

2

ASTEROIDS, COMETS, AND PLANET FORMATION

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INTRODUCTION

The solar system includes numerous small objects, generally classifiable as asteroids, comets, or interplanetary dust. Asteroids and comets are of considerable importance in the study of the terrestrial planets. The impacts of these bodies with the planets have repeatedly reshaped the planets' surfaces, redistributed the surface materials and changed their chemistry and mineralogy. In addition, impacts leave scars which provide a means of assessing ages. Asteroids, and possibly old comet nuclei, continually rain on the Earth, and many thousands are preserved and are displayed in our museums as meteorites. In this chapter the nature of comets and asteroids is briefly reviewed. The formation of planets is also examined here because most of the evidence as to how the planets formed comes from meteorites. The discussion is short and general. The chapter is included mainly to provide background for the subsequent more detailed treatment of the planets.

ASTEROIDS AND COMETS

Over 2000 asteroids are known (Chapman, 1975); the largest being Ceres, about 1000 km in diameter. They appear star-like on telescopic photographs, and are recognized as a result of their motions relative to the stars. Their shapes are not known, but variations in brightness suggest that they are irregular. Most asteroids are in orbits with relatively low eccentricities (<0.3) as compared with comets, and most are in the asteroid belt between Mars and Jupiter.

Asteroids have been classified in two ways. The first is according to their orbits, which is of interest to those attempting to estimate the rate of impact on the various planets. The Amor asteroids, for example, have perihelia (the point in the orbit closest to the Sun) inside Mars' orbit but outside Earth's. Clearly, objects of this class can impact Mars but not Earth. In contrast, the Apollo asteroids have perihelia inside the Earth's orbit and so can impact both Earth and Mars. Alternatively, the asteroids are also grouped according to their albedo and spectral reflectivity. This classification is useful in that the reflectivity gives some indication of composition, and tentative correlations have been made between the asteroid groupings and various types of meteorites.

Comets have also impacted the planets throughout their history and affected their geology much in the same way as asteroids. Comets appear to be agglomerations of ice and dust that have spent most of their lifetime far beyond the orbits of the planets (Whipple, 1974). They are believed to reside in large numbers (10^{11} – 10^{12}) in the most distant reaches of the solar system, in the so-called Oort cloud, which is estimated to be about 100 000 AU across. The cloud is believed to have formed early in the history of the solar system by ejection of material from the region of the planets, outward, almost to the edge of the Sun's influence. Ejection resulted from orbit perturbations induced by close passes by a planet. Distances from the Sun in the Oort cloud are so great, and motions of the comets in the cloud so slow, that perturbation of their orbits by passing stars are occasionally sufficient to cause a comet to plunge into the inner solar system on a

near-parabolic orbit around the Sun. As the ice-dust ball approaches the Sun, its surface warms and the ices start to sublime. The comet then becomes visible and develops its characteristic shape. The gases given off are ionized and swept away by the solar wind, along with any dust that is released. At this stage three parts can generally be distinguished: a bright head (coma) roughly spherical in shape, a tail of ionized gas which streams out from the head in a straight line radial to the Sun, and a tail of dust particles which extend in a slightly curved arc, also roughly radial to the Sun.

Comets are of two major kinds, periodic and non-periodic. The nonperiodic comets constitute the vast majority. They move in parabolic orbits and make only one pass through the center of the solar system. Their inclinations are random, with prograde and retrograde orbits equal in number. From these characteristics we can conclude that the Oort cloud, their source, is spherically disposed around the solar system and not restricted to the plane of the planets. In contrast, the periodic comets are all in low-inclination, prograde orbits. They are believed to be former parabolic comets whose orbits have been perturbed by the planets, mainly Jupiter. Such perturbations are possible only for those comets which initially moved in prograde orbits with low inclinations. Periodic comets have limited lifetimes in that they lose mass each time they pass the Sun, indicating some asteroids may be burned out comet remnants.

METEORITES

Meteorites provide us with samples of asteroids and possibly burned out comets, and are of fundamental importance for understanding the formation of the planets. They provide the best evidence of the nature of the materials that accumulated to form the planets, as well as the processes of accumulation. Meteorites have a wide range of composition and mineralogy (Wood, 1979; Wasson, 1974). Some, termed differentiated meteorites, resemble terrestrial igneous rocks. They appear to have been part of a larger body that broke up at some intermediate stage in the history of the solar system, after having gone through a stage of heating and magmatic differentiation. The other main class of meteorites, the chondrites, are distinctively different from any terrestrial rock. They are mostly agglomerates of fragmental debris and typically contain chondrules—spherical mineral aggregates, 1–2

mm across, consisting mainly of olivine and orthopyroxene, but possibly with minor amounts of clinopyroxene, iron sulfide and iron-nickel. The chondritic meteorites formed very early in the history of the solar system, while the planets were forming, and so provide direct evidence of conditions at that time.

The most primitive meteorites are the carbonaceous chondrites, in which the chondrules are embedded in a fine-grained, earthy matrix. This matrix consists of hydrated, platy minerals such as serpentine and montmorillonite, together with small amounts of magnetite, iron-nickel sulfide, sulfates and carbonates. Small amounts of organic compounds are also generally present. The matrix is thus a low-temperature, volatile-rich assembly, in contrast to the high-temperature assemblage of the chondrules. The chondrules and matrix are in disequilibrium and clearly formed under very different conditions.

Some carbonaceous chondrites also have small, irregularly-shaped inclusions composed largely of Ca-Al-Ti-rich minerals. The minerals in the inclusions are those which are expected to have condensed first from the nebular gas in the early stages of cooling of the primitive solar nebula. Their formation had been predicted from thermodynamical considerations (Grossman, 1972) before they were discovered in the Allende meteorite. The Ca-Al-rich inclusions are therefore samples of the most primitive matter of the solar system. Their irregular shape indicates that they have never gone through a melting stage but formed directly from the nebular gas.

Carbonaceous chondrites resemble the Sun in composition. The only significant differences are lesser amounts of hydrogen, carbon, nitrogen, and noble gases in the carbonaceous chondrites. These elements are unlikely to have condensed in the inner solar system because of their high volatility, so their lack of incorporation into the carbonaceous chondrites is not surprising. Because of (1) the compositional correspondence between the Sun and the carbonaceous chondrites, (2) the presence of the Ca-Al-rich inclusions, and (3) the disequilibrium mixture represented by the chondrules and matrix, the carbonaceous chondrites are believed to be indicative of the primitive solar nebula composition, depleted somewhat in the more volatile elements. In models of planet formation, therefore, carbonaceous chondrites are commonly used to represent the materials from which the planets formed. All carbonaceous chondrites have ages comparable to the age of the solar system (4.6 billion years).

Carbonaceous chondrites represent only a small fraction of all chondrites; ordinary chondrites are much more common. These also contain olivine-pyroxene chondrules but their chondrules are embedded in a matrix of the same composition as the chondrules themselves. Many of the ordinary chondrites have been heated so that the boundaries between chondrules and matrix have become diffuse, and the constituent minerals have been recrystallized to form granulitic textures suggestive of high temperatures. Exposure ages for the ordinary chondrites, that is, the time the meteorite has been exposed to cosmic rays, are mostly in the 10^6 – 10^8 year range—far shorter than the age of the solar system.

The carbonaceous chondrites are agglomerations of chondrules, the more primitive Ca-Al-rich inclusions, and volatile-rich materials. Throughout the history of the solar system, they have never been incorporated into bodies large enough to have caused significant heating, otherwise the disequilibrium assemblage would have been destroyed. Ordinary chondrites, on the other hand, appear to have been buried within larger bodies and subjected to various degrees of heating and metamorphism. Subsequently, the larger bodies were broken up, presumably as a result of impact, and their materials dispersed. Ordinary chondrites thus have metamorphic textures and young exposure ages. Depths of burial in the parent bodies are not known but estimated to be as high as a few tens of kilometers. The major uncertainties are whether the parent body originally incorporated the volatile materials that are present in the carbonaceous chondrites, and whether the volatiles were later driven off during the heating and metamorphism.

About 15 percent of meteorites are non-chondritic. Some are breccias and appear to be lithified regolith from an asteroid surface. Other achondrites have igneous textures and appear to have formed by magmatic processes within larger bodies. They have a range of composition and texture similar to that of terrestrial igneous rocks. These igneous-textured achondrites seem, as do ordinary chondrites, to have originated within larger bodies, but at such depths that melting occurred and the normal processes of magmatic differentiation followed. There are two main types of achondrites: stones and irons. Irons generally consist of intersecting plates of two nickel-iron alloys—kamacite and taenite. From variations in the composition of the two alloys, the temperature and rate of cooling of the iron-nickel, and hence the depth of burial, can be estimated. The method is crude but suggests that the irons

formed at depths of 30–50 km. These depths are probably representative of the radius of the parent body from which the meteorite formed.

In recent years the question of how bodies as small as a few tens of kilometers across could have heated up and created the metamorphic and igneous textures seen in meteorites has been resolved. It now appears that radioactive heating by the decay of short-lived radioisotopes, mainly ^{26}Al (half-life of 10^6 years), ^{244}Pu (82×10^6 years) and ^{129}I (16×10^6 years), was responsible, since the decay products of these nuclides have been found in the meteorites. Since these short-lived nuclides were incorporated into meteorites before they had decayed, the time interval between element formation and meteorite formation must have been relatively short—no more than a few million years.

FORMATION OF THE PLANETS

Our perception of how planets formed is based mainly on theoretical studies of stellar evolution and the study of meteorites. The planets are believed to have formed from a disk-like volume (nebula) of dust and gas that surrounded the protosun (see Wood, 1979; Lewis, 1974). The protosun grew by gravitational attraction of dust and gas from the surrounding interstellar medium, and during the process it inherited angular momentum from eddies in the interstellar gas. As accumulation proceeded and the protosun contracted, its angular velocity increased to preserve angular momentum, and a disk-like nebula formed around the protosun, rather than a spherically symmetrical cloud. Material outside the disc tended to move toward the protosun by gravitational attraction; material within the disc tended to assume a position where gravitational attraction was counterbalanced by centrifugal forces. A major uncertainty concerns the stability of the disc. Did local eddies within the disc cause it to fragment into numerous gaseous protoplanets, most of the solid particles being swept up to form dense solid cores, or did the disc remain continuous, allowing dust particles ultimately to accumulate into planetesimals without gaseous envelopes? The answer is not known but the latter hypothesis is the most widely held.

As the disc cooled, different materials began to condense and add to the inventory of solid particles. Grossman (1972) and Grossman and Larimer (1975) determined the sequence in which minerals would have condensed from a gas of solar composition under the expected nebular pressures (10^{-4} atm). The first

THE GEOLOGY OF THE TERRESTRIAL PLANETS

minerals to condense out are those found in the Ca-Al-rich inclusions (fig. 2.1). Last to condense are the carbonaceous compounds and ices of water, ammonia, and methane. The sequence assumes that the gases and dust are constantly in equilibrium, that is, that the higher temperature minerals react with the remaining gases as the nebula cools. If the condensed phases are removed and not able to react with the remaining gases, such as by incorporation into larger solid bodies, then the condensation sequence would be slightly different.

Recent evidence suggests some meteorites incorporate interstellar grains. Seemingly, parts of the nebula where the meteorites formed were never hot enough to vaporize all solid particles. The evidence is from the Ca-Al-rich inclusions and some chondrules which have oxygen isotope anomalies that cannot be explained by fractionation or diffusion processes within an isotopically homogeneous nebula; the oxygen in these grains is in isotopic disequilibrium with the rest of the matter in the solar system. The grains appear to have formed elsewhere, then were captured by the

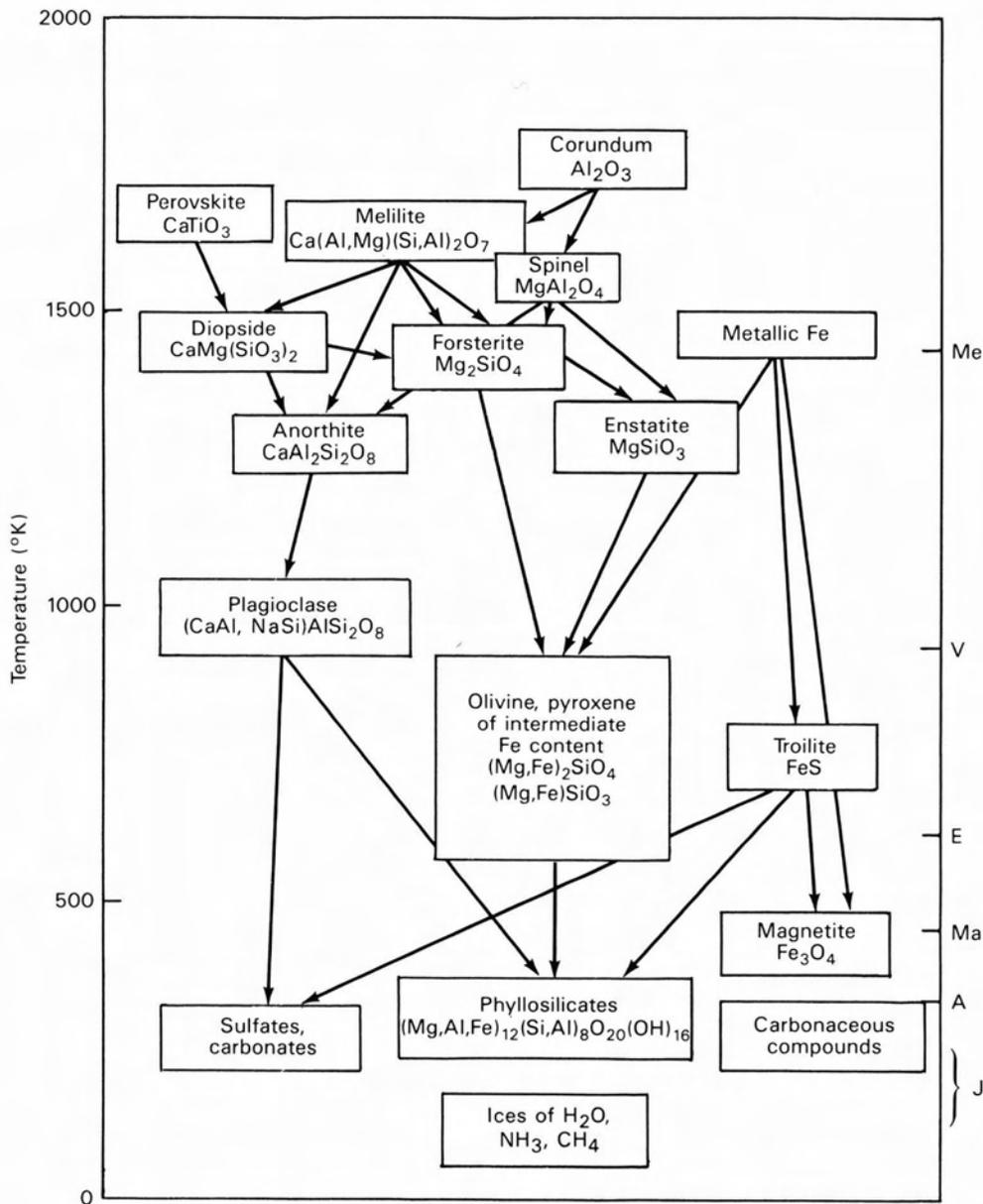


Figure 2.1. The sequence of condensation of minerals from a nebula of solar composition. As the nebula cools minerals high in the diagram react with nebular gas to form those lower in the diagram as indicated by the arrows. Many chondritic meteorites contain minerals from different levels in the diagram (different condensation temperatures), indicating their constituents were in partial disequilibrium with each other and the nebula gas. (After Wood, 1979.)

solar nebula and incorporated into meteorites without being vaporized and equilibrated with the surrounding materials.

Although chondrules, which are the dominant component of undifferentiated meteorites, are composed of minerals that are expected to condense in the 600–1500 K range, they do not appear to have been formed by simple condensation from the nebular gas. The globular shape of the chondrules suggests that they were liquid droplets, yet at the low pressures that probably prevailed in the nebula, solids rather than liquids should condense. Various suggestions have been made to explain the anomaly. First, condensation may have produced supercooled liquid droplets rather than solid crystals. Second, condensation could have occurred within gaseous protoplanets, where pressures were high enough for liquids to form. Third, the chondrules may be droplets produced during high energy impacts between small objects. Whatever the process, it had to be very efficient since a large fraction of the undifferentiated meteorites consists of chondrules, and some pre-nebular granular material had to be incorporated into the chondrules to explain their anomalous oxygen.

Thus, at some early stage in its formation, the solar system consisted of a protosun and a gaseous nebula disc, which, in the inner solar system at least, contained Ca-Al-rich aggregates and olivine-pyroxene rich chondrules. In the more distant parts of the solar system, low temperature minerals such as those found in the matrices of carbonaceous chondrites may also have been present. The next stage appears to have been the formation of asteroid-size bodies or planetesimals. Precisely how this occurred is uncertain. Gravitational instabilities may have developed and caused the particles to cluster. Growth of the clusters was aided by the presence of the nebular gas which ensured that relative velocities between particles was small. By the time asteroid size objects had accumulated, conditions in the solar system changed significantly as a result of removal of the nebular gas. After this time motions of the planetesimals were not constrained by the enclosing gas and their orbits could be perturbed by close approaches of other planetesimals. Many planetesimal orbits thus became highly eccentric and high velocity impacts became more common. Such conditions favored growth of the largest bodies. Very small bodies broke up on impact; intermediate sized bodies were eroded away because their low gravity fields allowed most of the impact-generated debris to escape. Only the largest bodies could grow by impact to ultimately form the planets.

The timing of planetary growth with respect to condensation from the nebula is unclear. Two main models have been proposed: the equilibrium condensation model in which the planets accumulated after condensation had essentially ceased, and the inhomogeneous accretion model in which accretion and condensation occurred simultaneously. According to the equilibrium condensation model, material condensed from the solar nebula following the scheme of Grossman (1972) already discussed. Condensation was arrested at different stages according to the local nebula temperature. Close in, near the orbit of Mercury, condensation ceased when temperatures were relatively high so the condensed materials consisted only of high-temperature minerals. In the more distant parts of the solar system, temperatures were low when condensation ceased so that the solid grains included low-temperature plately silicates and ices. They may also have retained high-temperature minerals that failed to react with the nebular gases as they cooled, possibly as a result of burial within the grains. The solar system was thus compositionally zoned, with predominantly high-temperature minerals in the particulates close in and with lower temperature minerals becoming more important farther out. These particulates ultimately aggregated to form the planets and resulted in the composition and density differences that are observed. In this model, accumulation is decoupled from condensation. Condensation is thought to have been accomplished in around 10^6 years; accumulation of the planets is thought to have taken around 10^8 years. The present layering of the planets is due to later heating and differentiation.

This model satisfactorily explains the density differences between the terrestrial planets (fig. 2.2). Mercury condensed largely from Ca-Al silicates and Fe-metal, materials that are expected to condense at temperatures of around 1400 K. The large proportion of metallic iron accounts for its high uncompressed density (5.4 gm/cc). Venus has accumulated largely from magnesium silicates and metallic iron, which would have condensed together at 900 K. The Earth accumulated from a 600 K assemblage of Fe-Mg silicates, troilite and metallic iron, and at the temperatures that the Mars-forming materials condensed (450 K) all the iron was oxidized to FeS, which accounts for its low uncompressed density. Two main difficulties with the equilibrium condensation model are that (1) the atmospheres of Earth and Venus require incorporation of some fraction of low temperature condensates along with the condensates which

THE GEOLOGY OF THE TERRESTRIAL PLANETS

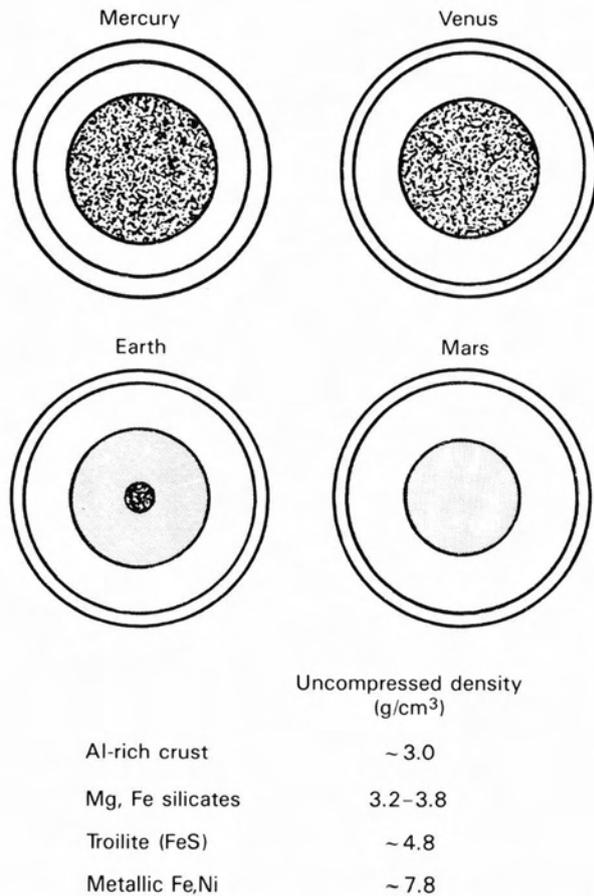


Figure 2.2. Internal structure of the terrestrial planets as predicted by the equilibrium condensation model. Moving outward from Mercury the mantle of each planet is richer in FeO and poorer in MgO, and the core is richer in FeS and poorer in metallic Fe. (After Lewis, 1974.)

formed at the planets' characteristic temperatures, and (2) the crust and upper mantle of Earth contain a higher abundance of siderophile elements than should be present if the Earth's core formed by segregation during global melting. Other evidence of disequilibrium between the upper mantle and core also indicated that the chemical layering within the Earth cannot be due entirely to melting and fractionation (see Earth chapter).

The heterogeneous accretion model was devised to account for some of these difficulties. According to this model, accumulation of the planets kept pace with condensation. As rapidly as the material condensed from the solar nebula, the material was swept up into the planets. The planets therefore developed an onion-ring structure, with the highest temperature condensates at the center and progressively less refractory materials toward the surface. Condensation was arrested at relatively high temperatures close to the

Sun. Mercury was, therefore, built mostly of refractory Ca-Al silicates and metallic iron. Further from the Sun the planets incorporated more materials from more advanced stages in the condensation sequence. Thus the density differences between the planets are explained in much the same way as the equilibrium condensation model.

The layering initially acquired by the planet was not retained. The refractory silicates were originally at the center surrounded by iron-rich material. Ultimately most of the refractory silicates reside in the crust and the iron in the core. Proponents of the model propose that the high rates of accretion caused early global heating during which the interior of the planet melted and iron fell into the center to form the core. Core formation took place before accretion was finished so that the final outer layers of the planet were never equilibrated with the core. The chemical anomalies of Earth's upper mantle are therefore resolved; while volatile-rich materials, which accumulated late, were a source of volatiles for the atmosphere.

A major problem with the heterogeneous accretion hypothesis is that no mechanism has been conceived whereby the planets could accumulate so rapidly as to keep pace with condensation. An additional problem concerns the core of Earth. The core's density implies that it is not metallic iron, as is required by the model, but instead incorporates some light element, probably sulfur, which should have been acquired late, after core formation was over.

Several attempts have been made to reconcile the two hypotheses. One such model has most of the planets accrete in around 10^8 years, roughly in accordance with the equilibrium condensation model. However, temperatures were too high in the region of the terrestrial planets for the lowest temperature condensates to form. They formed only in the asteroidal belt, or farther out, and became incorporated into planetesimals of carbonaceous chondrite composition. The last stage in accumulation of the terrestrial planets was capture of many of these planetesimals to form a volatile-rich veneer from which the atmosphere was derived. Capture of the volatile-rich material took place after core formation. The main disadvantage of the heterogeneous accretion model, the rapid accumulation, is thus avoided. At the same time the chemical disequilibrium between upper mantle and core is explained.

How the planets evolved between the time of accretion, 4.6 billion years ago, and the time when the geologic record emerged, 3.9 billion years ago, is

ASTEROIDS, COMETS, AND PLANET FORMATION

unclear. Meteorites tell us little about this era, and the planets themselves preserve almost no evidence of events prior to 4 billion years ago because of erasure by massive meteorite bombardment. After 4 billion

years ago the bombardment rate declined thereby allowing a fragmentary record of succeeding events to be preserved. Interpretation of this record is the concern of the chapters that follow.