

Origin and composition of the Earth

In this chapter we briefly review the origin of the Earth, from the Big Bang 14 billion years ago to the accretion of the Earth from the solar nebula some 4.56 billion years ago.

1. The Big Bang and atomic synthesis

The universe is thought to have begun as a tiny package containing all matter which burst apart about 14 billion years ago in what is known as “The Big Bang”. It is still expanding from this initial explosion. What happened before the Big Bang is unknown as is the fate of the universe – whether it will continue to expand, or whether gravitational forces will overcome the expansion and begin to recall the material to the center of mass perhaps to explode again. (Current observational evidence suggests that there is not enough mass to stop expansion though it is still possible that astronomers will find some previously-unknown mass sufficient to cause expansion to stop.)

We know the age of the universe and that it is expanding from examination of the light spectra coming to us from distant objects in the universe. The light is shifted to longer wave lengths (the “red shift”). This can be explained as a Doppler shift caused by the fact that the objects are moving away from us. Based on the rate of retreat, we can calculate that all the pieces must have been together about 14 Ga ago.

For some time after the Big Bang, the universe consisted only of gaseous hydrogen and helium – there were no stars or galaxies. All other elements were created during the life and death of stars. Normal stellar evolution produces only elements up to iron and so the heavier elements must have formed inside stars which subsequently exploded (“supernovae”), the ejected material helping to form interstellar clouds from which our Solar System subsequently grew. The Solar System is less than about 5 billion years old and large stars evolve to the supernova stage quite quickly so it is possible that many supernovae contributed to the material which makes up the planets. The heat released by gravitational collapse of the gaseous clouds into protostars is sufficient (in large enough clouds) for the core to ignite a nuclear fire. Very high temperatures are required for nuclei to overcome the repulsive forces and collide with sufficient velocity to fuse. But fusion (up to iron) releases energy and so once started, the fire keeps burning. Most stars run on hydrogen fuel converting 4 hydrogen atoms (protons) into 1 helium atom (2 protons and 2 neutrons). Some of the fusion pathways are shown in Figure 1. The Sun contains enough hydrogen to produce 10^{56} helium nuclei and is expected to burn for about 12 billion years!.

When the star exhausts its hydrogen supply, it must either step up the temperature by gravitational collapse and begin burning helium or it dies. The fate of a star depends on its size; small stars die as “white dwarfs” and large ones continue to burn successively heavier elements up to iron. Beyond iron, however, energy must be added to generate elements and we need a different mechanism for synthesizing these.

In big stars, death is the violent supernova. When the nuclear fuel is spent, the star collapses catastrophically. In the largest stars, the collapse becomes an implosion which throws off a spectacular cloud of material. It is in the supernova that elements heavier than iron are created.

The process for generating heavier elements is by “neutron capture”. During stellar collapse, a burst of highly energetic neutrons is created. If a neutron collides with iron with sufficient energy, the iron nucleus will absorb the neutron. Nuclei can be built up to the size of bismuth or even larger and then undergo radioactive decay to a stable nuclide. This process of synthesis by rapid bombardment during a supernova is called the “r-process”.

There are still some nuclides which can not be synthesized by the r-process. To generate these, we call on the neutrons which are generated as a by product of normal stellar combustion. These may also be absorbed and this so called “s-process” (s for slow) accounts for most of the remaining nuclides. The few nuclides which are not explained by the mechanisms already discussed could be created by collision with protons emitted during normal stellar combustion.

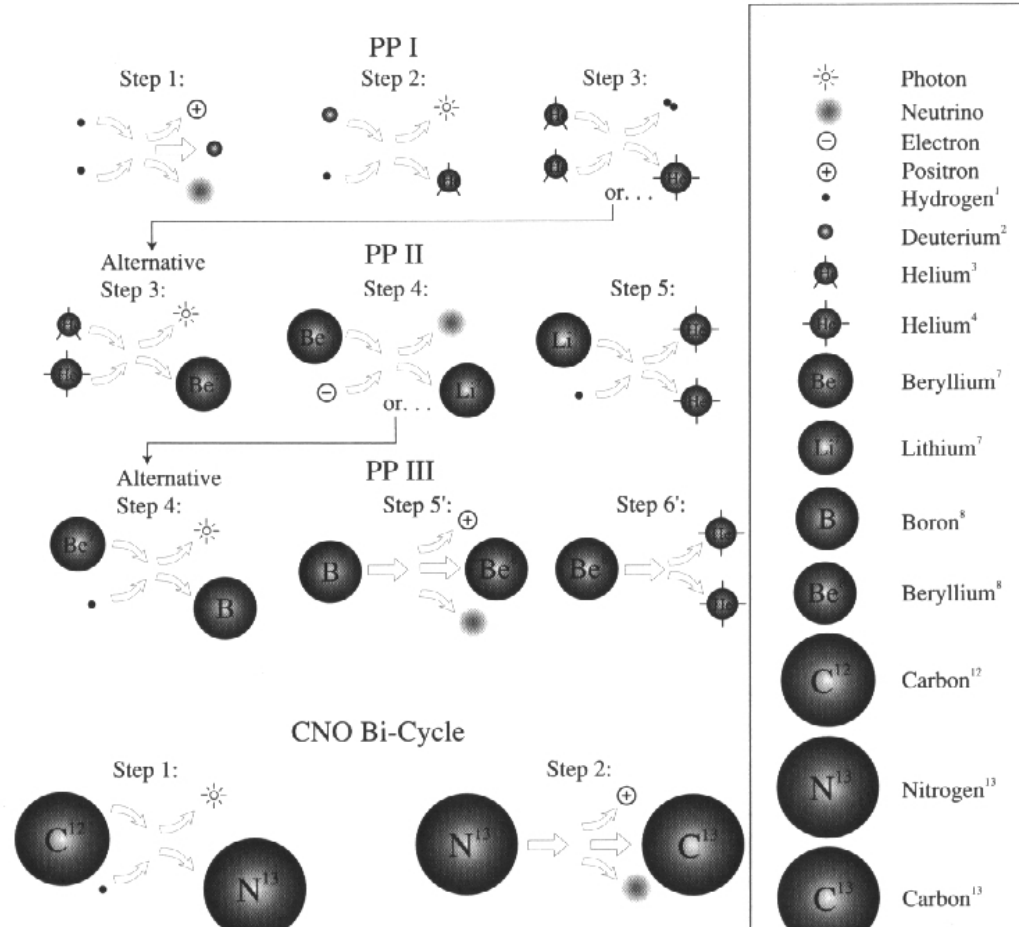


Fig. 1.1 Fusion pathways.

2. The Solar System

The Solar System is a highly structured system. For example, the planets have a common plane of revolution about the Sun which is close to the Sun's equatorial plane and planetary orbits are nearly circular. Orbital motions are all in the same sense. A table of planetary properties follows:

Object	Orbit rad. (AU)	Orbit rad. (10 ⁶ km)	Orbit period (yr)	Eccen- tricity	Inclin- ation	Axial Inc.	Period (days)	Radius (km)	density (kg m ⁻³)
Sun	-	-	-	-	-	7.2	25.4	696265	1410
Mercury	.387	57.9	.241	.206	7.0	0.0	58.6	2440	5430
Venus	.723	108.2	.615	.007	3.4	177.4	243.0	6052	5240
Earth	1.00	149.6	1.00	.017	0	23.4	.997	6378	5550
Mars	1.524	227.9	1.88	.093	1.8	25.2	1.026	3397	3940
Ceres	2.768	414.1	4.61	.077	10.6	54	.378	457	2700
Jupiter	5.203	778.3	11.86	.048	1.3	3.1	.414	71490	1330
Saturn	9.555	1429.4	29.42	.056	2.5	25.3	.444	60270	700
Uranus	19.218	2875.0	83.75	.046	0.8	97.9	.718	25560	1300
Neptune	30.110	4504.4	163.73	.009	1.8	28.3	.671	24765	1760
Pluto	39.545	5915.8	248.03	.249	17.1	123	6.387	1150	2100

The bulk of the mass (99.9%) is in the Sun (the Sun is 70% hydrogen, 28% helium and 2% of heavier

elements) but the bulk of the angular momentum is in the planets (98%). There is a radical difference between the “terrestrial planets” and the “major” planets in both mass and density. Pluto is an exception but is now thought to be a member of the Kuiper belt which is a region which extends from 29 AU to 50 AU and appears to be left over material from planetary formation (1 AU is the mean distance from the Earth to the Sun = 150 million km). As you probably have heard, Pluto has been demoted from planet status to “dwarf planet” status. Much further out is the Oort cloud which is the probably source of comets

You probably know about Bode’s Law which approximately predicts the positions of the planets. This “law” led to a search for a “missing planet” between Mars and Jupiter which led to the discovery of the asteroid belt. Asteroids are almost certainly not the remains of a planet which has broken up but collisions between asteroids can push material into Earth-crossing orbit and they are almost certainly the source of meteorites. (Meteors are usually different and are probably cometary material).

Finally, you should note that the axes of rotation of the planets are very variable in orientation relative to the orbital plane which is probably indicative of the importance of large impacts during the late stages of accretion (see below).

Only “nebula” theories are capable of explaining the observed features of the Solar System. Here is one version. An interstellar cloud enters a spiral arm of a galaxy. The resulting compression is sufficient to initiate self-contraction and the cloud divides into “proto-stars” (young stars are seen along the leading edges of spiral arms of galaxies). Contraction is accompanied by an increase in rotation (assuming some initial angular momentum) causing a flattening into a disc or “solar nebula”. The gravitational energy released by contraction causes the nebula to heat up initially though some heat is lost by radiation. The heating up continues (slowing down contraction) until grains of solid gases are evaporated. This absorbs heat allowing gravitational contraction to continue unimpeded until all material is vaporized, hydrogen is ionized, *etc.* The inner part of the nebula has now collapsed and has a temperature of thousands of degrees. The heat from this core prevents the rest of the nebula from completely collapsing. Turbulence must be invoked to stop all the angular momentum ending up in the core of the nebula; it also allows us to end up with a slowly rotating system.

Most of the mass is now in the core. There is material at planetary distances, either in a disc or in rings. These must now accrete to form the planets. Radiative cooling causes condensation of grains which fall towards the median plane a process which takes about 10 years. Chance concentrations of dust in the disc cause local aggregations of material which in turn coalesce to form planetesimals. It is estimated by computer simulation that diameters of 5 km are achievable after a few thousand years. Collisions between large planetesimals and growth by gravitational farming of the small material leads to planetary sized bodies in less than a million years. Many lines of evidence lead to the conclusion that major impacts occurred in the final stages of accretion leading to initial high temperatures and extensive melting. It is therefore probably true that chemical differentiation of planets occurred during accretion.

There is a temperature gradient within the nebula (obviously hottest near the proto-sun) which controls the composition of the condensing material as a function of radius. Mercury is anomalously dense, having only very refractory material. Venus, Earth, Mars and the asteroids are more similar to one another. (Mercury’s high density is actually most plausibly explained by removal of much of the silicate mantle by collision with a large body). The major planets are very different in composition being largely gaseous. Part of the difference could result from chemical separation caused by intense solar radiation which blew out the more volatile elements to the outer solar system.

3. The chemical composition of the Sun and the Earth

One reason for looking at the origin of the Solar System is to get an idea of the likely composition of the Earth (the Earth’s crust is unrepresentative of the average composition since chemical fractionation occurs during the magmatic processes which form the crust). We would therefore like to know the composition of the solar nebula. Since nearly all the mass is in the Sun, the abundances of the elements in the Sun should also be representative of the abundances in the nebula. Solar abundances are determined by absorption spectroscopy. Atoms present at the Sun’s surface absorb energy at characteristic wavelengths, leaving dark lines in the light’s spectrum. The spectral lines of light from the sun are produced by the elements

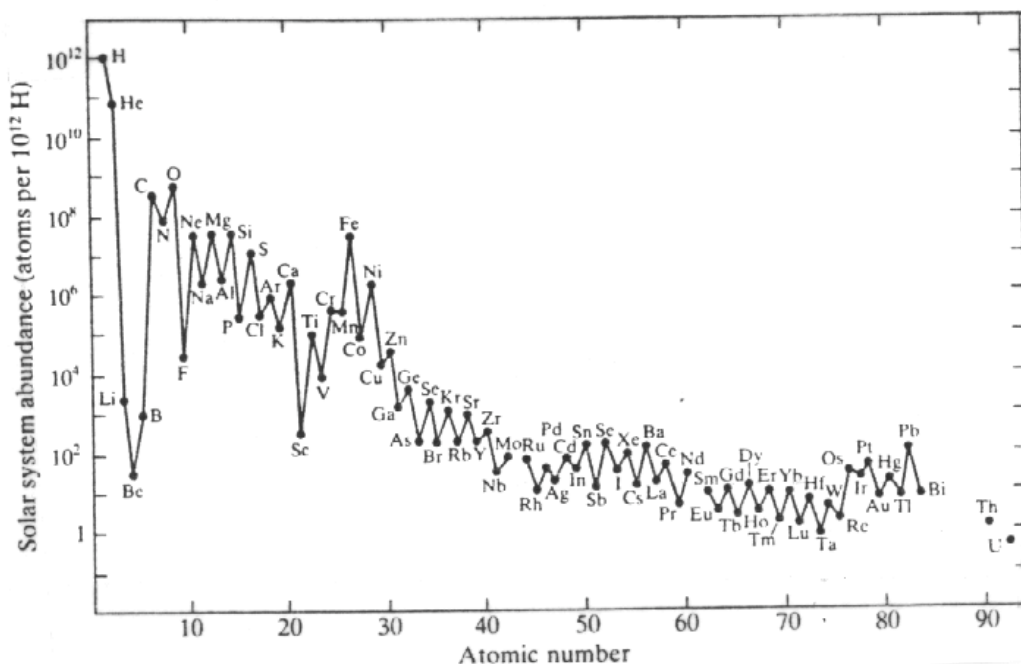


Fig. 1.2 Solar System abundances of the elements, showing the relative number of atoms present on a logarithmic scale, normalized to the value 10^{12} for hydrogen

contained at the sun's surface. We assume that the abundances that we measure near the surface of the Sun are representative of the solar nebula. This is a reasonable assumption since nuclear synthesis during the evolution of the Sun should only affect the composition of the deep interior (with the exception of Li, Be and B which are destroyed during hydrogen burning and so are depleted near the Sun's surface). The relative abundances of the elements are shown in Fig 1.2.

The main features of Fig. 1.2 make sense based on our discussions of element synthesis and solar evolution. H and He are most abundant since these are the primary constituents of the primitive universe. Li, Be and B are depleted due to subsequent nuclear burning. The elements up to Fe are most abundant since these are generated during normal stellar evolution. These elements include nearly all those which go up to make the silicate mantles of terrestrial planets. Furthermore, the high abundance of iron makes it a likely candidate for being a major constituent of planetary cores. Heavier elements than iron are less abundant since they are only formed under extreme (supernovae) circumstances.

Another clue as to the chemical composition of the Earth comes from the study of meteorites. Most meteorites that have been found are "chondrites" which are undifferentiated members of the "stony" meteorites (Table 1). Irons and achondrites are reminiscent of the "core" and "mantle" of a body while stony-irons are a mixture of the two.

Chondrites are most interesting since they seem to be the most primitive. Nearly all chondrites contain "chondrules" or near-spherical glassy inclusions. Most chondrites have been recrystallized to some extent leading to mineral assemblages in closer chemical equilibrium. The chondrites which are the furthest from equilibrium and so are the most primitive are the carbonaceous chondrites which contain significant amounts of water (of crystallization). They have not been heated above 180°C . No terrestrial rocks have fabrics like the chondrites.

Irons have substantial amount of nickel in them and interesting crystal structures can develop as an iron-nickel mixture cools. Above about 900°C only one iron-nickel alloy exists (taenite) but at lower temperatures another alloy (kamacite) with a different crystal structure also develops. The kamacite appears

				<i>Observed falls</i>		
				(%)	(No.)	
differentiated meteorites	{	irons	}	1.1	8	
		stony-irons		3.2	22	
		achondrites		8.3	57	
undifferentiated meteorites	chondrites	{		stones	{	87.4

Table 1.2 Classification of meteorites

in the form of thin sheets which grow through the original taenite crystal in special directions. Etching of iron meteorites reveals this interlacing of crystal structures (called a Widmanstätten pattern). As cooling continues, the compositions of the crystallizing alloys change, which is possible if nickel can diffuse through the crystal lattice. At sufficiently low temperatures, the diffusion of nickel is inhibited. The distribution of nickel within the various alloys allows an estimate of the cooling rate of the meteorite to be made. These cooling rates are 1 to 10 degrees per million years which are relatively slow and suggest the presence of an insulating mantle around the iron body while it cooled. A body of only a few hundred kilometers in diameter is required to give the observed cooling rates.

The differentiated meteorites (achondrites and irons) are probably fragments produced by collisions of larger asteroids (the current largest, Ceres, is about 1020km in diameter). This is supported by cosmic-ray exposure ages which suggest break up of parent bodies long after their original formation.

Solar abundances are very similar to elemental abundances in chondritic meteorite abundances (Fig. 1.3) so these meteorites are considered to be primitive material (also meteorites are old with ages comparable to the age of the Earth). Since solar abundances and chondritic meteorites are so similar, it is reasonable to suppose that the Earth has a similar overall composition. The crust, however, has quite a different average composition than that of the bulk Earth or of carbonaceous chondrites. The differences can be understood in terms of the chemical fractionation processes which have occurred to form the crust. The crust has been derived from the mantle by partial melting and so does not have the same composition as the bulk of the mantle. The crust is enriched in "lithophilic elements" (Na, Al, Ca, K, Sr, Rb, *etc.*). Chalcophilic and siderophilic elements which would be preferentially partitioned into the core are Zn, Cu, Cd, Ag, Ni, Pd, *etc.* The Earth therefore may be quite chondritic in character (actually, the best fit is to the carbonaceous chondrites though with most of the volatiles lost). The bulk earth model derived from carbonaceous chondrites and solar abundances is also consistent with the information we glean from mantle derived rocks and the composition of moderate to low volatility elements in the sun.

4. Accretion of the Earth

Accretion of the Earth may have been somewhat affected by the sequence of condensates from the solar nebula. At the radius of the proto-Earth, the pressure is guessed to have been about 10^{-4} atmospheres. Thermodynamic data can be used to predict the condensation series (Fig 1.4). Note that phases which condense out at high temperatures are called "refractory" while phases which condense at low temperatures are "volatiles".

The Earth contains volatiles such as water and CO₂ so the initial material which accreted to form the Earth evidently condensed down to temperatures of about 100° C. Since metallic iron condenses early in the sequence, there may be some differentiation of the planet going on during accretion while material is still condensing. There used to be a big argument about whether accretion was homogeneous or heterogeneous. In homogeneous accretion, a fairly uniform planet is envisaged with subsequent separation of the core. In heterogeneous accretion, a substantial iron core is thought to develop before later accretion of the mantle. These different hypotheses were developed when it was thought that accretion would favor one dominant body much larger than any others. While late impacts might be large, they would not substantially melt the

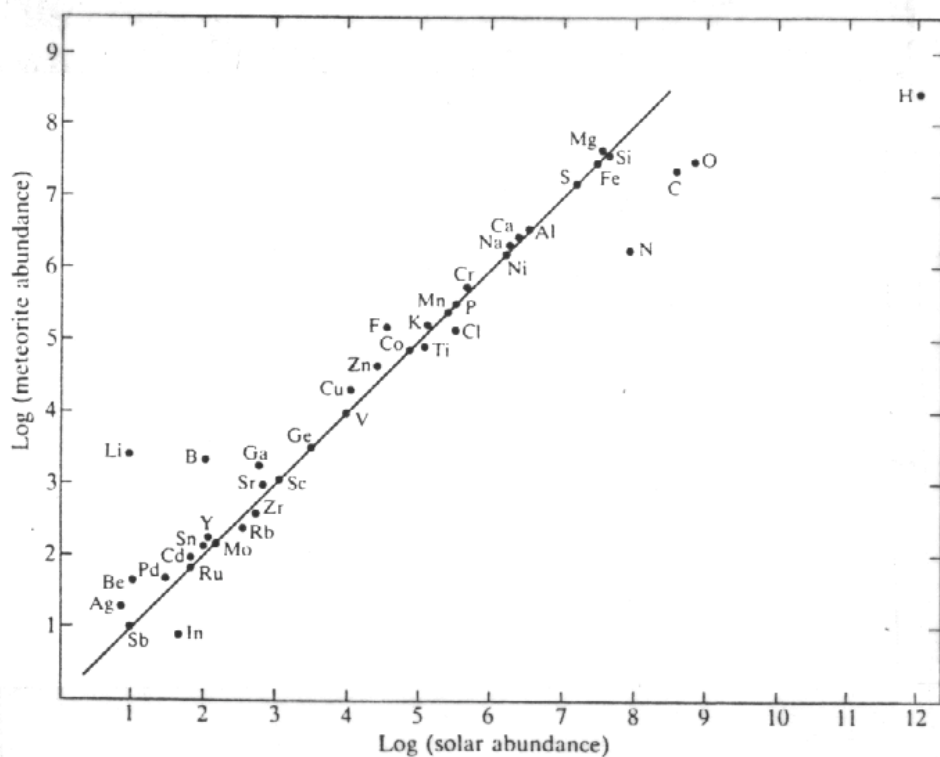


Fig. 1.3 Comparison of Solar abundances to those in carbonaceous chondrites

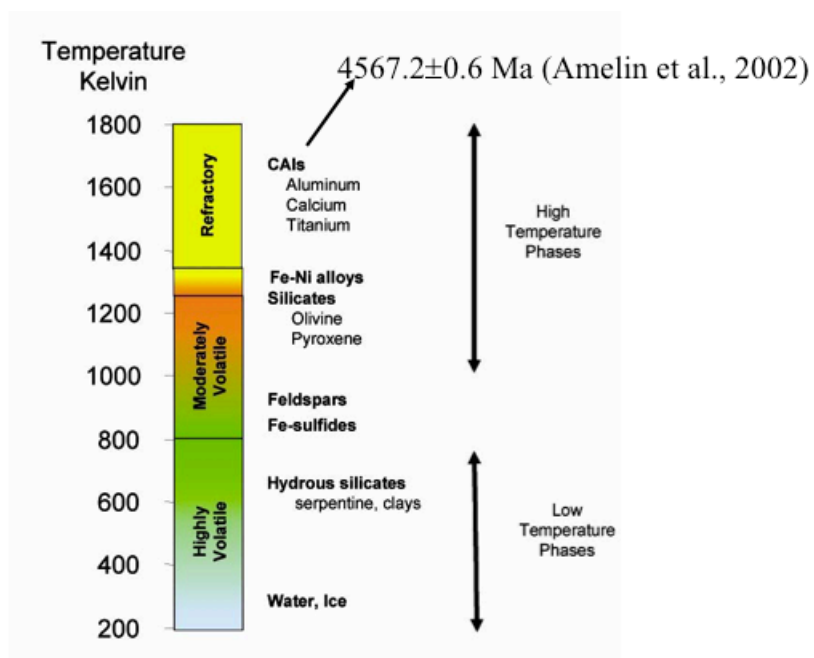


Fig. 1.4 Condensation sequence in the solar nebula

Earth. This idea is now thought to be wrong. Computer simulations indicate that many large bodies are produced and, indeed, it is now thought that the origin of the Moon was caused by impact with a Mars-sized object. Such an impact probably would melt the whole mantle. It therefore seems that large impacts during accretion would promote differentiation of the planet during accretion and no catastrophic core formation event occurred. (Note that the decay of short-lived radioisotopes can also cause substantial heating). This theory implies that most of the Earth was at least partially molten after completion of the accretion process.

5. Impact origin for Moon

Several theories for the origin of the Moon have been proposed though until recently none has been capable of explaining all the observed features of the Moon–Earth system. The major features to be modeled are summarized in the following list.

- 1) the large mass of the Moon (much bigger relative to its parent than a satellite of any other planet)
 - 2) the high angular momentum of the Earth-Moon system. Note that the Moon was once much closer (possibly a few Earth radii away) but tidal interactions have decelerated the Earth and accelerated the Moon and expanded its orbit. Current calculations put the Moon at about ten Earth radii 4.5 billion years ago.
 - 3) The Moon is depleted in volatiles, much more severely than the Earth and perhaps enhanced in refractory elements. It has a low density and so must be depleted in iron. If it has a core at all, it must be very small and iron must also be depleted in silicates.
 - 4) Oxygen isotopic signatures are similar for Earth and Moon suggesting a common origin.
 - 5) The amount of light plagioclase-rich highland rock on the Moon requires that at least 200 km of the Moon was partially melted implying the existence of a magma ocean on the Moon early in its history.
- Many theories which attempt to explain these observations have been postulated, a partial list follows.
- 1) Intact capture of the Moon. This is dynamically impossible to achieve unless the Moon has an almost identical orbit to the Earth (even then it is extremely improbable requiring some dissipative process during close encounter). Capture is usually invoked to explain the different iron contents but both bodies would have to be formed at the same distance from the Sun and so should be similar.
 - 2) Coaccretion. This model has difficulties with the compositional differences and the angular momentum. In this model, planetesimals are captured and form a disc with energetic collisions between planetesimals causing removal of volatiles. Gravitational instabilities cause the accretion of one or more moonlets, subsequent coalescence of large moonlets can give enough energy to form the magma ocean. The big problem with this idea is that computer simulations of impact accretion by small bodies shows that no net angular momentum is transferred to the accreting body. To get a rotating Earth requires accretion from bodies with a small range of orbital parameters.
 - 3) Fission. Modern versions of this hypothesis requires fission caused by a rotational instability. In this theory, the Earth rotates with a period of about 2.6 hours but core formation causes a sudden acceleration with subsequent ejection of the Moon. Computer simulations show that fission would result in dispersed material which would form a disc. Another point is that to get the chemistry right, core formation on the Earth would have to be 97% complete so that we need the instability to occur right at the end of core formation but not before! Finally, if the hypothesis is correct, the Earth-Moon system should have about four times as much angular momentum as it now has, indeed where did the pre-fission Earth get its initial large angular momentum?
 - 4) Large impact (Fig. 1.5). This hypothesis was not considered seriously for a long time because early semi-analytic theories of Earth accretion found that only one large body accumulated from small bodies (1/1000 Earth mass) which would not be large enough to eject enough material to form the Moon. Also, it was expected that such material would go into ballistic orbit and re-accrete onto the Earth after one revolution. Computer simulations now show that there may be on the order of 100 Moon sized objects or larger with several planetesimals approaching 1/10 Earth mass (*i.e.* Mars sized) in the inner solar system. These bodies are swept up to form the inner planets but note that an impact at about 5 km/s by a Mars-sized body on a proto-Earth is big enough to eject enough material to form the Moon. More importantly, the material is ejected as vapor which expands as it recedes and the material would be

accelerated into orbit (also the center of mass of the system is changed after such a large impact, helping to get material into orbit). Gravitational torques arising from the asymmetrical shape of the Earth after impact are also capable of helping to accelerate material into orbit. Such an impact is also capable of giving the angular momentum of the Earth-Moon system. The disk is expected to cool and, after about 100 years, gravitational instability causes a collapse into moonlets which coalesce to form the Moon. The Moon was probably partially or wholly molten when it formed. The model can also explain the iron-poor nature of the Moon since the core of the impactor tends to be assimilated by the core of the Earth (assuming both are differentiated).

Other models are possible, or hybrids such as a model where capture is followed by disintegration (subsequently shown to be unlikely since the body is not exposed to disruptive tidal forces sufficiently long to give significant disintegration). None now seem as likely as the giant impact model which may seem to require a felicitous event but which is consistent with the unique nature of the Earth-Moon system. The total energy in a Mars-sized impact is about 5×10^{31} joules which is enough to raise the temperature of the Earth by 10,000 K. Of course, energy transfer is not 100% efficient and temperature rises of 3000 – 4000 K are more likely (enough to completely melt the mantle). The resulting dense atmosphere would also cause slow cooling. Perhaps the Earth, as well as the Moon, had its own magma ocean. While there is no evidence of the existence of such a magma ocean, it is not clear if any evidence could be expected to survive the intense tectonic activity of the mantle.

6. Observational constraints on the timing of solar system formation.

Radioactive decay of both long- and short-lived isotopes can be used to put time constraints on the very early history of the solar system. The highest temperature condensates in primitive meteorites are so-called Calcium-Aluminum Inclusions (CAIs) and are probably the first solid materials in the solar system. These have been dated using the decay of long-lived radioactive isotopes such as the decay of ^{87}Rb to ^{87}Sr by beta decay. To remind you how this works, we start from the formula governing the decay of rubidium as a function of time (t):

$$^{87}\text{Rb}(t) = ^{87}\text{Rb}(0)e^{-\lambda t}$$

where λ is the decay rate which is related to the "half-life" by $\lambda = 0.693/t_H$. The half-life of this particular isotope decay is 47 billion years so this is a very useful system for looking at things which happened about 5 billion years ago. The amount of strontium at time t is therefore given by the initial amount plus the amount generated by the decay of rubidium:

$$^{87}\text{Sr}(t) = ^{87}\text{Sr}(0) + ^{87}\text{Rb}(0) - ^{87}\text{Rb}(0)e^{-\lambda t}$$

where the last two terms give the Sr converted from Rb . Rearrange and divide by a stable isotope ^{86}Sr to give:

$$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}(t) = \frac{^{87}\text{Sr}}{^{86}\text{Sr}}(0) + \frac{^{87}\text{Rb}}{^{86}\text{Sr}}(0)(1 - e^{-\lambda t})$$

We can measure the amount of parent (e.g. ^{87}Rb now in the rock and the amount of daughter (^{87}Sr) now in the rock at time t so we use the first equation above to give:

$$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}(t) = \frac{^{87}\text{Sr}}{^{86}\text{Sr}}(0) + \frac{^{87}\text{Rb}}{^{86}\text{Sr}}(t)(e^{\lambda t} - 1)$$

This is the equation of a straight line with an intercept which gives the initial amount of ^{87}Sr and a slope which gives the age. An application of this techniques to CAIs is given in figure 1.6 and more recent work gives an age is 4567.2 ± 0.6 Ma. We take this age as the date of the beginning of the solar system.

This example of using a long-lived isotopic system is probably familiar but it may be less obvious how you use short-lived systems. One example is Hafnium – Tungsten ($^{182}\text{Hf} - ^{182}\text{W}$) which has a half-life of 9 Ma. Clearly, the amount of (^{182}Hf rapidly decreases to an insignificant amount (we say it is "extinct"). The

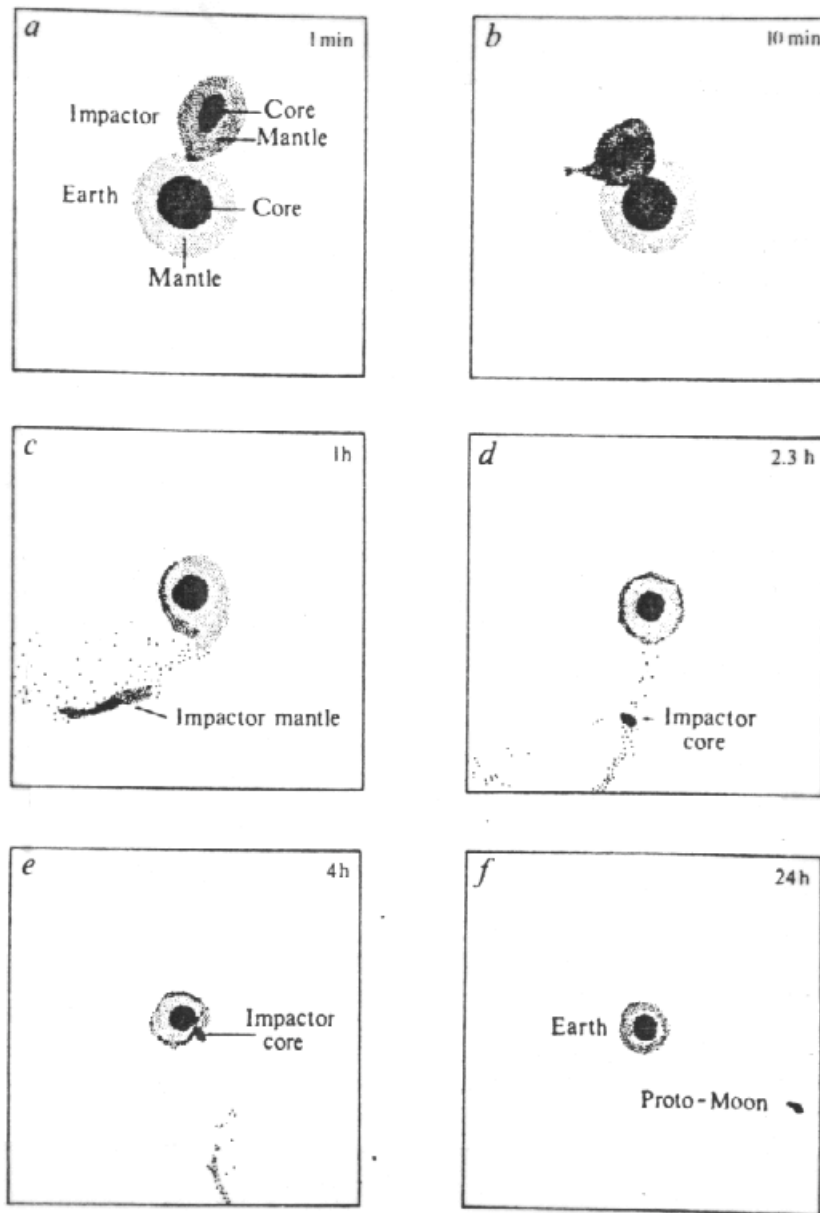


Fig. 1.5 Computer simulation of the formation of the Moon by a giant impact. This reconstruction shows the events following the oblique collision of an object slightly larger than Mars at a velocity of 5 km/s. Both the Earth and the impactor are differentiated. Following the collision, the impactor is spread out in space (c) but the debris clumps together. The iron core of the impactor separates (d) and accretes to the Earth (e) about 4 hours after impact. Nearly 24 hours later (f), a silicate lump of lunar mass is in orbit, derived mainly from the mantle of the impactor.

reason that this system is interesting is that the parent and daughter have very different chemical affinities. Hafnium is said to be highly "lithophile" which means it stays in the silicate part of the mantle. Tungsten is moderately "siderophile" (which means iron-loving) and so will preferentially go into the core.

Consider the equation above. Let D_r be the radioactively generated daughter and let D_s be a stable isotope of the daughter. Let P_r be the radioactive parent and P_s be a stable isotope of the parent. The above

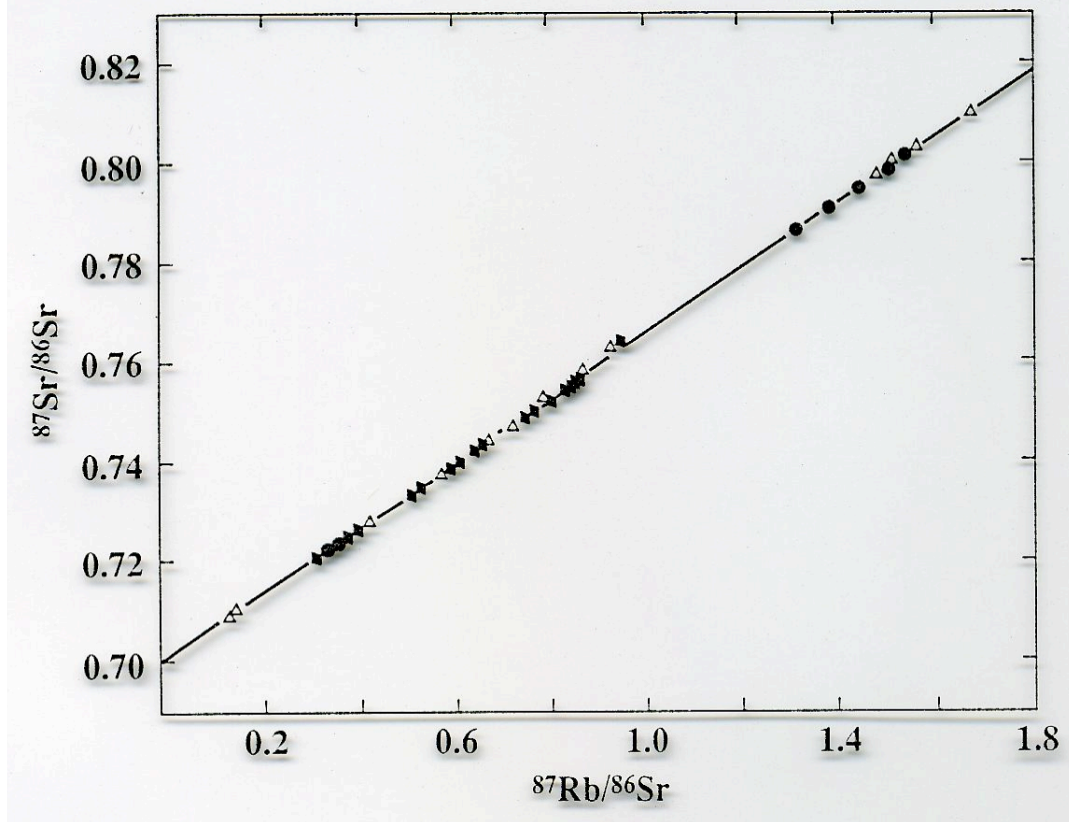


Fig. 1.6 Rb/Sr dating of a number of meteorites whose appearance and chemical composition suggest they have not been altered in planets. The slope of the curve yields an age of 4.56 billion years

equation for long-lived isotopes now reads

$$\frac{D_r}{D_s}(t) = \frac{D_r}{D_s}(0) + \frac{P_r}{D_s}(0)(1 - e^{-\lambda t})$$

For extinct radionuclides, this becomes

$$\frac{D_r}{D_s}(t) = \frac{D_r}{D_s}(0) + \frac{P_r}{D_s}(0)$$

Unfortunately, P_r doesn't exist anymore so we introduce a stable isotope of the parent to write

$$\frac{D_r}{D_s}(t) = \frac{D_r}{D_s}(0) + \frac{P_r}{P_s}(0) \frac{P_s}{D_s}$$

We can measure D_r/D_s at time now and we can measure P_s/D_s which is independent of time so, again, this is a straight line equation whose slope and intercept tell us about the initial amounts of ^{182}Hf and ^{182}W (for the Hafnium-Tungsten system, $D_r = ^{182}\text{W}$, $D_s = ^{184}\text{W}$, $P_r = ^{182}\text{Hf}$, and $P_s = ^{180}\text{Hf}$).

Consider now a scenario where core formation occurs sufficiently long after 4.567Ga that all the ^{182}Hf is extinct. Then terrestrial samples should look like the carbonaceous chondrites. Early measurements of tungsten isotopes indicated that this was the case so that core formation must have been a long drawn-out process (at least 60Ma). New measurements (fig 1.7) show that there is more ^{182}W in terrestrial samples than in chondritic meteorites.

To explain this, ^{182}Hf must have been still alive when core formation occurred. The data suggest a mean time of core formation of 11Ma and completion within 30Ma (after 4.567Ga). We take this to mean that the Moon forming impact occurred about 30Ma after the formation of solid matter in the solar system. This is

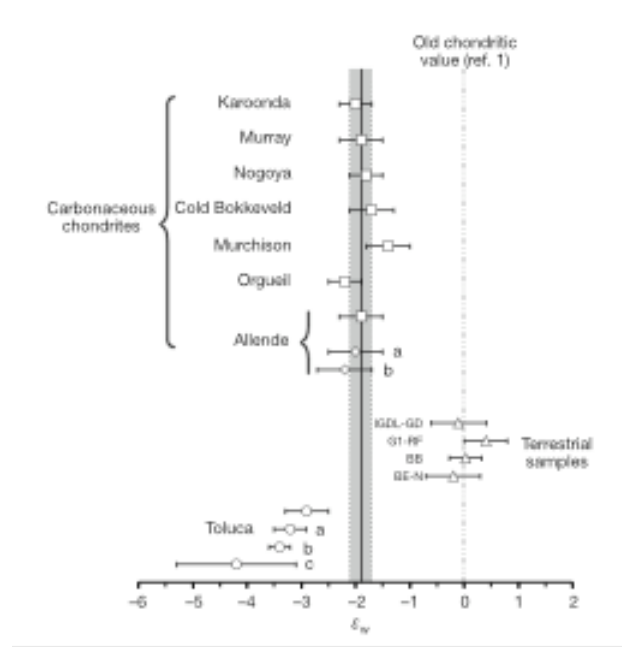


Fig. 1.7 Measurements of $^{182}\text{W}/^{184}\text{W}$ ratios in meteoritic and terrestrial samples. The ϵ notation is commonly used in geochemistry where changes can be very small. Here,

$$\epsilon_W = \left[\left(\frac{^{182}\text{W}/^{184}\text{W}}{\text{sample}} \right) / \left(\frac{^{182}\text{W}/^{184}\text{W}}{\text{standard}} \right) - 1 \right] \times 10^4$$

also consistent with dates of lunar highland rocks which are about 4.45Ga – i.e. about 100Ma younger. The oldest known terrestrial rock is about 4.1Ga old.

7. Later developments in solar system organization

Since the introduction of the "Nice" model in 2005, there have been several models of solar-system evolution which entail quite radical planetary migrations in the first 900Ma or so. Such models can explain the late heavy bombardment of the inner solar system, the formation of the Oort cloud and the existence of the Kuiper belt. The original Nice model has the four giant planets (Jupiter, Saturn, Uranus, and Neptune) starting in near circular orbits between 5.5 and 17 AU - much more closely spaced than at present. The proto-Kuiper belt extended from the outermost giant planet to a distance of 35AU and consisted of about 35 earth masses of rock and ice. Gravitational interactions of planetesimals on the inner edge of the belt with the outermost giant cause them to be scattered inward while the planet moves out to conserve angular momentum. This process continues with each successive planet so moving their orbits out until the objects reach Jupiter whose large gravitational effect can but them in highly elliptical orbits or even eject them from the solar system. Such objects could make up the Oort cloud. This makes Jupiter move slightly inwards.

After several hundreds of million years, Jupiter and Saturn cross their mutual 1:2 mean-motion resonance. This resonance is destabilizing and causes increasing orbital eccentricities and shifts Saturn out to its present position. This also pushes Neptune and Uranus out (they might even switch positions!) and the ice giants plough into the proto-Kuiper belt scattering material everywhere, including into the inner solar system resulting in the late heavy bombardment. Roughly 99% of the mass of the proto-Kuiper belt is removed by this process.

The original Nice model has some difficulties reproducing the current state of the Kuiper belt. Some more recent and more successful models start off with 5 giant planets with one getting (partially?) ejected from the solar system. There have been recent suggestions of a "Planet IX" from observations of orbital variations in Kuiper belt objects that could be just such an object.

8. Exoplanets

The first exoplanet was unambiguously identified in 1992 and was an example of a "hot Jupiter", i.e., a very large planet very close to its sun, usually with very fast rotation rates. Since the advent of the Kepler Space Telescope, the number of confirmed exoplanets is now 2098 in 1342 planetary systems. There are 509 known to have more than one planet and some planetary systems have as many as 7 planets. (These numbers are valid as of March 24th 2016 and seem to increase daily). Many of the "hot Jupiter" planetary systems are not "solar-system" like in that planets aren't always in a plane and may not all orbit in the same direction. As more planetary systems are discovered (mainly by Kepler), it is clear that "hot Jupiters" are in the minority and most systems are similar to our solar system. In any case, the Nice model suggests that planetary interactions can be important – particularly with very massive planets – perhaps making a great variety of final outcomes possible

9. Summary of the origin of the solar system

The evidence suggests that the Earth has an overall composition close to that of carbonaceous chondrites which are themselves similar to the composition of the Sun (but with the loss of some volatiles). After accretion, the Earth was hot with a substantially molten mantle due mainly to the effects of impacts with large bodies. Differentiation of the core was probably contemporaneous with accretion and was complete by about 30Ma after the first solid material formed in the solar system. This would also be the time of the giant Moon-forming impact (fig 1.5).

The relative abundance of elements suggests that the core of the Earth is predominantly iron while the mantle is made of iron-magnesium silicates.