Formation of the solar system took place as a coherent series of events stemming from a collapsing cloud of raw material present in a solar nebula. Most of the material in the nebula was drawn to the center to form the sun, giving it a composition very close to that of the original cloud. It contains 99% hydrogen and helium and only about 1% of the remaining ninety elements. A small amount of the matter in the cloud ended up in a nebular disk around the newly formed sun. A small percentage of this material condensed to solid form and then aggregated to form planets, moons, asteroids, and comets. The remaining gas was likely blown away by a violent solar wind. Fragments of materials from the early solar system occasionally reach Earth as meteorites. The composition of the primitive “chondritic” meteorites is very similar to the sun except for the very volatile elements. Other “achondritic” meteorites reveal much about early planetary differentiation.

The various objects in the solar system formed from a complex series of processes, understood well in general terms but with many details remaining to be clarified. The inner and outer planets differ greatly in size and density. The inner planets have densities greater than rocks, and based on evidence from meteorites, are comprised of a rocky exterior and an inner metallic core. The outer planets have very low densities, requiring a preponderance of ices and gases in their composition. The difference between inner and outer planets is largely the result of differential volatility. In the early solar system there would have been a
temperature gradient with distance from the sun. Closer to the sun, volatile molecules were gas and refractory molecules were solid. In those parts of the disk, only the least volatile molecules such as Fe, FeS, FeO, MgO, Al$_2$O$_3$, and SiO$_2$ were in solid minerals that could collect together to form dense planets. Farther from the sun, beyond the “snow line,” ices also crystallized and almost all the elements except hydrogen and helium were in solid form, leading to large planets of low density. Their large mass also allowed them to accumulate vast gaseous atmospheres. Because of differential volatility, the comets and planets of the outer solar system have a chemical composition very different from the asteroids and planets of the inner solar system. Materials accreted in cooler parts of the solar nebula, where volatiles were more abundant, are likely to have impacted Earth early in its history, bringing with them the volatile components (and possibly organic molecules) that were essential for the inception of life.

Solar system creation very likely took place in an interstellar cloud of gas and dust, which served as a “stellar incubator” (see frontispiece). Such clouds are common in the universe, and we can observe new star systems forming elsewhere in our galaxy. There is also evidence for the existence of many planets around other stars, indicating that creation of planetary systems is a normal and common event in our galaxy.

Introduction

Human beings have been looking at the sun and planets and pondering their significance for millennia. What was apparent to the earliest observers is still easily observable today (at least outside a city)—the sun, moon, and planets all move around the same narrow band of the sky, called the ecliptic, which is also the sun’s equator. The apparent position of the sun relative to the stars changes progressively—in winter and summer Earth is on opposite sides of the sun, so to an Earth observer the sun appears against different stellar backgrounds that vary regularly throughout the year. These backgrounds have stellar groups associated...
with them, called constellations, which gave rise in ancient times to astrology. The planets pass through the same swath of the sky, also with varying stellar backgrounds. They all move in the same direction but at different rates depending on their particular position relative to the sun as they revolve around it. These fundamental observations, apparent to any regular observer of the night sky, demonstrate that the sun and planets are all coplanar. Therefore from earliest times the planets and sun have intuitively all seemed to be connected to one another. They are not revolving in random directions and orientations around the sun; they all revolve together, in the same plane and in the same direction. Furthermore, this direction is consistent with the spin of the sun. A useful mnemonic is an association of the word planet with “plane.”

There are other striking regularities within the solar system. Using the surveying methods discussed in Chapter 2, astronomers have been able to determine the distance from the sun to each of the planets (see Table 5.1). Considering the asteroid belt between Mars and Jupiter as a failed planet, the spacing between the planets shows a remarkable regularity—the distance between orbits of successive planets increases by roughly a
factor of 1.7, an observation that was named after its discoverer—Bode’s Law (Fig. 5-1).

There are also significant differences between the inner and outer planets. Mercury, Venus, Earth, and Mars are all small; Jupiter, Saturn, Uranus, and Neptune are huge. Therefore the planets occur in two regular and organized groups (Fig. 5-2).

This clear organization of the solar system gave rise in the eighteenth century to the nebular hypothesis of Kant and Laplace. They suggested that the planets and sun formed from a single, spinning flat cloud; the spin of the planets and the existence of the ecliptic conform to the original plane and spin of the cloud. If instead the orbits were helter skelter, and the big and small planets randomly distributed, an alternative model would be tenable, where for example the planets formed elsewhere and were subsequently captured. The Kant-Laplace model was strenuously attacked over the centuries, but their fundamental ideas are retained in more detailed and quantitative modern models of solar system formation.
Fig. 5-2: Illustration of the approximate sizes of the planets relative to each other. The planets are ordered in their sequence from the sun. The sizes are proportional, but the distances in the figure do not correspond with their actual positions.

**Planetary Vital Statistics**

An understanding of the origin of the planets clearly must depend on knowledge of their physical and chemical characteristics. While we have a multitude of ways to determine these characteristics for Earth, it is more difficult for the other planets, because we only have samples or direct surface measurements from the moon, Mars, and Venus. However, measurements from satellites that orbited around the various planets can be combined with basic astronomical observations to provide us with substantial information.

**PLANETARY MASS**

The mass of a planet can be determined from the gravitational influence it exerts on the orbits of its moons, on other planets, and on the space probes sent out from Earth (Table 5-2). The primary method used is a
clever one, based on a law established in the early 1600s by Johannes Kepler, a German astronomer and mathematician. Kepler’s Laws were later explained by Newton, making use of a constant of gravitation, \( G \). Using Newton’s laws, there is a straightforward relationship between the location at which a moon orbits its host planet \( R \), the velocity of the moon around the planet \( V \), the mass of the host planet \( M_p \) and the universal constant of gravitation. The equation is:

\[
M_p = \frac{RV^2}{G}
\]  

(5-1)

Note from Equation (5-1) that the right hand term of the equation with the orbital velocity is independent of the mass of the orbiting object. All objects orbiting at the same distance from a planet will orbit at the same velocity. This is why astronauts need not be afraid to leave their spaceships or let go of their wrenches. Once the value of \( G \) was able to be measured accurately in 1811, the mass of planets with moons could be determined simply from measuring the time it takes a moon to make one rotation of the planet, and the distance of the moon from the planet’s center.

For those planets without moons (Mercury and Venus), the masses had to be calculated by a more elaborate scheme. The orbit of each planet is influenced by the gravitational attractions of neighboring planets. By careful observation of the perturbations caused by neighboring planets of known mass, the masses of Mercury and Venus have been able to be determined.

As can be seen from Table 5-2, the planetary masses change greatly as the distance from the sun increases. Mercury, closest to the sun, is the least massive. Venus, Earth, and Mars are larger (but note that Earth is ten times as massive as Mars), and then there is a huge jump to the giant planets Jupiter and Saturn. Uranus and Neptune, while somewhat less massive, are still far more massive than any of the four inner planets. So we see that the process responsible for planet building led to objects differing widely in size. The size variation does not vary linearly with distance from the sun. Instead there is clear demarcation between the inner planets, with masses of less than \( 6 \times 10^{27} \text{ g} \), and the outer planets, with masses greater than \( 87 \times 10^{27} \text{ g} \) (see Table 5-2).

While these first order regularities about the solar system strongly suggest that the objects within it are co-genetic, they do not indicate with any specificity how the planets formed. Greater understanding awaited the discovery of the chemical compositions of the various planets.
Table 5-2
Physical characteristics of the planets in the solar system

<table>
<thead>
<tr>
<th>Planet</th>
<th>Equatorial radius (10^9 cm)</th>
<th>Volume (10^26 cm^3)</th>
<th>Mass (10^27 gm)</th>
<th>Density (g/cm^3)</th>
<th>Corrected density (g/cm^3)</th>
<th>Moons</th>
<th>Most abundant atmospheric gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>2.44</td>
<td>0.61</td>
<td>0.33</td>
<td>5.43</td>
<td>5.40</td>
<td>—</td>
<td>Minimal</td>
</tr>
<tr>
<td>Venus</td>
<td>6.05</td>
<td>9.29</td>
<td>4.87</td>
<td>5.24</td>
<td>4.30</td>
<td>—</td>
<td>CO₂, N₂</td>
</tr>
<tr>
<td>Earth</td>
<td>6.38</td>
<td>10.83</td>
<td>5.97</td>
<td>5.52</td>
<td>4.20</td>
<td>1</td>
<td>N₂, O₂</td>
</tr>
<tr>
<td>Mars</td>
<td>3.38</td>
<td>1.63</td>
<td>0.64</td>
<td>3.93</td>
<td>3.70</td>
<td>2</td>
<td>CO₂, N₂</td>
</tr>
<tr>
<td>Jupiter</td>
<td>71.49</td>
<td>14,313</td>
<td>1,898.6</td>
<td>1.34</td>
<td>&lt;1.3</td>
<td>63</td>
<td>H₂, He</td>
</tr>
<tr>
<td>Saturn</td>
<td>60.26</td>
<td>8,271</td>
<td>568.4</td>
<td>0.69</td>
<td>&lt;0.69</td>
<td>61</td>
<td>H₂, He</td>
</tr>
<tr>
<td>Uranus</td>
<td>25.56</td>
<td>683</td>
<td>87.0</td>
<td>1.28</td>
<td>&lt;1.28</td>
<td>27</td>
<td>H₂, He</td>
</tr>
<tr>
<td>Neptune</td>
<td>24.76</td>
<td>625</td>
<td>102.40</td>
<td>1.64</td>
<td>&lt;1.64</td>
<td>13</td>
<td>H₂, He</td>
</tr>
</tbody>
</table>

*Densities are corrected to one bar pressure. Only maximum densities are known for the outer planets.

PLANEARY DENSITIES

The densities of the various planets (Table 5-2) can be determined by dividing the mass of the planet by its volume. We learned in Chapter 4 that the density of an object provides much information about the elements that make up the object—high atomic number elements are generally much denser than low atomic number elements. Hence the density of a planet has much to tell us about the planetary composition.

There is one more complication, however, before we can relate density to planetary composition—density also depends on pressure. As materials are squeezed, the atoms that make them up pack together more tightly and the density goes up. To know the densities of materials at high pressure requires careful experiments. For example, experiments have shown that Fe with a density of 7.9 g/cm^3 has a density of 13.5 g/cm^3 at Earth's center. To compare planet densities in terms of the materials of which they are made, we need to know the density the planet would have if all the material were at the same pressure. The choice is arbitrary, so we choose one atmosphere, the pressure at Earth's surface, which we can call the uncompressed density. Uncompressed densities are always less than the actual density, because squeezing always increases density.
This correction can be done well for the inner planets, but we cannot
give accurate corrected densities for the outer planets because we do not
know the densities of ices at the very high pressures that exist in the
interiors of these bodies. We do know, however, that the uncompressed
densities would be less than the observed density, as indicated in Table
5-2.

While the uncompressed densities give us an estimate of the average
number of nuclear particles contained by the atoms of a given planet,
there are a wide variety of combinations of elements through which this
could be achieved. To determine which of these possible combinations
is the correct one, we must use additional information. The situation is
similar to that faced by someone about to open a birthday present. From
the heft of the box many possibilities can be eliminated. If the box is
quite heavy for its size, it could be a book or a mineral specimen. If it
is quite light for its size, it could be a sweater or a very small present in a
big box of tissue paper. While providing an indication, the heft leaves
many options open!

**PLANETARY COMPOSITION**

Additional clues for planetary composition come from knowledge of
nucleosynthesis in stars and the compositions of interstellar clouds. As
we learned in Chapter 3, some elements, such as H, He, the alpha par-
itcle nuclides (C, O, Ne, Mg, Si), and Fe are created in far greater abun-
dance than other elements. We can observe from the sun’s spectrum that
these elements are also the most abundant in the sun, and therefore in
the cloud of gas and dust from which the sun and planets formed. The
candidate molecules for planets are then constrained to be made largely
of these elements, and these molecules are also those observed in inter-
stellar clouds. The molecules fall into three different classes—ices, ox-
ides, and metals, with very different densities and volatility (Table 5-3).
What then are the planets made of? To match the density of the outer
planets, with their uncompressed densities of less than 1.7 (see Table 5-2),
ices must be predominant. The inner planets, on the other hand, with
corrected densities higher than oxides, must consist of some mixture of
oxides and metal.

By examining the melting points given in Table 5-3, it is also clear that
the light molecules that make up much of the outer planets are very vola-
Table 5-3
Densities and melting temperatures of possible planet-forming solids

<table>
<thead>
<tr>
<th>Compound</th>
<th>Number of nuclear particles per atom</th>
<th>Density g/cm³</th>
<th>Melting point °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICES</td>
<td>CH₄</td>
<td>3.2</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>NH₃</td>
<td>4.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>H₂O</td>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>OXIDES</td>
<td>SiO₂</td>
<td>20</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Mg₂SiO₄</td>
<td>20</td>
<td>3.2</td>
</tr>
<tr>
<td>METAL</td>
<td>Fe</td>
<td>56</td>
<td>7.9</td>
</tr>
</tbody>
</table>

tile, and in order to accrete as ices the temperatures must have been very cold. The materials that make up the inner planets, on the other hand, remain solid at very high temperatures. This leads to the straightforward idea that the solar nebula around the sun had a range of temperatures.

Close to the sun the temperatures were hot, and oxides and metal were the only solid materials that could collect together to form planets. The volatile compounds were all gases, and the small gravitational fields of the early planetesimals (small precursors to planets) would not be great enough to retain them. Far from the sun, temperatures were much colder. There, ices as well as silicates and metals were solid and could collect together to form planets. Ices were also present in far greater amounts, since they are made up of elements such as C, H, and O that are about ten times more abundant than the heavier elements that make up metals and oxides (see Fig. 3-10, showing the abundances of elements made during nucleosynthesis). The outer planets then got an equal share of oxide and metal, and a huge additional mass of icy volatile compounds. Their large mass also allowed them to retain a massive atmosphere. Both these effects lead to their great size and low density.

These considerations based on differential volatility account for the first-order differences between inner and outer planets. Planets form from solid materials. Near the sun, temperatures were so high that only the most refractory elements were solid. Far from the Sun, the solar nebula was cold and most elements were solid. It's a bit as if a machine were able to sweep up all the solid materials in the room you are sitting in at very different temperatures. At a thousand degrees, all the wood,
Evidence from Meteorites

While differential volatility explains the gross differences between inner and outer planets, we would like to have more information about their compositional differences. One approach is to look at our own planet—rocks exposed on Earth. Measuring the densities of the rocks at Earth's surface we find they have densities between 2.7 and 3.0 g/cm³, far less than the uncompressed densities of all the inner planets (e.g., Earth's uncompressed density is 4.2 g/cm³). The inner planets' high densities mean there must be materials denser than rocks in the planetary interiors.

More constraints on planetary interiors come from the compositions of meteorites that fall from the sky. Most meteorites are pieces broken off from asteroids during violent collisions with one another. Since the asteroids were broken apart, the meteorites include both surface and interior fragments. In addition, a few rare meteorites have been shown to be hunks of rock blasted off the surface of the moon, and a few have been determined to be rocks blasted off the surface of Mars by the impacts of large objects from the asteroid belt. Meteorites provide invaluable information about the compositions of planetary interiors and also the exterior portions of Mars.

Our collections of meteorites come not only from objects whose fiery passages through the atmosphere have been seen by humans but also from the Antarctic ice sheet. The white ice collects the black meteorites on the surface, and they are carried by the ice for long periods of time.
In certain places wind scour and evaporation remove more material than falls as snow. Meteorites contained in the ice are left on the surface as a lag, just as pebbles are left behind in desert areas whose sands are being swept away by strong winds. Over the last decade thousands of meteorites have been recovered from Antarctica by expeditions of American and Japanese scientists.

Two crucial characteristics of meteorites help to advance our understanding of the early solar system. First, meteorites are the oldest known objects whose age we are able to measure directly, and their age is consistent with that of Earth. Second, about eighty percent of meteorites appear to be fragments of solids from the solar nebula that somehow avoided being accreted into planets. They then provide us with primordial planetary material.

Evidence for this assertion comes not only from their age, but also from a very characteristic texture that is never found in rocks on Earth. The characteristic texture is the presence of millimeter-sized spheres called chondrules (Fig. 5-3). These chondrules are unique to meteorites.

Much attention has been given to these little spheres, and the conclusion is nearly universal: they were once molten rock droplets that condensed in space. Some think these drops were formed like raindrops as
a hot nebular gas cooled; some think they were formed when small fragments of nebular dust were heated beyond their melting point. No one, however, has conceived a reasonable way to manufacture these spheres inside a planet—they appear to have formed in the very low pressures of space. Since the meteorites containing chondrules are of similar age to Earth and the moon, and the same composition as the sun, the logical conclusion is that these materials survived unchanged since the earliest history of the solar system. Chondrule-bearing meteorites, called chondrites, provide us with materials that formed in the solar nebula.

As the chondrules were once liquid, they formed at the high temperatures where rock and metal can melt—\( \geq 1,100^\circ \text{C} \). The matrix between the chondrules, however, appears to have formed at rather different temperatures in the various classes of chondrites. For this reason the volatile abundances of different classes of chondrites can vary. One particularly important class is the carbonaceous chondrites because of their high carbon content. In these meteorites, chondrules coexist with minerals that are only stable below 100\(^\circ\text{C}\), so they contain materials that formed in both high- and low-temperature environments and then collected together.

Further evidence for the primordial attributes of carbonaceous chondrites comes from the fact that they have compositions very similar to the nonvolatile element composition of the sun. The chemical composition of carbonaceous chondrites is compared to that of the sun in Figure 5-4. Included in this figure are only elements that do not have high volatility (i.e., not H, He, the noble gases, etc.). Not only does this agreement lend confidence to the spectral method of chemical analysis of stars, it also fortifies the conclusion that carbonaceous chondrites in particular provide a chemically unbiased sample of the solar system's less volatile elements. Thus these rock fragments likely carry the chemical information about the actual compositions that accreted to make the planets.

What are the characteristics of this composition? The most striking feature is the dominance of three metals: silicon, iron, and magnesium. As summarized in Table 5-4, these elements constitute 91% of the materials present in ordinary chondrites. Four elements—aluminum, calcium, nickel and sodium—form a group that runs a poor second, and six other elements a group that runs an even poorer third. Since all of these form minerals in combination with oxygen, oxygen is also among
Fig. 5-4: Comparison of the relative abundances of elements of low and moderate volatility in the sun’s atmosphere with those in carbonaceous chondrites, relative to $10^6$ atoms of Si. For these elements, carbonaceous chondrites provide a chemically unbiased sample of bulk solar system matter except for volatiles such as H, C, N, O, and noble gases. (Data from Anders and Grevesse, *Geochim. et Cosmochim. Acta* 53 (1989):197–214, and Anders and Ebihara, *Geochim. et Cosmochim. Acta* 46 (Nov. 1982):2363–80)

The most abundant elements. These elements must then make up most of the inner planets’ composition.

The chondrites also contain key clues about the origin of the high densities of the inner planets. Microscopic observation of chondrules shows that they consist of the silicate minerals olivine and pyroxene, sulfides, and iron metal. The olivine and pyroxene contain iron in the form of iron oxide, the sulfides have iron combined with sulfur. Therefore, it is apparent that in the solar nebula iron can occur in three different forms, as metal, as oxide (which combines with silicon and magnesium oxides to form silicate minerals), and as sulfide. Metallic iron has a density of 7.9, while silicates have a density of about 3. Varying proportions of iron in its different forms could give rise to large density differences indeed.
The importance of both rock and metal is confirmed by study of other meteorites that do not contain chondrules, called *achondrites*, or “differentiated meteorites.” Some of these meteorites, the basaltic achondrites, are lavas that clearly have undergone melting and processing in planetary objects in the early solar system. These rocks are rather similar to volcanic rocks erupted on Earth. Another class of nonchondritic meteorites is made of iron metal. When cut and polished, these objects show beautiful hexagonal patterns consisting of alternating bands of Fe-Ni alloys (Fig. 5-5) unlike anything that can be found or manufactured on Earth. Metallurgists recognize this pattern as one that forms when an alloy of iron and nickel is cooled very slowly—but they are unable in the laboratory to cool anywhere near as slowly as would be required to give rise to the patterns seen in the iron meteorites. Such slow cooling is what would be expected deep in the interior of a planetesimal where a core of metal was surrounded by a thick insulating blanket of rock.

The separate classes of silicate achondrites and iron meteorites if combined back together would be similar in composition to the chon-
Fig. 5-5: Polished section of an iron meteorite showing the characteristic banding of Fe-Ni alloys, called a Widmanstätten pattern. Such patterns are observed only in meteorites and result from a very slow cooling rate in the cores of ancient planetesimals. (Photo courtesy of Harvard Museum of Natural History)

drites. In fact, if we were to separate the metal out of chondrites with a magnet, we would create the compositions of two of the major classes of differentiated meteorites—those made almost exclusively of iron and those made up only of silicates.

These observations collected together suggest a rather straightforward scenario—that metallic and silicate achondrites were formed through the melting of chondrites. Because liquid iron and liquid silicate cannot mix together—like oil and water—the denser metal separates downward and the lighter silicate floats on top, creating a differentiated planetary object with a metallic core and a silicate mantle. Breakup of these objects would then lead to the creation of the achondritic meteorites.

The actual proportions of silicate and metal depend on the proportions of iron in its three stable forms: as metal, as iron oxide, and as iron sulfide. The amount of iron in each of these forms depends on the amounts of silicon, magnesium, oxygen, and sulfur available. The oxygen first combines with the Si and Mg. The available sulfur, which is relatively minor in abundance, combines with iron to make iron sulfide. If there is any oxygen left over it combines with Fe to make FeO. The remainder of the iron is in the metallic state. Therefore, a gradation in
oxygen content leads to different proportions of iron oxide to sulfide plus metal in chondrites. In this way solar system processes could lead to planets with slightly different densities, depending on the fraction of Fe tied up in silicate or metal.

These clues then lead us to be able to interpret the relative densities of the inner planets. The high densities of the inner planets relative to the silicate rocks we find at the surface could be due to deep-seated metal that separated to the planet’s interior to form a planetary core. Mercury, with the highest density of the inner planets, would have proportionately the largest core. Mars, with the lowest density, the smallest core. This scenario then gives a first-order account of many important observations—the compositions of chondritic and achondritic meteorites and how they tie in to the compositions of the four inner planets.

Scenario for Solar System Creation

These various lines of evidence, combined with increasingly detailed observations of nascent planetary systems in interstellar clouds and improved modeling thanks to increased computer power, provide an overall scenario for the early history of the solar system (Fig. 5-6).

When matter contracts toward the center of a protoplanetary disk, it heats up because of the conversion of gravitational energy to heat. This leads to a radial distribution of temperature, where material near the future star is hotter than material that is farther away. Recent estimates put the temperature at this early stage of solar system formation in excess of 1,000°K at the distance of Earth from the sun, and as low as 200°–100°K at the distances of Jupiter and Saturn. At the high temperatures appropriate for Earth, no volatiles would be in the solid state, and the dust would be made up of silicate and metal. Farther from the sun, the temperature was low enough that volatile elements would precipitate as ices. The two are separated by a “snow line” controlled by the temperature distribution around the Sun.

The solid particles within the disk then begin to stick together, forming small solid objects (a very small number of which were preserved to become meteorites and comets much later in solar system history). In a
Fig. 5-6: Schematic illustration of the steps in solar system formation from an initial nebula of dust and gas, to a collection of solids in the nebula, to the formation of planets and the ejection of excess gases from between the planets. Modified from Lifengastronomy website (lifenglamost.org)
from 1 to 10 km likely appeared. Such small accumulations, called planetesimals, all rotated in the same direction around the Sun and hence collided gently with one another to make larger and irregular objects. The largest ones would then have had sufficient gravitation to attract the smaller, and further growth no longer depended only on accidental impacts. This led to more rapid growth through increasingly energetic impacts to form the protoplanets—those objects that would eventually combine to become the planets. The later stages of solar system formation would have been marked by giant impacts among the protoplanets, which as we shall see in Chapter 8 had far-reaching consequences for Earth.

The outer reaches of the early solar system had a much higher quantity of solid material, because the lower temperatures made many of the volatile compounds solids. The protoplanets of the outer solar system were thus substantially larger than present-day Earth. These objects then had such a large gravitational field that they could attract and retain an immense gaseous atmosphere. Does this mean that Jupiter lacks iron and silicate? Not at all—the large circumference and gravitational attraction made Jupiter actually accumulate more silicate and metal than Earth; estimates are that Jupiter has a mass of silicate and metal 30 times the mass of Earth. This giant also accumulated the vast amounts of ices as well as hydrogen and helium leading to its low density and a total mass some 300 times that of Earth. Similar events happened for the other outer planets.

At this early time the solar system remained a very crowded space. There may have been many dozens of protoplanets in the inner solar system, many more planetesimals, and even vaster numbers of comets reflecting perturbed orbits of icy planetesimals from the outer reaches of the solar system. Small impacts of the planetesimals and huge impacts of the protoplanets eventually gave rise to single “winners,” the surviving planets. Of course, small numbers of impacts with comets and asteroids would continue, and indeed continue today.

There is a record on two of the inner planets of these final huge impacting events. As we will see in more detail in Chapter 8, a late impact of a Mars-sized object (about one-tenth Earth mass) with the proto-Earth likely led to the creation of the moon. Such an impact would explain why the moon has no core and has a composition that looks very
much like Earth's mantle, and why the moon is so large relative to the size of Earth. Mercury also seems to reflect a late large impact. If the Earth impact were grazing but the Mercury impact direct, then in one case the moon might have formed, and in the other much of the silicate mantle might have been lost to space, explaining the large core and high density of Mercury.

Two difficulties were encountered in early versions of the solar system scenario:

(1) One of the most puzzling properties of the solar system is the distribution of angular momentum. Just as a skater spins rapidly by starting to spin slowly and then collapsing her limbs around her body, the collapse of the solar nebula to the center should have transferred most of the rotation of the nebula to the center and made the sun spin very fast. The planets, staying far from the center, should orbit slowly. Yet while the sun has more than 99.9% of the solar system's mass, it has only 2.0% of the total angular momentum. How could the sun be spinning so slowly?

(2) The second and apparently unrelated difficulty was that the amount of solid dust that could accumulate to form planets made up just 0.2–2.0% of the mass of gas. Hydrogen and helium were by far the most abundant elements, and yet would never be in the solid state. Space between the planets is now empty—what happened to the most abundant elements that must have been the dominant components of the solar nebula?

A possible solution to both problems has been proposed based on observations of the early life cycle of stars. During a small star's earliest history, prior to the onset of fusion of hydrogen to make helium, violent winds emanate from the star that would push away the gas and particles that surround it. This effect, named T-Tauri after the first star where it was found, would have ejected a significant amount of mass from the early sun. Just as the skater stops her spin by throwing out her arms, the outward movement of material from the sun causes the spin of the sun to slow down. The T-Tauri wind also might blow away in very short periods of time the remaining gas and dust that have not accreted into protoplanets. The solar system would then be left with early planets in gasless space, orbiting a slow-spinning sun. This idea will be able to be tested further by more detailed analysis of stellar nurseries such as the
Orion nebula (see frontispiece), where solar systems in various stages of formation can be observed.

We have called this section a "scenario" because the understanding of formation of planetary systems is complex and occurred some 4.5 billion years ago. The meteorite record is incomplete; we have few samples from other planets; there is little data from comets; and modeling of such a complex process requires major simplifications and assumptions. New wrinkles in solar system formation come from increasingly complex models of accretion that show large numbers of protoplanets and suggest that early in the history of a solar system planets are not formed in fixed and stable orbits, but tend to migrate toward or away from their star. In particular the outer planets of our solar system are proposed to have migrated outwards from the sun in early solar system history. In other models, large planets can migrate inward toward their star, wreaking gravitational havoc in some early solar systems. It is heartening that new data from space-based telescopes have now identified other planets and planetary systems forming around other stars. While the first discovered planets were all massive, like Jupiter, the most recent results have found smaller planets as well (see Chapter 21). These new discoveries are for the first time giving us other examples of solar systems where solar system formation can be observed at various stages of development in other parts of the galaxy. Rather than having to rely only on inferred events billions of years ago, new constraints will come from direct observation of other solar systems. The interplay between models and observations will lead to substantial advances in coming years.

**Understanding the Chemical Compositions of the Terrestrial Planets**

We are now in a position to try to understand in more detail the compositions of the inner planets and how they came about. Let us run through the list of elements in order of increasing atomic number in Table 5-5 and see why inner planetary compositions are dominated by relatively few elements.

The first element on the list is hydrogen. Most hydrogen is in the form of hydrogen gas, while some is present as gases of carbon (CH₄, CHN), of
nitrogen (NH$_3$), or oxygen (H$_2$O). Earth and its fellow terrestrial planets accreted where none of these gases were solid. Only a small fraction of the least volatile of them arrived with later impacts from materials formed in the outer solar system. Therefore hydrogen should be scarce.

Helium exists only as a gas and furthermore is so light that it can escape from the top of Earth's atmosphere even today. The very small amounts of helium we find today are derived mostly from the radioactive decay of uranium and thorium.

The next three elements—lithium, beryllium, and boron—were produced in very small abundances by nucleosynthesis in stars. Their overall abundance in the universe is too small to permit them to be major constituents of planets.

Carbon and nitrogen, in the presence of the large amounts of hydrogen gas in the planetary nebula, would have been in the form of CH$_4$, NH$_3$, and CO—gaseous compounds that did not accrete.

The element oxygen is even more strongly attracted to the various metals than it is to hydrogen. In the nebular cloud there were five times as many oxygen atoms as all metal atoms taken together. Most of the oxygen combined with hydrogen and carbon, but there was enough oxygen left that most metals combined with oxygen to make oxides. Because most metals combine with oxygen, oxygen is present in great abundance and became a major planetary constituent.

After oxygen on the list in Table 5-5 come fluorine and neon. Fluorine is volatile and has a strong tendency to combine with hydrogen in the form of hydrofluoric acid (HF), a molecule that is also volatile under the conditions of the inner solar system. Neon is a noble gas like helium, remaining always in the gaseous state and therefore would not accrete.

So of the first ten elements, six formed gases and were largely lost. Three others had such small universal abundances as to be unimportant. Only oxygen was sufficiently abundant and prone to form solid phases that it became a major contributor to the terrestrial planets.

The next five elements on the list are all metals that prefer chemical unions with oxygen. Four of them (magnesium, aluminum, silicon, and phosphorus) were in solid form, while sodium is moderately volatile and thus less abundant. Both silicon and magnesium are alpha-particle nuclides produced in greater abundance in stars, and hence they are far more abundant than sodium, aluminum, and phosphorus. SiO$_2$ and MgO are major planetary constituents.
<table>
<thead>
<tr>
<th>Element number</th>
<th>Element name</th>
<th>Solid</th>
<th>Gas</th>
<th>Relative abundance in Sun**</th>
<th>Fate**</th>
<th>Relative abundance in Chondrites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>H₂</td>
<td>40,000,000,000 (1)</td>
<td>—</td>
<td>Trace</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Helium</td>
<td>He</td>
<td>3,000,000,000 (1)</td>
<td>—</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Lithium</td>
<td>Li₂O</td>
<td>60 (3)</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Beryllium</td>
<td>BeO</td>
<td>1 (3)</td>
<td>—</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Boron</td>
<td>B₂O₃</td>
<td>43 (2)</td>
<td>—</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Carbon</td>
<td>CH₄</td>
<td>15,000,000 (1)</td>
<td>2,000</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Nitrogen</td>
<td>NH₃</td>
<td>4,900,000 (1)</td>
<td>50,000</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Oxygen</td>
<td>H₂O</td>
<td>18,000,000 (2)</td>
<td>3,700,000</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fluorine</td>
<td>HF</td>
<td>2,800 (1)</td>
<td>—</td>
<td>Trace</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Neon</td>
<td>Ne</td>
<td>7,600,000 (1)</td>
<td>Trace</td>
<td>46,000</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Sodium</td>
<td>Na₂O</td>
<td>67,000 (2)</td>
<td>46,000</td>
<td>46,000</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Magnesium</td>
<td>MgO</td>
<td>1,200,000 (3)</td>
<td>940,000</td>
<td>1,000,000,000</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Aluminum</td>
<td>Al₂O₃</td>
<td>100,000 (3)</td>
<td>60,000</td>
<td>1,000,000,000</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Silicon</td>
<td>SiO₂</td>
<td>1,000,000 (3)</td>
<td>1,000,000</td>
<td>13,000</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Phosphorus</td>
<td>P₂O₅</td>
<td>15,000 (3)</td>
<td>13,000</td>
<td>13,000</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Sulfur</td>
<td>FeS</td>
<td>H₂S</td>
<td>580,000 (2)</td>
<td>110,000</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Chlorine</td>
<td>HCl</td>
<td>8,900 (1)</td>
<td>700</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Argon</td>
<td>Ar</td>
<td>150,000 (1)</td>
<td>Trace</td>
<td>3,500</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Potassium</td>
<td>K₂O</td>
<td>4,400 (2)</td>
<td>3,500</td>
<td>3,500</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Calcium</td>
<td>CaO</td>
<td>73,000 (3)</td>
<td>49,000</td>
<td>49,000</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Scandium</td>
<td>Sc₂O₃</td>
<td>41 (3)</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Titanium</td>
<td>TiO₂</td>
<td>3,200 (3)</td>
<td>2,600</td>
<td>2,600</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Vanadium</td>
<td>VO₂</td>
<td>310 (3)</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Chromium</td>
<td>Cr₂O₃</td>
<td>15,000 (3)</td>
<td>13,000</td>
<td>13,000</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Manganese</td>
<td>MnO</td>
<td>11,000 (3)</td>
<td>9,300</td>
<td>9,300</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Iron</td>
<td>FeO, FeS, Fe</td>
<td>1,000,000 (3)</td>
<td>690,000</td>
<td>690,000</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Cobalt</td>
<td>CoO</td>
<td>2,700 (3)</td>
<td>2,200</td>
<td>2,200</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Nickel</td>
<td>NiO</td>
<td>58,000 (3)</td>
<td>49,000</td>
<td>49,000</td>
<td></td>
</tr>
</tbody>
</table>

*Relative to 1,000,000 silicon atoms.

** (1) Highly volatile; mainly lost; (2) moderately volatile; partly captured; (3) very low volatility; largely captured.

***Plus metal oxides.
Next on the list is sulfur (S). Its situation is akin to oxygen. It can form the gas \( \text{H}_2\text{S} \) and also combine with iron to form a solid FeS. The evidence from meteorites is that a significant proportion of S would have been captured in combination with iron.

The next two elements on the list, chlorine and argon, were largely lost as gases. Chlorine was in the form of the volatile hydrochloric acid, HCl, while argon is a noble gas. Then come two more metallic elements, potassium and calcium. Calcium in the oxide form has a very low volatility. Potassium like sodium is moderately volatile and hence was less efficiently captured. (Despite its low abundance, potassium has an important role in Earth studies, however, because one of its isotopes, \(^{40}\text{K}\), is radioactive).

So we see that in the second group of ten elements, five of them (Mg, Al, Si, S, Ca) were largely captured. Three were partially captured and two were lost. Of the captured five, Mg and Si are ten to twenty times more abundant in the solar nebula than Al, Ca, and S and hence make up far greater proportions of planets.

Between calcium and iron there is a big sag in the abundance curve of elements created by nucleosynthesis (see Fig. 3-10). Although most of the elements in this interval are metals of low volatility that combine with oxygen, none has a sufficiently high cosmic abundance to be particularly important. In contrast, the abundance of iron, the ultimate product of nuclear fires, stands well above that of its neighboring elements and is close to Mg and Si in cosmic abundance. It occurs in three chemical forms, none of which are particularly volatile. As its cosmic abundance is similar to Mg and Si, it is also one of the major constituents of the inner planets.

Beyond iron, the abundance of the elements drops rapidly with increasing proton number. Only nickel is sufficiently abundant to be important.

Thus we see that overall chemical abundances are controlled by a combination of nuclear physics, which determines the cosmic abundances of the elements, and inorganic chemistry, which determines the molecular combinations and volatility of chemical compounds. Rocky planets like Earth consist primarily (>90%) of the “big four” elements—O, Mg, Si, and Fe. A secondary group that makes up most of the rest consists of Ca, Al, Ni, and S.

The relative abundances of most of the remaining elements in the table are strongly influenced by their volatility. Figure 5-7 shows how
the ordinary chondrites compare to the carbonaceous chondrites that appear to have formed further out in the solar nebula, where they retained greater proportions of the available volatiles. Elements that are highly refractory, such as Mg, Ca, Al, and Ti have abundances that are very similar in both types of chondrites (i.e., ratios very near 1). Elements of progressively greater volatility are increasingly depleted in the ordinary chondrites.

From what we know of the compositions of the inner planets, they all have similar relative proportions of the most refractory elements, and the volatile elements are all depleted relative to carbonaceous chondrites. In detail, however, the specific amount of volatile depletion is quite variable. A proxy for this variability is the ratio of a slightly volatile element, K, to a highly refractory element, U. The elements K and U are particularly useful for this purpose, because both of them tend to travel together during geochemical processes, and both have long-lived radioisotopes that emit gamma rays. These powerful electromagnetic radiations can be detected by instruments dropped toward the planetary sur-
Table 5-6

\[
\begin{array}{|c|c|}
\hline
\text{Component} & \text{K/U ratio} \\
\hline
\text{Venus} & 7,000 \\
\text{Earth} & 12,000 \\
\text{Moon} & 2,500 \\
\text{Mars} & 18,000 \\
\text{Ordinary chondrites} & 63,000 \\
\text{CI Carbonaceous chondrites} & 70,000 \\
\hline
\end{array}
\]

face. Hence, unmanned spacecraft landed on Venus have been able to send back estimates of the K/U ratio of the surface rocks, which can be compared to direct measurements of chondrites, Earth, and the moon, as well as to meteorites that are believed to have come from Mars. These ratios are shown in Table 5-6, from which it is apparent that the extent of volatile depletion can be quite variable.

The table is put in sequence of increasing distance from the sun. Formed farthest from the sun and with the highest ratio are the carbonaceous chondrites. Ordinary chondrites are only about 10% depleted in K relative to U. On the basis of current data, which is sparse for Mars and very uncertain for Venus, the three inner planets then become progressively more depleted in K passing from Mars to Earth to Venus. This result is consistent with an increasing nebular temperature toward the sun. Volatile depletion explains why Earth’s Na content, for example, is about 10% of its Ca content, despite the similar abundance in chondrites evident in Table 5-3. The moon stands out as being very volatile depleted, an important fact that bears on its origin, as we shall see in Chapter 8.

The greatest uncertainties in inner planetary compositions relate to the origin of the most highly volatile elements. Noble gases are always in the gaseous state in the solar nebula, and yet they are present on Earth in small but significant amounts. Furthermore, the ratios of Earth’s noble gas isotopes are clearly not the same as those of the solar wind, so direct trapping of gas from the nebula is not a possibility. While \( \text{CO}_2 \) is of minor abundance in the atmosphere, the total amount on Earth, now mostly
residing in carbonate rocks, is substantial, as is the amount of water, as discussed at length in Chapter 9. The appearance of these volatiles on Earth is essential for the subsequent development of life, and hence is of more than minor interest. One possibility that seemed promising was that cometary impacts and the dust from comet tails may have contributed to the total volatile budget. This seemed evident given calculations that there would be huge numbers of comets in Earth-crossing orbits in the early solar system.

A test of this idea became possible with recent missions to comets that would enable us to learn more details of their composition. One important measurement is the ratio of the two stable isotopes of hydrogen, $^2$H (deuterium) and $^1$H. The ratio $^2$H/$^1$H is referred to as the D/H ratio. The mass difference between these isotopes is so large that they can become separated during chemical processes, and the D/H ratio in various solar system materials varies by many tens of percent or more. If comets were the source of Earth's volatiles, comets should have the same D/H ratio as Earth. But the initial measurements showed that the measured ratios in comets were not consistent with Earth's ratio. Could earlier comets have come from a different part of the solar system with appropriate isotope ratios? New measurements in 2011 showed that at least one comet has a D/H ratio consistent with Earth's value. New observations will throw increased light on the origins of Earth's vital volatiles.

There is one other perplexing aspect of element abundances that has been difficult to explain, which is the variable ratios of refractory elements such as Mg to Si to Fe in the terrestrial planets, and why these ratios can differ slightly but significantly from those observed in chondritic meteorites. Some of the variation is now thought to reflect the importance of late impacts of large protoplanets. This might explain the exceptionally high Fe in Mercury, for example, if part of the silicate mantle of the protoplanet were lost to space. The Si/Mg ratio of Earth, however, also differs from the chondritic value. Since both elements reside entirely in silicate phases at low pressures, this cannot be explained by impacts. One possibility that is being actively considered is that at the very high pressures of Earth's deep interior, some Si can be dissolved in the Fe-core, but this conjecture remains unproven. Hence, while the broad points of planetary accretion are quite well understood, much remains to be discovered.
Summary

The solar system formed from a collapsing cloud of gas in an environment likely to have been very similar to the interstellar clouds where newly forming stars and planetary systems can now be observed elsewhere in our galaxy. Formation of solar systems therefore appears to be a regular and lawful process, not a random occurrence. The large differences between inner and outer planets can be explained well by the different thermal environments that existed in the early solar system. The hot regions of the nebular cloud close to the sun would precipitate solids made up only of metal and silicate, while the colder regions beyond Mars would also precipitate the major ices containing nitrogen, carbon, and hydrogen. Accretion of this dust into planetesimals and then protoplanets took place rapidly, likely followed by removal of the remaining gases by the hurricane of solar winds during the T-Tauri phase of the early sun. The protoplanets and remaining planetesimals then collided to form the planets observed today. The overall compositions of the inner planets can be well understood from the combined knowledge of nucleosynthesis, differential volatility, and increasingly detailed and quantitative models of solar system formation. Significant puzzles remain, particularly with respect to the abundances of the most volatile elements that are essential for the development of a stable climate and life.

Supplementary Readings
