1971) stated that there is no evidence for the presence of ^{26}Al at the time of final solidification of the meteorites, although it could have been a significant heat source before solidification.

Two Australian scientists, C.M. Gray and the physicist and geochemist William Compston, reported finding excess ^{26}Mg in the Allende meteorite in 1974. But their results were regarded as inconclusive by American scientists, an attitude that their Australian compatriot, geochemist and cosmogenist Alfred Edward Ringwood (1930–1993) (Fig. 6) later said was 'uncharitable and reflects the chauvinism of the U.S. scientists'. He argued that they should receive the credit for discovering the ^{26}Mg excess (see Brush 1996, vol. 3, note 5 on p. 120).

Following a number of other reports of isotopic anomalies in meteorites and speculations about their interpretation (Brush 1996, vol. 3, pp. 121–122), the first generally accepted proof of the presence of ^{26}Al in the early solar system came late in 1975 when Wasserburg's group at Caltech announced their discovery of a large anomaly in the isotopic composition of magnesium in a chondrule from the Allende meteorite. According to the report by Lee *et al.* (1976), ^{26}Mg is enriched by about 1.3%; 'the most plausible cause of the anomaly is the *in situ* decay of now-extinct ^{26}Al'.

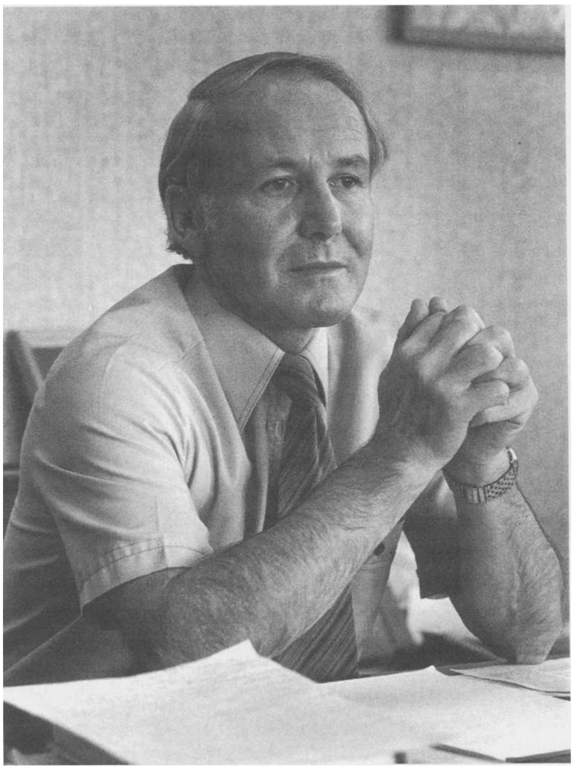

Fig. 6. Alfred E. Ringwood (1930–1993), Australian geochemist who developed the chondritic model for the origin of the Earth, Moon and planets.

Several scientists at the spring 1976 meeting of the American Geophysical Union discussed the possibility that a supernova explosion shortly before the formation of the solar system could be responsible for this and other recently discovered isotopic anomalies. One suggestion was that a supernova did explode in the vicinity of the present solar system but – contrary to the views of scientists at that time – the Sun already existed before explosion and had formed a binary system with the star that was to explode (Manuel & Sabu 1976; Sabu & Manuel 1976). Or perhaps the supernova was actually concentric with the Sun, which formed on its remnant core, while the planets condensed from the debris of outer layers (Manuel 1981). According to this theory, the Sun's interior should contain a significant amount of iron (Manuel & Hwaung 1983), a conclusion reached for completely different reasons by Rouse (1983, 1985).

Reviving an earlier suggestion of Cameron's, Cameron & Truran (1977) published a detailed 'supernova trigger' theory of the origin of the solar system: the same supernova that produced the short-lived radioactivities in meteorites also produced a shock wave that caused the presolar cloud to collapse. There was now much better evidence for the short-lived radioactivities, and the best alternative explanation (that they had been produced by irradiation in the early solar system) had been discredited. The idea was reinforced by new observations of supernova-induced star formation in Canis Major (Herbst & Assousa 1977).

The supernova trigger theory quickly became enormously popular, receiving wide publicity in both the technical journals and the popular press. The Cameron–Truran hypothesis was attractive because it promised to explain many diverse phenomena by a single event. But it promised more than it could deliver, as Cameron himself soon realized, and he subsequently admitted that the theory had been too ambitious. Other theories in the late 1970s invoked isotope anomalies and supernovae in various other ways to explain specific phenomena (Brush 1996, vol. 3, pp. 124–126).

In the early 1980s, evidence began to accumulate that ^{26}Al is much more abundant in the universe than previously thought; so abundant, in fact, that there are not enough supernovae to account for it. Moreover, according to Donald Clayton, the abundance inferred from the Allende meteorite 'was simply the average interstellar value at that time, negating the need for a "supernova injection" of ^{26}Al into the forming solar system' (Clayton 1984, p. 145). During the preceding decade Clayton had been undermining the supernova trigger hypothesis from another direction by showing that heavy element anomalies could be more plausibly interpreted in terms of presolar grains. The Ca–Al-rich inclusions in Allende are not condensates from a hot gaseous solar nebula but admixtures of precondensated matter. Other isotopic anomalies could also be explained, he argued, by gas/dust fractionation in the protosolar accumulation rather than by supernova injection (Clayton 1978*b*, 1979*b*).

Early in 1984, Cameron (1984*b*) announced that the reasons that led Truran and he to propose that the supernova trigger no longer seemed compelling, so he abandoned it (only to revive it 11 years later, see Cameron *et al.* 1995).

Chemical cosmogony: a cold origin

In his early writings on the origin of the solar system, Harold Urey had started with the classical assumption that the solar nebula 'was once completely gaseous and at very high temperatures' (Urey 1951, p. 237). For a chemist, the problem was to determine which compounds would form and condense as the nebula cooled down. He had initially supposed that the Earth accumulated at about 900 °C as a 'concession to traditional high-temperature assumptions relative to the Earth's origin', but quickly revised this estimate downward on the basis of chemical reasoning (Urey 1953, p. 290). He suggested that the accumulation of the Earth must have started at temperatures below 100 °C. Much higher temperatures would be incompatible with the presence of iron sulphide and silicates mixed with the metallic iron phase in meteorites, as iron sulphide is unstable in the presence of cosmic proportions of hydrogen and iron at about 600 °K. Silicon dioxide and silicates are unstable at higher temperatures, yet both are present in meteorites. Urey thus assumed that the terrestrial planets accumulated at low temperatures from small solid planetesimals.

Having initially adopted Kuiper's (1951) giant protoplanet theory, Urey later assumed on the contrary that two sets of objects of asteroidal and lunar size, called 'primary' and 'secondary' objects, were accumulated and destroyed during the history of the solar system. The primary objects were suddenly heated to the melting point of silicates and iron, perhaps by explosions involving free radicals triggered by solar-particle radiation. After cooling for a few million years these primary objects 'were broken into fragments of less than centimeter and millimeter sizes. The secondary objects accumulated from these ... and they were at least of asteroidal size. These objects were broken up ... and the fragments are the meteorites' (Urey 1956, p. 623). The reason for constructing this scheme was to explain the presence of diamonds (presumably formed only at very high pressures) in meteorites; but the scheme also might explain the origin of the planets and their satellites.

In the 1960s Urey turned his attention increasingly to the Moon, as the US space programme began to plan for lunar landings that might uncover information about the Moon's origin. Other scientists took up the challenge of reconstructing the chemical history of the entire early solar system. One was Ringwood, who proposed to interpret the densities of the Earth, Venus and Mars as representing different redox states of primordial condensed material of chondritic or solar composition. This became known as the 'Chondritic Earth Model'. Like Urey, Ringwood (1960) assumed that the Earth formed by accretion of planetesimals in a cold gas-dust nebula, and that meteorites can provide clues to the nature of the primeval material. Carbonaceous compounds would initially be mixed with non-volatile oxides, silicates and ices. The heat generated by accretion would raise the temperature high enough to allow carbon to reduce iron oxide to metallic iron; the Earth would melt enough to allow the denser iron to sink to the centre. At the same time H_2O and CO_2 produced by the reduction reactions would provide an atmosphere.

CI carbonaceous chondrites, according to Ringwood (1962), are similar in chemical composition to the Earth. Unlike other meteorites, they have the same abundances of non-volatile elements as the Sun (with the possible exception of iron and copper), and those abundances are consistent with those calculated from the nucleosynthetic models of astrophysicists. They contain some iron that, after reduction and heating, could have constituted the core. But they contain large amounts of volatile substances, suggesting that they have not undergone the kind of thermal evolution that other meteorites have experienced. Moreover, the fact that iron and nickel are found to be completely oxidized in these chondrites indicates that they have always been cold.

Ringwood's hypothesis that the primordial Earth-substance resembled CI carbonaceous chondrites, composed of low-temperature minerals, was threatened by the discovery that high-temperature minerals have been replaced by low-temperature minerals in carbonaceous chondrites, hence the high-temperature minerals were earlier (DuFresne & Anders 1961, 1962; Sztrokay *et al.* 1961). Ringwood (1963) retreated somewhat from the position that carbonaceous chondrites are primordial, conceding that they must have been radioactively heated for a short time (not more than 10^8 years), as suggested by Fish *et al.* (1960), but insisted that they are still 'the nearest approach which we possess to primordial material'.

In order to construct an Earth model from carbonaceous chondrites, Ringwood found that not only iron and nickel but another metallic component must be transferred from the mantle to the core. As SiO_2 is the common oxide most easily reduced to metal after the oxides of iron and nickel, he proposed that the core contains some silicon (Ringwood 1966, p. 296). Because silicon is less dense than iron, this hypothesis was qualitatively consistent with the shock-wave compression experiments indicating that pure iron is too dense to be the sole constituent of the core (Al'tshuler *et al.* 1958).

Ringwood considered his own scheme for the evolution of the Earth to be much simpler than Urey's; the latter postulated a complex multi-stage process involving high-temperature processing of the material (e.g. in lunar-sized bodies) before it was assembled into the Earth, whereas Ringwood's did the job in a single step.

In keeping with the desired simplicity of his theory, Ringwood then abandoned his earlier hypothesis that the primeval material had been subjected to radioactive heating in the nebula, and with it the assumption that this material is similar to carbonaceous chondrites. Instead he postulated a higher proportion of hydrogen in the primordial material and gave a more important role to a primeval atmosphere, consisting primarily of H_2, CO and H_2O in reducing iron oxides.

Chemical cosmogony: a hot origin

In the early 1960s several events encouraged cosmogonists to include a high-temperature stage in their scenarios for the formation of terrestrial planets. One was the development of astrophysical models that implied a superluminous phase for the early Sun. Another was Paul W. Gast's (1960) finding that alkali metals are depleted in the Earth's upper mantle compared with chondrites, suggesting that some volatilization had occurred during the Earth's formation. The Harvard–Smithsonian astrophysicist and meteoriticist John A. Wood proposed that chondrules are direct condensates from the solar nebula (Wood 1958, 1962); they could have formed near the Sun's surface, then been pushed out by electromagnetic forces and radiation. Thus, chondrules are surviving planetesimals of the type from which the terrestrial planets formed (Wood 1963; see McCall 2006).

Edward Anders became an advocate of the hot-origin hypothesis. He accepted Wood's proposal for the origin of chondrules (Anders 1963) and considered this an argument in favour of an early high-temperature phase for the solar nebula. He pointed out that after Urey had proposed his cold-origin theory, new evidence indicated that many volatile elements are depleted in chondrites, implying a high-temperature process. But 'no model involving a common, unitary history of chondrite matter can account for this abundance pattern. One is driven to the assumption that chondritic matter is a mixture of at least two kinds of material of widely different chemical histories' (Anders 1964, pp. 5–6). One kind has been significantly more depleted than the other and was therefore separated at higher temperatures.

Hans Eduard Suess (1909–1993), an Austrian-American nuclear chemist at the University of California, San Diego (La Jolla) recalled that direct condensation of chondrules from a gas phase had been popular 30 or 40 years earlier, Urey had persuaded him to abandon it in the

1950s (Suess 1963). But now, with new evidence and the recognition of different kinds of chondrules, the idea could be revived. Contrary to the results of Burbidge *et al.* (1957), who assumed that solar system material is a mixture of atoms from several sources, Suess (1964, 1965) argued that the solar nebula was quite homogeneous: 'Among the very few assumptions which ... can be considered well justified and firmly established, is the notion that the planetary objects ... were formed from a well-mixed primordial nebula of chemically and isotopically uniform composition. At some time between the time of the formation of the elements and the beginning of condensation of the less volatile material, the nebula must have been in the state of a homogeneous gas mass of temperature so high that no solids were present. Otherwise, variations in the isotopic composition of many elements would have to be anticipated' (Suess 1965, p. 217).

A pioneering calculation of the molecular equilibria and condensation in a solar nebula was carried out by Harry C. Lord (1965), with support and encouragement from Urey. Previous calculations had been limited to only a few major species or assumed conditions more appropriate to stellar envelopes. Lord considered 150 species in a gas with cosmic elemental abundances, at temperatures of 2000 and 1700 K, and total pressures of 1 and 5×10^{-4} atm. John W. Larimer, in Anders's group, generalized Lord's calculations to determine the temperatures at which a number of elements and compounds would condense, using pressures indicated by Cameron's (1962, 1963) models of the solar nebula. He attempted to trace the entire cooling history of a gas of cosmic composition in order to account for the fractionation patterns observed in meteorites (Larimer 1967; Larimer & Anders 1967, 1970). In particular, Larimer used the same kind of data that Urey had previously used to infer low-temperature formation to support high-temperature formation.

Anders (1968) argued that evidence on the depletion of volatile elements, obtained by the precise techniques of neutron activation analysis, made it necessary to reverse Urey's conclusion that the Earth and meteorites had accreted at temperatures of about 300 K. Elements that are depleted by factors of 10–100 in ordinary chondrite, such as Hg, Tl, Pb and Bi, often occur in nearly their cosmic abundances in carbonaceous and enstatite chondrites (Reed *et al.* Turkevich 1960). Anders concluded that the Earth and ordinary chondrites accreted at about 600 K.

The attractive idea that meteorites are direct condensates from the primordial solar nebula was apparently refuted by the fact that the abundance of iron in the solar atmosphere is 5–10 times smaller than in meteorites. Several more or less plausible mechanisms to separate iron from silicates in the solar nebula had been proposed. Urey (1967) had concluded that probably no meteorite is accurately representative of the composition of the solar nebula. But then Garz & Kock (1969) found a systematic error in earlier determinations of the solar abundance of iron; the earlier numbers had to be increased by an order of magnitude, and the corrected values were now in good agreement with meteoritic abundances (Garz *et al.* 1969; Pagel 1973, p. 5; Ross & Aller 1976). Later data indicated that the abundance had to be increased even more, suggesting that meteorites are unrepresentative of the solar nebula because they contain *too little* iron (Breneman & Stone 1985).

At the same time new evidence emerged for the hypothesis that some meteorites are early high-temperature condensates from the solar nebula. Shortly after the fall of the Allende meteorite in 1969, Marvin *et al.* (1970) pointed out that its Ca–Al-rich phases have the composition to be expected for early condensates according to Lord's (1965) calculations. This interpretation was supported by Lawrence Grossmann (1973) and his colleagues.

Another version of the initially uniform, high-temperature hypothesis was proposed by the American geochemists Karl Karekin Turekian and S.P. Clark (Turekian & Clark 1969). Rather than assuming that the Earth was initially homogeneous and later evolved into its core–mantle–crust structure by a segregation process, they proposed that the present stratification directly reflects the sequence of condensation: iron condensed first and formed the core, then silicates condensed around it to form the mantle, and finally the volatile elements and gases were collected. Their model became known as 'inhomogeneous accumulation' or 'heterogeneous accretion'; like the Larimer–Anders model it was based on a condensation sequence starting with a low-pressure gas at 2000 K, but differed from it in one significant feature. As each element or compound condensed, it was assumed to be sequestered inside a solid body so that it could no longer react chemically with the remaining nebular gas. The late-condensing material that forms the crust and upper mantle has never been in contact with the core. This explains the absence of chemical equilibrium between core and mantle, which had been a paradox for Ringwood's theory. But the same feature prevents the inhomogeneous theory from explaining the presence in meteorites and the Earth of those minerals that were apparently formed by chemical reactions between gases and previously condensed compounds, such as troilite (FeS) (Lewis 1974; Wood *et al.* 1981). It is also inconsistent with hypotheses that assume the Earth's core must contain sulphur or silicon in addition to iron.

During the 1970s there was considerable discussion of the merits of homogeneous v. inhomogeneous condensation. Some authors questioned whether the assumption of thermodynamic equilibrium could legitimately be used to describe the condensation process. But new developments in astrophysics threatened to make *all* these theories obsolete, by undermining the basic assumption that the terrestrial planets and meteorites were formed from material that had been completely vaporized when the solar system was formed.

Astrophysics trumps meteoritics

The first challenge to the 'hot-origin' postulate came from calculations of Richard B. Larson (1969, 1972, 1988) on the dynamics of a collapsing protostar. He found that, contrary to earlier results of the Japanese physicist Chushiro Hayashi, the Sun probably did not go through an early high-luminosity phase; instead, it may have been formed without reaching very high temperatures until after the planets had been accumulated. Cameron, whose earlier research (Cameron 1962, 1963) had provided much of the justification for high-temperature condensation models, announced in 1973 that his latest calculations indicated that 'the temperature will not rise high enough to evaporate completely the interstellar grains, contained within the gas, beyond about one or two astronomical units' (Cameron 1973, p. 545). Thus, it is possible that in some of the meteorites in our museums are interstellar grains that survived the formation of the solar system without being vaporized. Cameron later concluded (Cameron 1978) that the high temperatures needed to evaporate solid grains were never present anywhere outside the orbit of Mercury.

A conflict thus developed between astrophysics and meteoritics. In the words of UCLA meteoriticist John Wasson: 'At the present time most numerical models of cloud collapse yield the result that temperatures were never above about 1000 K $\geq$ 1 AU from the axis of the forming solar system. In contrast, most meteorite researchers hold that higher temperatures were necessary to account for a variety of elementary fractionations found between groups of meteorites, between members of a single group, and between components of a single meteorite' (Wasson 1978, p. 489).

Wasson argued that simple aggregation of interstellar grains could not have produced the observed range of properties of chondrites. He concluded that meteoritic evidence required maximum nebular temperatures greater than 1500 K in the region from 1 to 3 AU, and insisted that 'satisfactory astrophysical models for the formation of the solar system must be able to generate' such high temperatures' (Wasson 1978, p. 501; see also McCall 2006).

Wasson continued to defend the high-temperature hypothesis throughout this period, suggesting that astrophysicists should be willing to modify their models in order to agree with meteoritic evidence rather than expecting meteoriticists to look for ways to produce high-temperature assemblages in a low-temperature nebula (Wasson 1985, pp. 156 and 184). J.R. Arnold (1980) also maintained that solar system material was completely mixed at high temperatures, despite the view of astrophysicists.

Wood, who worked in the same institution as Cameron, pointed out several times that meteoriticists were basing their theories on models that Cameron himself proposed but had now rejected (Wood 1979; Wood & Motylewski 1979). Yet, there was still strong evidence from the Ca–Al-rich inclusions in Allende and from other meteorites that material was condensed from hot gases in the early solar system (see also Wood & Morfill 1988). For example, the infalling interstellar material might have been heated on passing through a standing shock wave as it entered the nebula (Wood 1982; see also McCall 2006).

For geologists and biologists, this controversy is reminiscent of the 19th century debate about the age of the Earth. After the French mathematician Baron Jean Baptiste Joseph Fourier (1768–1830) showed from his theory of heat conduction that the Earth must have taken a very long time – hundreds of millions of years – to cool down, geologists felt at liberty to postulate indefinitely long periods of time. Then Lord Kelvin criticized them for taking that liberty and estimated that the Earth is only 20 or 30 Ma old. This would not be enough time for Darwinian evolution. Darwin's defender, the English biologist Thomas Henry Huxley (1825–1895), then complained: 'We take our time from the geologists and physicists; and it is monstrous that, having taken our time from the physical philosopher's clock, the physical philosopher should turn round upon us, and say we are too fast or too slow' (Huxley 1894, p. 134). Wood's complaint is similar to Huxley's. In the 20th century planetary science was still regarded as somehow inferior to fundamental physics, and any disagreements would have to be resolved in favour of the latter (Brush 1996, vol. 2, chapter 1.4). Or, as George Wetherill remarked about the post-Second World War period: 'It was fashionable at that time for physicists to feel that if given the opportunity to work in some other science, e.g. biology, geology, or astronomy, naturally something great would come out of it. They were sometimes correct' (Wetherill 1998, p. 5).

But in the late 1970s and early 1980s, most meteorite researchers concluded that meteorites did *not* provide strong evidence that the solar nebula was hot throughout. Insofar as meteorites appeared to have been formed at high temperatures, other explanations such as local heating events might be found (Smith 1979, p. 11). According to the Canadian cosmochemist and geochemist Robert N. Clayton and his colleagues, existing data on Ca–Al-rich inclusions 'are totally incompatible with a simple history of a single stage of condensation during monotonic cooling from an initially hot gas, the first-order framework on which many cosmochemical models have been built' (Clayton *et al.* 1985, p. 765).

The discovery of isotopic anomalies in meteorites also encouraged scientists to abandon the hot-nebula hypothesis, as that hypothesis as formulated earlier by Suess (1965) and Anders (1971) implied that the nebula material was well mixed. The easiest way to account for the anomalies was to assume that presolar grains had survived without being vaporized (Smith 1979; Wood 1981).

Donald D. Clayton was one of the strongest critics of the hot-nebula hypothesis and an advocate of the view that surviving presolar grains carry a 'cosmic chemical memory' (Clayton 1981, 1982) that may provide the key to the origin of the solar system. He argued in a series of papers that the concept of 'high-temperature thermal condensation in the early solar system', which meteoriticists had come to accept as an established fact, should be completely abandoned (Clayton 1978*a*, p. 110; see also 1978*b*, 1979*a*, 1980*a*, *b*). By the early 1980s he was able to claim widespread support for his views.

There seems to be no final resolution of this debate, at least during the time period covered by this article (through 1985). At the end of this period there was some indication that high-temperature models might again come into favour (Cameron 1984*a*, 1985; Boss 1988*b*).

Schmidt's meteoritic theory

During the 1940s the Russian geophysicist Otto Iulevich Schmidt (1891–1956) developed a new meteoritic theory and founded an influential school of planetary cosmogony in Moscow. He originally proposed (Schmidt 1944) that a meteoritic swarm had been captured by the Sun as it passed through an interstellar dust cloud, citing the work of Lindblad and Alfvén. Formation of the planets from this swarm would explain why most of the angular momentum of the solar system is contained in the major planets (especially Jupiter) rather than the Sun. His theory was debated by other Russian astronomers during the next few years, with political considerations occasionally intruding on the scientific discussions (Levin 1995). Like Alfvén, Schmidt (1958) assumed that the Earth was formed by accretion of cold solid particles. This assumption provided a common basis for the discussion of questions about the thermal history of the Earth, evolution of its core and so forth for scientists who disagreed on whether the Sun itself was formed from the meteorite swarm or encountered it later. After his death, Schmidt's colleagues and students under the leadership of Russian scientist Victor Sergeyevich Safronov (1917–1999) (Fig. 7) abandoned the 'capture' assumption and developed a theory consistent with (but more detailed than) the

Fig. 7. Victor S. Safronov (1917–1999), Russian theoretical astronomer who proposed a theory of the accumulation of planets from planetisimals.

nebular/planetesimal theory being developed in the United States (Levin & Brush 1995).

Safronov's planetesimal theory

During the 1960s, Safronov worked out in considerable detail the dynamical and thermal properties of a model of colliding, accreting and fragmenting solid particles (Safronov & Vityazev 1985; Safronov 1995). The earliest comparable work in the West, using this kind of model, was that of Stephen H. Dole (1970), but his calculation was much less ambitious.

Although a few of his papers appeared in English translation shortly after publication (Safronov 1959, 1962, 1966, 1967), Safronov's achievements were not generally recognized in the West until 1972 when an English-language version of his 1969 book, *Evolution of the Protoplanetary Cloud*, became available (Safronov 1972*a*). Since then the Safronov model or one of its variants has been the most popular explanation for the formation of the terrestrial planets. It has also played a major role in the leading theories of the origin of the giant planets and their satellites, as well as asteroids, comets and meteorites.

Safronov urged a division of labour in cosmogony. The problem of the origin of the protoplanetary cloud (PPC) itself could be treated separately from the problem of its evolution into planets, and that problem in turn was distinct from the history of planets after their formation. He preferred the hypothesis of common formation of the Sun and PPC over Schmidt's assumption that the PPC was formed elsewhere and later captured by the Sun, but considered himself a proponent of Schmidt's ideas as his model pertained only to the second stage. Thus, Safronov's theory did not compete with those of Hoyle and Cameron in trying to explain the formation of the Sun. He did dispute Cameron's assumption that the PPC was very massive (2–4 solar masses), preferring a low-mass PPC (about 0.05 solar mass). He also rejected the assumption of Weizsäcker, Cameron, Hoyle and others that turbulence played an important part in the evolution of the cloud.

Starting with a relatively low-mass, gas-dust cloud in which any primeval disordered motions have been damped out, Safronov assumed that dust particles would settle to the central plane and grow to centimetre size. As suggested by Edgeworth (1949) and by Gurevich & Lebedinsky (1950), the dust layer breaks up into several condensations by local gravitational instability. These condensations then combine and contract.

Coagulation theory goes back to the work of Marion von Smoluchowski on Brownian movement at the beginning of the 20th century, as presented to astronomers and physicists in the Indian-American theoretical astro-physicist Subrahmanyan Chandrasekhar's (1910–1995) influential review article (Chandrasekhar 1943). In Safronov's first model, fragmentation by collisions was ignored; the coagulation coefficient was assumed to be proportional to the sum of the masses of two colliding bodies. The number of particles with mass m was found to vary approximately as $m^{-2/3}$ for long periods, except for large m where an exponential damping factor becomes important. Fragmentation does play a role, especially when the relative velocities of two colliding particles is high. But if the relative velocity is very small, the particles will tend to move in similar orbits and collide so rarely that growth cannot occur. Safronov argued that, as the particles grow, encounters that do not lead to collisions will increase their relative velocities. The relative velocities most favourable for growth are those somewhat less than the escape velocity, which of course depends on the mass of the particles. The average relative velocity tends to increase as the particles grow so that it remains in the range favourable for further growth (see also Wetherill 1980, p. 5; Fisher 1987, pp. 224–226).

Safronov also concluded that when one body in a region happens to become significantly larger than the others, it will start to grow even faster because its effective cross-section for accretion of other bodies is enhanced by gravitation. In this way a single planet can emerge in each 'feeding zone' within the PPC and then sweep up the rest of the material in that zone. In this way the Safronov theory explains the observed fact that one never finds more than one planet in orbit at a given distance from the Sun.

Safronov (1959) emphasized the importance of high-speed impacts of a few large bodies in the formation of the Earth, a feature he attributed to the Russian astronomer B. Yu. Levin (1912–1989). He estimated that the formation of the Earth was essentially completed in 10^8 years, and that in spite of the large impacts the initial temperature inside was only a few hundred degrees. Using an equation derived by E. A. Lyubimova (1955) he found that heating by contraction would raise the central temperature to about 1000 K at the end of the formation process; radioactive heating would later raise this to several thousand degrees. Thus, the 19th century scenario – cooling from an initial temperature of several thousand degrees – was completely reversed. Here Safronov's model was in agreement with Western studies of the thermal history of the Earth (e.g. Urey 1951).

Using a theoretical relation between the impacts of small bodies on the accreting planets and the resulting inclination of their axes, Safronov estimated from the observed inclinations that the largest bodies striking the Earth during its formation had masses about 1/1000-th that of the present Earth (Safronov 1966, 1972*a*, p. 134). Thus, the large tilt of the Uranian axis was ascribed to impact of a body having 1/20-th the mass of that planet.

If the initial temperature of the Earth was only a few hundred degrees, one might think that planets further from the Sun started out much colder – perhaps cold enough to freeze hydrogen and helium from the PPC. But Safronov (1962) argued that the gas-dust layer is so thin that the Sun's radiation goes not only through it but along its surface so that it can be scattered into it through a boundary layer. This effect would keep the temperature from falling below 30 K at the distance of Jupiter and 15 K at the distance of Saturn. Thus, these planets could not condense hydrogen directly but could only accrete it gravitationally after reaching a sufficiently large mass at a later stage of their growth.

A major drawback of Safronov's theory was that the estimated time for formation of the outer planets, using the equations derived for the terrestrial planets, was about 10^{11} years. In addition to the obvious disadvantage of requiring a time longer than the present age of the solar system (4.5×10^9 years) to form these planets, it is inconvenient not to have a fairly massive proto-Jupiter present while Mars is being formed, if one wants to attribute the small size of Mars (relative to Earth) to interference from its giant neighbour.

To alleviate this difficulty Safronov assumed that the outer regions of the PPC originally contained a much larger amount of material, much of which was ejected by gravitational encounters with the growing embryos of massive planets. This hypothesis would accelerate the early stages of the accretion process, while gravitational trapping of gas would accelerate the later stages (Safronov 1972*a*, chapter 12, 1972*b*). But the ad hoc or qualitative nature of these hypotheses damaged the credibility of the theory.

The extremely low initial temperature of the Earth on this model also created a problem if one wanted to explain the segregation of iron into the core. Safronov was temporarily attracted by the idea that the Earth's core is not iron but silicate, chemically similar to the mantle but converted to a metallic fluid by high pressure. This was the hypothesis of V.N. Lodochnikov (1939) in Russia and W.H. Ramsey (1948, 1949) in Britain, widely discussed in the 1950s (Brush 1996, vol. 1, section 2.4). As pointed out by Levin (1962) it had cosmogonic advantages that Safronov recognized (1972*a*, p. 152). But the postulated silicate phase transition proved elusive, and it was shown both experimentally and theoretically that silicate compounds did not have high enough density at core pressures to account for the observed average density of the Earth. So Safronov was forced to accept either the traditional iron core or a compromise iron oxide core, with a correspondingly higher internal temperature.

Safronov's programme lacked the glamour of more ambitious schemes that promised to explain the formation of the Sun as well as the planets from a simple initial state, and it encountered difficulties in explaining the properties of the present solar system. Yet, he was successful in building up a body of basic theory that turned out to be useful as a starting point for other cosmogonists.

The Americanization of Safronov's programme

Following the English translation in 1972 of Safronov's 1969 book, his theory became widely known and influential in the West (Brush 1996, vol. 3, pp. 135–136). In 1976 the American geophysicist George West Wetherill (Fig. 8) announced the first results of his calculations on a modified version of Safronov's theory. Wetherill's work was motivated in part

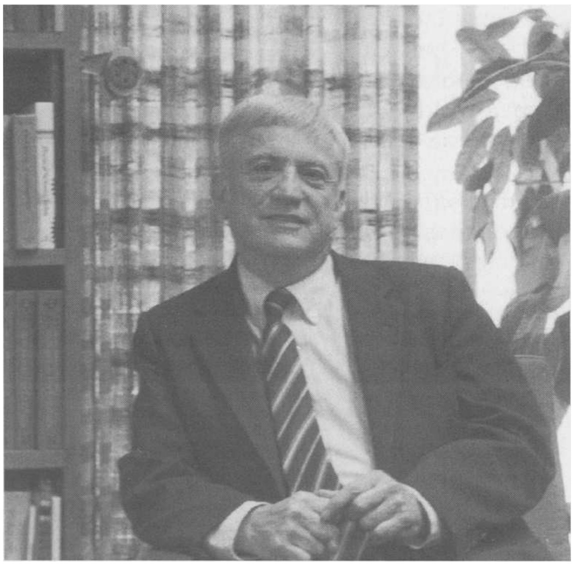

Fig. 8. George W. Wetherill, American geophysicist who developed and revised Safronov's theory of the accumulation of planets from planetesimals. (Photograph courtesy of G.W. Wetherill.)

by photographs of Mercury's surface taken by the *Mariner 10* spacecraft on 29 March and 21 September 1974, analysed by Bruce Murray's group (Murray *et al.* 1975). It appeared that Mercury, like the Moon, had suffered a 'late heavy bombardment' after its formation (Wetherill 1975). Hence, it was likely that there was a high flux of asteroid- or Moon-sized bodies throughout the inner solar system, 4500–400 Ma ago, encouraging the revival of meteoritic (planetesimal) theories of the origin of the solar system.

Wetherill's research, unlike Safronov's, made extensive use of computer simulation. In an autobiographical memoir, he recalls that he had been fascinated by the problem of the origin of meteorites and in particular the possibility that some of them might have been rocks ejected from the Moon. The Estonian–Irish astronomer Ernst Öpik had worked out a theory of the probability that a lunar rock could hit the Earth, and James Arnold developed a Monte Carlo program to implement this theory. When William Kaula at UCLA introduced him to the recently published translation of Safronov's book, Wetherill realized that he could apply Arnold's meteorite trajectory program, with appropriate modifications, to check Safronov's approximate calculations (Wetherill 1998).

Although Wetherill confirmed many of Safronov's results, he found one important difference. When the Earth is half formed, its 'feeding zone' merges with that of Venus. The resulting perturbations produce higher relative velocities and thus reduce the cross-section for capture of planetesimals by massive bodies. This will prevent runaway growth of the largest embryo in a zone. The second-largest body in the Earth's zone may then have a mass as large as 1/20-th of the Earth's rather than only 1/1000-th.

Such large bodies, although having only a transient existence in the final stage of accretion, would produce substantial heating by their impacts on the terrestrial planets and the Moon (Kaula 1979). As Safronov accepted the conclusion that the Earth has been heated by large impacts during its formation (Safronov & Kozlovskaya 1977; Safronov 1978, 1981), Wetherill (1981) could say that every current theory predicts high initial temperatures for the formation of planets.

Around this time Richard Greenberg and his colleagues at Tucson, Arizona, announced another numerical simulation based on a modification of Safronov's theory (Greenberg *et al.* 1978*a*, *b*). They supported the idea that large bodies were prevalent in the early solar system by showing that planetesimals as large as those generated in Wetherill's scheme could have been produced without invoking perturbations by proto-Venus (Greenberg 1979). Further numerical results (Greenberg 1980) generally supported Safronov's analytic work but contradicted his conclusion that relative velocities of planetesimals would tend to be comparable with the escape velocity of the dominant body. More of the total mass of the system was found to carried by smaller planetesimals, which would collide mostly with each other and therefore tend to have smaller velocities; hence, when they did collide with a large body they would be more likely to accrete and promote its runaway growth (cf. Levin 1978*a*, *b*). One consequence of this result was that Uranus and Neptune could grow 'in a reasonably short time, well below the actual age of the system, without the need for ad hoc assumptions about excess mass or artificially-low relative velocities among the icy planetesimals' (Greenberg *et al.* 1984).

A paper by Wetherill published in 1985 suggested that a modified Safronov model may be able to explain the existence of four terrestrial planets starting from 500 bodies each of mass 2.5×10^{25} kg (one-third lunar mass). But this result was clearly stochastic and depended on the existence of large impacts. Several computer runs gave three or four planets but none reproduced precisely the observed distribution of masses and distances. So the best theory of the formation of terrestrial planets, as of 1985, was not quite capable of explaining the simplest properties of those planets as known 200 years ago. On the other hand, it did fit remarkably well with the 'giant impact' theory of the origin of the Moon, proposed in the 1970s by William Hartmann, Donald R. Davis, A.G.W. Cameron and William R. Ward, and gaining general acceptance by planetary scientists in the mid-1980s (Brush 1996, vol. 3, pp. 241–258). The Safronov theory as revised by Wetherill predicted that a terrestrial planet is likely to be hit by an object as large as Mars during the final stage of its growth, a conclusion that is consistent with the formation of Earth's Moon by a giant impact, even though this is only one of several processes that can be expected to provide material for the formation of the Moon (Wetherill 1986).

Reconciliation of meteoritics with astrophysics

Although this article does not cover the developments of the last 20 years, the reader may like to know that some progress was made in that period toward resolving the conflict between meteoritics and astrophysics that existed in the early 1980s.

Recognizing the strength of meteoritic evidence for high temperatures in the early solar system, astrophysicists saw the need to improve their models to account for this evidence. They accepted that, in the words of Alan Boss (pers. comm. 2005): 'there was no such thing as a single temperature (hot or cold) to characterize the solar nebula. The nebula's temperature varied with space and time ... The nebula cooled with time, and was cooler farther away from the protosun. Achieving high temperatures to account for the refractory inclusions (e.g. CAIs) and the thermal processing experienced by chondrules is now explained by combinations of forming objects close to the protosun and transporting them outward and/or thermally processing them *in situ* in a cooler region of the nebula by transient, high temperature shock fronts, i.e. by flash heating' (for details see Boss 2004; Boss & Durisen 2005; for a review see Boss 1998). Hap McSween (pers. comm. 2005) agrees: 'The consensus now is that the solar nebula was never really hot, except in close near the protosun ... or in local spots'; the model by Shu et al. (1996) 'provides a way to reconcile that' with the meteoritic evidence for high temperatures 'by forming these objects close to the protosun and then ejecting them in arcs out to distances appropriate to the asteroid belt where they accreted to form meteorites. There are some other models as well for generating local high temperature excursions, such as shock fronts ... ' (see also his book, McSween 1999).

Donald D. Clayton (pers. comm. 2005) gives a concise summary: 'Meteoriticists, chemists all, simply posited the simplest chemical explanation rather than building a physical model. Astrophysicists ignored chemical data and emphasized that thermodynamic laws determined how hot the disk gases were ... But in time we all see that the truth is complex and somewhere in between our once-simpler views'.

This chapter is based on parts of my book (Brush 1996), reprinted here by permission of Cambridge University Press. I thank A. Boss, D. Clayton and H. McSween for additional information about the subject.

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