

CHAPTER 1

Origin, composition and structure of the Earth

The emphasis in this class is on global geophysics. We will be interested in understanding large scale features of the Earth though the physical formulations and mathematics we use can often be fruitfully applied to small scale problems. In this chapter we set the stage by reviewing briefly the origin of the Earth, from the Big Bang 16 billion years ago to the accretion of the Earth from the solar nebula some 4.55 billion years ago. We turn then to a discussion of the major structural divisions of the Earth.

1.1 The Big Bang and atomic synthesis . The universe is thought to have begun as a tiny package containing all matter which burst apart about 16 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 16 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). The energy released by this fusion is phenomenal. Using Einstein’s famous equation: $E = mc^2$, where c is the velocity of light, we may calculate the energy produced, E , from the mass lost, m . The mass of 4 hydrogen atoms is 6.696×10^{-24} gm and the mass of 1 helium atom is 6.648×10^{-24} gm so the mass loss of 0.048×10^{-24} gm generates about 4×10^{-12} Joules. This is enough to power a 40 watt light bulb for 10^{-13} seconds! This may not seem much but 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.

1.2 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)

You probably know about Bode’s Law (Fig 1.1) 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).

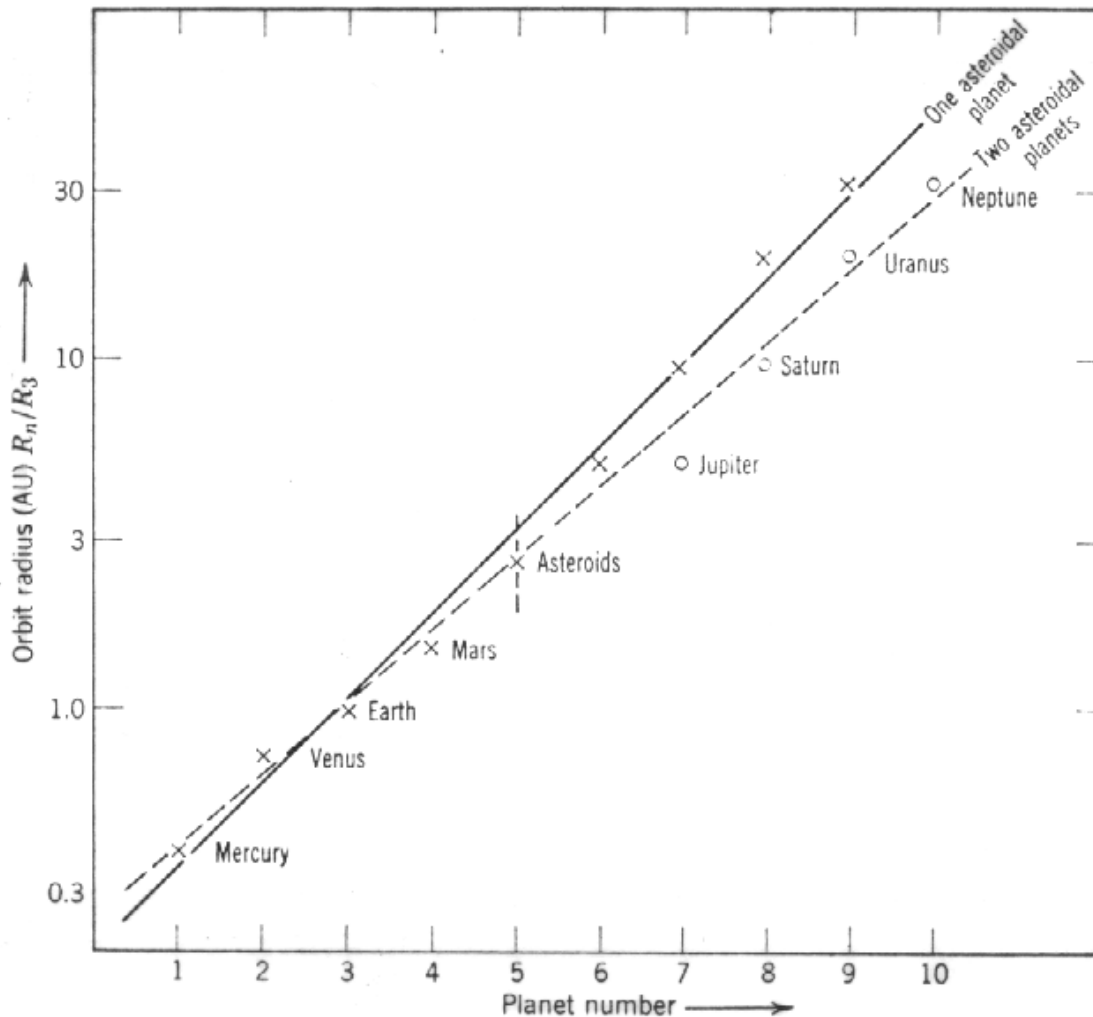


Fig. 1.1 Radii of the planetary objects, plotted to show the geometrical progression ($r = r_0 p^k$ where k is planetary index). Crosses and the solid line apply to the assumption that there is one “missing” planet; circles and the broken line assume two missing planets.

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 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.

1.3 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.

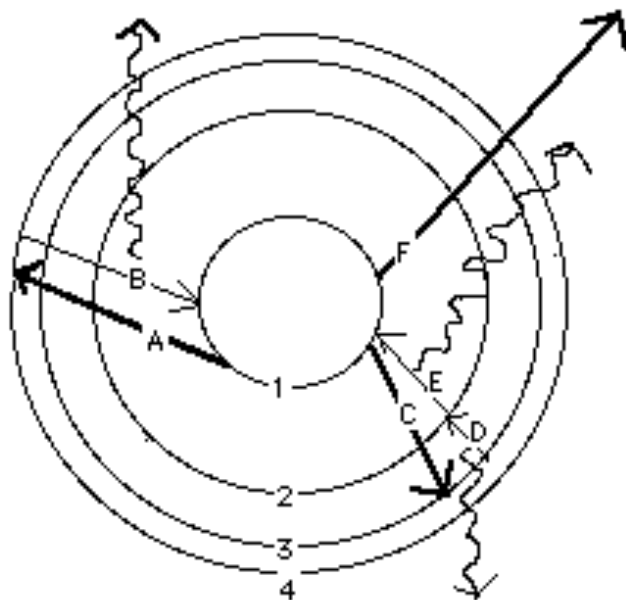


Fig. 1.2 Absorption and emission

In Figure 1.2, we illustrate atomic energy absorption and emission. The electron is normally in the lowest energy state (level 1). The atom may absorb energy quantum A and be moved to level 4. It may

then drop back down to level 1 emitting a photon (B) of the same energy. Alternatively, it may drop in two steps as shown by quantum energy jump C followed by drops D and E. If the atom absorbs quantum F, the electron is lost entirely. The spectral lines of light from the sun were produced by the elements 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 1.3.

The main features of Fig. 1.3 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.

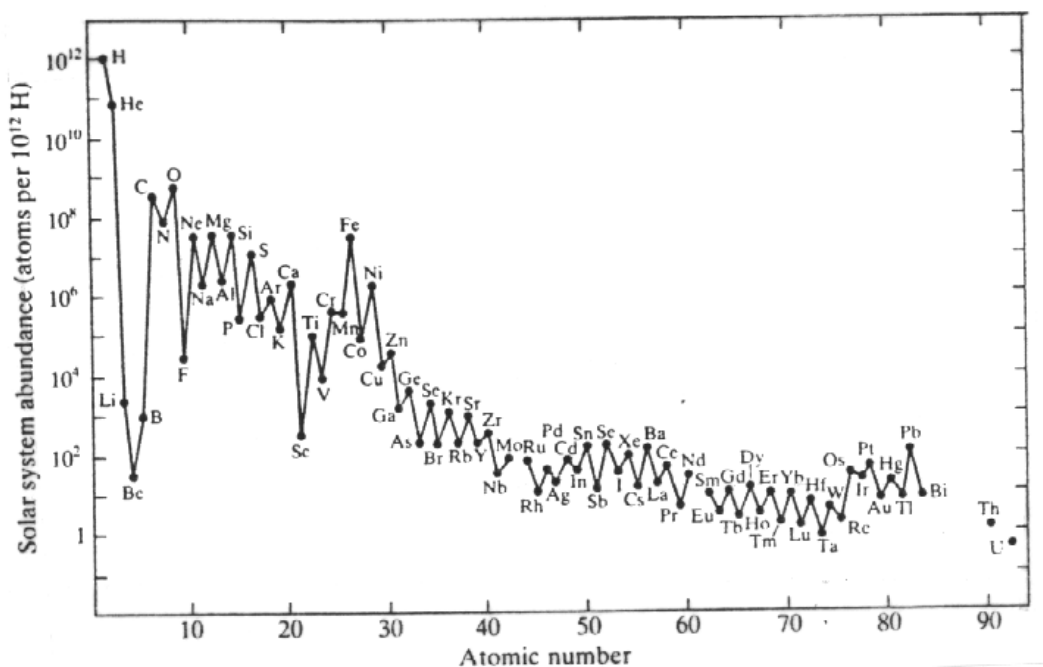


Fig. 1.3 Solar System abundances of the elements, showing the relative number of atoms present on a logarithmic scale, normalised to the value 10^{12} for hydrogen

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.

			<i>Observed falls</i>	
			(%)	(No.)
differentiated meteorites	irons	stones {	1.1	8
	stony-irons		3.2	22
	achondrites		8.3	57
undifferentiated meteorites	chondrites	}	87.4	602

Table 1.2 Classification of meteorites

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 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. 1.4) 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.

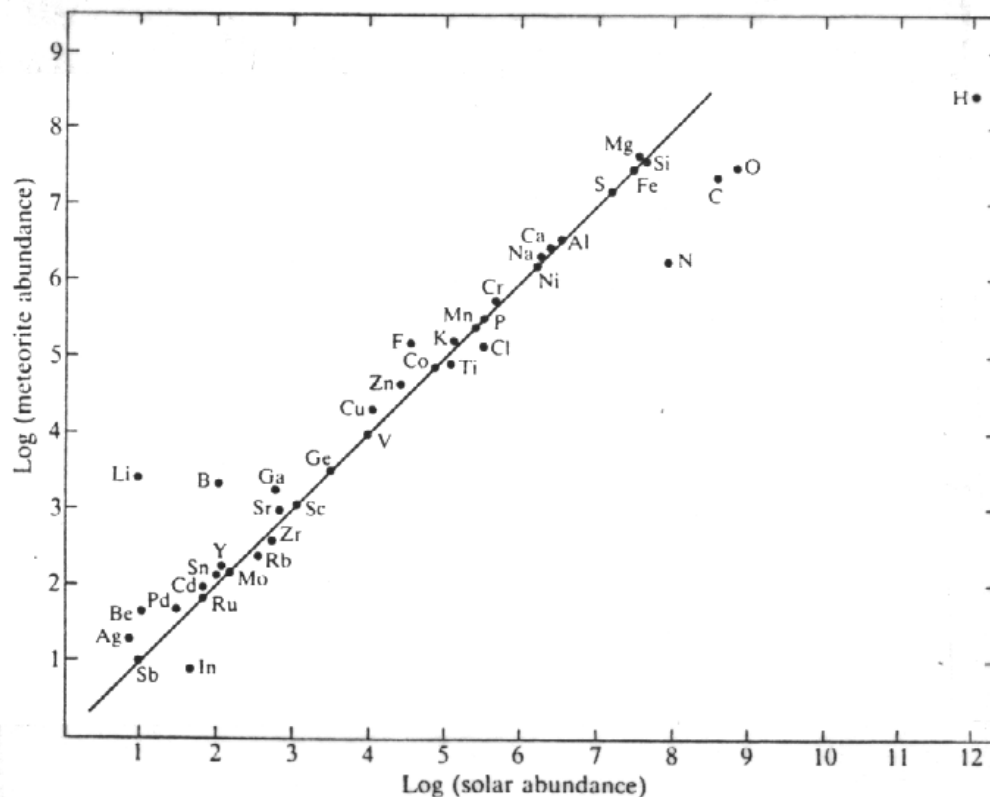


Fig. 1.4 Comparison of Solar abundances to those in carbonaceous chondrites

1.4 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 (Table 1.3).

Table 1.3 Temperature of condensation of solids in a nebula with hydrogen gas at a pressure of 10^{-4} atm

Corundum	1680K
Spinel	1440K
Iron metal	1360K
Olivine	1350K
Pyroxene	1300K
Feldspar	1000K
Iron sulfide	650K
Ice and methane	$\leq 270K$

The Earth contains volatiles such as water and CO_2 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 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. We can use radioactive clocks to estimate the age of the solar system by looking at meteorites which all seem to have formed at about the same time, ~ 4.56 Ga ago. We suppose that the Earth formed at about the same time (although the oldest surviving crustal rock is only about 4.1 Byr) because the accretion process is quite rapid and probably takes only a few hundred thousand years to complete.

1.5 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 modelled 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 lithosphere.

1.6 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 so it is unlikely that any massive core-formation event occurred. The relative abundance of elements suggests that the

core of the Earth is predominantly iron while the mantle is made of iron-magnesium silicates.

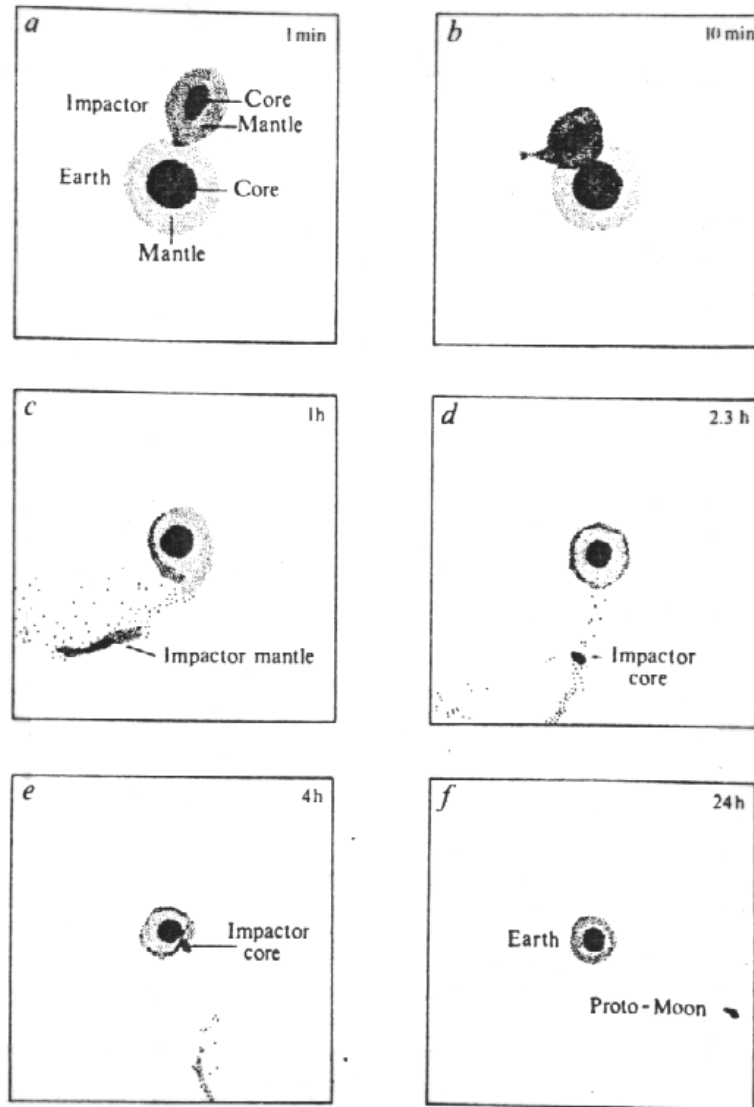


Fig. 1.5 Computer simulation of the formation of the Moon by a giant impact. This reconstruction shows the events following the oblique collision of an object slightly larger than Mars at a velocity of 5 km/s. Both the Earth and the impactor are differentiated. Following the collision, the impactor is 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.

1.7 Major structural divisions of the Earth . Now that we have some idea of how the Earth formed, it is useful to summarize what we know about the major structural divisions of the Earth, so we can get a picture of the body with which we are dealing. Later we will learn that the Earth is not a static body but is extremely dynamic. The processes of mantle convection and the resulting

plate tectonics allow the Earth to continue to evolve with time.

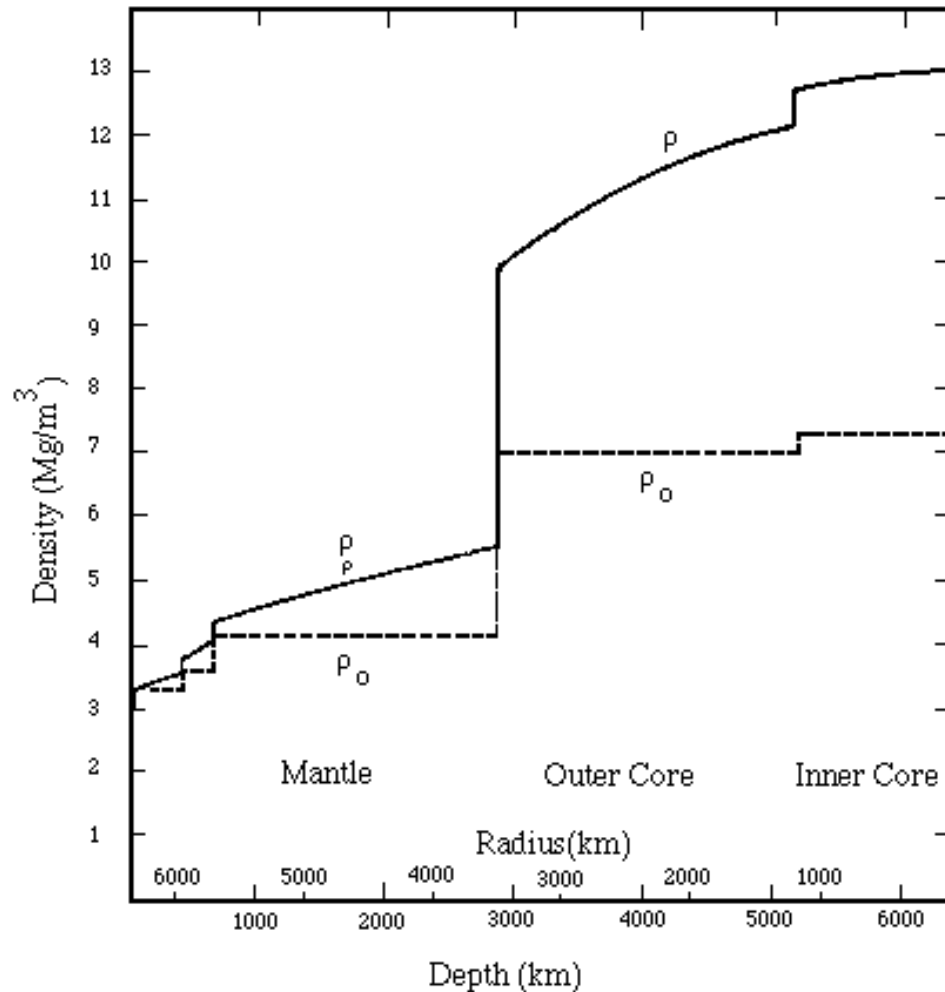


Fig. 1.6 Density profile of the Earth (solid line) with the extrapolated zero pressure, room temperature density (dash)

A model of the variation of density with depth is shown in Figure 1.6. The major subdivisions are the crust, mantle, outer core and inner core; the mantle is usually divided into a lower and upper part.

The outermost layer of the Earth is the crust. The crust may be separated into oceanic and continental types which are dominantly basaltic and andesitic in average composition respectively. Oceanic crust is some 7 km thick and is relatively denser than the thicker (30–60 km) continental crust. The oceanic crust undergoes continual renewal, having a maximum age of less than 200 Ma. In contrast, continental rocks as old as 4.1 Ga have been found.

Below the crust is the mantle. Though we divide the mantle into an upper and lower part, the division between the two is not well defined. The upper mantle is characterized by abrupt changes in properties at certain depths (410 and 660 km are the depths of the major jumps). If the lower mantle contains such jumps they are small and presently unresolvable. The properties of the lower mantle are consistent with those of a homogeneous material though there could be

some complexity in the structure near the core-mantle boundary.

The discontinuities in upper mantle structure are thought to be caused by major structural rearrangements (phase changes) in the material as a result of increasing pressure with depth. The dominant elements in the mantle are silicon, oxygen, iron and magnesium. They form rocks made principally of the minerals olivine and pyroxene in the uppermost part of the upper mantle. These minerals transform to a spinel structure and garnet at the pressure and temperature conditions at the 410 km discontinuity. The discontinuity at 660km probably reflects another structural change to a silicate perovskite structure with some oxides. Most people regard the 660 km discontinuity as the boundary between upper and lower mantles though phase changes probably still occur down to a depth of about 750km. (To confuse matters further, some people regard the upper mantle as the mantle above 410 km and the region between 410 and 660 is called the "transition zone")

The material of the mantle behaves as an elastic solid to seismic disturbances – however, it behaves as a viscous fluid on long time scales ($10^{11} \rightarrow 10^{17}$ sec). Such a material is called a viscoelastic material and several models are available for analyzing its properties. It is the slow motion of this viscous fluid that is responsible for many of the geological and geophysical phenomena that we observe. The causes and effects of this motion are the subject of this class.

The outer core is a spherical shell whose outer radius is about 3480 km. The pressure increases with depth in the Earth because of the increasing amount of material pressing downwards. This increase in pressure squeezes or compresses the material so the mass/unit volume (density) increases. The density distribution in the outer core is consistent with that of a material of roughly uniform composition undergoing compression because of the increasing pressure. It need not reflect a change in composition of the material with depth.

From consideration of the relative abundances of the elements in the solar system (and the fact that the crust and mantle are inferred to be severely depleted in iron), we conclude that the core is most likely composed dominantly of iron. The study of meteorites suggests that some nickel may be present. From comparison with high pressure experimental data, we know that there are some lighter "impurities" in the core as well. Candidates for the main impurity are silicon, oxygen, sulphur or carbon. (The choice between these depends upon which model of the formation of the Earth you prefer.) The outer core behaves as a fluid to seismic disturbances, meaning that if you shear the material it does not deform elastically but flows instead. It is the motion of this fluid (which is also electrically conducting) that is thought to maintain the Earth's magnetic field by some sort of dynamo action.

The inner core has a radius of approximately 1225 km and a density of about 13 gm/cc. It is also dominantly iron. The pressure at the center of the Earth is quite well known and is about 3.5 Mb (1 bar \approx 1 atmosphere). On the other hand, the temperature is quite poorly known and is about 5500 ± 1500 K. We know that the inner core behaves almost as an elastic solid to seismic disturbances (these disturbances have time scales of $1 \rightarrow 10^4$ sec).

There is another way of subdividing the upper mantle and crust. Instead of using composition as the basis for classification, it is often useful to use mechanical properties. The uppermost part of the mantle and the crust behave almost rigidly and can undergo brittle fracture under high stress (so causing earthquakes). This layer of strength is called the lithosphere and overlies a weaker layer called the asthenosphere. At temperatures exceeding about 1600K, rocks can deform by flowing (ductile creep) under long-term stress. High stresses cannot build up so there are no earthquakes. As you will learn later on in the class, earthquakes can occur in special places (subducting slabs) to depths of about 680 km but the mechanism of failure is still not well-understood for the deepest earthquakes.

ORIGIN, COMPOSITION AND STRUCTURE OF THE EARTH

- Handout from notes compiled by Guy masters and Lisa Tauxe. It is a brief summary of the origin and composition of the Solar System, the accretion of the Earth/moon system and the differentiation of the Earth into a Crust, mantle and Core.

Nucleosynthesis

10-18 Gy (Hartman)

- Just after the big bang, which occurred 16 B yr ago, the universe consisted of hydrogen and helium.
- All of the other elements we find in the solar system were generated in stars.
- When a star first condenses from interstellar gas, it consists mainly of hydrogen.
- At sufficiently high temperatures and pressures, the hydrogen undergoes a fusion reaction to form helium. When most of the hydrogen fuel is exhausted, the star contracts slightly raising its interior temperature to the point where helium ignites. (about 5 solar masses)
- Depending on the mass of the star, this fusion process continues until iron is formed at which point the star either dies as a white dwarf or collapses into a neutron star.

- r-process up to Bi
- created by nuclear fusion

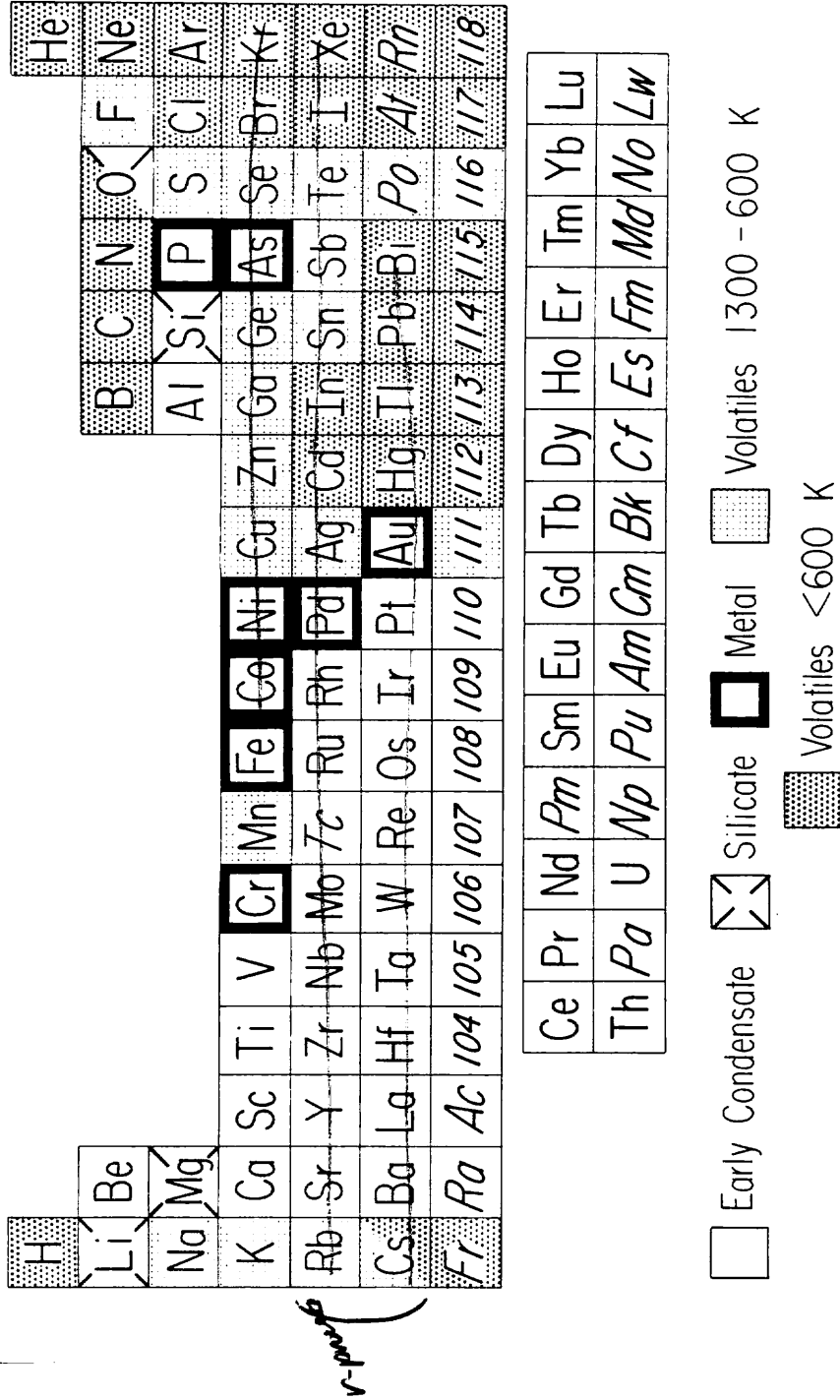


FIGURE 1-5
Condensation behavior of the elements. Short-lived radioactive elements are shown in italics (after Morgan and Anders, 1980).

- During gravitational collapse and supernova explosion, the heavier elements are created by neutron capture.
- Since star formation and destruction takes less than a few billion years, the material which makes up our solar system may have undergone several of these cycles.
- The result is that the most abundant elements in the solar system have periodic numbers less than or equal to that of iron.

Composition of the Sun and the Earth

- The best way of determining the bulk composition of the earth would be to drill to the center of the core.
- Rocks found at the Earth's surface are not representative of the bulk composition because the Earth has differentiated over its 4.6 Byr lifetime.
- Two methods are used to estimate the Earth's bulk composition, solar spectroscopy and analysis of meteoritic composition.

Solar Spectroscopy

- Most of the mass in the Solar System is contained in the sun so its composition should be somewhat representative of the average composition of the primitive solar nebula.
- High temperatures at the Sun's surface produce a broad spectrum of electromagnetic energy.
- Atoms at the Sun's absorb energy at characteristic wavelengths related to their atomic structure leaving dark lines in the emitted spectrum.
- Sequences of lines can be related to particular elements, thus providing an estimate of the Sun's composition.
- It is assumed the material at the interior of the sun has undergone a greater degree of nucleosynthesis while the material at the Sun's exterior better represents the composition of the solar nebula.

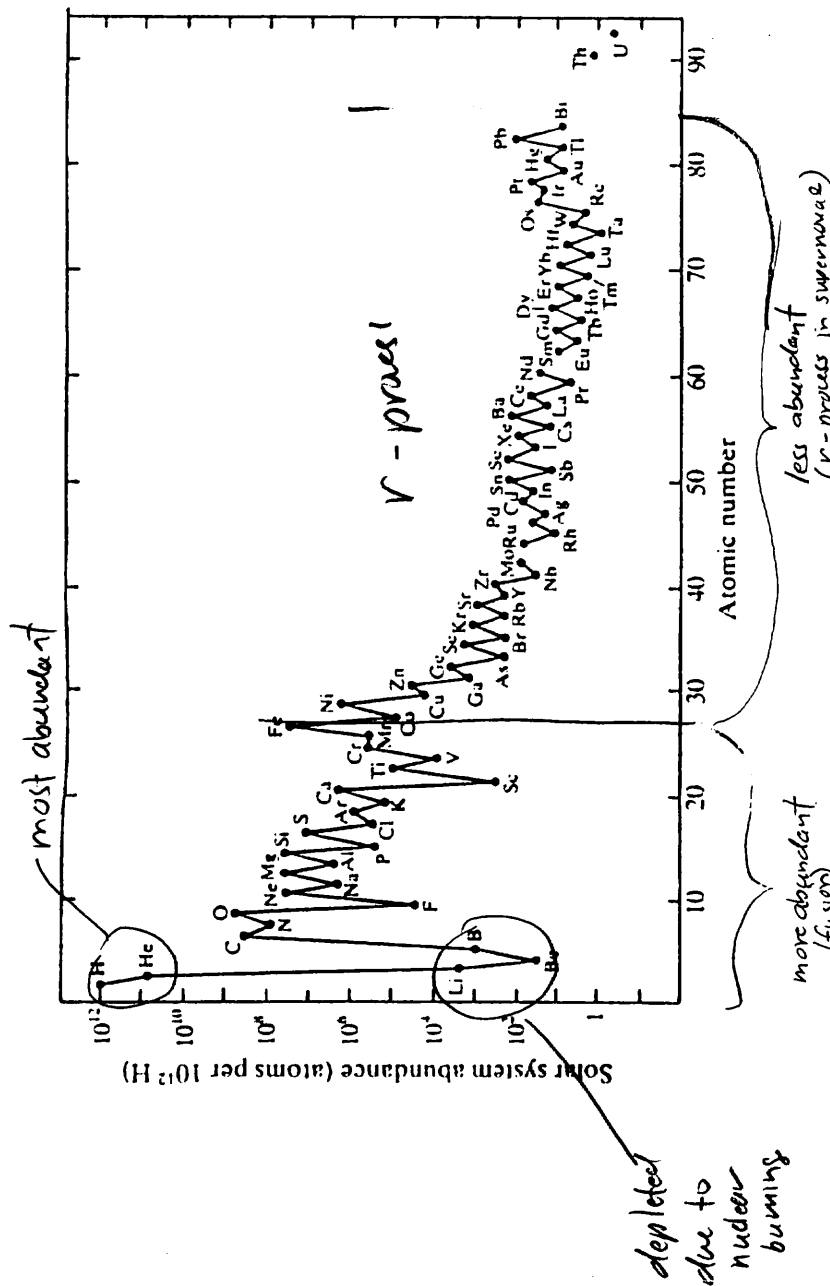
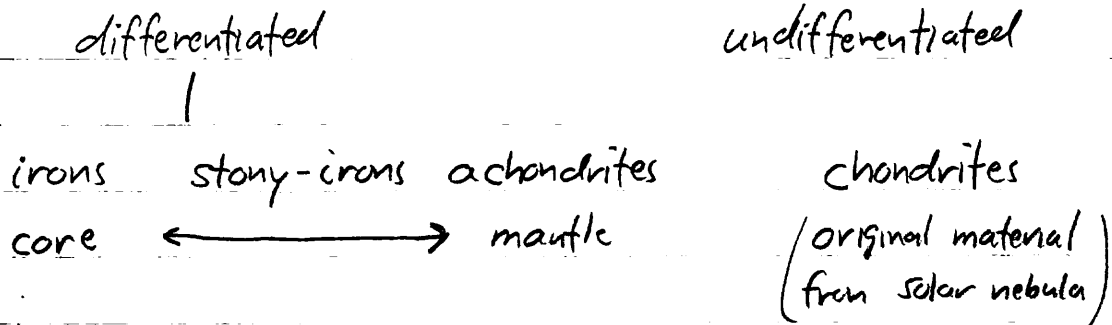


Fig. 1.3 Solar System abundances of the elements, showing the relative number of atoms present on a logarithmic scale, normalised to the value 10^{12} for hydrogen

Meteorites

- Another way to estimate the bulk composition of the earth is to examine meteorites.
- Meteorites can be divided into two broad categories depending on whether they were differentiated during the formation of a planetessimals or whether they ^{have} their primitive composition.



chondrites

- 4.6 Byr old (4559 ± 5 Ma Hartman)
- chondrules - spherical glassy inclusions
- contain H_2O so they formed $< 100^\circ C$ and have not been heated above $180^\circ C$
- have elemental abundances similar to those found in the atmosphere of the sun.

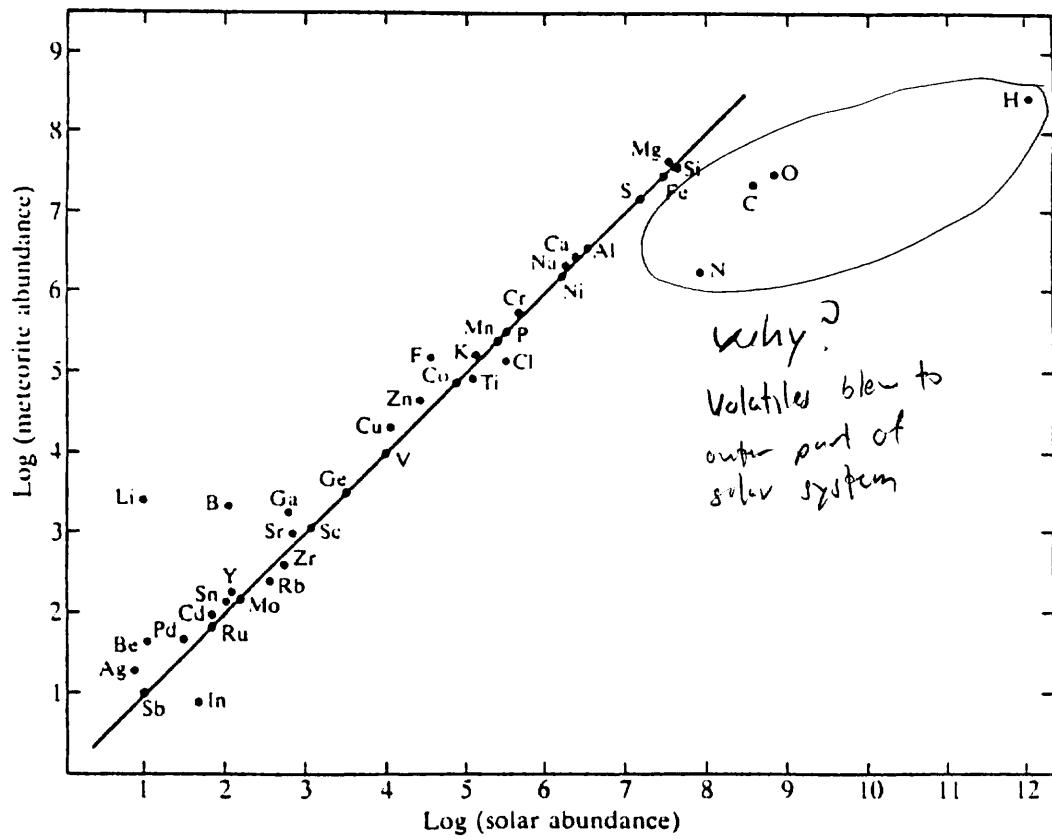


Fig. 1.4 Comparison of Solar abundances to those in carbonaceous chondrites

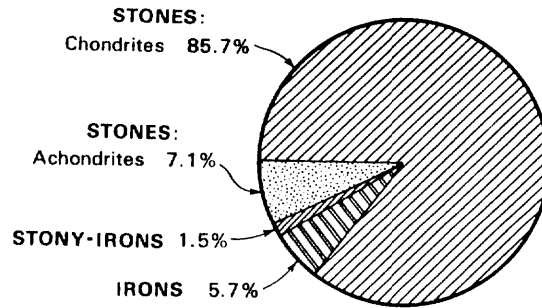


Fig. 2-2. Relative proportions of chondrites, achondrites, stony-irons, and irons among the meteorites actually seen to fall.

18 Meteorites and the Origin of Planets

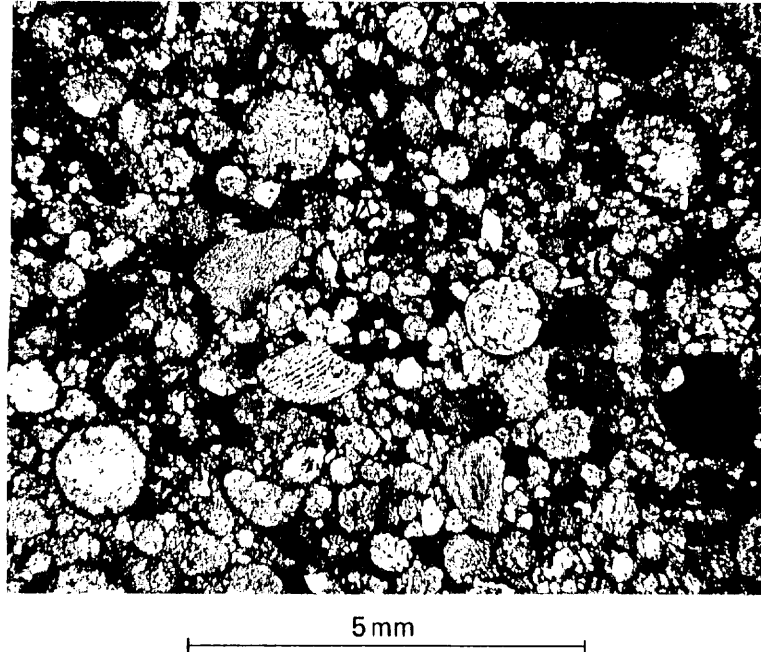


Fig. 2-3. Microscopic view of a thin section of the Tieschitz (Czechoslovakia) chondrite. Relatively transparent minerals appear light; opaque substances are darker. It can be seen that the stone is an aggregation of rounded structures; these are chondrules, once droplets of a "fiery rain."

Differentiated meteorites

- Differentiated meteorites are believed to be the products of chemical fractionation inside of a relatively large body.

Scenario

- chondrites condense from solar nebula
- material accumulates into large planetessimals about the size of the moon.
- collisions between large planetessimals will provide enough energy to melt the entire body.
- the higher density iron and nickel would sink into the center of the body while the lower density silicate and oxide compounds would remain on top.
- later on, the planetesimal is fragmented by a second collision leaving behind the differentiated meteorites.

Irons

- The iron meteorites show a particular structure that reveals the temperature and cooling rate when the meteorite formed.
- At 1400°C iron-nickel solidifies to a uniform ^{alloy} taenite.
- Below 700°C the material should reequilibrate to a combination of taenite and kamacite.
- Windmanstatten structure requires a cooling rate of 1-10 degrees/myr at a temp between 400 and 600°C .

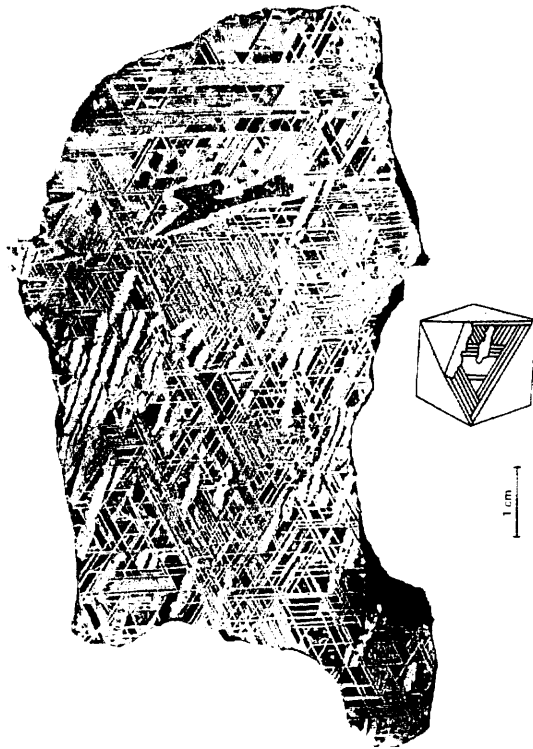


Fig. 3-1. Windmanstätten pattern in the Edmonton (Kentucky) iron meteorite. Systems of bands are kamacite lamellae, which parallel faces of a reference octahedron (sketched). Specimen surface cuts the reference octahedron almost parallel to one face. Irregular inclusion at right center of meteorite slab consists of troilite (FeS). (Smithsonian Astrophysical Observatory photograph.)

$$T_d \approx 500^\circ\text{C}$$

$$\frac{dT}{dt} = 5^\circ\text{C/ma}$$

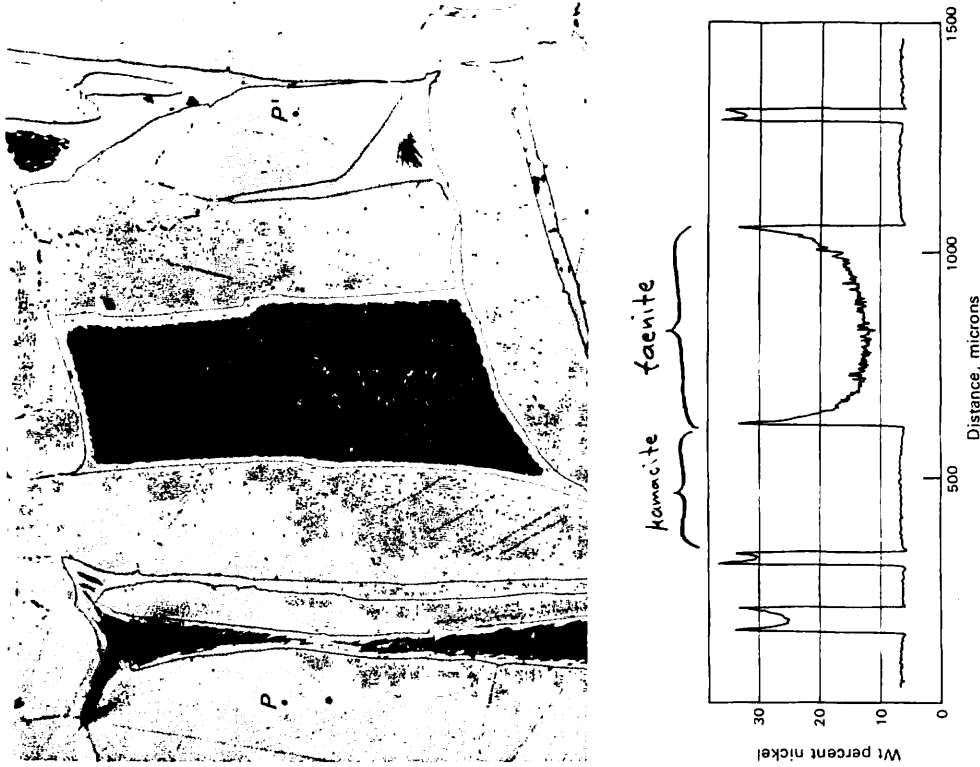


Fig. 3-2. (Above) Microscopic view of Widmanstätten structure in the Anoka octahedrite, viewed by reflected light. Dark plessite areas thinly rimmed by taenite; separated by broad, light-colored lamellae of kamacite. (Below) Electron microprobe profile across the structure (from P to P'), showing variation in Ni content. (Figures from J. A. Wood, *The Cooling Rates and Parent Planets of Several Iron Meteorites*, Icarus, vol. 3, pp. 429-459, 1964; courtesy of Academic Press Inc., New York.)

PROBLEM: Depth and time required for Windmanstatten structure

The Windmanstatten structure, observed in iron meteorites, is produced by very slow cooling (5°C per million years) of nickel-iron alloy through a temperature of 500°C . Given a large planetesimal, about the size of the earth's moon (made entirely of Fe-Ni alloy, $\kappa = 1.2 \times 10^{-5} \text{ m}^2/\text{s}$), calculate the time and depth when the patterned formed.

Assume that the planetesimal is cooling from a uniform melting temperature of 1400°C at time = 0. Moreover, assume half-space conductive cooling of the planetesimal so that the temperature is:

$$T(z,t) = T_m \operatorname{erf} \left[\frac{z}{2\sqrt{\kappa t}} \right]$$

where z is depth beneath the surface, t is time, T_m is melting temperature and κ is the thermal diffusivity of iron given above.

$$T_d = 500^{\circ}\text{C} \quad - \text{critical diffusion temperature}$$

SOLUTION:

$$\dot{T}_d = -5^{\circ}\text{C/ma} = -1.59 \times 10^{-13} \frac{^{\circ}\text{C}}{\text{s}} \quad - \text{critical rate}$$

$$T(z,t) = T_m \operatorname{erf} \eta \quad \eta = \frac{z}{2\sqrt{\kappa t}}$$

$$\frac{T_d}{T_m} = \operatorname{erf} \eta = 0.357$$

$$\eta = 0.33$$

$$\frac{\partial T}{\partial t} = T_m \frac{\partial}{\partial \eta} \operatorname{erf} \eta \frac{\partial \eta}{\partial t} \quad \text{but } \operatorname{erf} \eta \equiv \frac{2}{\sqrt{\pi}} \int_0^{\eta} e^{-\xi^2} d\xi$$

$$\frac{\partial}{\partial \eta} \operatorname{erf} \eta = \frac{2}{\sqrt{\pi}} e^{-\eta^2} \quad \text{and} \quad \frac{\partial \eta}{\partial t} = -\frac{\eta}{2t}$$

$$\frac{\partial T}{\partial t} = \frac{-T_m \eta}{t \sqrt{\pi}} e^{-\eta^2} = \dot{T}_d$$

$$t = \frac{-T_m \eta}{\dot{T}_d \sqrt{\pi}} e^{-\eta^2} = \underline{\underline{46 \text{ ma}}}$$

$$z = 2\sqrt{\kappa t} \eta = \underline{\underline{87 \text{ km}}}$$