The Terrestrial Planets

EPSC 180 Winter Term 2018

Prof. Olivia Jensen, McGill University ©

1 Creation of the universe, solar system, planets and satellites

Pluritas non est ponenda sine necessitate.
... William Ockham (c 1285?-1349)

1.1 Creation mythologies

1.1.1 Pre-civilization, primitive peoples

- What records do we have? While we have no written records, we do live with myriad cultural and religious traditions that derive from ancient mythical explanations of the origins of humanity, nature and the cosmos.[1] There is a human need to create the story of our own creation. Our myths are the symbolic narrative of our traditions, cultures and world views. We shall follow a thread through to our current creation narrative based in empirically testable scientific metaphors and models.

1.1.2 Civilized man

- ***religious and cultural mythologies:***
  - We might begin our thread with oldest known, preserved and deciphered writings of mankind from the Sumerian mythology: the **Epic of Gilgamesh**[2]. The adventures of this King of Uruk (somewhere between 2750 and 2500 BCE) lead us to the edge of the creation.
  - Probably near coincidentally in Ancient Greece a more mechanical creation story forms in which the forces of nature, the gods are serially created from the Chaos.
  - The creator God who **Genesis 1:1**[3] " *In the beginning God created the heaven and the Earth....*" celebrated in the Jewish tradition during Rosh Hashanah: the creation 5776 years ago. It is similarly described in Sura - 57:4 (Q'aran)–*"He is the One who created the heavens and the earth*

[1]Ancient religions and myths: Metareligion
[2] The Epic of Gilgamesh: http://www.ancienttexts.org/library/mesopotamian/gilgamesh/
Enuma Elish: the Sumerian Epic of Creation
The Dispilio Tablet - the oldest known written text
[3] King James version of the English bible

in six days..."[4]. The great western/middle-eastern monotheistic religions, Judaism, Christianity, Islam and their many offshoots essentially hold to a common myth: creation of all and its continuing "management" by a still-interested ompnipotent and omnscient God, Jehova, Allah whose name is unspeakable.

  - Archbishop Usher (17th Century English cleric) took the biblical story and record to be factual data and used it to calculate the year of creation to be 4004BCE. Cambridge secularist scientists derisively precised the date to 9:00AM, on October 26. Some Christian fundamentalists still hold to this date as the "Creation".

- ***Other traditions:***
  - The Haida peoples – creation by the Raven trickster[5]; the Plains Amerindians – the coyote trickster,
  - Mayan (Central America): the four gods (yellow, red, black and "without colour") conspire to create humankind and Earth. (Note that the world did not come to its end on December 20, 2012 as some have interpreted from Mayan mythology.)
  - Shinto (Japan): Kunitokotatchi arises as a reed out of the ocean of chaos, the first of the gods, then Izanami and Izanagi.
  - Hindu: remarkably, the length of one day and night of Brahma (that is, one *cycle* of the Universe) is calculated to be $\mathbf{8.4 \times 10^9}$ years, [6]
  - China: One early creation story describes Pangu separating the world egg-like Hundun, the "primordial chaos" into Heaven and Earth.

- ***Contemporary philosophical mythologies***
  - *Neocreationism – Intelligent Design Hypothesis* – A long time ago and according to a conscious design, the Universe was formed; the Universe is so remarkably "*tuned*" for life and existence that it must have been designed on purpose.

- ***Scientific mythologies(?),models(?) – the narrative***
  - Properly science doesn't address the moment of creation but rather attempts to understand what has happened since. Our cosmologies are properly models of the evolution models of the Universe ***describe*** that we; they do not ***explain*** the moment of creation of the Universe.

[4] The Islamic New Year counts from the revelation of the creation to Mohammed: 1439AH and does not date creation itself

[5] Bill Reid's *Raven and the First Men*

[6] $\mathbf{10^9}$ means 1 followed by 9 zeros or 1 billion

We glibly address the question ***"Why?"***. We retreat to the metaphysical edge of physics – ***a quantum fluctuation of the nothing***[7] – as an admittedly lame explanation of its ***"creation"***.

Scientific, physical models evolve:

- The ***Big Bang*** hypothesis (Georges LeMaître[8], 1894-1966) of the post-creation evolution with a beginning,
- ***de Sitter Universe***[9] modelled through solution of Einstein's general relativistic field equations in which time itself begins with the bang but the Universe is otherwise ever-expanding *empty* space,
- the ***Inflationary Big Bang*** (Alan Guth[10] - MIT), modified in *explanation* of homogeneity and distribution of observed matter,
- its currently fashionable variation, the ***Concordance Model***[11] that allows for acceleration of universal expansion of space and time driven by a mystical ***Dark Energy***, a model that *fits* all contemporary observations, and one which opens us
- to the possibility of many ***earlier***, ***subsequent*** and ***other "Multiverses"*** that might exist or come to pass in some hyperspace-time[12]. We have backed ourselves again into a corner where we want to describe ***elsewhere*** and ***"else-time"***.
- At this point, some of us retreat from science to invoke an external creative agent: ***God!***.

While it might seem that science offers nothing more than just another *point-of-view*, it expects that we humans can come to know the full story and workings of the Universe following the moment of creation through a process of continuing development of theory tested by empirical discovery. This is the process of science.

Let us first try to answer the question ***"When?"***. I suggest that we can already answer the question ***Where?"***: ***"Right here!"***

[7] Scientific models, while nicely described by mathematics and shown to hold in accord with known physics can appear just as fanciful as other creation myths:
Lawrence Krauss' lecture: "A Universe from Nothing"

[8] On Georges LeMaître

[9] Willem de Sitter, 1872-1934

[10] Alan Guth on Inflation

[11] Concordance model

[12] The "Multiverse" Hypothesis: see Tegmark's classifications.

2 A scientific "narrative"

2.1 Early attempts at quantifying the moment of creation[13]

- Leonardo da Vinci (1452-1519) recognized that "fossil" shells in Tuscan sedimentary rocks were emplaced in ancient seas, the rocks now lifted from the depths
- Nicolas Steno (1669) ... recognized that the layering of Tuscan sediments ordered the history of Earth... but how old?
- Immanuel Kant (chemistry)... How long has the ***Sun*** been ***burning***?
- James Hutton (1785, father of geology) – Why has Hadrian's wall not shown more erosion?
- von Helmholtz (introducing physics) – The gravitational energy of the Sun could account for 20 million years!
- Lord Kelvin (1897, geophysics and 1900, solar physics[14]) – less than 100 million years
- John Joly (evaporation of river waters into salt water oceans) at least 90-100 million years
- Charles Walcott (paleontology - fossils and the geological clock)
  - by the beginning of the 20^{th} century, it was recognized that the fossil record and sedimentation precdeding the fossil record required at least 1.6 billion years. Then...
- Modern Physics – discovers a radioactive clock
  - John William Strutt (1905) measured the radium content of **uranite**-containing rocks to find an age of 1.65 billion years,
  - Bertram B. Boltwood (also 1905), working with the more stable uranium-lead system, calculated the numerical ages of 43 minerals to be in the range of 400 million to 2.2 billion years
  - by the 1950s, the oldest materials found on ***Earth*** were geochronologically dated using a radioactive clock, based upon the ***U-Pb*** (uranium-lead) decay sequence, to more than 4.5 billion years...

[13] On early attempts at calculating the age of the Earth
[14] Lord Kelvin's argument for the age of Sun and hence Earth

2.1.1 Geological Time

The geological time-line orders the "*history*" written by life fossils and elemental isotopes[15] into the rocks of the Earth[16]. Geologists have known that Earth is very, very old since the early 19th century.

2.1.2 Modern Physics and the Radioactive Clock

The discovery of radioactivity by Becquerel[17] about 100 years ago provided science a "clock" with which the "age" of rocks could be measured .... numbers in years could be assigned to events in the geological record.

Radioactive decay

Start with a sufficiently large number, N, of radioactive atoms... their nuclei would decay according to a simple statistical law, here described as a ***differential equation***:

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau}$$

where τ is a time constant related to the ***half-life*** $t_{1/2}$ as $\tau = t_{1/2}/ln\,2$ and $ln\,2 = 0.69314718...$.

The rate $dN(t)/dt$ of increase of number of atoms $N(t)$ at any moment of time t is proportional to the number of atoms that still exist at that moment, scaled by a negative number ($-0.693.../t_{1/2}$). i.e., the rate of increase is actually a decrease and indicated by the negative sign on the right side of the equation above.

If we start our clock at time $t = 0$ and then have $N(t = 0) = N_0$ atoms, we can "solve" this differential equation to describe the functional dependence of $N(t)$ with time. We find that:

$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-ln\,2\,t/t_{1/2}} = N_0 2^{-t/t_{1/2}}.$$

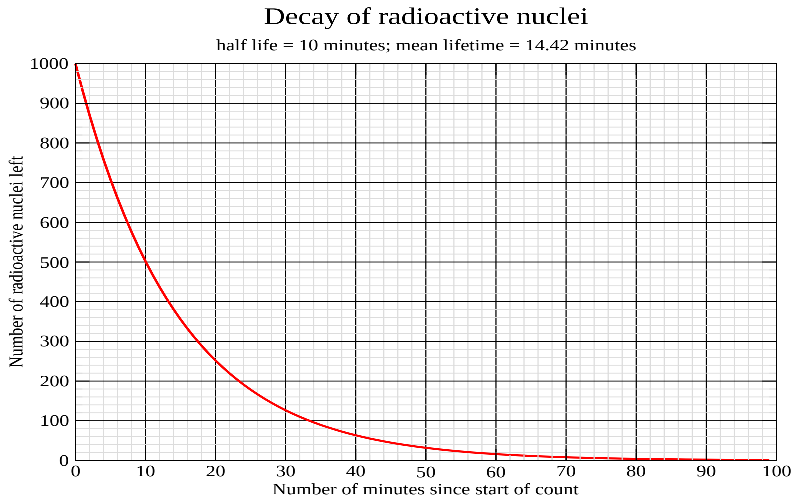
Note $e = 2.7182818...$ is one of the important constants of mathematics: Euler's number. That is the number of atoms that we started with at the start of our observations and time $t = 0$ decays exponentially with time t.

Let us look at this equation with a graphical example.

[15] Elemental isotope: a chemical element is determined by the number of core protons; isotopes of that element vary according to the number of neutrons

[16] The geological clock

[17] The 1903 Nobel Prize in Physics



.

The measure $\boldsymbol{t_{1/2}}$ is called the ***half life***[18] of the nucleus. In a time equal to the half life, half of all the atoms we started with have decayed into another element, the ***daughter***. That is, when $\boldsymbol{t = t_{1/2}}$, then $\boldsymbol{t/t_{1/2} = 1}$ and $\boldsymbol{e^{-\ln 2} = 1/2}$ so that $\boldsymbol{N(t_{1/2}) = 1/2\, N_0}$**.** In one half life, 50% of original nuclei will have decayed to the daughter; in one time constant, $\boldsymbol{\tau}$, 63.2% of original nuclei will have decayed to the daughter.

In the case of the diagram above, we have started with 1000 nuclei ($\boldsymbol{N_0 = 1000}$) of which **7.7%** are lost by decay each minute. After about 10 minutes, we only have 500 nuclei left.

Now, on average, how long does one of our initial nuclei last? The time constant, $\boldsymbol{\tau}$, measures the expected ***mean lifetime*** of any one of the original nuclei.

An atomic ***nucleus*** is composed of 1 or more $\boldsymbol{p^+}$ ***protons*** and 0 or more $\boldsymbol{n^0}$ ***neutrons***. Each ***chemical element***[19] is uniquely characterized by the number of protons in its nucleus. The nucleus, though, may contain differing numbers of neutrons according to the elemental ***isotope***. Protons and neutrons can be expelled from the nucleus in radioactive decay processes. As well electrons, $\boldsymbol{\beta^-}$ particles, can be expelled in conversion of a neutron into a proton within the nucleus. In $\boldsymbol{\beta^-}$-capture, an external electron is captured by the nucleus effectively combining with a $\boldsymbol{p^+}$ within to reduce the nuclear proton count and increase the nuclear neutron count by 1. Effectively, $\boldsymbol{p^+ + \beta^- \rightarrow n^0}$. A third radioactive decay process, $\boldsymbol{\alpha}$-decay (in which an $\boldsymbol{\alpha}$-particle comprising two $\boldsymbol{p^+}$, protons, and two $\boldsymbol{n^0}$, neutrons, is expelled from the atomic nucleus thus decreasing its proton and neutron count each by 2) is a common mode among the heavier elements like uranium and thorium. All of these processes

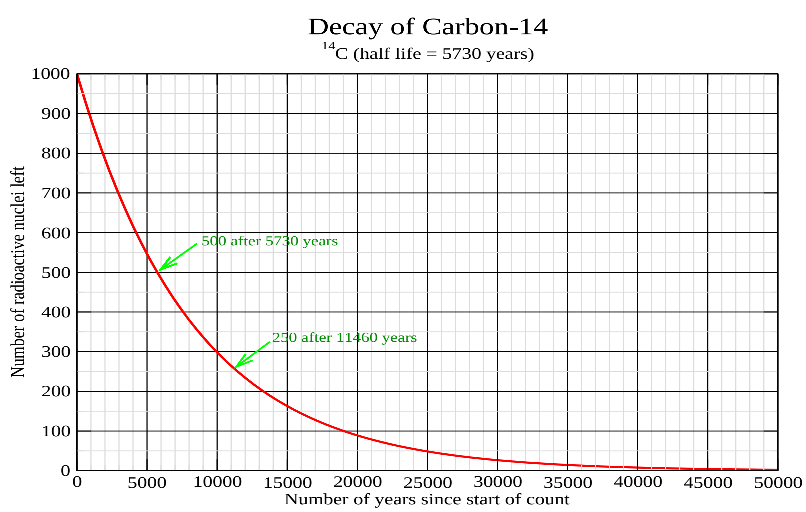
[18] On half-life

[19] A periodic table of the chemical elements

are characterized by a decay constant or half-life $\boldsymbol{t_{1/2}}$ which is accurately determined by statistical fitting to the decay curve such as that diagrammed above.

This constant, the half-life, $\boldsymbol{t_{1/2}}$ is, in most radioactive decay processes, unaffected by anything we might be able to do to the atom under decay or to any condition of temperature or pressure under which we confine it. It is not, however, the case for all radioactive decays. The decay that involves $\boldsymbol{\beta^-}$-capture (equivalently $\boldsymbol{\beta^+}$ or positron emission) is known to be pressure affected[20]. In the $\boldsymbol{\beta}$-capture decay process, increased density of the S-shell electron field proximal to the atomic nucleus does enhance the probability of the decay. The S-shell electron density in the nuclear region does depend upon the confining pressure. While this is almost an insignificant effect for pressures in the outer regions of Earth, it can effect a shortening of the half-life constant for $\boldsymbol{\beta}$-capture processes at pressures equivalent to those deep in Earth's mantle and core. Radioactive decay processes via $\boldsymbol{\beta}$-decay (in which an electron is spontaneously released from an atomic nucleus so increasing its atomic number and proton count by 1) and $\boldsymbol{\alpha}$-decay (in which an $\boldsymbol{\alpha}$-particle comprising two $\boldsymbol{p^+}$, protons, and two $\boldsymbol{n^0}$, neutrons, from the atomic nucleus thus decreasing its proton and neutron count each by 2) are not known to be affected by any externally imposed conditions.

- ***Carbon dating***: The half life of a particular ***isotope*** of carbon, $\boldsymbol{^{14}C}$, is 5730 years. $\boldsymbol{^{14}C}$ is created in the upper atmosphere through bombardment of $\boldsymbol{^{14}N}$ by cosmic rays from the depths of the Universe. This is the radio-isotope used in the method of ***radio-carbon dating***. $\boldsymbol{^{14}C}$ (6 $\boldsymbol{p^+}$ and 8 $\boldsymbol{n^0}$) decays via $\boldsymbol{\beta^-}$-decay back to stable $\boldsymbol{^{14}N}$ (7 $\boldsymbol{p^+}$ and 7 $\boldsymbol{n^0}$) according to a rule determined by its **5730**-year half life[21]. Recall that $\boldsymbol{\beta^-}$-decay is not pressure or temperature dependent.

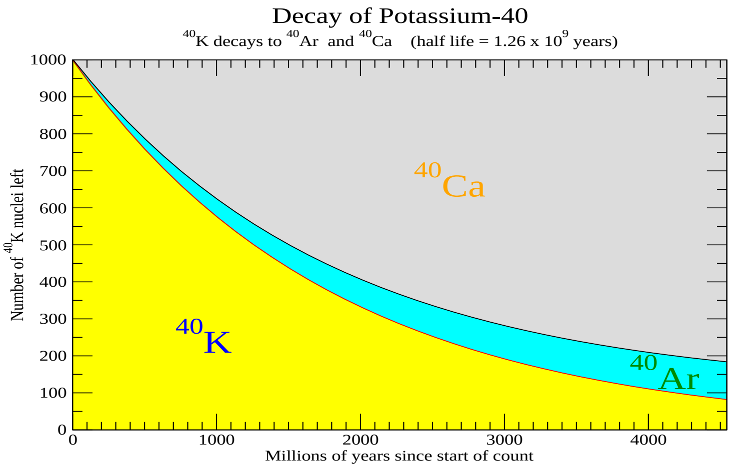


.

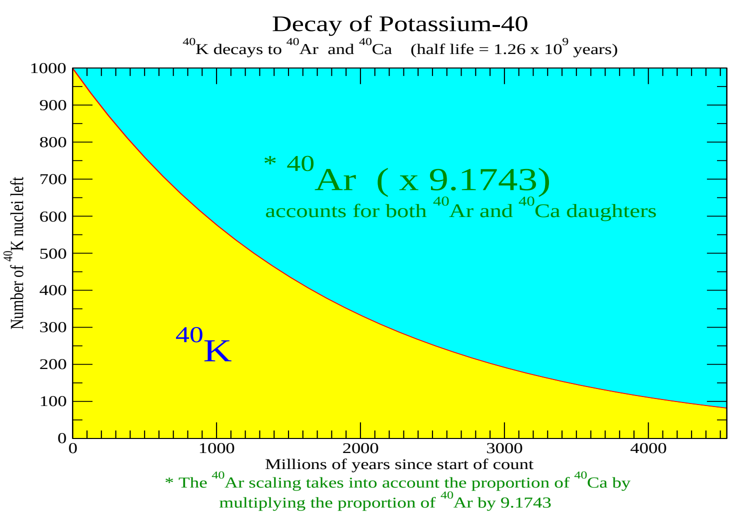
[20] $\boldsymbol{^{40}K}$ $\boldsymbol{\beta^-}$capture is pressure dependent

[21] The periodic table of the "elements"

- ***Potassium-Argon dating***: There are many, many radioactive decay clocks available to us that may be used in determining the ***"age"*** of minerals within rocks. $\boldsymbol{^{40}K}$ decays to $\boldsymbol{^{40}Ar}$ (10.9% of decays via $\boldsymbol{\beta}^-$-capture) and to $\boldsymbol{^{40}Ca}$ (89.1% of decays via $\boldsymbol{\beta}^-$-emission) with a half-life of about 1.3 Ga ($\mathbf{1.3 \times 10^9}$ years). This long half life makes it a useful tool in aging the oldest materials on Earth.



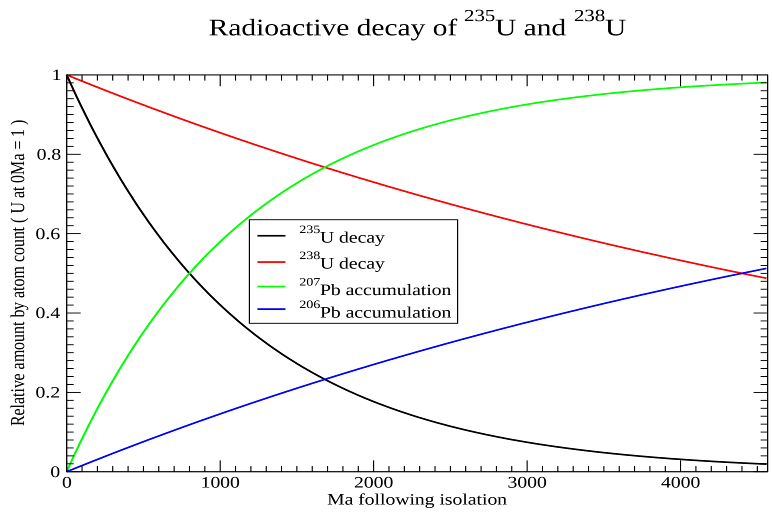
We can't distinguish the decay daughter $\boldsymbol{^{40}Ca}$ from any original $\boldsymbol{^{40}Ca}$ that might have been assembled into the mineral when it crystallized but we do expect that all of the $\boldsymbol{^{40}Ar}$ in the mineral has resulted from the decay of $\boldsymbol{^{40}K}$. Any original $\boldsymbol{^{40}Ar}$ would have escaped during original crystallization because $\boldsymbol{Ar}$ is a noble gas that doesn't combine chemically with other elements in minerals. Knowing, then, that 10.9% of the decay daughters are $\boldsymbol{^{40}K}$ and 89.1% are $\boldsymbol{^{40}Ca}$, we make a simple correction to the $\boldsymbol{^{40}Ar}$ amounts by multiplying them by 9.1743 (equivalently dividing by 0.109) to account for the total number of daughter isotopes.



.

- ***Rubidium-Strontium dating***: $^{87}\boldsymbol{Rb}$ decays to $^{87}\boldsymbol{Sr}$ via $\boldsymbol{\beta}^-$-decay (emission of an electron) with a half-life of about 47 Ga. (A very slow ticking clock!)

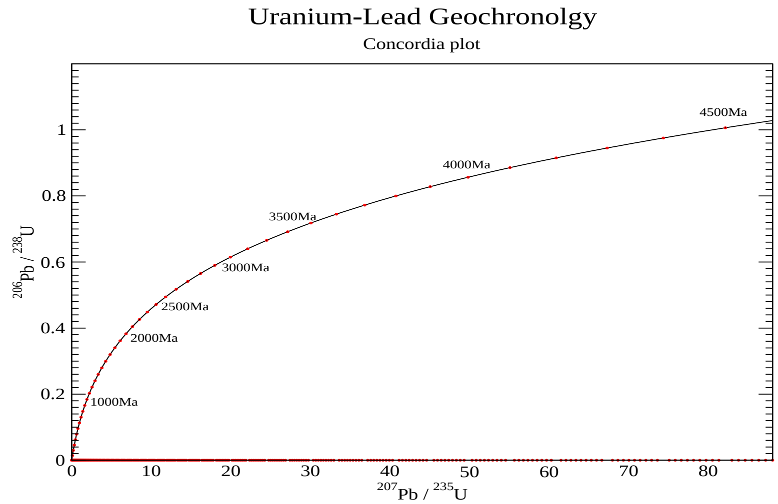
- ***Uranium-Lead dating***: $^{238}\boldsymbol{U}$ decays in a complicated cascade of processes involving $\boldsymbol{\alpha}$-decay, $\boldsymbol{\beta}^-$-decay and $\boldsymbol{\beta}^-$-capture to $^{206}\boldsymbol{Pb}$ with a half-life of 4.47 Ga. $^{235}\boldsymbol{U}$ decays similarly to $^{207}\boldsymbol{Pb}$ with a half-life of 704 Ma.



.

We can use the two $\boldsymbol{U}$-$\boldsymbol{Pb}$ decay series to develop an even better scheme for determining the age of a mineral. The most common isotope of lead, $^{204}\boldsymbol{Pb}$, does not derive from a radioactive decay process while all of $^{206}\boldsymbol{Pb}$ and $^{207}\boldsymbol{Pb}$ do. While we normally reference the lead-isotope daughters to their uranium source, we can also reference the radiogenic lead to the non-radiogenic lead isotope, $^{204}\boldsymbol{Pb}$. The relationship between the ratios $\frac{^{207}\boldsymbol{Pb}}{^{204}\boldsymbol{Pb}}$ and $\frac{^{206}\boldsymbol{Pb}}{^{204}\boldsymbol{Pb}}$ [22] also well (better?) determines ages as all isotopes of $\boldsymbol{Pb}$ would be expected to submit to the same chemistry and diffusion from a crystal. Uranium-lead dating on zircon ($\boldsymbol{ZrSiO_4}$) crystals is probably the most trusted of methods.

[22] The ***U-Pb concordia*** system:
http://www.colorado.edu/GeolSci/courses/GEOL5690/U-PbNotes.pdf



.

- ***Samarium-Neodynium dating***: $\boldsymbol{^{146}Sm}$ decays by release of an $\boldsymbol{\alpha}$ particle to $\boldsymbol{^{142}Nd}$ with a half-life of about 0.103Ga ($\mathbf{1.03 \times 10^8}$ years or 103 million years). $\boldsymbol{^{146}Sm}$ from our Earth's earliest days has largely decayed. How much of that original samarium isotope is left? By simple calculation, about **1.7** part in $\mathbf{10^{1335}}$. There are thought to be fewer than $\mathbf{10^{80}}$ atoms or atomic nuclei in the entire Universe. There is no original $\boldsymbol{^{146}Sm}$ left on Earth. There is, though, the record of its original presence in $\boldsymbol{^{142}Nd}$.

The setting of the clock and the "Oldest Materials"

"***Age***" in the context of rocks and minerals is the time since the radio-decay clock was last set.

- Oldest mineral... ***zircons***[23] found in Australia have been dated by the uranium-lead decay sequence to approximately $\mathbf{4.4 \times 10^9}$ years[24] [25] [26].

- Oldest rocks... zircons within a large assembly of rocks in Northern Canada and Greenland date to between $\mathbf{3.96 \times 10^9}$ and $\mathbf{4.03 \times 10^9}$ years – the ***Acasta Gneiss***[27] complex. The Acasta Gneiss is a metamorphic rock, one which has undergone some important physical and even mineralogical-chemical

[23] Zircons, $\boldsymbol{ZrSiO_4}$, are not *cubic zirconia*, the artificial gemstone, which is primarily $\boldsymbol{Zr0_2}$ with some stabilizing $\boldsymbol{YtO_2}$:
http://www.emporia.edu/earthsci/amber/go340/students/berg/cz.html

[24] U-Pb dating and zircons: http://geology.about.com/od/geotime_dating/a/uraniumlead.htm?p=1

[25] Oldest minerals: http://www.livescience.com/43584-earth-oldest-rock-jack-hills-zircon.html

[26] Concordia plot(image 6): note age of zircon #36-7:
http://www.geology.wisc.edu/zircon/Earliest%20Piece/Earliest.html

[27] Story of the Acasta gneiss

changes during its history. A mantle-derived ***igneous***[28] rock that has more nearly maintained its physical integrity since its solidification has been found in the ***Nuvvuagittuq greenstone*** complex[29] near Porpoise Cove in northwestern Quebec with zircon $\boldsymbol{U-Pb}$ ages of about $\mathbf{3.86 \times 10^9}$ years. More recent isotopic analysis ($\boldsymbol{Sm-Nd}$) of bulk samples of the now-famous ***faux-amphibolites***[30] in this Nuvvuagittuq greenstone belt show a deficiency of $\boldsymbol{^{142}Nd}$ in comparison to all other known rock masses on Earth. The $\boldsymbol{^{142}Nd}$ deficiency is argued to result from the crystallization of the rock minerals from a magmatic mass that was originally deficient in $\boldsymbol{^{146}Sm}$ and therefore a magma that was not well mixed with the mantle and crust during the formation of the early Earth. The amount of deficiency argues for an age of $\mathbf{4.28 \times 10^9}$ years. That is, this mass has retained its distinctive negative isotopic anomaly in $\boldsymbol{^{142}Nd}$ from its original placement within the Earth until the present time. Clearly, some areas of the continental surfaces are very, very old.

- But, even older...

  Meteorites which fall upon the Earth – almost all seem to have set their clocks before $\mathbf{4.55 \times 10^9}$ years ago (4.55 Ga). The oldest cluster has been dated to $\mathbf{4.567 \times 10^9}$ years. This latter date is now ascribed to the age of condensation of the solar nebula from which the Sun and planets formed. The former represents a minimum age to ascribe to the formation of the ***terrestrial planets***. The unique ***Tagish Lake meteorite*** that fell on the lake in northern British Columbia in 2000 is believed to represent the most primitive materials from the condensing solar nebula[31].

[28]Igneous rocks are those formed in solidification of molten materials – ***magma***.
[29] The Nuvvuagittuq Greenstones
[30] Jonathan O'Neil's original paper
...as the story broke in September, 2008
[31] Tagish Lake Meteorite

2.2 Nucleosynthesis and the Sun's fire

We might ask: "*Where did all the elements and isotopes come from?*". In 1957, Burbidge, Burbidge, Fowler and Hoyle[32] described a sequence of development for the origin of normal elements and materials.

Their process begins with a ***Big Bang*** that produces the original hydrogen, helium with traces of lithium and beryllium from which all ordinary or ***baryonic*** matter (i.e., that which can form atoms) is eventually synthesized. The moment of the Big Bang is that time in the past at which our "*physics condenses*" and where and whence "*time*" and "*space*" emerge. Later we shall learn that this moment was about $\mathbf{13.8 \times 10^9}$ years ago.

- In an infinitesmal moment of time after some initiating process, an incredibly hot (perhaps more than $\boldsymbol{10^{27}K}$) extremely compressed ball of pure energy exploded forth our universe... the ***Big Bang***...
- As this explosion expands, it cools (***adiabatic expansion***[33]).
- At 1 second, it has become cool enough for ***leptons***[34] and ***quarks***[35] to condense out of the energy. Note that mass and energy are equivalents by Einstein's most famous equation: $\boldsymbol{E = mc^2}$. The temperature is more than $\boldsymbol{10^{12}K}$. The average energy in each particle in this hot plasma is a measure of the temperature[36]. These temperature/energy conditions can be explored with modest particle accelerators. The LHC (Large Hadron Collider)[37] produces momentary proton-proton collision temperatures of $\boldsymbol{10^{20}K}$.
- By 3 or 4 seconds, all the ***baryonic matter***[38] [39] of the universe has largely formed by the combination of quarks into ***protons***, the nuclei of the simplest hydrogen atom, $\boldsymbol{^1H}$, and ***neutrons***. Charge balance is thought to be maintained by the leptons, largely ***electrons*** which contribute about 0.06% to the mass of ordinary matter in the universe. By now, the temperature has cooled to $\boldsymbol{10^{10}K}$.
- Neutrons begin to decay with a half-life of 12 minutes into electrons and protons.

[32] The BBFH theory of stellar nucleosynthesis: the original paper

[33] At the present time, the flash of that first explosion of energy has cooled to only $\boldsymbol{2.72K}$, the temperature of the ***Cosmic Microwave Background – CMB***.

[34] electrons, muons, tau particles and their associated neutrinos

[35] http://en.wikipedia.org/wiki/Quark

[36] $\boldsymbol{1K = 8.62 \times 10^{-5} ev}$; $\boldsymbol{10^{12}K = 86.2 Mev}$

[37] The LHC

[38] particles comprising 3 quarks – essentially the ordinary matter of our experience

[39] About matter... and anti-matter

- Some neutrons attach to protons to form $\boldsymbol{^2H}$, ***deuterium***, the atomic-mass-2 ***isotope***[40] of hydrogen.

So now, we have a neutrally charged plasma of protons, neutrons, deuterium nuclei, electrons and other leptons and "exotic particles". As far as we know, we don't need to look towards the exotic particles for the subsequent process of ***nucleosynthesis***, the formation of the nuclei of all known chemistry. Such is the story of the first few seconds following the Big Bang.

Now, as this proto-universe continues expanding and cooling, the following processes arise:

- during the next 500 or so seconds:

$$\boldsymbol{^1H + {^1H} \rightarrow {^2H} + \beta^{+}}\text{[41]}$$
$$\boldsymbol{^1H + {^2H} \rightarrow {^3He} + \gamma}\text{[42]}$$
$$\boldsymbol{^3He + {^3He}}\text{[43]} \boldsymbol{\rightarrow {^4He} + {^1H} + {^1H} + \gamma}$$
$$\boldsymbol{^3He + {^4He}}\text{[44]} \boldsymbol{\rightarrow {^7Be}}\text{[45]} \boldsymbol{+ \gamma}$$
$$\boldsymbol{^7Be \rightarrow {^7Li}}\text{[46]} \boldsymbol{+ \beta^{+}}$$
$$\boldsymbol{^7Li + {^1H} \rightarrow {^4He} + {^4He} + \gamma}$$

  In order to produce the two $\boldsymbol{^4He}$ nuclei, we would have to start with eight $\boldsymbol{^1H}$ nuclei (protons) and the net result of this process is:

$$\boldsymbol{8\ {^1H} \rightarrow 2\ {^4He} + 3\gamma + 4\ \beta^{+}.}$$

  Note that we use up just as much $\boldsymbol{^7Be}$ and $\boldsymbol{^7Li}$ as we produce. Still in the plasma, there remain traces of these elements left behind that haven't been consumed in a subsequent stage.

- After about 500 seconds, the exploding universe is too cool and with too low a particle density for any further creation of the elements of chemistry. The ***hydrogen fusion*** reaction (as above) stops. The nucleosynthetic processes of the Big Bang stop. We shall have to wait another 100 to 200 million years for stellar nucleosynthetic processes to continue the synthesis of the rest of chemisty.

[40] Isotopes of the elements differ according to the number of neutrons in their atomic nuclei. The number of protons in a nucleus defines the element. Hydrogen has 1 proton but may have 0, 1 or 2 neutrons according to isotope.
[41] ***positron*** – *electron-like but with positive charge*
[42] Photonic radiation
[43] Nucleus: 2 protons, 1 neutron
[44] Nucleus: 2 protons, 2 neutrons
[45] Nucleus: 4 protons, 3 neutrons
[46] Nucleus: 3 protons, 4 neutrons

We are left with a still hot ***plasma*** (i.e., the electrons are not attached to the nuclei to form normal atoms because the gas still remains too hot). By atom count, the plasma is about 95% $\boldsymbol{^1H}$, 5% $\boldsymbol{^4He}$ and with very small amounts of the other elements in the sequence above. This plasma will remain opaque to the transmission of light and other electromagnetic radiation for another 380 000 years when the plasma has cooled sufficiently for electrons to attach to the positively charged nuclei to form neutral atoms – $\boldsymbol{\sim 3000K}$. At this time the Universe still contained 95% $\boldsymbol{^1H}$, 5% $\boldsymbol{^4He}$. We have recently obtained a thermal "baby picture" of the universe at this age[47].

A great blast of explosive radiant energy is released in a wave radiating out at the speed of light and creating the very geometry of our universe. Our universe is enclosed by this radiant wave-front. We see this radiant wave-front in every direction at the edge of the Universe.

2.2.1 Where did the energy come from?

If we look carefully at this result, we find that there is a slight loss of mass as $\boldsymbol{H}$ fuses into $\boldsymbol{He}$. That mass has been converted into energy in an ***exothermic***[48] reaction; that the process is exothermic is necessary for its occurrence.

- We start with 8 hydrogen nuclei (each a proton) each of 1.00896 amu[49] and obtain 2 helium nuclei each of 4.00388 amu. We also produce 4 positrons each of 0.00055 amu and some massless $\boldsymbol{\gamma}$-rays and some (probably) massless neutrinos. $\boldsymbol{\gamma}$-rays are high-energy electromagnetic radiation like ordinary light; neutrinos are strange particles that carry momentum, angular momentum and energy away from the fusion processes.

- Starting mass: $\boldsymbol{8 \times 1.00896amu;}$

  Resultant mass: $\boldsymbol{2 \times 4.00388amu + 4 \times 0.00055amu;}$

  Mass lost: $\boldsymbol{0.06172amu.}$ is lost

- $\boldsymbol{E = mc^2}$ where $\boldsymbol{c}$ is the velocity of light in perfect vacuum, $\boldsymbol{2.997 \times 10^8 m \cdot s^{-1} \approx 300000 km/sec}$. The energy released for every 8 $\boldsymbol{^1H}$ atoms: $\boldsymbol{9.20 \times 10^{-12}}$ joules. This is the energy carried away in $\boldsymbol{\gamma}$-rays such heat and light and in the accelerated motions of the masses themselves.

47 WMAP image of the universe: http://map.gsfc.nasa.gov/media/poster2002/WMAP_poster2002a.jpg A higher resolution map from the Planck mission

48 *exothermic:* energy producing

49 $\boldsymbol{1amu = 1.659 \times 10^{-27} kg.;}$ It is defined as 1/12 the mass of an **atom** of $\boldsymbol{^{12}C}$, (6 protons + 6 neutrons + 6 electrons)

2.2.2 Where do all the other elements come from?

After about 500 seconds, the universe is too cool and too much expanded for further nucleosynthetic processes to continue on to produce the rich chemistry we know of.

Nucleosynthesis in stars and the Sun

The ordinary matter which has been created in the primordial fire ball has mass and mass is attracted to other mass by gravitational force.

- Here and there in our expanding universe, material begins to congregate under electrostatic and gravitational forces.

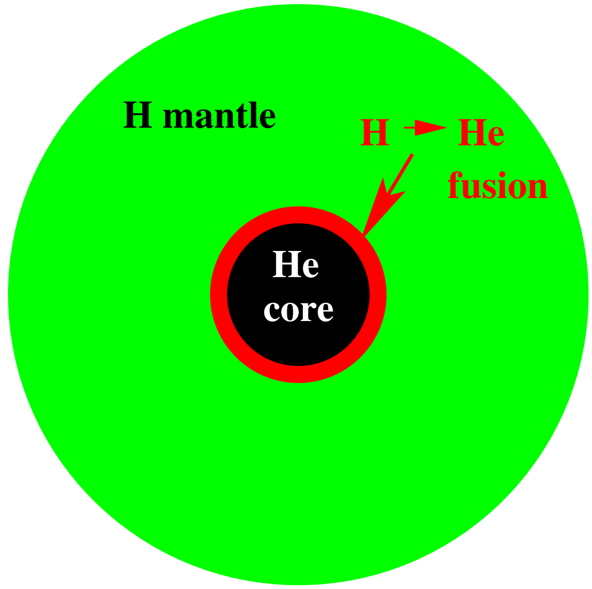
- As gravity compresses material together, the material is again heated (by ***adiabatic compression***) and when it gets hot enough and when the densities are high enough, the nucleosynthetic processes restart – massive ***protostars*** form. A star is born[50]. It is now believed that this process began within about **200** million years of the Big Bang.

- $\boldsymbol{H \longrightarrow He}$ fusion in stars (the reaction sequence above)...

  For our Sun, such processes started about $\mathbf{4.6 \times 10^9}$ years ago and will, according to theories of ***cosmogony*** or ***stellar evolution*** continue for another **6** or $\mathbf{7 \times 10^9}$ years. The Sun is in its ***hydrogen burning*** stage. It produces prodigious amounts of heat and light.

  - Mass of the Sun: $\mathbf{1.99 \times 10^{30}}\boldsymbol{kg}$
  - Composition of Sun: $\approx \mathbf{93\%}\boldsymbol{H}$, $\approx \mathbf{7\%}\boldsymbol{He}$ by atom count ($\approx$ **75%** and **23%**, respectively, by mass). The heavier elements, usually termed ***"metals"*** in astronomical jargon, contribute less than **1.5%** to the total mass (less than **0.1%** to the atom count) of the Sun. While the fusion reactions in the Sun itself account for traces of this already small "metals" mass, the composition of the Sun tells us that it condensed from clouds of gases that had been cycled through several previous generations of larger stars.
  - Power of the Sun: $\mathbf{3.84 \times 10^{26}}\boldsymbol{J \cdot s^{-1}}$ or 384 000 000 000 000 000 000 000 000 watts, as bright as 4 sextillion 100W light bulbs.

[50] The birth of stars

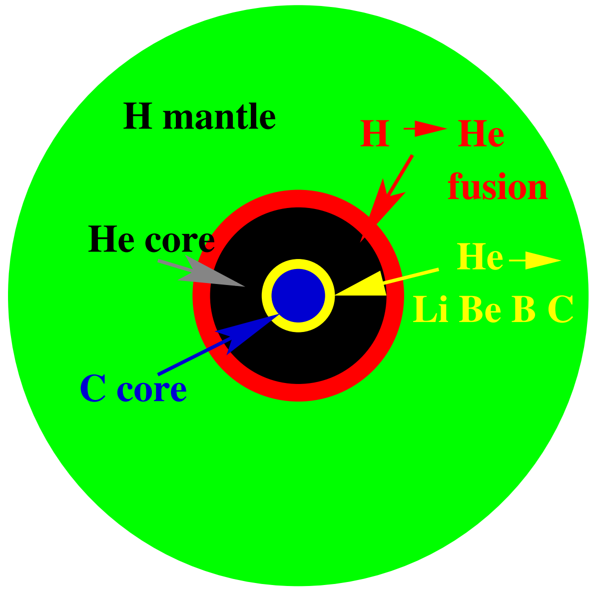


.

- Further nucleosynthetic reactions within stars[51] ...whence the other elements, isotopes and the full chemistry[52]??
  - Small stars, those smaller than the Sun, produce no elements beyond the small amounts of $\boldsymbol{Li}$ and $\boldsymbol{Be}$ via the $\boldsymbol{H}$ to $\boldsymbol{He}$ fusion process. Strangely, though, the smallest stars burn slowest and live longest.
  - Another process mediates $\boldsymbol{H}$ to $\boldsymbol{He}$ fusion within stars of the size of the Sun and larger: the $\boldsymbol{CNO}$ process.
  - In stars comparable in size to the Sun or larger, helium (denser than hydrogen) sinks into a core. There, it too can only be ignited into the ***helium burning*** stage if the star is large enough that its overlying mass compresses this core to temperatures exceeding about $\boldsymbol{10^{10}K}$.

[51] The evolution and death of stars

[52] A periodic table of the elements: http://www.webelements.com

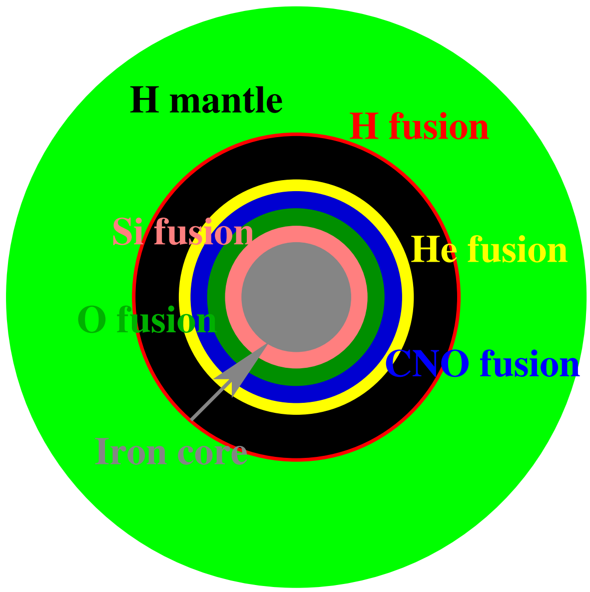


.

    * $^{4}\boldsymbol{He}$ fusion produces elements boron, $\boldsymbol{B}$, more lithium, $\boldsymbol{Li}$, and beryllium, $\boldsymbol{Be}$, as well as substantial quantities of carbon, $^{12}\boldsymbol{C}$. In this stage, the star expands into a ***red-giant*** star.
    * If the star is large enough (Our Sun is, barely large enough!), it will even bring this $^{12}\boldsymbol{C}$ to burn in fusion to produce substantial quantities of $^{13}\boldsymbol{C}$, $^{13}\boldsymbol{N}$, $^{14}\boldsymbol{N}$, $^{15}\boldsymbol{N}$ and $^{15}\boldsymbol{O}$.
      This is the expected end-point of our Sun's evolution in about $\boldsymbol{7 \times 10^9}$ years. Its nuclear fires burn out and it will collapse into a ***white dwarf***. Larger stars proceed through their evolutionary stages much more quickly than our Sun.
  - Fusion processes in large stars, up to 3 or 4 times the mass of the Sun, can fuse all elements and isotopes up to and including those of iron $\boldsymbol{Fe}$... but, then, nothing further can be formed through these fusion processes. The overlying mass of the mantle of the star is held up from collapse by energy radiating from the core. No fusion of iron is possible and so no further energy is being released in the core. With the core, now, producing no further energy, the star collapses in on itself and then quickly expands as a very bright, but short-lived, ***nova***... or if the star is large enough, at least 3-4 times the mass of our Sun, the expansion explodes as a ***supernova***.
  - The larger the star, the more rapidly it evolves through its stages to its end point. In a giant star (say 20 × the size of our Sun) the fusion stages are:
    * Hydrogen fusion (from $\boldsymbol{H}$, produce $\boldsymbol{He}$ and traces of $\boldsymbol{Li}$ and $\boldsymbol{Be}$[53]): $\approx$ 10,000,000 years.

[53] See a periodic table of the elements for meaning of the elemental symbols – see previous footnote link.

- Helium burning (produce $\boldsymbol{Li}$, $\boldsymbol{Be}$, $\boldsymbol{B}$ and $\boldsymbol{C}$): $\approx$ 1,000,000 years.
- Carbon burning (produce $\boldsymbol{N}$ and $\boldsymbol{O}$): $\approx$ 300 years.
- Oxygen burning (produce $\boldsymbol{F}$, $\boldsymbol{Ne}$, $\boldsymbol{Na}$, $\boldsymbol{Mg}$, $\boldsymbol{Al}$ and $\boldsymbol{Si}$): $\approx$ 8 months.
- Silicon burning (produce $\boldsymbol{P}$, $\boldsymbol{S}$, $\boldsymbol{Cl}$, $\boldsymbol{Ar}$, $\boldsymbol{K}$, $\boldsymbol{Ca}$, $\boldsymbol{Sc}$, $\boldsymbol{Ti}$, $\boldsymbol{V}$, $\boldsymbol{Cr}$, $\boldsymbol{Mn}$ and isotopes of $\boldsymbol{Fe}$ of atomic mass 56 or less): $\approx$ 2 days... then ***nothing?*** ... ***supernoval explosion!***



.

Where do the heavy elements come from?

– Fusion comes to an end when it is no longer an exothermic process. It is the release of fusion energy (exothermic fusion) that holds a star up against gravitational collapse. [54].

  - Still small quantities of heavy elements are being produced in stars like our Sun through ***endothermic*** fusion. Rather than giving up energy in fusing, say 1 proton, $^{\boldsymbol{1}}\boldsymbol{H}$, or 1 free neutron (with the release of an electron or $\boldsymbol{\beta}-$particle) into an $^{\boldsymbol{56}}\boldsymbol{Fe}$ nucleus to produce $^{\boldsymbol{57}}\boldsymbol{Fe}$ and then again to $^{\boldsymbol{58}}\boldsymbol{Co}$, etc., energy is absorbed.
  - By this ***s-process***, "***s***" for "*slow*", traces of all elements, even those heavier than $^{\boldsymbol{56}}\boldsymbol{Fe}$, are produced via the slow ***endothermic processes***[55] in stars even as small as our Sun. The energy required for this slow fusion derives from the continuing exothermic fusion of the lighter elements.

[54] exothermic: energy-producing
[55] endothermic: energy-absorbing

... But we know that on Earth we have significant quantities of many heavier elements – ***Pb*** (lead) for example. Where do these come from?

- From ***Novae*** and ***supernovae!***: When the fusion fires burn down, a star collapses in upon itself, compressing deep layers and if it is sufficiently massive, say $\boldsymbol{8 - 10 M_{\odot}}$[56], it violently explodes as a supernova as the fusion fires of all these deeper layers are re-ignited. This scenario describes a ***massive star supernova*** or a ***type II supernova***. There exists another sub-classification of very rare ***type IIn hypernova*** which are the death-throws of super-giant stars.

  In type II supernoval explosions tremendous flux of neutrons and energy is available for a fast incremental neutron-nucleus fusion via the endothermic ***r-process***... "***r***" for "*rapid*". Starting with the iron of the collapsing star's core, all known natural and artificial elements up to, at least, $\boldsymbol{^{255}Cf}$ are so formed[57] in this neutron-fusion process. The tremendous energy released in the explosion sustains these endothermic reactions, sequentially pushing ever more neutrons and protons into the nuclei starting with $\boldsymbol{^{56}Fe}$.

  To account for the proportions of the heavier elements such as ***Au*** and ***Pt***, other processes are necessary. For example, kilonovae (neutron star collisions) have recently been observed to produce quantities of these elements by the neutron-fusing ***r-process***[58].

- If a lone star isn't quite large enough to explode (i.e. our Sun, for example, is not) it finally collapses into a dwarf while radiating away the gravitational energy of its collapse. Such stars cease their nucleosynthetic processes and slowly die to a cold state.

  There is, however, another mechanism that can create supernoval explosions[59] even for stars of the mass of our Sun. Stars that are smaller than about $\boldsymbol{1.5 M_{\odot}}$ collapse into ***white dwarf*** stars after passing through their ***red giant*** carbon-burning phase at the end of their lives. They were not large enough to evolve large silicon or iron cores and so are seen as have a low metallicity. If, however, these stars have a close binary companion or come close enough to another star, these very dense white dwarfs can tidally pull material away from their companion onto themselves and so become ever more massive. When their mass is sufficient to compress the cinder of nuclei that was the original core of the white dwarf to temperatures and pressures that reignite fusion fires, the star can explode as what is sometimes called a ***carbon-oxygen bomb***, a ***white dwarf supernova*** or as classified, a ***type Ia supernova***.

[56] the symbol $\odot$ represents the Sun

[57] More on supernovae: http://imagine.gsfc.nasa.gov/science/objects/supernovae1.html

[58] Kilonova

[59] http://imagine.gsfc.nasa.gov/science/objects/objects.html

Type Ia supernovae have such well understood brightness evolution[60] upon explosion that they are used to help calibrate distances of galaxies near what we see as the edge of the Universe; they form the ***standard candle***. They are easily identified by their light spectra which show them not to contain the heaviest elements; this and the fact that their luminosity decays more quickly distinguishes them from the type II supernovae. There is, however, another group of extremely bright supernovae of low metallicity classified as type ***type Ic hypernovae***. They are distiguished from type Ia by their spectral emission and absorption lines. The are often associated with strong bursts of gamma rays which are extremely high energy electromagnetic wavebursts. We know less about their evolution.

– ***Kilonovae***[61] Recently, collisions of neutron stars have been observed through gravitational radiation, gamma-ray bursts and broad-band electromagnetic radiation. Continuing observations of such phenomena will surely bring us to ever deeper knowledge of the formation and death of stars and the formation of the elements.

The remnants of all these exploding stars become neutron stars or, perhaps, black holes.

The ***Theory of Nucleosynthesis*** described by Burbidge, Burbidge, Fowler and Hoyle describes these various processes in detail and also explains how it is that the current relative abundances of the elements arises. This is beyond the needs and interests of this course.

We are stardust! Our chemistry, the very chemistry of our own bodies, was formed within hot stars and through supernoval explosions of the largest ones.

2.3 Stars and Galaxies

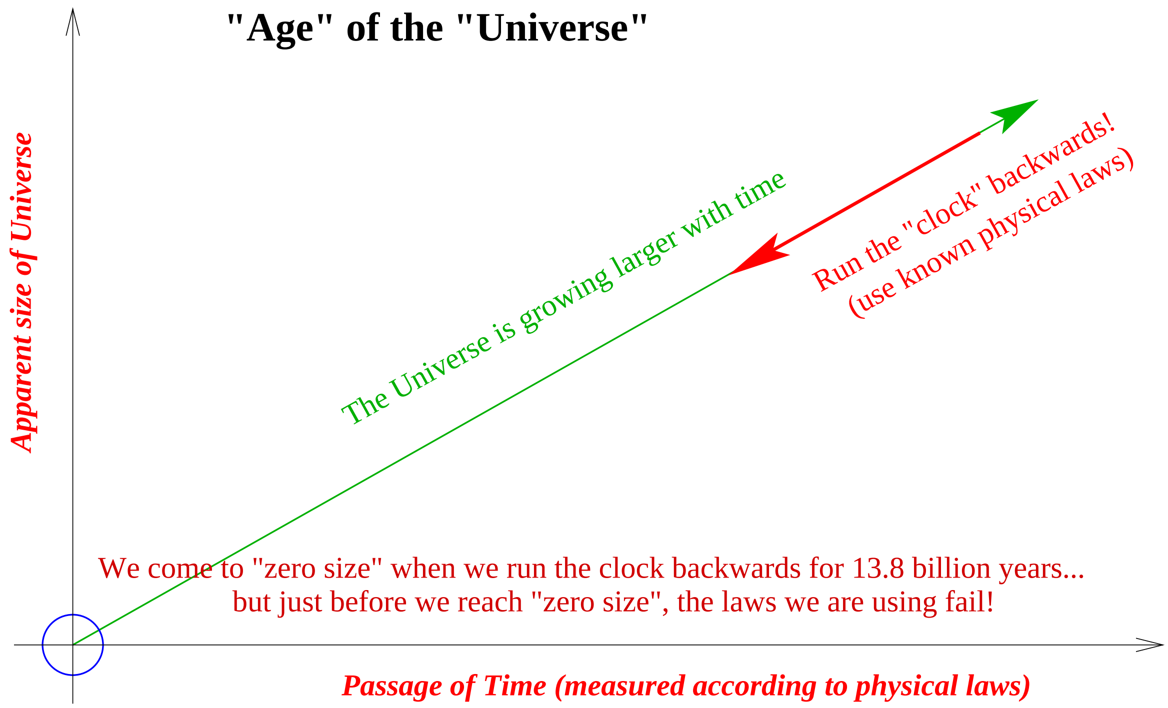
Early in the history of the Universe, perhaps during its first 200 million years but perhaps as late as 500 million years[62], supermassive stars may have formed as individuals. Without the sequential development of the heavy elements over time, these stars show very low metal content. Their lives were short and their death-explosions especially energetic. Their explosions form a special class of hypernovae, the ***pair-instability hypernovae***[63] in which the explosive mechanism involves the anhilation of matter-antimatter pairs.

[60] Light curves for various super/hypernoval explosions
[61] Kilonova light curves
[62] The reionisation and first stars
[63] http://en.wikipedia.org/wiki/Pair-instability_supernova

Since this very early epoch of the Universe, however, almost all stars have been forming within large assemblages, the ***galaxies***, the largest of which, presently, may contain 1 trillion (i.e. $\mathbf{10^{15}}$) stars. We have, probably more than a half trillion galaxies in the observable Universe. Mostly, they are in motion relative to one another in a manner that suggests that they were once, long ago, all in the same place – at the origin in space and time of the Big Bang.

2.4 The *Big-Bang* scenario

Our best evidence for a Big-Bang origin of the universe is that it is presently expanding in every direction from every place within. The rate of expansion corresponds to a single event, $\mathbf{13.799 \pm 0.021 \times 10^9}$ years ago[64] when every piece of the present universe existed at the same place. Where was that place? Right here!



Our ***physics*** is based upon two grand theories, ***Gravitation Theory***, often called ***General Relativity*** developed by Einstein in 1915 and ***Quantum Mechanics*** developed by many physicists including Bohr, Planck, Heisenberg and Dirac. Gravitation best describes the large scale properties of nature and Quantum Mechanics, the small. These two grand theories have still not been integrated into one coherent physics. It may be that ***String Theory*** will finally integrate physics.

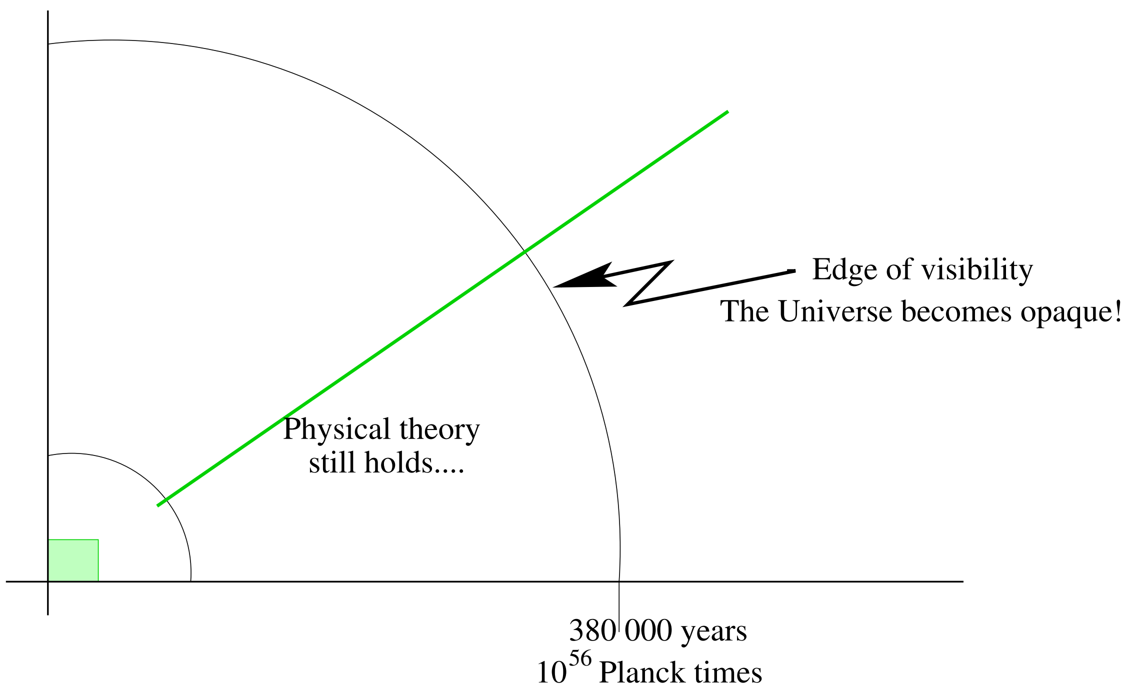
Our physics describes the interactions between "things" according to four fundamental forces: the ***Strong interaction*** which affects only "quarks" and "***gluons***" which hold protons and neutrons together, the ***Weak interaction*** which holds atomic nuclei together, the ***Electromagnetic force*** which holds atoms together and is involved in the propagation of light and ***Gravity*** which attracts bodies together according to

[64] The age of the universe based on the best fit to Planck 2015 data alone is $\mathbf{13.813 \pm 0.038}$ billion years (the other estimate of $\mathbf{13.799 \pm 0.021}$ billion years uses Gaussian priors based on earlier estimates from other studies to determine the combined uncertainty).

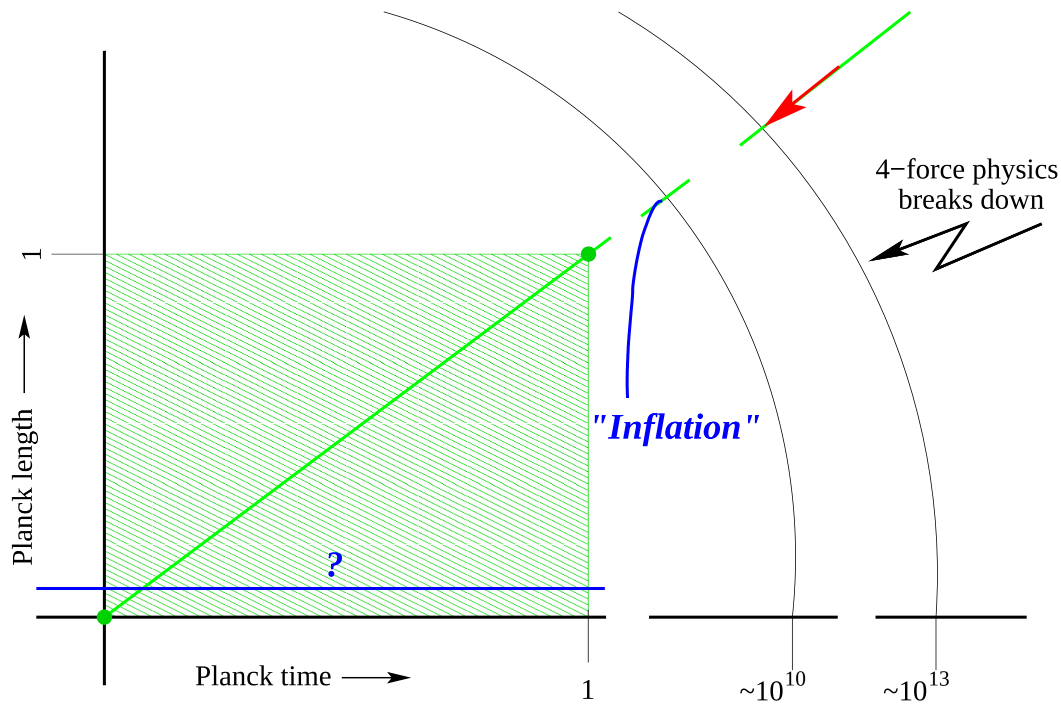
their mass. Our physics appears to hold in a 4-dimensional space-time. A String theory extension will require a 10-dimensional or even 11-dimensional space-time.

Based upon our current understanding of physics, we can *back up time* to describe the conditions of the universe at earlier times. If we back up time by about $\mathbf{13.8 \times 10^9}$ years, we come to a time when the universe would seem to have been of zero size. We call this the origin of the Big Bang or the ***age of the universe***. We seem to see a beginning. Or more properly, we can see back in time into the universe to about **380 000** years after this beginning. The universe is opaque to our vision earlier than that time. Still, our physics should be able to carry us farther back theoretically. In fact, it should hold as long as the 4-force/4-space-time conditions are retained. This should take us to about $\mathbf{10^{-30}}$***sec*** after the apparent origin. We explore such conditions using high energy particle accelerators and now hope to explore conditions that would have existed possibly even earlier than this time experimentally with the CERN-LHC (Large Hadron Collider).

.



Quantum Mechanics suggests that time is naturally incremented with fixed steps between which no time exists. The time step is called the ***Planck time***, $\boldsymbol{(\hbar G/c^5)^{1/2}}$ and corresponds to $\mathbf{5.391 \times 10^{-44}}$ seconds. This is the apparent tick-rate of the universal clock. Similarly, space itself would seem to exist in fixed steps between which no "place" at all exists. The spatial step is called the ***Planck length***, $\boldsymbol{(\hbar G/c^3)^{1/2}}$, and corresponds to about $\mathbf{1.616 \times 10^{-33}}$ cm. Before, however, we come to the first of these small time and space increments (following the apparent "0"), the 4-force/4-dimensional nature of our physics fails. It fails somewhere around $\mathbf{10^{13}}$ Planck times.[65] We need a new physics to describe the conditions of the universe before about $\mathbf{10^{-30}}$ seconds after what we see to be the origin of the universe. ***String theory***[66] may be that physics.



What we do know is that for the universe to look as it does at $\mathbf{+380\,000}$ years, sometime in the hidden period before the 4-force/4-space-time physics takes hold, a remarkably rapid (relative to the green line on the graphs which represents the speed of light) expansion had to have taken place. This is called the ***inflation***. The ***Inflationary Big Bang***[67] model tightly describes the distribution of matter, the presence of dark matter and dark energy and the observed past evolution of the universe; it remains our best physical description of the early universe[68].

[65]We also define the Planck mass, $\boldsymbol{(\hbar c/G)^{1/2}}$, about $\mathbf{2.176 \times 10^{-8}}$ kg that determines the mass of a black hole that can be contained with a Schwartzchild volume of 1 cubic Planck length.

On the "natural" Planck units

[66] String theory?: http://superstringtheory.com/

[67]The Inflationary Big Bang model: http://aether.lbl.gov/www/science/inflation.html

[68]See lecture slides by Alan Guth: http://insti.physics.sunysb.edu/itp/OWP/talks/aguth/

2.4.1 Geometrical approaches

While String Theory and its cousin, Membrane (or ***'brane***) Theory, are currently the major endeavour of theoretical physics in uniting the physics of the earliest moments of the Universe, there are other contenders that show promise. ***Loop Quantum Gravity***[69] which builds out of Gravitation Theory (General Relativity) rather than Quantum Mechanics. Another new and exciting contender attempts to describe the essential physics in terms of geometric objects called ***Amplitudhedrons***[70].

2.5 What of before? – Metaphysics, Philosophy, Theology

Many physicists and cosmologists regard this as a non-question or, at least, a question that transcends any physics that still might be testable and so trusted. Some mathematical cosmologists do attempt to address the question with scientific rigour. One, **Neil Turok**[71], Director Perimeter Institute, with his colleagues is trying to develop a new mathematical physics that might address the excitation or cause of "our(?)" Big Bang, the possibility of others preceding ours, perhaps elsewhere coincident with ours and possibly following ours. Turok works to develop a variation of 'brane theory" which extends the still-undeveloped "string theory" within an 11-dimensional space, that is with one more dimension than would seem to be minimally required by string theory. Turok's cosmology offers an alternative to the Inflationary Big Bang model which also seems to correspond to those observations of the universe that we can make. Recently, Neil Turok gave a series of 5 lectures in the CBC series, ***"The Massey Lectures"***. These lectures have been assembled into a book, "**The Universe Within**"[72]. He and his co-workers have modelled a cycling universe that spawns Big Bangs over and over again. We may, here, have transcended physics entirely to enter a world of cosmic philosophy.

Here, we/I are only attempting to describe the evolution of our Universe since its Big-Bang birth. We don't attempt to address "***cause***"; in fact, our perspective is that "cause" is not at all within the domain of science, physics and astrophysics. In preference for "***origin***" – and one should not see this as the same as "cause" – we lean on the argument: ***"A quantum fluctuation of the nothing."***[73]

You might note that our arguments depended on some measure of the passage of time and some measure of the size of and distances in the Universe. We shall now argue how we are able to determine distance and time.

[69] "Big Bang Theory" addresses the contest
[70] A description of the Amplitudhedron model
[71] Neil Turok
[72] Debate: Neil Turok, David Albert, Jim Holt; moderator Steve Paulson
[73] The Universe - Created Out Of Nothing? [part 1] [part 2]

3 The size and age of our universe

We know that materials in the Solar System condensed as long ago as $\mathbf{4.567 \times 10^9}$ years ago. We also know that our Solar System comprises elements that must have been formed in earlier phases of solar evolution. How have we actually measured the age, and hence size, of our universe?

3.1 Measuring astronomical distances and time

We require a methodology for determining the scale of the universe. Later, we will see how this scale relates to the ***age*** of the universe. We shall bootstrap a scaling method for measuring distance.

3.1.1 A brief history of astronomical measurement

Our current understanding of the universe is importantly dependent upon our models and our understanding of the scales inherent in those models. Astronomy is an old science in that astronomical measurements were being made at the dawn of recorded civilization.

- It is known that the ancient Sumerians studied the heavens; the ***Sumerian Animal Round***[74]may be the first known astronomical instrument.
- The earliest scientific enquiry focussed on the heavens. That science that evolved into contemporary astronomy had already established its roots by the time of the earliest historical records. En Hedu'anna[75] (circa 2354 BCE), high priestess of the Moon Goddess of Babylon is one of the first known names in the science. She is also regarded as the first poet!
- The ancient Druids of Britain, the Inca of Peru, the Mayans of Central America, the Aztecs of Mexico and all the peoples of the Middle East looked to the sky for order and predictability... Stonehenge
- The ancient Babylonians were keen observers of the stars and planets.
- The Phonecians, the Greeks, the Indians, the Chinese, the Persians, the Mesopotamians ... navigation (the astrological signs)
- The Polynesians almost surely navigated by the stars, Sun, Moon and planets as they sailed the Pacific Ocean a thousand years ago.

[74] The zodiacal story of Sumer
[75] En Hedu'anna – Babylon

- It is arrogant of us to want to believe that the ancients were astronomically ignorant.
  - 2000 years BC, the Babylonians already had obtained an accurate measurement of the length of the ***year***[76] [77].
  - Our western thread of astronomical science is based in the early Greek civilization. It is remarkable how much the early Greeks actually knew about the Earth and Solar System.
    * Thales (624-527 BC)... the Ionian school of thought promoted the possibility of *understanding* rather than simply *describing* nature.
    * Anaximander (611-546BC) and the Ionians, developed a primitive cosmology which attempted to describe a universe as consequent to the basic element, water.
    * Pythagoras (570-500BC) attempted a mathematical basis in describing natural phenomena. He discovered that the planet Earth was a sphere and that the heavenly bodies moved in circular paths, though as Plato (428-347BC) followed in believing, about the central Earth.
    * Anaxagoras (500-428BC) already knew that the Moon's light was reflected from the Sun. He had a "correct" explantion for both Lunar and Solar Eclipses.
    * Eudoxus (408-356BC) developed a mathematical-geometrical cosmology based upon a nesting of celestial spheres.
    * Aristotle (384-322BC) obtained *proof* that the Earth was a sphere and described a more complex basic chemistry based earth, air, fire and water. The chemistry of the universe exterior to Earth was made of a fifth element: aether.
    * Aristarchus (310-230BC) was the first to adopt the Sun as the centre of the universe and Solar System. Still, the Aristotilean view that the Earth centred everything would hold until the Renaissance in Europe in the 1500s. Aristarchus' measurements of the relative sizes of the Earth whose actual size was later accurately measured by Eratosthenes[78] (273-?BC), and of the Moon and Sun[79] were refined by Hipparchus (200-100BC). He also determined the precession of equinoxes.
    * One may argue that the advent of Christianity and its fundamentalist adherence to the ancient writings of Biblical myth retarded the the development of astronomy and of our understanding of nature for the next 1500 years.

[76] 1 year corresponds to one Earth orbit of the Sun. It is 365.24 solar days of 86400 seconds

[77] The story of Aplum

[78] The size of the Earth is determined!

[79] Aristarchus' measurements of the relative size of and distance to the Sun and Moon

* Christianity adopted the elaborate epicyclic Ptolemaic (Ptolemy, AD 100-200) theory of an Earth-centred universe, the ***Amalgest***.
* The pre-Christian-era understanding of the Solar System was retained in the cultures of the region; they were refined and especially in the area of mathematics, improved upon by the Persians and Arabs.

Two thousand years ago, we knew that the Earth was round. We knew its size. We had measured the relative sizes of and distances to the Moon and the Sun. We had discovered the simplicity of the ***heliocentric*** reference frame. Five hundred years ago, we rediscovered this knowledge.

3.1.2 Scaling the Solar System

It is required that, in order to measure scales of the Universe, we establish more local scales for reference.

- Copernicus: The great Polish thinker, Niklas Koppernigk precipitated the scientific renaissance in astronomy with the publication of a manuscript called ***Commentariolis***. He recovered the Aristarchian heliocentric viewpoint. The Sun becomes the reference point in the Solar System.

- Tycho Brahe, a Danish (then, Swedish now) astronomer made the important measurements. Still, Tycho Brahe at his death in 1601 had not embraced the Copernican explantion but his data still allowed for accurate relative scalings of distances in the Solar System.

- Johannes Kepler, his student assistant, used Brahe's precise measurements to discover the laws of planetary orbital motion which he published in 1609 in a book ***The New Astronomy: Commentaries on the Motions of Mars***. We know the paths of the planetary motions.

- Galileo provided supporting evidence of Kepler's work. The intolerant Christian church repudiated the challenging science, sentencing Galileo to house arrest for the last decade of his life. The Lutherian Christian Reformation in Northern Europe saved Kepler from a similar fate.

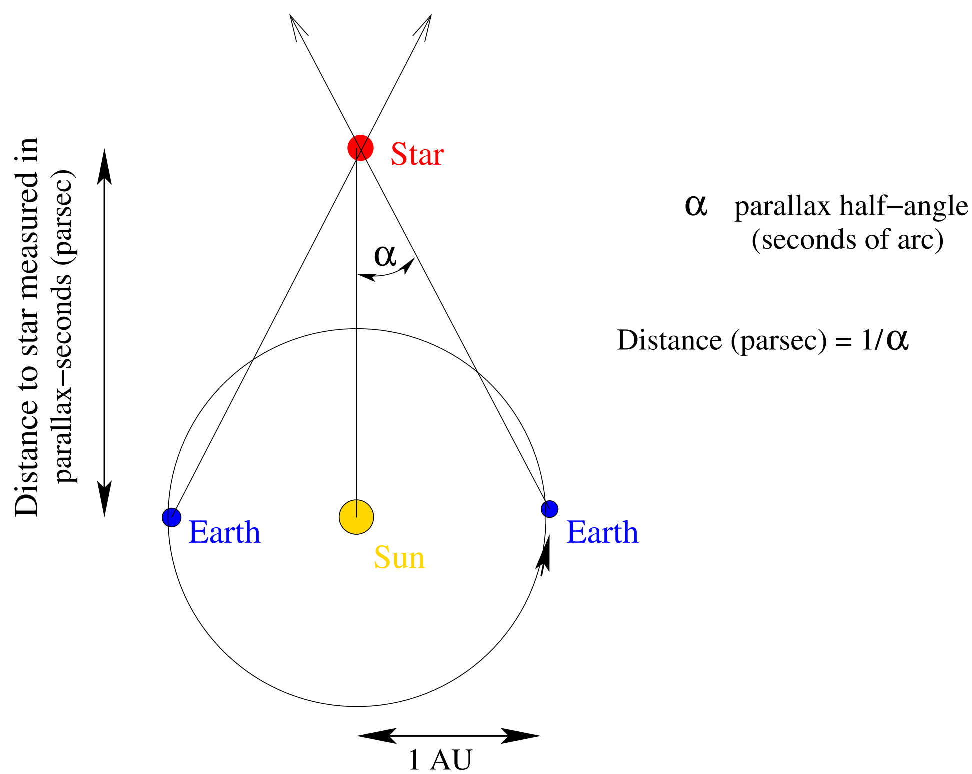
The work of these great scientists allow us to scale the solar system. Later in the course, we shall learn more of the detail of ***Kepler's Laws*** and of ***Newtonian Mechanics*** which explains them.

3.1.3 Parallax triangulation

For nearby stars, we can actually triangulate to determine their distance. For the most distant objects we can "see", the most distant ***quasars***, we shall have to develop other methods.

The Earth orbits the Sun with orbital diameter of about $\mathbf{300 \times 10^6}$ ***km*** or **2** AU (astronomical unit). Until the $\mathbf{19^{th}}$ century, we didn't have a good measure (in kilometres, for example) of the AU (the average distance of Earth from the Sun) so all large distances were simply measured in terms of this AU unit. If we look towards a nearby star from two separated times in our orbit about the Sun which are 6 months apart and therefore across this distance of **300** million kilometers, we see the star with two different perspectives.

.



- For stars far away, the ***fixed stars***, the perspective doesn't vary significantly.
- For close-by stars, the perspective does vary and they are seen at different times of the year overlain at different places on the background of the fixed stars.
- The ***parallax second***: If a star describes an apparent movement across the

background of fixed stars with a maximum half-angle of $\mathbf{1"}$[80]of arc during our orbit, it is said to be $\boldsymbol{1\,parallax-second}$ distant. This distance, $\boldsymbol{1\,parsec = 1\,pc = 3.08 \times 10^{13}\,km = 3.26\,light\,years}$[81]. The greater the distance to the star, the smaller the angle so distance is related to the inverse of the angle.

Now, with high precision astronomical measurement using the ***Hipparcos***[82] ***satellite's*** dual telescopes, we can deterimine the distance to stars with distances of less than about 300 pc ($\approx$ 1000 light years) with an accuracy of 10%... This accumulates about 28 000 stars.

3.1.4 Distance measured by apparent brightness of stars

The next step in developing our scale for distance measure is to use the fact that light emitted from a source spreads over an area which is proportional to the distance from the source, squared.

$$\boldsymbol{A_{wavefront} = 4\pi r^2}$$

where $\boldsymbol{r}$ is the distance from the source to the present wavefront. As the energy carried by the wavefront of light is being spread over an ever greater area with increasing $\boldsymbol{r}$, its intensity, $\boldsymbol{I}$, decreases with distance from the source. That is:

$$\boldsymbol{I \propto 1/r^2.}$$

The apparent magnitude scale

Astronomers have developed a curious scale to describe how bright a source of light appears to be. The curious scale derives from Hipparchus' original definition of the brightness of stars in his catalog. His brightest stars, as seen by the human eye, were described with a ***magnitude***[83] of 0, those noticeably dimmer, by 1, and dimmer again, by 2 until the dimmest visible were give a scale of 6.

The Sun's ***apparent magnitude*** as measured by this scale would be $\mathbf{-26.8}$. A $\boldsymbol{100W}$ lightbulb at a distance of $\boldsymbol{25m}$ shows a magnitude of about $\mathbf{-14}$ a little brighter than the full moon. Of course, the magnitude of brightness of light can depend on colour too. The ***visual magnitude*** scales according to the light at wavelengths between about $\boldsymbol{400nm}$ and $\boldsymbol{700nm}$, the human visual color range. What is called ***bolometric magnitude*** measures the total brightness by all wavelengths of

[80] The symbol $\mathbf{"}$ describes 1 second of arc. This is the angle one would see across the thickness of a sheet of paper at $\boldsymbol{20m}$ distance.

[81] $\boldsymbol{1\,light\,year}$, $\boldsymbol{1ly}$, is the distance light travelling at $\boldsymbol{299\,792\,458ms^{-1}}$ travels during $\boldsymbol{1year}$, about $\mathbf{9.46}$ trillion kilometres

[82] Hipparcos (or Hipparchus) in 129BC in ancient Greece assembled the first star catalog.

[83] We call this magnitude the ***apparent magnitude*** because it measures how bright a star appears in the sky from our vantage point on Earth.

light emitted by stars. Small cool stars emit most of their radiant power at long infra-red wavelengths while the hottest stars emit theirs at shorter, visible, ultra-violet and X-ray wavelenths[84] [85].

In this curious scale, each step in increasing magnitude represents a dimming of the apparent brightness of the object by a factor of $\mathbf{2.5}$. That is, a magnitude increase of $\mathbf{3}$, represents a dimming by a factor of $\mathbf{2.5 \times 2.5 \times 2.5 = 2.5^3 = 16}$. In reverse, lessening magnitude represents a brightening. The Sun is $\mathbf{2.5^{14.2} = 447000\times}$ brighter than the full Moon. We would have to fill the entire sky with full Moons to produce the daylight brightness provided by the Sun.

The visual apparent magnitude scale

Magnitude	**Vision condition**	**Example**
-26.8		the Sun
-12.6		the full Moon
-6		crescent Moon
-4	naked eye at sunset	planet Venus
-2	naked eye in dusk	planet Jupiter
-1	naked eye in dusk	Sirius (the brightest star)
0	naked eye at dark	Vega (a bright blue star)
+1	naked eye/dark night	planet Saturn
+2	naked eye/dark night	stars of Big Dipper
+6	naked eye/darkest night	the faintest stars we can see
+25	largest telescopes	the photographic limit

3.1.5 The brightest stars, distance and *absolute magnitude scale*

Clearly, the inherent brightness of a source itself is important to the apparent brightness we see in it. The Moon is much closer to the Earth than is the Sun but it is much dimmer because it is not, inherently, as bright. The star, Sirius, is actually about 24 times brighter than the Sun but it is very far away and so not nearly so bright in appearance.

Two of the brightest stars that we see in our night sky, ***Rigel*** and ***Deneb*** are very far away but are about $\mathbf{60000\times}$ brighter than our Sun. In fact, only a few stars which we see in our night sky with the naked eye are not inherently much brighter than our

[84] Radiation "colour" spectrum of stars.

[85] The perceived colours of stars determines a subjective classification (OBAFGKMLT); a better measure of the colour and hence the temperature of the star is given by the *Johnson UBV measure* which determines the difference in radiance between blue (B) and visible (V) light, the B-V scale.

Sun. The Sun is a very modest star and we can really only see the exceptional ones.

Nearby stars and their brightness

Star	App. mag.	Abs. mag.	Distance	Spectral Type
Sun	-26.8	4.83	4.85×10^{-6} pc	G2
Proxima Centauri (C)	11.5	15.5	1.29	M5
α Centauri A	0.01	4.4	1.29	G2
α Centauri B	1.5	5.8	1.29	K5
Barnard's star	9.5	13.2	1.81	M5
Wolf 359	13.5	16.8	2.33	M6
Lalande 21185	7.5	10.4	2.48	M2
Luyten 726-8A	12.5	15.4	2.52	M5
Sirius A	-1.47	1.4	2.67	A1
Sirius B	7.2	11.5	2.67	A0 white dwarf

α Centauri A (proper name: ***Rigel Kentaurus*** meaning "heel of the Centaur") is a star very like the Sun, slightly brighter ($2.512^{(4.83-4.4)} \approx 1.5\times$ brighter)[86] and larger. It is second closest of all stars at a distance of about $4.2\,ly.$ (light years). The nearby star, possibly its distant orbital companion, ***Proxima Centauri*** is the closest of all known stars but we can't see it with the naked eye. The apparent visual magnitude of α *Centauri A* is about 0. Its close binary companion ***α Centauri B*** at the same distance and intrinsicly about half as bright as the Sun has an apparent magnitude of **1.5**. We can see fewer than 10 stars in the darkest night sky with our unaided eye that are intrinsically less bright than our Sun. We don't make much of a show in our ***galaxy***.

- If all stars were at the same distance from us, those intrinsically brightest would shine brightest. Astronomers describe an ***absolute magnitude*** scale that measures the brightness of stars as if they were all placed[87] [88] at a distance of $10pc$ (parsec or parallax second). $1pc = 3.26ly.$ Even at this distance, the very brightest of all known stars, **R136a1**, would not shine as brightly as the full

[86] What is the absolute magnitude of a 100W bulb? Answer ≈ 66.3! The Hubble Deep Field telescope can resolve to absolute magnitude ≈ 30.

[87] To calculate the change in apparent magnitude of a star as a function of distance: If a star shows magnitude m_1 at distance d_1, it will show as magnitude $m_2 = m_1 + \frac{\log(d_2/d_1)}{\log(1.5849)}$ at distance d_2.

[88] The ***radiance*** or ***luminosity*** of a star with absolute magnitude $= 0$ is $\approx 3.30 \times 10^{28} W$. The luminosity of a star of absolute magnitude m_a is $L = 2.512^{-m_a} \times 3.30 \times 10^{28} W = 2.512^{(71.29-m_a)} W$.
If the luminosity, L, of a star or light source is measured in W (watts) then its absolute magnitude is obtained as $m_a = 71.29 - \frac{\log L}{\log 2.512}$.

Moon in our night sky. Furthermore, because it is so huge and hot and radiates most of its light in the ultra-violet which is invisible to our eye, it might not be seen as brighter to our eye than **Rigel** or **Deneb** at this distance[89].

- In fact if all the light emanating from the 400 billion stars in our neighbouring ***Andromeda galaxy***[90], which has absolute visual magnitude $-\mathbf{21.1}$, were to be concentrated into a star-sized spot at $\mathbf{10}\boldsymbol{pc}$, it would not brighten our day as much as does our nearby Sun.

- The Sun's absolute magnitude is $+\mathbf{4.83}$. We probably wouldn't be able to see the Sun if it were at $\mathbf{10}\boldsymbol{pc}$ in the night sky of the lit city. Such is the distance in, even, our local environs of the universe.

- ***Rigel*** and ***Deneb*** are of absolute magnitude $-\mathbf{7.1}$. At $\mathbf{10}\boldsymbol{pc}$, they would offer about as much brightness as does our nearby Moon in its crescent phase.

- An single exploding supernova at this distance would blind and bake us!

The brightest stars

Star	App. mag.	Abs. mag.	Distance	Spectral type
Sun	-26.8	4.83	$\mathbf{4.85 \times 10^{-6}}$ pc	G2
Sirius A ($\boldsymbol{\alpha}$ CMa A)	-1.47	1.4	2.67	A1
Canopus	-0.72	-3.1	30.1	F0
Arcturus	-0.06	-0.3	11.0	K2
Rigel Kentaurus ($\boldsymbol{\alpha}$ Cen A)	0.01	4.4	1.29	G2
Vega	0.04	0.5	7.36	A0
Capella	0.05	-0.6	13.8	G8
Rigel ($\boldsymbol{\beta}$ Ori A)	0.14	-7.1	276	B8
Procyon	0.37	2.7	3.50	F5
Betelgeuse ($\boldsymbol{\alpha}$ Ori)	0.41	-5.6	159	M2 red giant

The brightest stars generally shine with the whitest or bluest light though very large but cooler stars such as ***Betelgeuse***, a star in its late ***red giant*** phase of life (the He-burning stage), are also quite bright. Generally, the brightest stars shine bluest (class O)[91] [92] and the dimmest stars with reddish (class K or M) or brownish (class T – and somewhere between a giant gas planet and a fusion star) light during most

[89] Hertzsprung-Russell chart
[90] Andromeda galaxy: http://antwrp.gsfc.nasa.gov/apod/image/0210/Andromeda_gendler_s60.jpg
http://apod.nasa.gov/apod/image/0801/M31_hallas.jpg
[91] Diane Nalini, now Policy Advisor Environment Canada
[92] CBC interview
OBAFGKMLT: "Kiss Me Like That";... the lyrics

of their lives. During the middle age of a star, it is said to be a ***main sequence*** star. It lies on a trend in the ***Hertzsprung-Russell***[93] diagram of stellar luminosity as a function of temperature or colour. In this Hertzsprung-Russell diagram for all 16 331 single stars in the Hipparcos catalog whose distances have been measured to better than 10% accuracy and whose absolute magnitudes have been determined to within 0.025 [94], the broad band of stars slanting from upper left to lower right on the diagram are *main-sequence* stars in their hydrogen fusion stage. Off the main sequence, stars are in other periods of their evolution; Hipparcos has obtained **H-R** diagrams for nearby variable stars as well.

3.1.6 Stellar Evolution

- A star relatively quickly condenses from a distributed cloud of ***H-He*** gas and dusts towards the the *main sequence*.
- Spending most of its life on the main sequence, a star then produces energy by hydrogen-to-helium fusion. During this phase of life, it slowly becomes hotter and brighter.
- It moves off the main sequence as it begins helium fusion... it typically becomes larger, cooler and brighter.
- Large stars become extremely bright during the short oxygen burning and silicon burning phases and then explode as supernova. Very large stars move through all stages very quickly – perhaps in as little as 1 million or fewer years. Stars larger than about 8× the size of our Sun finish their lives as supernovae after lifespans shorter than a couple of billion years.
- Stars smaller than about 3-4×$\boldsymbol{M_\odot}$ just slowly die, collapsing under their own gravity, becoming smaller and temporarily hotter as gravitational energy converts into heat... *white dwarfs*. If they have close companion stars or if a star wanders too close, they can pull materials off their companion because of their high gravitational fields and form as a ***type Ia supernova***.
- Stars the size of the Sun move into a *red giant phase* before gently collapsing into white dwarfs, or if a little larger, into neutron stars or black holes. Betelgeuse[95] is such a star, only about 18× more massive than our Sun in its He-burning, red giant phase of life. Betelgeuse is large enough, though, that its eventual end will be in a supernoval explosion.

[93] In 1913, Henry Norris Russell noticed the correlation between spectral colour or type and the luminosity of stars as measured by their visual absolute magnitude.

[94] https://www.cosmos.esa.int/web/cesar/the-hertzsprung-russell-diagram
http://stars.astro.illinois.edu/sow/hrd.html

[95] https://www.princeton.edu/∼achaney/tmve/wiki100k/docs/Betelgeuse.html

- Very large stars (between 5× and $20 \times M_{\odot}$) go through a yellow-supergiant, ***Cepheid-variable*** phase late in their lives. During this phase, the period of their variation in brightness is related to their intrinsic brightness (absolute magnitude)[96].

3.1.7 A distance scale based on the intrinsic brightness of stars

Knowing its spectral type and that a star is in its main-sequence phase of life, we can know how intrinsicly bright it is (i.e. from Hertzsprung-Russell). If we know how bright it is and how bright it looks (remembering that the apparent brightness decreases as the inverse square of the distance from the star), we can determine how far away it is. We calibrate this method of distance measurement with all those stars which are close enough to the Solar System that we can survey their distance by "parallax triangulation".

- Once our brightness scale is calibrated, we use it to measure the distance to stars which are too far away to measure via parallax. In particular, we can measure the distance to stars in other galaxies in our local group. Our large ***Milky Way*** [97] galaxy has two small satellite galaxies which seem to be gravitationally bound to us – the ***Large*** and ***Small Magellanic Clouds***. We determine their distances to be **46 000 *pc*** and **64 000 *pc*** distance from the Sun. respectively.
- The next closest galaxy, the large ***Andromeda galaxy***, one which is probably very much like our own Milky Way, is at a distance of about **700 000 *pc*** or **0.7 *Mpc***. We need another scale to measure to this distance as we can't sufficiently well resolve "ordinary" individual stars.

3.1.8 A distance scale based on the intrinsic brightness of galaxies

Galaxies come in several "types" and "sizes"[98]. For the closest galaxies, we can quite easily determine their diameters if we know their distance.

> If you could see Andromeda, it would appear as an elliptical cloud with a diameter just a little smaller than that of the Moon in our sky. With binoculars with large enough lenses or with a low-power astronomical

[96] Cepheid variability

[97] All-sky images of Milky Way: http://antwrp.gsfc.nasa.gov/apod/image/0005/nir_cobe.jpg
A 360 degree view

[98] Galaxies
Hubble classifications of galaxy types

telescope, you actually can quite easily see it. The larger galaxies are the brighter galaxies.

- We assemble a scale of distance versus size and brightness for a local group of galaxies, measuring their distance by the apparent brightness of the very brightest resolvable stars in these galaxies. One of the brightest kinds of stars is the *Cepheid variable* type. These are extremely large, yellow, stars now thought to be in a stage of life following their $\boldsymbol{H \longrightarrow He}$ fusion. They pulse with a period which is very closely related to their intrinsic brightness and which may be more than 10 000× brighter than our Sun[99]. ***Polaris***[100], our *North Star* is a Cepheid. ***RR Lyrae*** stars, about 100× brighter than our Sun are also variable.

- RR Lyrae and, especially, the brightest Cepheids can be resolved in nearby galaxies and so we can know their distance. We can now measure distance to galaxies out to $\boldsymbol{10 Mpc}$ ($\mathbf{32.6}$ million light-years).

- If we can recognize their kind and now knowing how far away they are, we know how intrinsicly bright they are.

- Different classes of galaxies show different brightnesses and so we can begin to use the type or class to give us intrinsic brightness.

- This doesn't take us anywhere near to the limits of the universe. Now, however, knowing the apparent diameters of various kinds of galaxies, their distance and their intrinsic brightness, we can use, again the $\boldsymbol{1/r^2}$ law which explains apparent brightness as a function of distance to measure distances out to about $\boldsymbol{1000 Mpc}$.

- At great distances, we run into another kind of galaxy, the ***Quasar***. These are probably enormous, young galaxies in formation in which ***black holes*** are consuming enormous amounts of mass from the galaxies. They are all very far away, it seems, and as we shall see, ancient.

- Quasars are extremely bright and their brightness allows us to extend our brightness-correlated distance scale out to as far as, perhaps, $\boldsymbol{3000 Mpc}$. This is very close to the boundaries of our universe both in distance and in time.

3.1.9 Hubble: "Red-shift" and the "age" of the universe

Until the 1920s, it was thought that the fuzzy images astronomers saw in their telescopes were planetary nebulae in formation. Then they were understood to be galax-

[99] Cepheid variability
[100] Polaris: http://stars.astro.illinois.edu/sow/polaris.html

ies comprising hundreds of millions of stars. Our own Milky Way contains about 200 billion stars.

- In the 1920s, astronomers had also noticed that known spectral lines such as the lines of sodium vapour in the light emanating from the distant nebular clouds (later to be known as galaxies) tended to be more shifted towards the red end of the spectrum as they appeared smaller in the field of vision. When distances were obtained for the closest of these clouds in the late '20s, they were understood to be at great distance and of enormous size and brightness.
- ***Edwin Hubble***[101] had, in the 1930s, used the luminosity-period relationship of Cepheid variable stars as a means of measuring distance to many galaxies.
- He found that the farther they were away, the more the light they emitted was shifted to redder colour. The ***red shift*** of their spectral lines correlated with their distance.
  - A ***Doppler shift***[102] of light towards a reddening (i.e *red shift*) is caused by the galaxy moving away from us.
  - The amount of red shift which is known to be proportional to the velocity of recession formed a straight-line relationship with distance.
- Hubble computed an ***age of the universe***, let us call it the ***Hubble age***, from this straight-line relationship between distance and speed of recession.
  - His first determination (1929) offered an age for the universe of $\mathbf{1.8 \times 10^9}$ years.
  - By the early 1950s, geophysicists had already determined that Solar System was at least $\mathbf{4.5 \times 10^9}$ years old but it wasn't until 1955 that Humason found the age of the universe to be older that which we knew for the Earth. The recent Planck Mission[103] which mapped the CMB (Cosmic Microwave Background) with, now, greater resolution determines the beginning of time, that moment when the universal expansion began, at almost $\mathbf{13.8 \times 10^9}$ years ago. Currently, the most precise estimate of the "age of the Universe" is $\mathbf{13.799 \pm 0.021 \times 10^9}$ years[104].

[101] It was Edwin Hubble who, in 1924, following the discovery of the luminosity-period relationship for Cepheid variable stars by Henriette Leavitt, recognized that there were such stars within the Andromeda nebula and came to the unambiguous conclusion that Andromeda was, in fact, a galaxy of billions of stars at great distance and well beyond the stars in our own Milky Way.

[102] Doppler shift: http://www.astro.ucla.edu/∼wright/doppler.htm

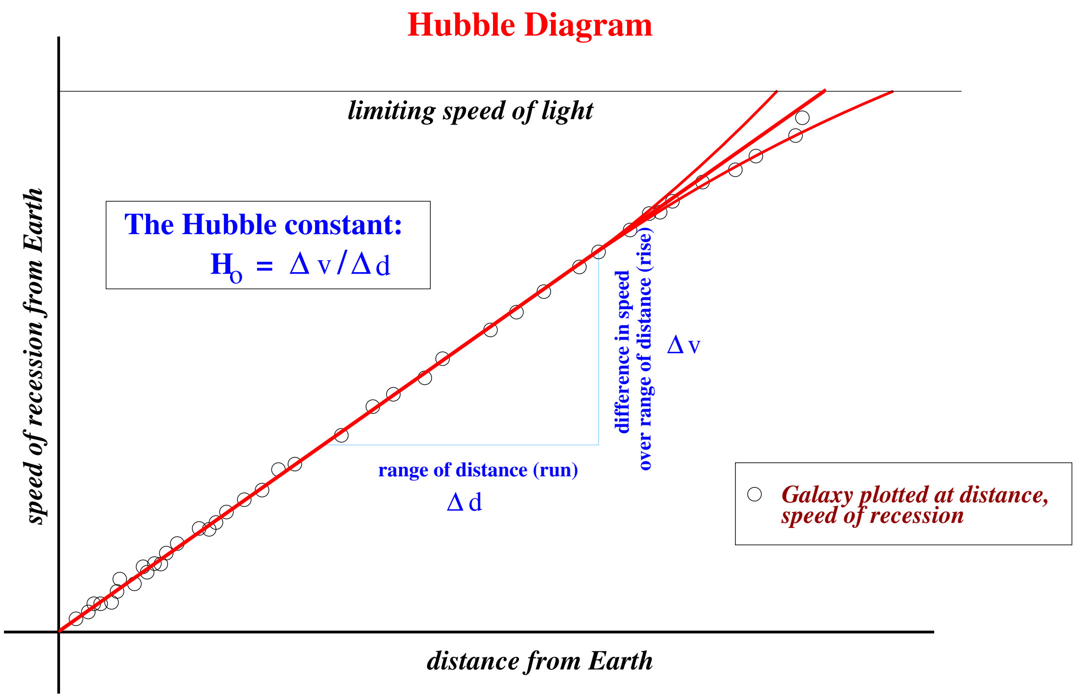
[103] The Planck Mission homepage

[104] On the age of the universe

The velocity of recession versus distance

If we plot the velocity of recession (i.e. the speed at which they are moving away from us) of galaxies as a function of their distance which we might infer from their apparent visual magnitudes, we find they fall on a fairly straight line in this ***Hubble diagram***.

.



- The slope of this nearly straight line divides a velocity in say, $\boldsymbol{km \cdot s^{-1}}$ by a distance typically measured in astronomical units such as $\boldsymbol{Mpc}$.

- The best recent determination[105] of the current and recent value of this slope give us a ***Hubble constant*** of

$$\boldsymbol{H_o = 67.74 \pm 0.46 km \cdot s^{-1}/Mpc.}$$

- This constant has units of $\boldsymbol{1/time}$. Its inverse has units of $\boldsymbol{time}$.

- Today, we generally accept that the Universe appeared $\boldsymbol{13.8 \times 10^9}$ years ago. One way of explaining the apparent rate of separation of all the galaxies is to regard them as all having left from the same place that long time ago with those which left fastest having moved farthest away.

[105] ...on "precision cosmology"

$\boldsymbol{H_o^{-1}}$ counts to that time in the past when all galaxies were in the same place – the centre of **Big Bang**. The *age* or, better ***Hubble age*** of all that we see in the heavens is what we regard as the age of the universe.

Einstein's Relativity shows that masses travelling through space cannot be accelerated to speeds beyond that of light and that nothing, even massless particles like photons, can travel faster than the speed of light. If the galaxies we observe are moving through space, $\boldsymbol{H_o^{-1} \cdot c}$, then, is as far as light has travelled from the centre of the Big Bang – from the "*birth of the universe*". While the geometry of the universe is understood to be more complicated than that of a simple Euclidean 3-space with time, we argue that the "*radius*" of the presently observable universe is thus about $\boldsymbol{13.8 \times 10^9\ light \cdot years}$ or $\boldsymbol{4\,200 Mpc}$.

From a more contemporary perspective, the Big Bang forms space-time and we regard space itself to be expanding such that the distance between objects tied to place within that space is increasing as space is stretched in accord with the Hubble constant. From this perspective, our galaxies are not moving through space, they are ever increasing their distance from us and from each other as they ride with the expanding space. The relativistic limitations would then, at least seemingly, not apply. The limiting distance to the "*beginning of the universe*" would not be this simple radius. Some arguments as to just how far away the "*beginning*" is suggest distances of many times $\boldsymbol{13.8 \times 10^9\ light \cdot years}$[106]. This latter perspective is one that is gaining ever more credence among physicists[107]

While we can, perhaps, agree on the "***age of the universe***", there is much subtlety in argument as to the "***size of the universe***".

Using a distance scale based on the apparent brightness of ***type Ia supernovae***, it seems that the slope of the Hubble plot was less in the distant past than it has been in more recent time (and closer distance). If true, this means that the universe is expanding more quickly now that it did in the distant past. It is accelerating. In 1998, the term ***dark energy***[108]. was introduced to describe that which is forcing the apparent acceleration. Current measurements of the rate of acceleration lead to the troubling conclusion that almost 70% of everything in the Universe is comprised of

[106] On expanding space

[107] The radius is further complicated by the *perspective* we choose in our physical sense of the moment. In *relativistic* physics, we connect "now" through "null geodesics" which are the connection between events determined by their distance within space and the velocity of light. The photon feels itself to have left the distant object of observation and to arrive at the observer at the same time, the "now". From the perspective of the observer, it has taken some time for this transit and the background universe has evolved and expanded during that time. In the colloquial sense of the "now" of the observer, the radius of the Universe as measured by the light-transit distance of the most distant objects that we can see is greater, possibly very much greater, than the relativistic "now" distance to that same object. The object will eventually be lost to our future observation as it is carried beyond the future visible universal horizon by the spatial expansion.

[108] http://www.esa.int/esaSC/SEMLK4VZJND_index_0.html

this undetectable dark energy. There is also unseen mass in the Universe which may be exotic matter (WIMP[109]) or just cold ordinary matter (MACHO[110]) that is not revealing itself as concentrated into objects that show their presence by their glow – stars[111]. Typically, 27% of everything in the Universe is thought to be this ***dark matter***. Later in the course we shall see how we might determine the existence of dark matter by its gravitational effect. The remaining 5% of gravitational matter is what we see and know about, ordinary matter. There remains 68% of the "*stuff*" of the Universe in dark energy. These are the ratios described by the currently fashionable ***Λ-CDM Concordance cosmological model***[112] a variant of the ***inflationary Big Bang***. This model accommodates dark energy through the relativistic ***cosmological constant***[113], $\boldsymbol{\Lambda}$, accounting for the accelerated expansion, and ***CDM***, cold dark matter, with these quantities best adjusted to fit all available observations. Presently, we obtain a value for the cosmological constant of about $\mathbf{10^{-52}}\boldsymbol{m^{-2}}$. It remains an unresolved and much argued question in theoretical physics as to why it is not exactly $\mathbf{0}$.

[109] Weakly interacting massive particles – so far, unobserved

[110] Massive compact halo objects – unseen by telescopes

[111] WIMPs or MACHOs? What is dark matter and dark energy?

[112] Concordance model: https://en.wikipedia.org/wiki/Lambda-CDM_model

[113] The cosmological constant $\boldsymbol{\Lambda}$

4 The condensation of our Sun and the accretion of the planets

In the beginning, the Big Bang created the simplest of atomic nuclei, $^{1}\boldsymbol{H}$, $^{4}\boldsymbol{He}$, $^{2}\boldsymbol{H}$, $^{3}\boldsymbol{He}$, $^{3}\boldsymbol{H}$, $^{7}\boldsymbol{Be}$, $^{7}\boldsymbol{Li}$ and $^{6}\boldsymbol{Li}$ but nothing much else. All the more massive nuclei were created in the nuclear fires of stars.

From the dust of this nucleosynthesis, the elements of our Earth were assembled into gases and mineral dusts and from these our Earth and Sun and planets condensed.

4.1 The condensation of the Solar System

About $\mathbf{5 \times 10^9}$ years ago, when the Universe was already, perhaps $\mathbf{8 \times 10^9}$ years old, at some gravitational centre, material from the clouds of dust and gas left behind by supernoval explosions began to assemble the mass of our Solar System. The gravitationsal condensation of the dispersed cloud may have been triggered by shock waves created in the explosion of a nearby low-mass core-collapse supernova[114].

- All elements known to still exist in our Solar System, except for promethium, $^{141-156}\boldsymbol{Pm}$, and technitium $^{93-99}\boldsymbol{Tc}$ and the trans-bismuth elements, those with atomic numbers greater than $\mathbf{83}$, pre-existed in the condensing cloud.

- Why no promethium? Why no technitium? The longest lived isotope of promethium, $^{145}\boldsymbol{Pm}$ has a half life, $\boldsymbol{t_{1/2}}$ of only $\mathbf{30}\,\boldsymbol{years}$ and so all of this element would have been quickly lost to the cloud since no nucleosynthetic processes in the now cool cloud could produce it in replacement. The longest lived isotope of technitium, $^{98}\boldsymbol{Tc}$, has a half-life of only $\mathbf{4.2 \times 10^6}$ years and would have been quite quickly lost.

- If the cloud of dust and gas had assembled from very recent supernoval dusts, it may have contained some residual and temporary $\boldsymbol{Tc}$, technitium (element 43) along with several trans-bismuth elements such as $\boldsymbol{Po}$, polonium, $\boldsymbol{At}$, astatine, $\boldsymbol{Rn}$, radon, $\boldsymbol{Fr}$, francium, $\boldsymbol{Ra}$, radium, $\boldsymbol{Ac}$, actinium, $\boldsymbol{Pa}$, proactinium, $\boldsymbol{Np}$, neptunium, $\boldsymbol{Pu}$, plutonium, $\boldsymbol{Am}$, americium and $\boldsymbol{Cm}$, californium. None of these elements have stable or long-lived isotopes and any that now exist on Earth or in meteorites that have come to Earth do so as temporary daughters of the $\boldsymbol{U}$ and $\boldsymbol{Th}$ decay sequences. Uranium and thorium are found in substantial amounts because some of their isotopes have long half-lives.

- At the centre of this condensing cloud, a great mass of gas, largely hydrogen and helium began to form a proto-sun.

[114] Supernoval triggering of condensation

- About the proto-sun, local centres of condensation formed orbits and concentrated the planets.

- These proto-planets were brought into orbit because the condensing cloud possessed angular momentum and as the infalling material in the gravitational condensation approached the proto-sun, its angular momentum accelerated its rotation rate just as a figure skater accelerates her spin by pulling in her arms.

- ***Angular momementum***, usually designated, $\vec{\mathbf{L}}$, is a *conserved quantity*[115] of physics.

- Conserving angular momementum, the infalling dust and gas starts revolving ever faster, spinning out into a nebular disk.

- We cannot account for the exact distribution of planets about our Sun but we do know that by almost any possible process of condensation, these planets would form orbits which are largely aligned near a plane with all planets revolving about the gravitational central Sun in the same direction.

- It is also most likely that they rotate (spin on their own axis) in the same sense as they revolve (orbit) about the Sun.

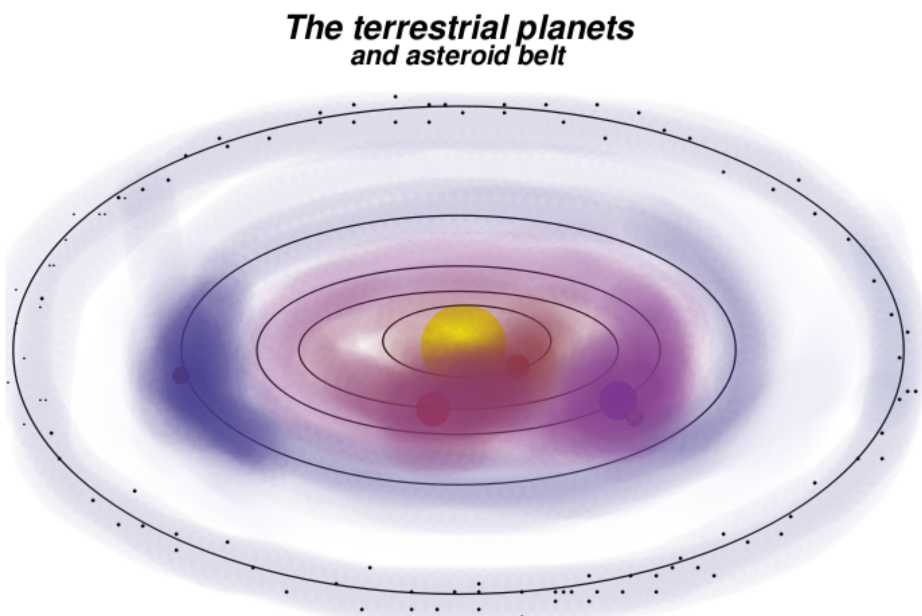
- Exceptions? ***Venus***, ***Uranus*** and ***Pluto***[116] among the planets actually rotate about their own axis in a contrary sense.

[115] *Law of Conservation of Momentum and/or Angular Momentum*

[116] Politics in science: Pluto was "demoted" from the official category of "***planet***" by a vote taken during the August, 2006 meetings of the IAU (International Astronomical Union). We, in this course, are choosing to accept Pluto as a planet for reasons of cultural consistency in spite of the recent redefinition of "*planet*". With another redefinition, Pluto may well again be promoted to the category in the future.

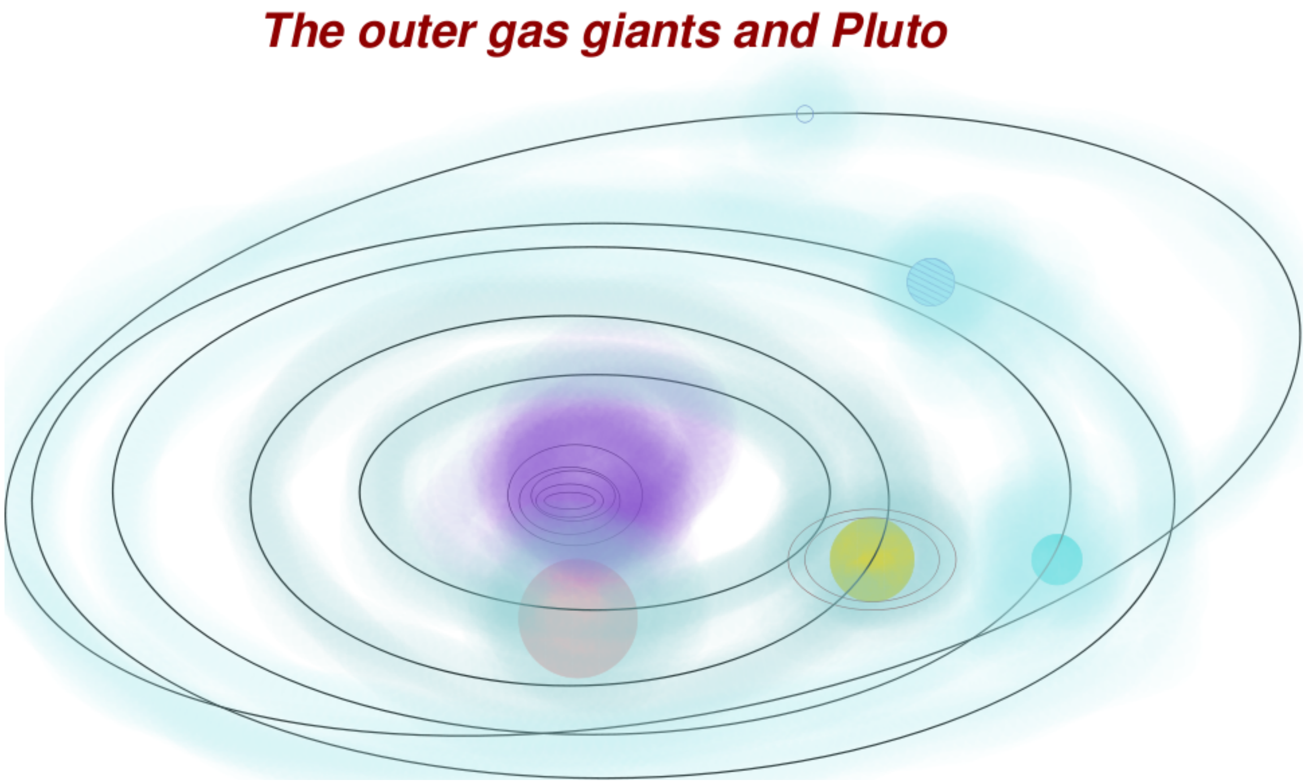
4.2 The solar nebular cloud

By about 4.6 billion years ago, the Sun at its centre and planets around it had begun to assemble in the rotating disk of dust and molecular gases derived from previous supernoval explosions[117].



The central proto-sun accreted most of the mass from the cloud and became so massive that even the lightest of gases, ***H*** and ***He***, could not escape its gravity. The gravitational energy from its condensation lifted the mass of this proto-sun to extremely high temperature and the nuclear fusion reactions were ignited. At distance from the proto-sun, proto-planets were condensing. Those closest to the proto-sun that would become the terrestrial planets formed largely of those refractory minerals within the nebular cloud that could exist at the temperatures of their region of the cloud. Those closest in formed of the highest melting-temperature metals and silicates which are also the densest of material comprising our planets. Farther from the proto-sun, lighter minerals could form. Beyond what was the distance of proto-Mars, ice minerals formed including water and methane snows and at greatest distances even solidified nitrogen and oxygen.

[117] Actual image of stellar-planetary formation in a nebular cloud obtained by radio-telescope



There was so much of these lighter ice minerals and gases that giant proto-planets formed. The proto-Jupiter and proto-Saturn became so massive that they could gravitationally bind even the lightest of the gases, $\boldsymbol{H}$ and $\boldsymbol{He}$. These element now account for most of their masses. Proto-Uranus and proto-Neptune formed more slowly and so comprise largely water and methane ices as the solar wind had already purged their region of the nebular cloud of $\boldsymbol{H}$ and $\boldsymbol{He}$ before they had acquired a mass sufficient to contain these gases. Beyond present Neptune, the accretion process was so slow that only relatively small ice-dwarf planets formed; present Pluto is the inner-most of these though one might well consider the largest of the moons of present Neptune, Triton, to be a captured ice-dwarf similar in composition and size to Pluto.

4.3 Temperature in the Solar System

The Sun, with its surface temperature of $\mathbf{5800}\boldsymbol{K}$ largely determines the temperature of materials distributed throughout the Solar System. Obviously, the farther we find ourselves from the warming Sun the colder our region of the Solar System is.

A "***black body***" is a body which absorbs all wavelengths of electromagnetic (microwave, light, X-ray, $\boldsymbol{\gamma}$-ray) radiation incident upon it. The surface of a black body comes to equilibrium at a temperature that is determined by the in-flux and reradiation of radiant energy according to the Stefan-Boltzmann law[118]:

$$\boldsymbol{R = \sigma T^4.}$$

where $\boldsymbol{R}$ is the radiant energy measured in $\boldsymbol{W \cdot m^{-2}}$, $\boldsymbol{T}$ is the equilibrium temperature measured in $\boldsymbol{K}$ (kelvins) and $\boldsymbol{\sigma = 5.670 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}}$, the Stefan-Boltzmann constant.

The Sun presently radiates energy at the rate of $\boldsymbol{L_S = 3.839 \times 10^{26} W}$. At the distance of the Earth, $\boldsymbol{d_E = 1AU = 1.497 \times 10^{11} m}$ from the centre of the Sun, that radiant power is distributed over an area of $\boldsymbol{4\pi d_E^2\ m^2}$; then, $\boldsymbol{R_E = L_s/(4\pi d_E^2) = \sigma T_E^4}$. We can determine the black body temperature, $\boldsymbol{T_E}$, of a surface at Earth's distance from the Sun as

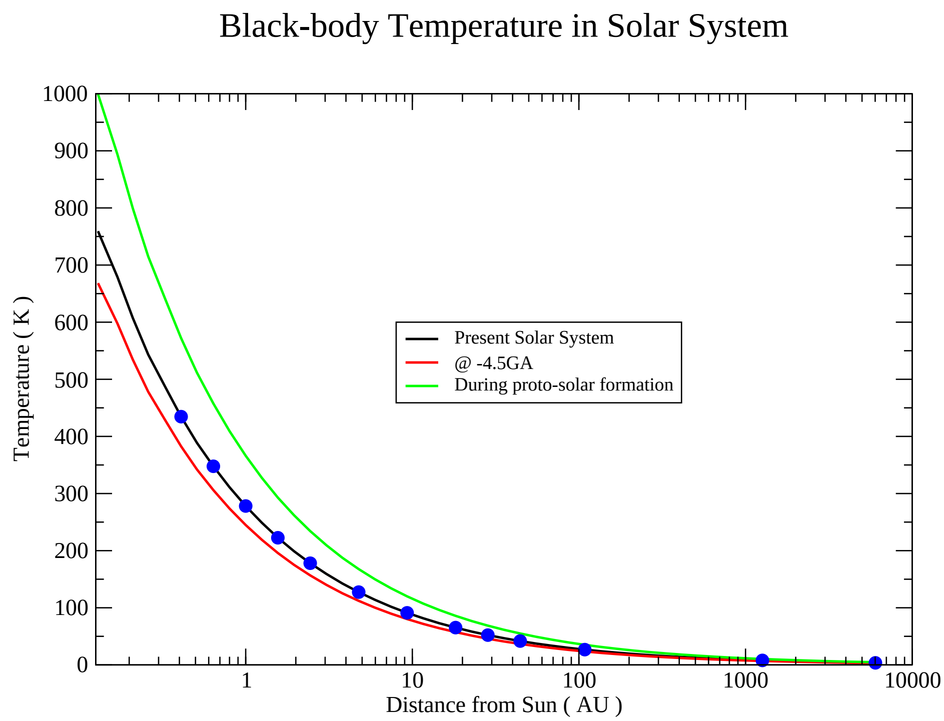
$$\boldsymbol{T_E = (L_s/(4\pi\sigma d_E^2))^{\frac{1}{4}} = 393.8K.}$$

Notice that the black-body temperature within the Solar system is proportional to $\boldsymbol{\frac{1}{\sqrt{d}}}$.

Planets in the Solar System are not black bodies. They reflect some of the radiant energy that falls upon them. The "***bond albedo***" of Earth $\boldsymbol{\alpha_b = 0.29}$, for example, tells us that 29% of the infalling radiation from the Sun is not absorbed onto the surface. Moreover, the spinning Earth receives infalling radiation only over the surface disk equivalent facing the Sun with area $\boldsymbol{\pi r_E^2}$ and distributes that energy over the surface of its sphere, $\boldsymbol{4\pi r_E^2}$. For a rotating spherical body in the Solar System, then, we must correct for its albedo and for its $\boldsymbol{4\times}$ spherical surface. For example, for the Earth, the effective $\boldsymbol{R_{E_e} = \frac{1-\alpha_b}{4} R_E}$ and the black-body surface temperature must be adjusted to $\boldsymbol{T_{E_{corr}} = 255.6K}$. A greenhouse effect due to the gas composition and water vapours of our atmosphere re-absorbing part of the energy reflected from the surface lifts that black-body temperature by about $\boldsymbol{33K}$.

The following figure shows the black-body temperature, that is not corrected for albedo but corrected for the spherical surface of the bodies of the Solar System, throughout the Solar System. The black line shows us temperatures corresponding to the current solar irradiance. 4.6 billion years ago, our Sun was just stabilizing with a then-smaller fusion core; it was cooler, radiating at only about 60% of the rate it does today. That temperature line is shown in red. On the other hand, just as the proto-Sun was forming, the combination of the gravitational energy of collapse and the initiation of nuclear fusion within the Sun may have lifted its radiative power by a factor of 3: the green line. Note that the current planetary and asteroidal distances are shown by blue dots on the current black-body temperature line. The three final dots are for distances of $\boldsymbol{100AU}$ ($\boldsymbol{2.5\times}$ the distance to Pluto) and $\boldsymbol{0.1}$ and $\boldsymbol{0.5}$ light-years. At $\boldsymbol{0.5}$ light years, $\boldsymbol{1/8\times}$ the distance to the nearest neighbouring star, the temperature has already dropped to the level of the coldness of empty space: the CMB temperature.

[118] The Stefan-Boltzmann Law



.

4.4 The distribution of the planets

There ***seems to be some "pattern"*** in the distribution of planets. In 1766, J.D. Titius described a simple mathematical relationship describing the distribution of planets in distance from the Sun. Another German astronomer, Johann Bode, popularized the relationship as ***Bode's Law*** or, modified, as the ***Titius-Bode Relationship***.

- We still cannot obtain this relationship from *first principles* through physics; moreover, we do not believe that the distribution in our Solar System is "*representative*" of all planetary systems. *Bode's Law* is described by the *empirical* relationship

  $$\boldsymbol{r_k = a + b \cdot 2^k}$$

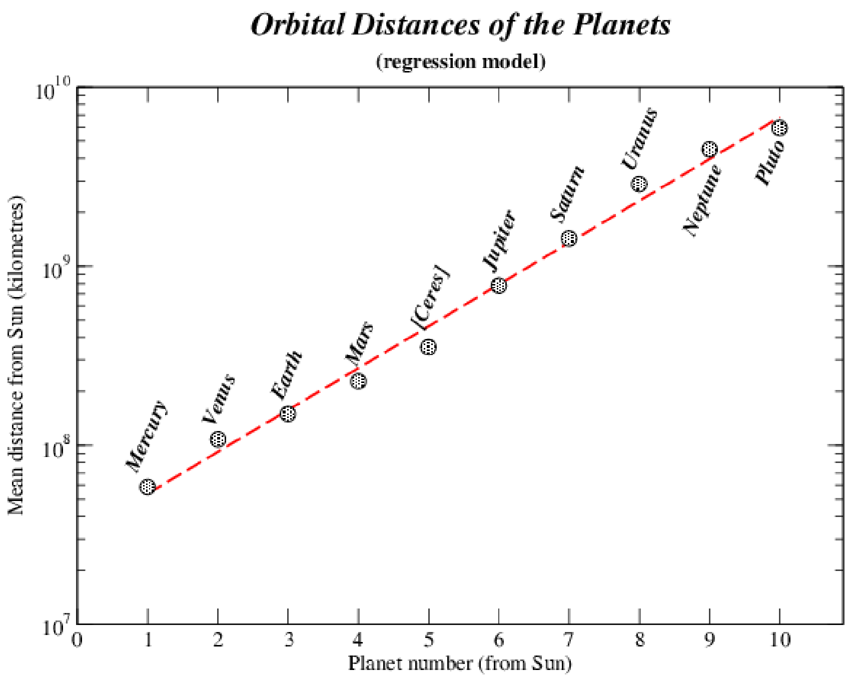
  where $\boldsymbol{k}$ is the planetary number as we count out from the Sun (i.e. $\boldsymbol{k_{Mercury} = 1, k_{Earth} = 3}$), $\boldsymbol{a}$ and $\boldsymbol{b}$ being parameters which best fit the planetary distance distribution from the Sun.

- A slightly better relationship is offered by the Titius-Bode relationship

  $$\boldsymbol{r_k = r_0 \cdot p^{k-1}}$$

where $\boldsymbol{r_0 = 0.4AU = 6 \times 10^7 km}$, the orbital distance of ***Mercury*** from the Sun and $\boldsymbol{p = 1.73}$ for a best average fit through the whole planetary system when we count the belt of ***asteroids***[119] between ***Mars*** and ***Jupiter*** as a planet and exclude Pluto which seems to be anomalously closer to the Sun than so predicted by this empirical law[120].

- A simple regression model... $\boldsymbol{r = 3.13 \times 10^7 km \cdot e^{0.54k}}$.



.

Note the nearly straight line... Does it really mean anything at all? Probably not! We need more data and we are beginning to collect it.

We have now found well over 5400 "exoplanets" (i.e. planets exterior to our Solar System; 1642 confirmed, 3787 possible as of 2016-01-01) in orbit about other stars. While only a few of these stars show more that a few orbiting planets, it would seem that the simple patterns of our own Solar System are not followed by these other systems[121]. The **Kepler Mission** observed over 150 000 main-sequence stars in our galactic neighbourhood looking for planetary

[119] Where are the asteroids?
Plot of distance from Sun

[120] An empirical law is one for which we cannot establish a theory based upon fundamental principles or laws.

[121] California Planet Search

transits across the stellar disks until its reaction flywheels used for pointing to chosen stars failed in the summer or 2012.

4.4.1 The "habitable zone"

In our search for possible life elsewhere in the Universe, we are now concentrating on exoplanets that exist within the so-called **habitable zone**. This is a zone of distances from the mother star where surface waters can exist at temperatures amenable to life on Earth. Life on Earth is found in water ices at $-5C$ and in superheated waters issuing from fissures in the deep ocean at $+120C$. Now that we have found planetary systems about many stars, we are looking carefully at those that are "earth-like" in that they have rocky surfaces, atmospheres and indications of H_2O. For our solar system, Earth sits on the inside (warmer) edge of the habitable zone and Mars nearer the outer (cooler) edge.[122] Still, even on Mercury, where we now know that there is water ice in shaded polar craters, it is possible that life could exist in water melts. Mars and even some of the larger asteroids could harbour life. We will learn, later, that among our best candidates for bodies in the solar system harbouring life are some of the moons of Jupiter and Saturn which are being internally heated by radioactive decay and tidal stressing or which are large enough to still hold some of their original heat of accretion. A planet's proximity to its mother star really only constrains the possibility of exposed surface life; life might find safe harbour at depth.

4.5 Gravitational energy retained as heat in a condensing planet or the Sun

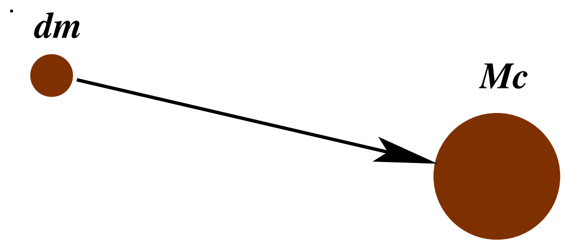
Recall that von Helmholtz recognized that the gravitational energy contained within the Sun could account for its shining for between 20 and 40×10^6 years.

How can we estimate this energy? Let's do the physics and calculate the heat equivalence of the gravitational accretion energy for the Earth.

- Starting from an extended and "absolutely" cold (i.e. $0K$) cloud...
- Somewhere a small mass M_c of radius r assembles, perhaps under electrostatic or magnetic forces.
- The volume of our centre, presume a sphere, is then, $V_c = 4/3\pi r^3$ and its density, ρ is such that $M_c = \rho V_c$.

[122] The habitable zone for our Solar system and that of Gliese 581

- Now, suppose that at some great distance $\boldsymbol{R_{start}}$ a small element of mass, $\boldsymbol{dm}$, is waiting to fall in upon this gravitating centre.



The small difference in ***potential energy*** of this small mass in the gravitational field of our central mass from that which it would have on the surface at $\boldsymbol{r}$ is determined by ***Newton's Law of Gravity***[123] as

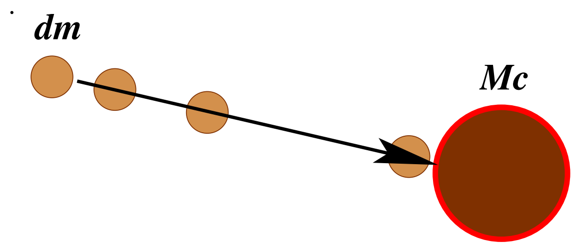
$$\boldsymbol{dE = dm \cdot (GM_c/r - GM_c/R_{start}).}$$

- For large enough $\boldsymbol{R_{start}}$, it doesn't make much difference to this form if we assume $\boldsymbol{R_{start} = \infty}$. And, then, the difference in potential energy of our small element of mass is

$$\boldsymbol{dE = dm \cdot GM_c/r.}$$

- Now if our small element of mass were to fall in towards our condensation centre, it would ***accelerate*** gaining ***velocity*** and ***kinetic energy*** of motion equal to its continuing loss of potential energy[124].

- Eventually, it would, moving perhaps very fast, hit our central mass centre and release all of its kinetic energy in heat.



[123] $\boldsymbol{G = 6.67 \times 10^{-11} m^3 \cdot kg^{-1} \cdot s^{-2}}$ is the universal Cavendish gravitational constant.
[124] This is consequent to the ***Law of Conservation of Energy***.

- The little condensation centre increases slightly in volume $dV_{layer} = 4\pi r^2 dr$ and if this layer density is just like that of our initial mass centre, the relationship between these elements is

$$dm = \rho\, dV_{layer} = 4\pi\rho r^2 dr,$$

and remembering that $M_c = 4/3\pi r^3 \cdot \rho$, the energy contributed by the infalling dm is

$$dE = 4\pi\rho r^2 dr \;\cdot\; 4/3\pi\, r^3\, \rho\, G/r = G\frac{16}{3}\rho^2\pi^2\, r^4\, dr.$$

- Now we have a mathematical description of how much energy is contributed to a mass centre of radius r when a small amount of material of density ρ falls in from infinite distance.

- All we have to do to find the total energy accumulated in the accretion is to add up all the contributions of the small infalling masses – We ***integrate*** our functional relationship.

- We start our summation or integration a radius $r = 0$ and continue to add up contributions until we come to the full radius $r = R_p$ of our planet.

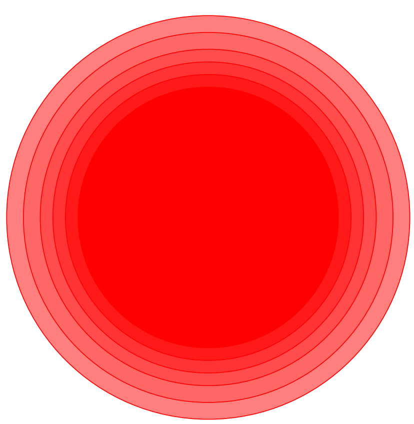
$$E = \int_{r=0}^{r=R_p} \frac{16G\pi^2\rho^2}{3} r^4 dr.$$

- Those who know some calculus might be able to do this simple integration to obtain

$$E = \frac{16G\pi^2\rho^2\, r^5}{15}\Bigg|_{r=r_0}^{r=R_p}$$

or

$$E = \frac{16}{15}\pi^2\rho^2 R_p^5 G.$$



Layer–by–layer, the Earth forms.... hotter and hotter it becomes as more and more gravitational energy is converted to heat!

- Note that the total mass of our now-condensed planet, $\boldsymbol{M_p = \frac{4}{3}\pi\rho\, R_p^3}$, so

$$\boldsymbol{E = \frac{3}{5}\frac{GM_p^2}{R_p}.}$$

For the Earth:

$$\begin{aligned} \boldsymbol{M_\oplus} &= \boldsymbol{5.97 \times 10^{24} kg,} \\ \boldsymbol{R_\oplus} &= \boldsymbol{6.371 \times 10^{6} m;} \end{aligned}$$

.... the total energy, measured in ***joules*** ($\boldsymbol{1J = 1kg \cdot m^2 \cdot s^{-2}}$) accumulated in the condensation of the Earth: $\boldsymbol{E = 2.24 \times 10^{32} J}$.

For the Sun:

$$\begin{aligned} \boldsymbol{M_\odot} &= \boldsymbol{1.99 \times 10^{30} kg,} \\ \boldsymbol{R_\odot} &= \boldsymbol{6.96 \times 10^{8} m;} \end{aligned}$$

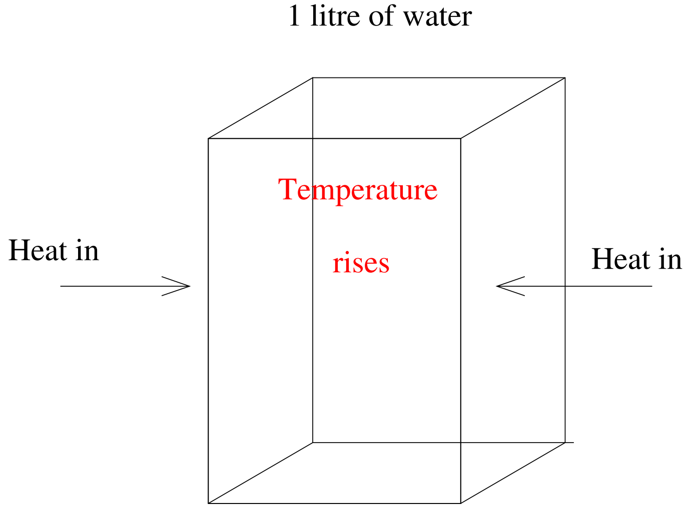
...... I leave it to those of you who are itching to do some little physics. Following the arguments offered next, you might be able to estimate the original *average temperature* of the Sun.[125]

Well, now for our nascent Earth, we have a lot of energy largely contained as ***heat***... How hot might the Earth have been, originally? It depends on how well the Earth can hold heat.

4.5.1 Internal temperature of a condensing planet

The temperature of a material which internally holds energy in the form of heat depends upon its ***heat capacity***, its ability to hold heat. Water is very efficient, one of the most efficient of all materials, for holding heat.

[125]By my calculation $\boldsymbol{\approx 114\,000\,000 K}$, easily hot enough to start the nuclear fires.



- The ***calorie*** is a measure of quantity of heat. If we were to introduce $\mathbf{1000}\,\boldsymbol{calorie}$ into $\mathbf{1}\,\boldsymbol{litre}$ or water at $\mathbf{4^oC}$, we would increase the temperature of the water to $\mathbf{5^oC}$. The heat capacity of this litre of water is then $\boldsymbol{C_H = 1000\,cal/litre/\,K.}$ As $\mathbf{1}\,\boldsymbol{l}$ of water at $\mathbf{4^oC}$ has a mass of $\mathbf{1}\,\boldsymbol{kg}$, $\boldsymbol{C_H = 1000\,cal\cdot kg^{-1}\cdot K^{-1} = 1\,cal/g/^oC}$. As $\mathbf{1}\,\boldsymbol{cal = 4.180\,J}$, it then requires $\mathbf{4180}\,\boldsymbol{J}$ of energy in the form of heat to raise the temperature of $\mathbf{1}\,\boldsymbol{kg}$ of cold water through $\mathbf{1^oC}$. The heat capacity of water in liquid form doesn't depend very strongly on temperature: $\boldsymbol{C_H \approx 4.180\times 10^3 J\cdot\ kg^{-1}\cdot\ K^{-1}.}$

- The ***Calorie***...... We all know that weight watchers watch Calories. In food measurements of energy equivalents, the Calorie used is really $\mathbf{1}\,\boldsymbol{kcal = 1000\,cal}$. The energy equivalent in 1 pat of butter is about $\mathbf{100}\,\boldsymbol{kJ}$ which if efficiently metabolized or burnt could raise the temperature of $\mathbf{1}\,\boldsymbol{kg}$ of body mass, mostly water, by $\mathbf{24^oC}$ or the body of a young woman of $\mathbf{48}\,\boldsymbol{kg}$ by $\mathbf{0.5^oC}$. Fats are obviously rich hoards of chemical energy.

- The heat capacity of rocks....
The heat capacity of rock and metals is quite a lot less than that of water. Typically, rocks show $\boldsymbol{C_{H_{rock}} \approx 10^3 J\cdot\ kg^{-1}\cdot K^{-1}.}$

- Now we can calculate something of a temperature for the nascent Earth...
Considering that all of the mass of the Earth is made of rock-like materials or metals, what would be the temperature of the Earth if all the gravitational energy of condensation were retained? It is easy to show that, if the Earth had retained all of this energy at condensation, its temperature would have started at a ridiculously high $\mathbf{37\,000^oC}$!

- We now think that the interior of the proto-Earth was actually quite cool....
$\mathbf{37\,000}\boldsymbol{K}$ is $\mathbf{6.5}\times$ hotter than the surface of the Sun. All Earth materials would

have vapourized and all the atoms and molecules dissociated into a plasma. We actually know that the Earth must have condensed quite cool.

- What is wrong with the physics in our simple argument? Why do we calculate such a high temperature?
  We have not considered that heat could be lost, through radiation out into a cold empty space, during condensation. By current modelling of Earth formation, it seems that more than 95% of the gravitational energy of condensation would be re-radiated into space.
  - The average temperature of the early proto-Earth was probably not much more than about $\mathbf{1100^oC}$ and certainly very much lower than the ridiculous value, $\mathbf{37\,000^oC}$.

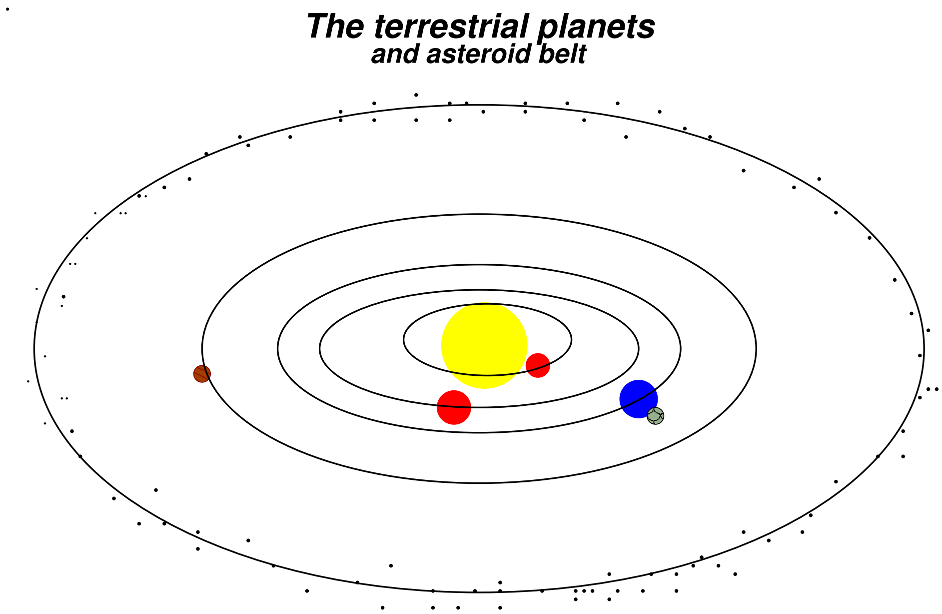
We now have good evidence that the Earth condensed relatively cool and has subsequently heated up. What heated it up?

4.6 The accretion and differentiation of Earth

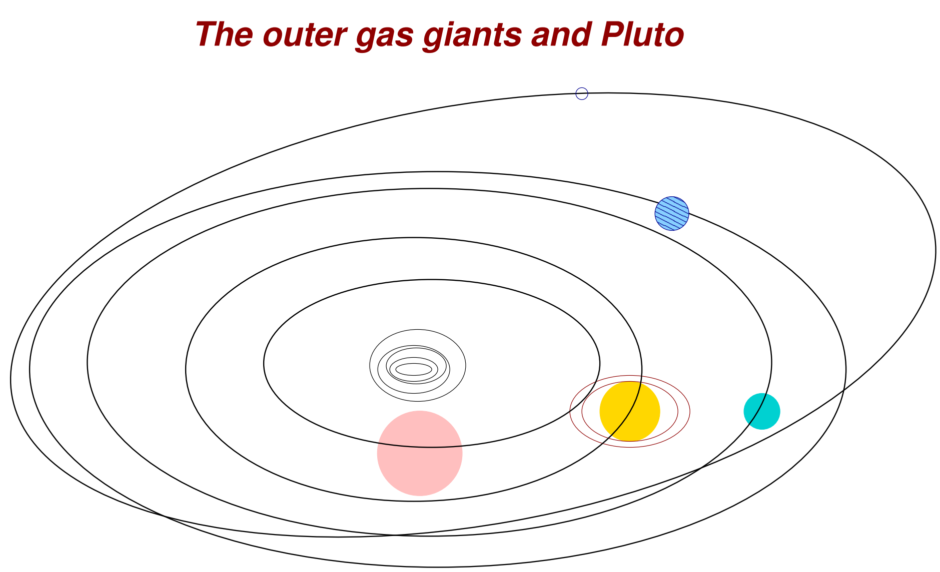
Out of a cloud of dust and gas that comprised all of the elements known to exist today in our Solar System except for promethium, the terrestrial planets condensed from planetesmal fragments in orbits about a proto-sun about $\mathbf{4.6 \times 10^9}$ years ago. Most of the hydrogen and helium from that primordial cloud condensed into the central Sun whose nuclear fires started to burn in its core.

- Many of the lighter elements such as hydrogen and helium and those elements which do not easily chemically combine with others (e.g. $\boldsymbol{He}$ and $\boldsymbol{Ne}$) were not easily contained by the gravitational field of the condensing ***terrestrial planets*** but were easily held by the enormous gravitational pull of the massive Sun. The terrestrial planets, Mercury [126], Venus[127], Earth[128], and Earth's Moon[129], Mars[130] and the Asteroids[131], held those heavier elements which formed them as rocky-metallic bodies.

[126] Mercury
Mercury Messenger mission
[127] Venus
[128] Earth
[129] Moon
[130] Mars
[131] Asteroids



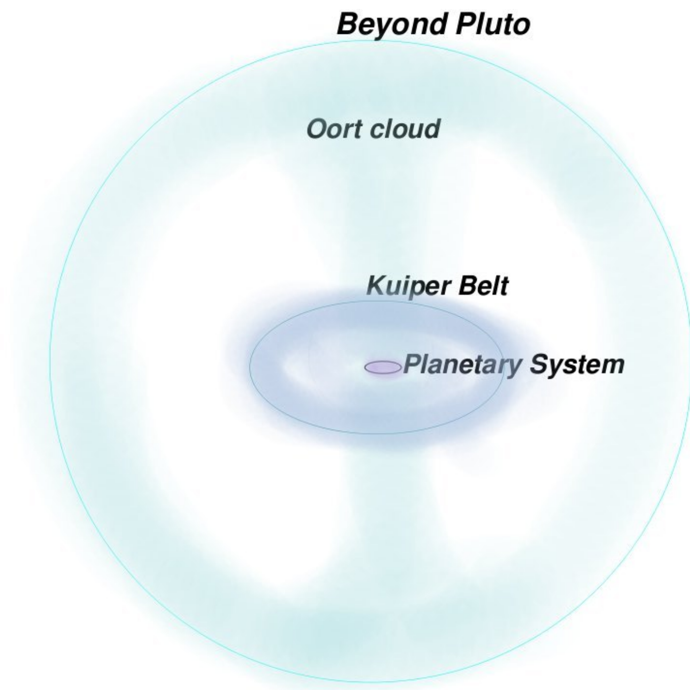
- Beyond the terrestrial planets and asteroids, the environment was much cooler in the early Solar System and so the lighter elements like $\boldsymbol{H}$ and $\boldsymbol{He}$ as well as water, $\boldsymbol{H_2O}$, were available to condense into the formation of the ***gas giants***, Jupiter[132], ***Saturn***[133] , Uranus[134] and ***Neptune***[135]. Uranus and Neptune are now sometimes called the ***water giants***.



132 Jupiter
133 Saturn
134 Uranus
135 Neptune

- Beyond Neptune, lonely Pluto[136], probably largely composed of water-ice, formed as the ninth of the *traditional* planets.

- One may, though, regard Pluto, a ***dwarf planet***, as just the closest of the ***Kuiper objects***[137] that form a belt[138] out to distances of a hundred times that to Pluto.



- And beyond the ***Oort cloud***[139], a possibly spherical cloud of comet-like bodies – snowballs of water-ice, volatiles and original cosmic dust.[140] [141]

---

[136] Pluto
[137] Trans-neptunian dwarf planets
[138] Kuiper belt
[139] Oort cloud
[140] Solar system
[141] Planets

Elemental abundances in the Solar System by atom-relative

Element	Atomic number	Atomic weight	Abundance (Urey, 1950)
Hydrogen	**1**	**1**	**400 000 000**
Helium	**2**	**4**	**31 000 000**
Oxygen	**8**	**16**	**215 000**
Neon	**10**	**20**	**86 000**
Nitrogen	**7**	**14**	**66 000**
Carbon	**6**	**12**	**35 000**
Silicon	**14**	**28**	**10 000**
Magnesium	**12**	**24**	**9 100**
Iron	**26**	**56**	**6 000**
Sulfur	**16**	**32**	**3 750**
Argon	**18**	**40**	**1 500**
Aluminum	**13**	**27**	**950**
Calcium	**20**	**40**	**490**
Sodium	**11**	**23**	**440**
Nickel	**28**	**59**	**270**
Phosphorus	**15**	**31**	**100**
Chlorine	**17**	**35**	**90**
Chromium	**24**	**52**	**78**
Manganese	**25**	**55**	**69**
Potassium	**19**	**39**	**32**
Titanium	**22**	**48**	**24**
Cobalt	**27**	**59**	**18**
Fluorine	**9**	**19**	**16**

In the table above, the abundances take into account the preponderant mass of the Sun in our Solar System.

The planets and especially the smaller inner terrestrial planets could not gravitationally hold onto the hydrogen and helium but as their contribution to the overall mass of the Solar System is so small, their lacking in these light elements has little bearing on overall abundances.

These relative abundances are essentially well predicted by the Theory of Nucleosynthesis described by Burbidge, Burbidge, Fowler and Hoyle in 1957[142] [143].

[142] The BBFH theory of stellar nucleosynthesis
[143] On nucleosynthesis theory

On the abundances... Implications?

- almost all the elements listed are produced in the nucleosynthetic fusion processes
- two elements, with nuclei more massive than iron, namely nickel, $\boldsymbol{Ni}$, and cobalt, $\boldsymbol{Co}$, are also quite abundant. These with iron are most stable (i.e. they have the greatest nuclear binding energy) of all nuclei.
- $\boldsymbol{Ni}$ and $\boldsymbol{Co}$ are not produced by the fusion reactions of Sun-like stars; they are among the very first stage elements to be produced in the *r-process* of neutron capture in supernoval explosions.
- the elements with massive nuclei can only have been produced to observed levels of abundance by supernovae.

On the abundances....on Earth?

Several lines of argument bring us to know that the Earth contains (by mass rather than atom-number):

- $\boldsymbol{Fe}$: 35%
- $\boldsymbol{O}$: 30%
- $\boldsymbol{Si}$: 15%
- $\boldsymbol{Mg}$: 13%

If we were to assemble these four elements in just this abundance, melt them together and then let them cool and crystallize at relatively low pressure, we would form the mineral *olivine*: $[\boldsymbol{Mg, Fe}]\boldsymbol{SiO_4}$. In the nebular cloud formed about the protosun, such temperatures and pressures are thought to have existed at distances from Mercury out to the asteroids.

4.6.1 The accretion of a terrestrial planet – Earth

During a few tens of thousands of years preceding the birth of our Earth, $\mathbf{4.567 \times 10^9}$ years ago, material out of the primordial dust cloud was being attracted to a gravitational centre in orbit about the already brightening proto-Sun. Materials first coalesced chemically into minerals like olivine or water ice where temperatures were low enough and these, then under physical forces formed into *planetesmals* which bombarded the ever growing Earth. It is thought to have taken less about 10 million years and perhaps as little as a few hundred thousand years for most of Earth's mass to have been assembled. During this process of accretion, most of the heat of bombardment derived from the gravitational potential energy was reradiated into space resulting in a body that was probably not extremely hot or molten throughout. Late in this relentless bombardment, one last large object, perhaps the size of Mars, crashed into the proto-Earth and splashed up an enormous volume of material which itself coalesced in orbit about the Earth and formed our Moon. The energy from this "***Big Whack***" left the outer regions, perhaps to a depth of 1000km, molten. When did this happen? We are quite sure that it happened somewhat before $\mathbf{4.4 \times 10^9}$ years ago (the famous Jack Hills zircons[144] have not been melted since then!) and probably before $\mathbf{4.42 \times 10^9}$ years ago (the recent measurement of the ages of the oldest rocks returned from the Moon).

What do we know of the Earth at the time of the Big Whack? The Earth was already partially ***differentiated***.

- Overall, the Moon – we know from its density – contains much *less* ***Fe*** than does Earth: little of the deep iron core was spashed from the Earth.
- The surface rocks of the Moon contain *more* ***Fe*** than surface rocks of Earth: the Earth has further differentiated since that catastrophic collision.
- The age of the oldest rocks on the Moon are about $\mathbf{40 \times 10^6}$ years older than the oldest minerals found on Earth and about $\mathbf{200 \times 10^6}$ years older than the oldest rock masses found on Earth – the recently famous ***faux-amphibolites*** from the Porpoise Cove area of Northern Quebec[145] which were discovered by Jonathan O'Neil, Ph.D. student in McGill's own Department of Earth and Planetary Sciences.

  Why? How?

  - The small Moon solidified quickly after the collision...
  - The surface of the Earth remained largely molten – and possibly originally to a depth of hundreds of kilometres – for another **200+** million years.

The greater amount of iron in lunar surface rocks tells us something about the degree of ***differentiation***[146] of Earth that had already happened by the time of the collision. The geochemistry of these rocks is our best model for that of the outer regions of Earth 4.44 billion years ago.

[144] The Earliest Piece of the Earth
[145] O'Neil, J., Francis, D.F. and .... Science article
[146] Differentiation: the denser elements and minerals fall toward the centre of the Earth and the lighter elements and minerals rise towards the surface.

4.6.2 Accretion Models

Cold (slow) accretion

While there remains a healthy argument concerning the early condition of the Earth and especially as to whether or not it had ever undergone a general melting, one classical model leads us to a ***cold accretion***. According to this model, most promoted by Hanks and Andersen starting in the 1970s, the original temperature profile within the Earth as the bombardment of condensing materials came to an end didn't exceed $\mathbf{2000°}\boldsymbol{C}$ anywhere. For a cool accretion, the Earth could not have assembled so quickly that the heat of formation could not largely be lost through radiation. Today, the deep interior of the Earth is very much hotter than $\mathbf{2000°}\boldsymbol{C}$. Temperature at the centre of the Earth's solid iron core is demonstrably at least $\mathbf{5000}^{\boldsymbol{o}}\boldsymbol{C}$. Even magmas erupting from Hawaïan volcanoes show temperatures exceeding $\mathbf{1500}\boldsymbol{K}$. If accretion was cool, the Earth has heated up internally since.

If the Earth started out cold, how did it become sufficiently internally heated to differentiate the iron core?

Two processes are surely implicated: the "***big whack***", the late collision with a large, Mars-sized planetesmal that splashed the Moon into orbit about Earth and ***radioactive decay***.

- Aluminum is abundant on Earth. One isotope of aluminum, $\mathbf{^{26}}\boldsymbol{Al}$, would have been relatively abundant if the condensing supernoval explosion cloud of debris from which the Sun and planets formed had not long lingered before condensation began.
  - $\mathbf{^{26}}\boldsymbol{Al}$ decays to $\mathbf{^{26}}\boldsymbol{Mg}$ by emitting a $\boldsymbol{\beta}^+$ particle with a half-life of only $\mathbf{7.3 \times 10^5}\,\boldsymbol{yr}$.
  - Enough of this best-candidate isotope condensed into the Earth to have produced the sufficient heat distributed throughout the Earth to have already started the physical differentiation during the period of accretion.
  - Also, many other short-lived isotopes of the lighter elements must have condensed with the cloud and so contributed to a rather rapid early internal heating of the Earth.
  - If the cloud had been produced by a supernoval explosion, it is possible that it contained quite a lot of $\mathbf{^{60}}\boldsymbol{Fe}$ which again decays to $\mathbf{^{60}}\boldsymbol{Ni}$, the second most abundant isotope of nickel on Earth, in a short, $\mathbf{3 \times 10^5}\,\boldsymbol{yr}$ half-life.
  - As well, if the cloud condensed soon enough after a supernoval explosion – and stellar and planetary formation[147] seems to be happening today in

[147] http://hubblesite.org/discoveries/10th/vault/in-depth/search.shtml

the young ***Crab***[148] and ***Orion Nebulae***[149] [150] which are understood to be supernoval remnants – highly radioactive and fissionable transuranic elements such as einsteinium, ***Es***, fermium, ***Fm***, europium, ***Em***, and californium, ***Cf***, may have still existed in quantity and their decay could have produced prodigious amounts of heat within the newly condensed Earth.

None of these original radioisotopes are naturally occuring in measurable quantities today.

– Now, substantial quantities of only uranium, ***U***, thorium, ***Th***, and potassium $\boldsymbol{^{40}K}$ are contributing to the planetary heating and these are largely concentrated in the outer rocky crust and upper mantle of the Earth though recent research has shown that $\boldsymbol{^{40}K}$ could alloy with iron and so might exist in the inner core. These radionuclei contribute significantly to the internal heating of the planet at present. The now-high internal temperature of the planet still partially derives from the very early radioactive heating of the planet by the short-lived radioisotopes but most of the present internal heat and consequently high internal temperature, especially of the mantle, is due to the continuing decay of ***U***, ***Th***, and $\boldsymbol{^{40}K}$. The decay of $\boldsymbol{^{40}K}$ into $\boldsymbol{^{40}Ca}$ and $\boldsymbol{^{40}Ar}$ now contributes most to the continuing internal heating of the Earth's mantle. Still, all the early heat of original accretion has not yet been entirely radiated away from the Earth through its surface into cold space.

- Importantly, now, the deepest interior heating derives from the continuing geochemical differentiation and from the release of the latent heat of fusion of iron as the Earth's inner core slowly freezes. As it has been shown that potassium can alloy with iron at very high temperatures and pressures, $\boldsymbol{^{40}K}$ could also be contributing to the heating of the deepest interior regions of the planet.

Other arguments...

One alternative argument for the early stages of differentiation and iron melting in the upper mantle relates to the formation of the Moon. It must be noted, though, that most of the iron on Earth had already been concentrated in the core at the time of the "Big Whack". This collision with a Mars-sized object reasonably accounts for the formation of the Moon, for the Earth's rather high angular rotation rate and, perhaps, for its inclined rotation axis. Had such a collision occured, as argued above, it must have occured very early on in the Earth's history and certainly before ***4.4Ga***[151] for we have minerals of that age on Earth and they could never have been since melted.

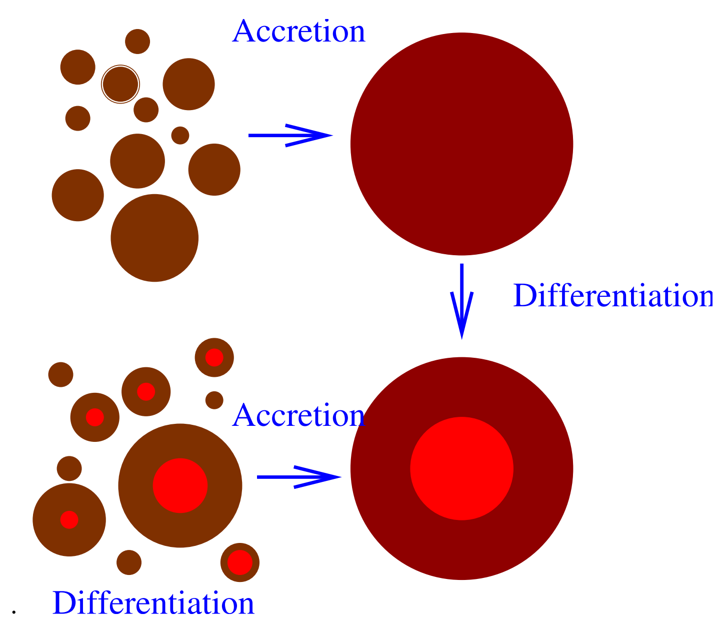
[148] Crab Nebula: 1054AD
[149] Orion Nebula: ∼3 million years ago
[150] Star formation in Orion nebula
[151] We often use Ga, "giga-ans", to describe a billion years past.

Such a collision would have caused global and deep melting of the mantle of the Earth... the Earth would have been awash in a deep "***magma ocean***" of molten rock from which the melted iron would sink to depth. Recall that the Moon seems deficient in iron relative to the Earth. If radioactive heating of cold-accreted Earth had already taken place and so started the migration of iron towards the Earth's core, this would account for a lower abundance of iron on the Moon which would have formed of material from the colliding object and from only the outer regions of the Earth. Of course, it could well be that the colliding object was poorer in iron than the Earth and so diluted the iron abundance of the splashed-up mix of material. It could well be that both bodies were already differentiated with an iron core and that mostly mantle layer materials from both objects contributed to the splash which condensed into the iron deficient Moon. The iron core of the impactor may well have assembled into the inner Earth.

The isotopic composition of the Earth and Moon are very similar. This fact argues for a source region for the impactor that is in the region of Earth itself, surely well within the orbital distances between Venus and Mars.

There are several alternative scenarios for the process of differentiation that are arguable – the one presented in detail is that that many planetologist see as most reasonable.

A second model (Scenario 2 of next section) variation for planetary formation argues that even relatively small planetestmals that assembled to form the Earth and terrestrial planets had, themselves, already differentiated out iron from the essentially *olivine* mineral matrix.



Two models for accretion: (top) homogeneous, (bottom) planetesmal differention.

A third scenario (See Scenario 3 in next section) follows from a very rapid accretion of Earth and, presumably, the other terrestrial planets. In a sufficiently rapid accretion, the outer regions of the neo-planet could remain essentially molten, perhaps to depths of hundreds or even a thousand kilometres in the case of Earth. In this molten magma ocean, metallic iron could have separated and sunk away to depth as a consequence of its high density. The unknown chemical oxidation state of the condensing materials becomes an important factor is this latter scenario for if the ocean were sufficiently oxidizing, the iron would have remained combined as $\boldsymbol{Fe_2O_3}$ which may not have easily and quickly sunk to depth.

Whether the iron was originally relatively homogeneously distributed within the proto-Earth or was already assembled and separated in the planetesmals or quickly melted away into the deep interior of the proto-Earth is now a matter of intense debate among planetologists. When we better understand the environment and condition of the solar nebula, we may be able to differentiate between these scenarios.

The environment in which the Solar System formed is still under debate. A cold, slow accretion model for the formation of planets would require a rather stable environment such as that of the ***Tauri Auriga molecular cloud***[152]. Recently, a more violent and chaotic environment, such as that in the Orion[153] or Crab[154] Nebulae, has been argued as being more probable for the formation of our Solar System. The violent environment could account for the rather small distance to the edge of *our* Kuiper belt and for the fact of Uranus and Neptune having much less $\boldsymbol{H}$ and $\boldsymbol{He}$ than do Jupiter and Saturn. In an environment with many supernoval explosions, the outer regions of the proto-planetary Solar System could be stripped away. Moreover, the violent environment can account for many details of the cosmochemistry of meteorites. It could explain a heating for the possible partial differentiation of iron in olivine minerals before accretion.

The Crab Nebula is the remnant of a supernoval explosion that was observed and documented by Chinese astronomers in 1054. A rapidly rotating ***neutron star*** or ***pulsar*** exists within the nebular debris cloud; this fact tells us that the explosion was that of a massive-star supernova as the white-dwarf supernoval explosions leave no cores behind.

4.7 Geochemical differentiation of an Earth-like planet

In the previous section, three scenarios have been described for the formation and earliest condition of the Earth. Whatever its early state, the Earth quickly separated

[152] Hubble image of the Taurus-Auriga cloud
http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/32/

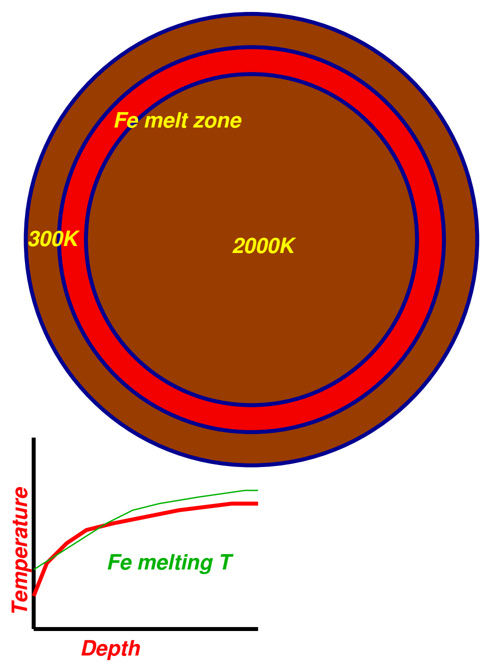
[153] http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/49/image/b

[154] http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/15/

out a deep iron core. The differentiation of the iron core must have been almost complete by the time of formation of the Moon through the "Big Whack". How this prior differentiation might have happened depends on which scenario we follow.

- **Scenario 1:** Homogeneous accretion (that early model that still "works")
  - An initial geochemical differentiation of the Earth from a cool, relatively homogeneous accretion would require that the Earth accreted relatively slowly – over a few million years.
  - The subsequent differentiation process was rapid enough that the Earth had already differentiated its core before the collision of a Mars-sized object with Earth splashed up the Moon, perhaps within less than **100** million years of the accretion.
  - Following this scenario, we presume that the Earth accreted with an internal temperature probably not exceeding about $\mathbf{2000}\boldsymbol{K}$ anywhere. That temperature would result from adiabatic compression during the slow accretion.
  - Surface temperature: $\approx \mathbf{270}\boldsymbol{K}$ in equilibrium with our cool station in the Solar System.
  - Temperature at depth: $\approx$*adiabatic* rising to perhaps $\mathbf{2000}\boldsymbol{K}$ at depth.
  - Homogeneous composition... heat sources in radionuclei.

.



Iron melts in a shallow zone when it is warmed beyond the melting point for the containing pressure.

- Subsequent heating: as the relatively short-lived radionuclei within decayed, the Earth heats up.... until...
- At some depth (perhaps $\boldsymbol{200-300km}$), the pressure-equilibrium melting temperature of iron is exceeded and a layer of liquid iron begins to form...
- Iron, being very dense and now liquid, would tend to work its way deeper into the Earth releasing gravitational potential energy.
- Now, heat derives from Earth's continuing geochemical differentiation and from the release of the latent heat of fusion of iron as the Earth's inner core slowly freezes as well as decay of radionuclei and other possible nuclear processes.

- **Scenario 2:** The Earth may have assembled from already iron-differentiated planetesmals.
  - The dense iron is liquified as the planitesmals assemble the Earth and sinks into the deep core.
  - The lighter fractions rise toward the surface and the least dense of the minerals are left behind in the upper mantle to form the early crust.
- **Scenario 3:** It may have been substantially heated through one or many post-accretion collisions or if the accretion of the Earth happened sufficiently quickly – over say, a few 10s of thousands of years – the Earth would have retained much of its gravitational energy of accretion as heat.
  - Large enough collisions or sufficiently quick accretion causes a melt of a thick outer layer of the newly accreted Earth.
  - The olivine-like composition of this layer separates
  - The iron-rich composition of olivine melts at a lower temperature than the magnesium-rich component. The iron-rich partition stays in the liquid state to lower temperatures as the melt cools and the iron leaches out.
  - The lighter elements like $\boldsymbol{Ca}$, $\boldsymbol{Na}$, $\boldsymbol{K}$, $\boldsymbol{Al}$ float in the melt and form the minerals of the crust of the Earth.

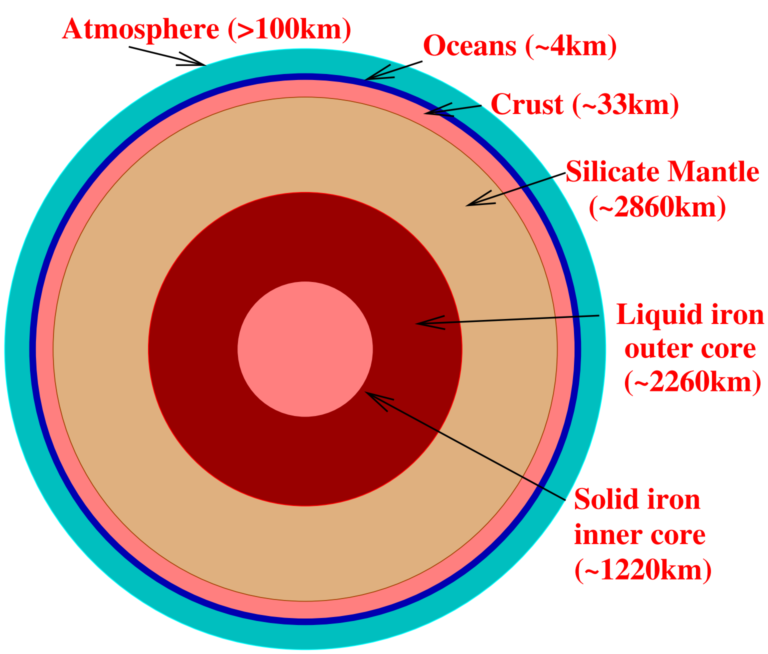
4.7.1 The warming Earth and iron melting

The early Earth was rich in radioisotopes. Some decayed quickly releasing heat to contribute to the earliest differentiation. Some, the longer lived, continue to release the heat that has much contributed to warming of the Earth. Dense iron melted and worked its way down into the deeper Earth forming an iron core within only a few million years of formation and thus displaced the lighter minerals – largely $\boldsymbol{SiO_4^{4-}}$

and $\boldsymbol{O^{2-}}$ combined with $\boldsymbol{Ca^{++}}$, $\boldsymbol{Mg^{++}}$, $\boldsymbol{Na^{+}}$, $\boldsymbol{K^{+}}$, $\boldsymbol{Al^{3+}}$ and some $\boldsymbol{Fe^{++}}$ or $\boldsymbol{Fe^{3+}}$ – and lighter elements which then rose to shallower depths. ***Silicates*** are minerals combining metal ***cations*** (eg. $\boldsymbol{Fe^{2+}}$ or $\boldsymbol{Mg^{2+}}$) with the $\boldsymbol{SiO_4^{4-}}$ ***anion***, as in, for example, ***olivine*** $\boldsymbol{[Fe, Mg]_2SiO_4}$ or with $\boldsymbol{SiO_3^{2-}}$ as in, for example, ***perovskite***, $\boldsymbol{[Fe, Mg]SiO_3}$. ***Oxides*** are minerals combining metals such as $\boldsymbol{Fe^{2+}}$ or $\boldsymbol{Mg^{2+}}$ with $\boldsymbol{O^{2-}}$ as in, for example, ***magnesiowustite***: $\boldsymbol{[Fe, Mg]O}$. At depth in the mantle, olivine separates into magnesiowustite and perovskite. Very deep in the mantle, perovskite probably undergoes a chemistry-preserving mineralogical ***phase change*** into ***post-perovskite***.

Within a few million years the Earth had largely differentiated into having an iron core, a silicate mantle and a proto-crust though the mineralogical characteristics of the contemporary crust has formed through subsequent geological processes. The process of differentiation has continued throughout the 4.567 billion year history of our planet.

4.7.2 The contemporary Earth



A model of the contemporary Earth

Overlain by a thin crust of ***granitic***[155], the continental masses, and ***basaltic***[156] rocks, the oceanic crust, the greatest part of the Earth's volume comprises its *silicate*

[155] On granites: http://en.wikipedia.org/wiki/Granite#Mineralogy
[156] On basalts: http://en.wikipedia.org/wiki/Basalt#Petrology

mantle. The chemical composition of the mantle is like that of an iron-depleted olivine $\approx \boldsymbol{Mg_{1.8}Fe_{0.2}SiO_4}$. By mass, its elemental composition is approximately: 44.8% $\boldsymbol{O}$, 22.8% $\boldsymbol{Mg}$, 21.5% $\boldsymbol{Si}$ and only 5.8% $\boldsymbol{Fe}$! The remaining 0.3% of its mass is thought to be comprised of $\boldsymbol{Ca}$, $\boldsymbol{Al}$, and $\boldsymbol{Na}$, in that order, with perhaps some $\boldsymbol{S}$ and $\boldsymbol{C}$ and 0.03% $\boldsymbol{K}$ which provides a major radioactive heat source within the body of the Earth.

About half way from the surface to the centre, we come to the ***core*** which is largely composed of iron.

The ***outer core*** is a liquid mix of $\boldsymbol{Fe}$ with traces of $\boldsymbol{Ni}$ and $\boldsymbol{Co}$ along with, probably, some $\boldsymbol{S}$ and $\boldsymbol{O}$ and perhaps $\boldsymbol{C}$. When observed over even short times, it flows easily. Resistance to liquid flow is measured by the ***viscosity*** of the fluid; the Earth's outer core has been variously estimated to have a viscosity of $\boldsymbol{\eta \approx 0.01 - 10^5\, Pa \cdot s.}$ Water, for comparison, has a viscosity of $\boldsymbol{\eta \approx 0.001\, Pa \cdot s}$, liquid mercury, $\boldsymbol{\eta \approx 0.0015\, Pa \cdot s}$. The outer core's viscosity is low enough that over periods of seconds to hours, it shows no measurable rigidity; rigidity is a mechanical property that distinguishes solids from fluids.

At depth, the mixture forms into a solid ***inner core*** which is probably almost pure $\boldsymbol{Fe}$. The inner core is a near spherical ball, about **2500** km in diameter. Over periods from seconds to months or years, the Earth's inner core does express significant rigidity. Over much longer periods, it may, however respond to stresses (distributed forces) like a very high viscosity fluid. Buffet[157] has estimated the viscosity of the inner core on very long time scales to be about $\boldsymbol{\eta \approx 5 \times 10^{16}\, Pa \cdot s.}$ The inner core may flow like a fluid on timescales beyond hundreds of years.

The Earth continues to differentiate itself both geophysically (density) and geochemically (mineralogy). How did the early and how does the continuing differentiation arise? Heat!

The major source of interior heat at present

For most materials, compression brings them to solidfy. That is, for most materials, the higher the pressure, the higher the temperature at which they solidify or freeze. Water is an exception[158]. Water freezes (or melts) at lower temperatures as pressure increases. Water as ice can be melted by applying pressure. Iron, for example, and contrarily, can be frozen by applying pressure.

Within the Earth, pressure increases from the pressure of the atmosphere at the surface, $\boldsymbol{1\, bar = 101.3\, kPa}$ to about $\boldsymbol{360\, GPa = 3.6\, Mbar}$ at its centre[159].

[157] Bruce Buffett

[158] Phase diagram for water ($\boldsymbol{1 torr = 133 Pa}$):
http://www.its.caltech.edu/ atomic/snowcrystals/ice/h2ophase.gif

[159] $\boldsymbol{1\, Pa}$ or $\boldsymbol{1\, pascal}$ is equivalent to $\boldsymbol{1\, N \cdot m^{-2}}$. $\boldsymbol{1\, N}$ or $\boldsymbol{1\, newton = 1\, kg \cdot m \cdot s^{-2}}$ is a measure of *force* approximately equivalent to the weight of sandwich. A pressure of $\boldsymbol{1\, Pa}$ is equal to the pressure exerted on ones body by a single thin bedsheet.

Deep within the Earth, iron is freezing onto the inner core at a temperature of about $\boldsymbol{4500^oC}$; at the surface, iron would remain liquid at this temperature and at any temperature above $\boldsymbol{1600^oC}$. The interior temperature, even in the upper regions of the Earth, is now well above the melting temperature of $\boldsymbol{Fe}$. The pressure-freezing of iron releases its ***latent heat of fusion***. This source of heat accounts for, perhaps, 5% to 10% of the heat flowing from Earth's interior.

The outer core of the Earth is a fluid of iron, nickel and cobalt mixed with lighter elements. As pure iron or an iron-nickel-cobalt mix freezes onto the inner-core, the dense metals are depleted in the outer core, lowering its density. The corresponding density differentiation releases gravitational potential energy of these sinking metals as heat. This probably accounts for as much or even more release of heat than does the direct latent heat of fusion of iron freezing onto the inner core.

The major radioactive elements, $\boldsymbol{U}$, $\boldsymbol{Th}$ and $\boldsymbol{K}$, probably still account for a major source of internal heating but there remains a problem that wherever deep materials come to the surface, the amounts of these radionuclei in the issuing ***magmas*** (*molten rock*) are very much less than that required to account for the heat flow from the interior. J. Marvin Herndon[160] speculates that the required additional heat is now being produced in a small ***U-Th fission reactor*** deep within the frozen inner core. The existence of such a reactor could be, in principle, recognized via the ratio of helium isotopes, $\boldsymbol{{}^3He/{}^4He}$, issuing from the planet's interior.

4.7.3 Geophysical-geochemical differentiation and the formation of Earth's core

The warming and melting iron in the upper regions of the eartly Earth sinks into the depths, displacing lighter materials towards the surface... this is *differentiation*!

Iron in differentiation

- The early Earth lost most of its ***volatiles***: $\boldsymbol{H}$, $\boldsymbol{He}$, $\boldsymbol{Ne}$, etc.
- Iron (35% of Earth's mass), silicon, aluminum and magnesium were retained because of their density and/or lack of volatility.
- Oxygen (30% of Earth's mass) was retained largely bound with silicon in silicates ($\boldsymbol{SiO_4^{4-}}$).
- These elements along with calcium, sodium and potassium are the most common elements making up rocks and the Earth.

[160] A nuclear reactor in Earth's core?: http://nuclearplanet.com/index.html

- ***Fe*** was probably quite evenly distributed through nebula from which the planetesmals that formed the body of the proto-Earth. A train of partitioning processes has taken iron to the deepest interior of the Earth and other planets.

  As the iron reaches the deep interior of the Earth pressures begin to compress it into a solid. Whether or not the iron is solid at any particular depth depends upon the pressure (its depth) and the local temperature. Increasing pressure and/or decreasing temperature solidify iron. When the pressure-temperature conditions at the centre of the Earth are amenable, a solid *inner core* forms surrounded by a still liquid *outer core*, both largely composed of iron. As the Earth cools, the inner core grows larger and larger. The pressure-freezing of the iron onto the inner core releases heat – the *latent heat of fusion*. This heat raises the temperature of the liquid iron outer core and helps to maintain its liquid state. Our magnetic field derives from the differentiated core.

The Geodynamo in the Earth's core

Heat flows from hot towards cold. The heat so-released at the inner core boundary seeks to flow towards the surface. As it flows towards the surface through the liquid outer core, an organized convective motion of the core's fluids is initiated.

- The outer core fluid, being largely iron, is conductive of electricity.

- If a conductor is moved through a ***magnetic field***, an ***electrical current*** is generated in the conductor: ***Faraday's Law***.

- Current flows in closed loops and a loop of current generates a magnetic field: ***Ampere's Law***.

- We have a process in which a magnetic field induces a current which produces a magnetic field – a feedback loop!

- The Earth's spin helps to align the new field with the original field, thus maintaining the global magnetic field of the Earth. This is the only conceivable way the Earth's magnetic field could arise.

- Convective motion of the outer-core fluids forces the geodynamo's feedback process. The convection is powered by the escape of the heat generated in the differentiation and freezing of the inner core and the decay or fission of possible radioactive isotopes within the solid core. A $\boldsymbol{U - Th}$ fission reactor in the core as speculated by Herndon could produce sufficient heat to drive the convection. Alternately, recent research has shown that potassium can be alloyed into the crystalline structure of the inner core. Even with only traces ($\boldsymbol{\sim 300ppm}$) of potassium so-alloyed, the decay of $\boldsymbol{^{40}K}$ to $\boldsymbol{^{40}Ar}$ could provide sufficient power

($\sim \boldsymbol{1TW}$ is required[161]) to maintain the Earth's magnetic field for eons without the inner-core having completely solidified in the process.

- This ***geodynamo*** is the source of the Earth's magnetic field.

As we shall learn later, magnetic fields can be frozen into a rock as it cools through the ***curie temperature***. Magnetic fields can also be frozen into mineral crystals as they crystallize from hot geothermal fluids. Some of the oldest rocks and minerals known on Earth show frozen-in magnetic fields.

The geodynamo had surely started by $\boldsymbol{3.5\,Ga}$ because mineral crystals found in Komati, South Africa show remnant magnetic fields. This proves that Earth had, grosso-modo, already geophysically and geochemically differentiated by that time.

The Moon again... the "Big Whack" scenario

Somewhere preceding about $\boldsymbol{4.4\,Ga}$ and probably following quite a lot of geochemical differentiation during which much of the iron must have already assembled at depth, Earth was impacted by a Mars-sized body. The collision splashed up material from the outer shells of the Earth and from these materials and whatever came from the collider, the Moon formed:

- The Moon is less rich in iron than is Earth.

  Argument: lower density and $\boldsymbol{Fe}$ is the only abundant dense element.

  Implications?

  - At the time of lunar formation, the Earth had already partially differentiated with much of its $\boldsymbol{Fe}$ already in the core and so not splashed up from Earth's outer layers.

    Argument: that zircons, $\boldsymbol{ZrSiO_4}$, formed at almost $\boldsymbol{4.4\,Ga}$ tell us that the Earth's surface had begun to cool from the general melting of the outer regions (perhaps to $\boldsymbol{1000\,km}$ depth). Zircons melt at $\boldsymbol{1859^oC}$; they can also "dissolve" into acidic aqueous solutions rich in flourine or chlorine as well as into several magmatic melts. We know, then, that these zircons have not faced such destructive conditions in the past 4.4 Ga. Zircons can entrap traces of $\boldsymbol{Ti}$ (titanium) and the quantity and isotopic composition of the $\boldsymbol{Ti}$ entrapped can tell us something about the temperature conditions that existed at the time of their crystallization. These oldest zircons formed under relatively cool, aqueous conditions: the Earth's surface was already cool and wet by $\boldsymbol{4.4 \times 10^9}$ years ago!

  - The magma ocean would have geochemically differentiated with the least dense materials floating to the surface forming ***continental cratons***, the earliest masses of rock.

[161] $\boldsymbol{1TW = 10^{15}}$ watts

Argument: we have continental cratonic materials by $\mathbf{4.03}\boldsymbol{Ga}$... the Acasta Gneiss.

4.7.4 Mantle, crust, the continents and oceans

As heat from the Earth flowed towards the Earth's cool surface, a process of convection began in the silicate surrounding the iron core. This silicate mantle now extends from a depth of about $\mathbf{3000}\,\boldsymbol{km}$ almost to the surface.

Crust

The very lightest materials which first froze out of the magma ocean, also silicates, formed the Earth's overlying crust.

- The *granitic* or granite-like crust formed the continents. Granites are ***felsic***[162] rocks high in silica, $\boldsymbol{SiO_2}$, and lighter metallic elements $\boldsymbol{Na}$, $\boldsymbol{K}$, $\boldsymbol{Al}$ that form ***feldspars*** with silicates, $\boldsymbol{Si_xO_y}$. A common chemical composition of the mineral feldspar has the stoichiometries of the forms: $\boldsymbol{KAlSi_3O_8}$, $\boldsymbol{NaAlSi_3O_8}$, $\boldsymbol{CaAl_2Si_2O_8}$.

- The denser *basaltic* or basalt-like crust formed the ocean basins. Basaltic rocks have low, less than about 40%, silica content. They are denser than granites. Basalts are ***mafic***[163] rocks; mafic means that they are largely composed with $\boldsymbol{Mg}$ and $\boldsymbol{Fe}$ as the metals combining with silicates. Typical mafic minerals are ***olivine***, $\boldsymbol{Fe_xMg_{2-x}Si0_4}$, ***pyroxene***[164], ***amphibole***[165], and ***biotite***[166]

The denser basalt floated deeper on the still-*plastic* mantle and the cooling magma ocean and gave room for the waters of the oceans to in-fill. The less dense granitic rocks floated higher, forming the continental masses.

Oceans

Where the ocean water came from is a matter of some continuing debate.

- possibly (and at least partially) through outgassing of hydrogen and oxygen from the Earth's interior during differentiation.

[162] Felsic minerals - These are minerals which are $\boldsymbol{Si}$ (silicon) rich, and most also have abundant $\boldsymbol{Al}$ (aluminium), $\boldsymbol{Na}$ (sodium) and $\boldsymbol{K}$ (potassium). Felsic minerals are typically light in colour and may be transparent or translucent. They are commonly white, light grey or pink. The derivation of the term is **fel** for feldspar and **sic** for silica.

[163] Mafic minerals - These are minerals which are rich in $\boldsymbol{Fe}$ (iron) and $\boldsymbol{Mg}$ (magnesium). Mafic minerals are generally dark in colour - usually green, brown or black. The derivation of the term is **ma** for magnesium and **fic** for iron (from ferric).

[164] Pyroxene

[165] Amphibole

[166] Biotite

- probably, also, asteroidal[167] and cometary bombardment[168] brought vast amounts of water to the Earth's surface in its early history.

But then why is there no ocean on the Moon, Mercury, Venus or Mars as they should have been similarly bombarded?

- gravity was not great enough on the Moon or Mars to hold the water onto its surface against its vapourization.

- Mercury and Venus were just too hot for the water to remain on the surface and it largely escaped into space.

It seems that Mars did have surface waters and perhaps even large oceans which slowly evaporated into space because its gravitational force was insufficient to contain it. Presently, Mars holds vast quantities of water in its polar glaciers which are almost $\boldsymbol{4\,km}$ deep in places and probably as permafrost throughout the ***regolith*** regolith. It is estimated that there is enough water on Mars to cover its entire surface to a depth of about $\boldsymbol{20\,m}$.

Water ice has been detected in permanently shaded craters on Mercury and water droplets are known to exist in the very high ($\boldsymbol{+50km}$) atmosphere of Venus. There may also be water in the regolith, the mineral soils, of the Moon.

Water is is an abundant molecule in the inner Solar System and ice an abundant mineral.

The present oceans of Earth are "***saline***[169]" with a content of dissolved salts of about $\boldsymbol{3.5\%m}$ (by mass). The salts have been leached from the continents and released from the interior of the Earth by volcanism during the past $\boldsymbol{4Ga+}$.

Atmosphere

The lighter volatile molecules and elements that do not condense into liquid at the temperature and pressure on the Earth's surface formed a thin atmosphere enveloping the planet. Presently, Earth's atmosphere is composed of:

- 78%v (by volume) $\boldsymbol{N_2}$, from the primordial condensation and subsequent outgassing of the planet

- 21%v $\boldsymbol{O_2}$, reduced from combination with $\boldsymbol{C}$ and in $\boldsymbol{SiO_4^{4-}}$ by lifeforms

- a little less than 1%v $\boldsymbol{Ar}$, primordial and outgassed and derived from $\boldsymbol{\beta}$-capture decay of $\boldsymbol{^{40}K}$

167 Rosetta-Philae mission
168 Origin of Earth's water
169 Salinity of oceans: http://www.marinebio.net/marinescience/02ocean/swcomposition.htm

- a varying amount of water ($\boldsymbol{H_2O}$) vapour evaporating from surface liquid water and transpiring from plant life (at saturation, $\mathbf{20^oC}$, $\sim \mathbf{0.4\%v}$ by volume)
- an ever-increasing component of $\boldsymbol{CO_2}$ (presently 0.04%v = 397.1 ppmv[170])
- traces of $\boldsymbol{NO_x}$ and $\boldsymbol{CH_4}$, both of which are strong infrared absorbers (greenhouse gases) like water vapour and $\boldsymbol{CO_2}$.

The effect of the major $\mathbf{300K}$ (temperature of Earth's surface) infrared radiation absorbers in our atmosphere (namely, $\boldsymbol{H_2O, CO_2, CH_4, N_2O}$ in order of importance) is to maintain the surface temperature about $\mathbf{35K}$ warmer than it would be if none of these gases were present. The Earth would be hard frozen everywhere without the greenhouse effect trapping heat near the surface. There is evidence that the Earth was completely frozen, with tropical oceans frozen to depths of hundreds of metres, about 2.2 billion years ago, $\mathbf{2.2Ga}$ (the ***Archean-Proterozoic*** boundary)[171] and only recovered because $\boldsymbol{CO_2}$ levels in the atmosphere, fed by continuing volcanism eventually reached levels of $\mathbf{20\%v}$ resulting in a super-greenhouse warming that melted all this ice in as little as a few hundred years. Such "***Snowball Earth***" glaciations seem to have occurred again $\mathbf{710Ma}$ and $\mathbf{640Ma}$ just preceding the explosion of life that characterizes the ***Phanerozoic***. Recovering from each of these extreme glaciations, the diversity of plant and animal species on Earth increased spectacularly.

The internal dynamics of our Earth

The crust of continents and the ocean basins is dynamic. The continents move slowly across the surface of our planet and the floors of the oceans recirculate into the mantle under the process of mantle convection which is necessary to the continuing cooling of the Earth's interior. Both the continental granitic and oceanic basaltic crusts are continuously being consumed and reformed through erosion and global-scale convective tectonic processes. Shortly, we shall study the physics and later again the geochemical consequences of this convective process.

Next, however, we shall learn something about the paths, orbits, of the terrestrial planets about the Sun, about the orbits of the moons about their mother planets and what we can learn about planets by studying these orbits.

[170] 1 ppmv = 1 part in 1 million by volume; current levels
[171] Snowball Earth: http://www.snowballearth.org/

5 The present Solar System

Presently, our Solar System[172] comprises

- 9 *planets*[173] , all but two of which have associated satellite *moons*
- a belt of at least 6000 and probably 100 000 *asteroids* mostly orbiting the Sun between the orbits of Mars and Jupiter
- a *Kuiper Belt* of perhaps **200** million *comets* spreading from the orbit of Pluto out to about **20**× that distance from the Sun
- a spherical halo of several billion comets filling the *Oort Cloud* extending almost half way to the next nearest star
- and possibly one or more companion ***brown dwarf*** stars that are just too dim to see.

5.1 Collisions with comets and asteroids?

5.1.1 Comets

Most ***comets*** that enter the inner Solar System, those that we see in the heavens from time-to-time, venture in periodically from the Kuiper Belt or infrequently from the Oort Cloud along highly eccentric ***elliptical*** or even almost ***parabolic*** orbits. Those that cross the Earth's orbit may intersect at speeds as high as $\mathbf{80\,000}\boldsymbol{km/hr}$.

Some comets, such as the famous ***Halley's Comet*** have become trapped within the inner reaches of this vast Solar System. With its current orbit, its greatest distance from the Sun, at ***aphelion***, it travels out almost as far as the orbital distance of Pluto. At closest to the Sun, ***perihelion***, it falls within the orbit of Venus. Earth passed through the tail of Halleys's Comet in 1910 without catastrophe.

5.1.2 Asteroids

Most asteroids are gathered in their orbital ring beyond the orbit of Mars.

---

172 Orbits in the Solar System: http://janus.astro.umd.edu/javadir/orbits/ssv.html
An excellent site for images of the planets and other bodies in our Solar system: http://pds.jpl.nasa.gov/planets/welcome.htm
JPL Solar Systems Dynamics Site: http://ssd.jpl.nasa.gov/

173 For reasons of tradition, we shall remember ***Pluto*** as a planet.

Name	Size (km) (km)	Mass ($\times 10^{15}$kg)	Distance (AU)
	The Major Asteroids		
Ceres	960x932	870,000	2.767
Pallas	570x525x482	318,000	2.774
Juno	240	20,000	2.669
Vesta	530	300,000	2.362
Eugenia	226	6,100	2.721
Siwa	103	1,500	2.734
Kleopatra	217x94		2.79

Some, even large ones, do fall into the inner Solar System on Earth-crossing orbits. They, as do large comets, present something of a hazard to life on Earth. We now know that large asteroids or comets have hit the Earth and seriously disturbed the evolutionary track of life at least twice in the past **100** million years.

- The *Chicxulub impact event*[174] : **64.98** million years ago, a large asteroid, perhaps $\boldsymbol{10\,km}$ in diameter struck the Earth from the south-east at Chicxulub on the northern tip of the Yucatan Penninsula in Mexico. The impact caused a crater $\boldsymbol{180\,km}$ in diameter and splashed up materials which are found in the Canadian Yukon. The atmosphere was so filled with dust that solar insolation was blocked for years and the Earth became very cold. Dinosaurs starved to extinction. The impact vapourized a great volume of carbonate rocks, limestones and dolomites, which are largely $\boldsymbol{(Ca, Mg)CO_3}$, releasing vast stores of $\boldsymbol{CO_2}$ into the atmosphere. When the dust clouds finally settled from the atmosphere, the $\boldsymbol{CO_2}$, carbon dioxide gas, remained and the greenhouse sheilding of escaping heat provided by this gas caused the Earth to warm to very high temperatures. Again what life had survived the ***asteroidal winter*** faced a long and scortching ***greenhouse summer***. Life was challenged and only the Darwinian winners, among them our mammal ancestors, survived. Another such event, less well studied and well known, occurred about **35** million years ago with, again, profound influence on the course of evolution of life. The Earth has been impacted innumerable times in its history, but only a few remnant craters remain due to the continual renewal of the oceanic basins and erosion of evidence on the continents.[175]

- In 1908, a relatively small comet or meteroid crashed into the upper atmosphere of the Earth above Tunguska, Siberia in Russia[176]

  For thousands of square kilometers around the impact centre, trees were laid down radially. A man was blown off his portch $\boldsymbol{60\,km}$ from the impact and

174 http://en.wikipedia.org/wiki/Chicxulub_crater
175 http://www.passc.net/EarthImpactDatabase/index.html
176 ...Tunguska event...see: http://www-th.bo.infn.it/tunguska

the explosion of the impact was heard **1000 *km*** away. Still, there is no evidence that any materials reached the ground at the impact centre. The high velocity of a comet – and cometary paths intercept the Earth with much higher velocity than do asteroids because comets have fallen in from much greater distances – would have caused its explosion in the upper atmosphere. The effects on the surface were caused by an atmospheric shock wave from this explosion. Had this comet hit the atmosphere above a major city, hundreds of thousands of lives might have been lost. Even though no debris from the impactor has been found at the Tunguska site, some planetary astronomers now believe the cause was a ***meteoroid*** about **80 *m*** in diameter which, in falling in from very great distance from the Sun, hit the Earth's atmosphere with a speed of about **80 000 *km/hour*** and so broke up explosively in the atmosphere before touching ground.

- The assembly of meteoroids, asteroids and comets formed and forms our Earth and the other planets. This planet building process continues to this day though with a much reduced rate. We know of the great Chicxulub event of **65** million years ago. Such globally devastating events might still be expected with an average interval of, perhaps, **100** million years. It is not only these extreme events that reshape our planet.[177]

5.2 What are comets, meteroids and asteroids?

Since the dawn of recorded history, comets[178] have been observed to visit the inner Solar System where they sometimes display spectacularly bright and long tails. In fact, along with an historical record of eclipses of the Sun, the record of returns of periodic comets has provided us with some of the best evidence for the known dynamics of the Earth's and Moon's orbits and rotations. We are now fairly sure that comets are of the primoridial material from which our Solar System condensed. They are assemblages of water and methane ice which have trapped dusts and gases. They are "dirty snowballs". When their orbits bring them into proximity with the heating Sun, the ice begins to vapourize, releasing dust and molecules of the volatiles. This dust and volatiles trail is carried away from the comet in a direction out from the Sun by a relentless high-speed ***solar wind*** and thus the sun-illuminated tail. In recent years, two spectacular comets, Comet Hayakutake and Comet Hale-Bopp, have

[177] Impacts on the Earth by asteroids and comets: assessing the hazard

[178]...Halley's comet returns to the inner solar system every 76-79 years. It appeared in 11BC, for example, and also in 1066 at the time of the Norman invasion of Britain.
Image of the comet on the Bayeux Tapestry
It's last visit to the inner Solar System was in 1986.
http://nineplanets.org/halley.html
The story of the Bayeux Tapestry

offered show. During mid-March, 2013, Comet PanSTARRS was visible for a few days in the western sky just after sunset; we awaited what was to be the most spectacular comet in the past few hundred years: Comet ISON. It was a fizzle. Over the new year of 2015, Comet Lovejoy[179], the "Green Comet" was visible in the southern sky just below and right of the constellation Orion. It had been discovered in summer of 2014. We normally don't get much warning of a comet's appearance. Some of the brightest comets have only been discovered a year or two before their brightest displays.[180]

Asteroids and meteoroids are the metallic or rocky debris which clutters the Solar System. Most asteroids are organized into a near-circular orbit about the Sun at a distance of about $\boldsymbol{420 \times 10^6\, km}$, between the orbits of Mars and Jupiter. The largest known is $\boldsymbol{Ceres}$ which has a diameter of $\boldsymbol{940\, km}$, about $\boldsymbol{1/4}$ that of our Moon. A few asteroids, perhaps a hundred have such orbits mapped, have orbits which cross the orbit of Earth and so, one day, could encounter the Earth in a collision. Astronomers are now monitoring[181] such close encounters though we still have no proven means of preventing a collision. We take solace in the lack of discovery of large asteroids in such orbits.

Asteroids are thought to be debris left behind when a planet was unable to coalesce from planetesmal pieces due to the periodic perturbations of Jupiter's gravitational field. Still we have some indirect evidence, from meteorites that have fallen to Earth and that are thought to have originated in the asteroidal belt, that the largest objects have geochemically and geophysically differentiated. The failed planet may once have been somewhat better assembled than it is now.

Smaller pieces of rocky and metallic debris not organized into semi-stable orbits are called *meteoroids*. By some definitions, meteoroids are just smaller asteroids, with diameters of less than **100** or so metres. They may arise from inter-asteroidal collisions. Meteoroids so formed could easily be disturbed from the asteroidal orbital belt and fall into the inner Solar System. When and if they strike the Earth's atmosphere, small ones burn up leaving straight-line trails of light – ***meteors***. Larger ones produce brighter trails – ***fireballs***. If a meteoroid descends to the surface of Earth, we call its remnant a ***meteorite***.

Meteorites fall on the Earth in great numbers. An interesting fact of them is that their ages as dated by the radioactive dating clock bunch up against a limiting age of $\boldsymbol{4.567\, Ga}$. We find no older material on Earth[182].

---

[179] Comet Lovejoy

[180] ...some recent bright comets...
http://science.nationalgeographic.com/science/photos/asteroids-comets-gallery/
http://www.ifa.hawaii.edu/images/hale-bopp/hb_images.html
Comet panSTARRS
Cometography.com – http://www.cometography.com/

[181] The NEAT program: http://neat.jpl.nasa.gov/

[182] Some geologists and geophysicists have argued that they have dated an exceptional meteorite

Several annual showers of meteors[183], the most prominent of which is the ***Perseid shower*** of August 12 arise as our Earth crosses debris following their own orbit about the Sun. The debris might be left behind from an evaporated comet. The ***Leonid shower*** of mid-November is sometimes very spectacular with thousands of meteor tracks observed per hour. The Leonids seem to show a period of great activity every $\boldsymbol{33 - 35\, yrs}$. It is thought that they derive from a recently evaporated comet from which the debris has not yet evenly distributed itself along the orbital path. Major activity was observed in 1998 and 1999 but not from our north-western quarter sphere. The great showers are not likely to recur again for another 30 or so years. [184]

5.2.1 Types of meteorites

Meteorites are variously divided into three main classes[185] and many sub-classes according to their kind, here as:

Iron meteorites

- These meteorites are largely composed of iron alloyed with as much as 20% nickel. They are also rich – a few parts per billion – in $\boldsymbol{Ir}$, iridium, which is not very abundant in the outer regions of the Earth as it was mostly carried to depth with iron in the Earth's early differentiation. It is a ***siderophile*** element meaning that it likes to be associated with iron. What is exceptional about this type of meteorite is that their internal structure is made of very large crystals. Large crystals have to form very slowly and that suggests that as the iron cooled through its freezing temperature it was cooling extremely slowly, perhaps at rates of only $\boldsymbol{0.4^oC/Ma - 40^oC/Ma}$. In order to have been protected from losing heat more quickly, these meteorites must have formed under a thick layer of insulation – of overlying materials. They seem to have cooled within the *cores* of bodies of at least $\boldsymbol{100 + \; km}$ diameter.

Stony-iron meteorites

- Some iron, characteristic of the class above, are sometimes mixed into a stony matrix as in the next class.

Stony meteorites

- These are meteorites which look very much like silicate rocks on Earth having relatively small – as small as microscopic – crystal structure. Their small crystal

at $\boldsymbol{7\, Ga}$ but their claims have largely been discounted. More recently, the Tagish Lake (Yukon) meteorite of January, 2000 has been found to be the most primitive to have ever been discovered

[183] Calendar of showers during 2016: http://www.imo.net/calendar/2016

[184] See website: http://www.amsmeteors.org/

[185] Meteor types: http://www.nhm.ac.uk/nature-online/space/meteorites-dust/meteorite-types/index.html http://www.nineplanets.org/meteorites.html

structures suggest much more rapid cooling through their freezing temperature. They probably froze at shallow depths within bodies. They may represent an insulating *mantle* which enclosed an iron core of a fragmented planetesmal.

Stony meteorites are sub-classed as ***chondrites*** and ***achondrites***

Chondrites

- This sub-class of meteorites is characterized by the presence of glassy ***chondrules*** like very tiny beads.

  Glass forms when solids freeze too quickly to organize a crystal structure. This suggests that these chondrules[186] were melted and then solidified before they could crystallize. It is thought that these materials come from the surface of bodies which have been rather continuously or often bombarded in collision with other bodies, causing some surface melting and extremely rapid solidification. They could well represent a surface area covering a mantle from which the stoney meterorites derive and which enclosed the core from which the iron meteorites derive. Another explation for chondrules is that they formed by the rapid cooling of *rains* of melted minerals within the dust cloud of the primordial solar nebula.

  Chondrites can also contain substantial amounts of carbon and complex carbon compounds. These rarer ***carbonaceous chondrites*** can even contain ***amino acids***, the protein building blocks of terrestrial life. It may well be that the elements of life fell upon an Earth following the surface freezing of a deep magma ocean which would have resulted from the collisional process which might have formed the Moon. These compounds on Earth would have been completely destroyed in a $\mathbf{2000^o C}$ magma ocean.

  A particular subclass of chondrite, the ***enstatite chondrites***, are thought by many cosmochemists to represent the most primitive materials that coalesced in the primordial solar nebula – the materials that futher assembled into our terrestrial planets. The composition of these chondrites is often taken as the reference composition of Earth.

Achondrites

- These contain no chondrules and look more like ***igneous rocks***, those which have cooled from a melted state, on Earth. They have evolved and differentiated into their rock-like form on other planets, asteroids or our Moon. One group, the ***SNC*** meteorites are now known, through their geochemical and mineralogical signatures, to have been splashed off Mars[187]. One of the most famous of these

[186] Chondrules: a biproduct of early protoplanetary collisions?
[187] Martian/SNC meteorite story.

ALH84001[188] has important connections to McGill scientists.

[188] ALH84001 found in Antartica

6 Orbital dynamics and Kepler's Laws

In our Solar System comprising the central Sun, 9 planets, the asteroids, comets and objects in Kuiper Belt and Oort Cloud, we observe that the planets and asteroids mostly follow very nearly circular elliptical orbits in the ***ecliptic*** plane, the plane of Earth's orbit, about the Sun

While the ancient Greeks knew that the Earth was spherical – they actually had a very good idea of its size too – and that the planetary system, then known to comprise only the 6 inner planets, was most simply viewed from a ***heliocentric*** (Sun-centred) perspective, Europeans did not accept this knowledge until **Nicolas Copernicus** in the early 1500s and **Galilie Galileo** a century later promoted the heliocentric viewpoint.

The planetary system: orbital parameters

Planet	Period (year = **365.26** days)	Distance $\frac{a+b}{2}$ ($1AU = 1.497 \times 10^8 km$)	Eccentricity	Inclination (° to Ecliptic)
Mercury	**0.2408**	**0.39**	**0.206**	**7.0**
Venus	**0.6152**	**0.72**	**0.007**	**3.4**
Earth	**1.0000**	**1.00**	**0.017**	**0.0**
Mars	**1.881**	**1.52**	**0.093**	**1.9**
Ceres (asteroid)	**3.63**	**2.36**	**0.237**	**7.1**
Jupiter	**11.86**	**5.20**	**0.049**	**1.3**
Saturn	**29.46**	**9.54**	**0.056**	**2.5**
Uranus	**84.01**	**19.19**	**0.047**	**0.8**
Neptune	**164.79**	**30.00**	**0.009**	**1.8**
Pluto	**248.5**	**39.53**	**0.250**	**17.2**

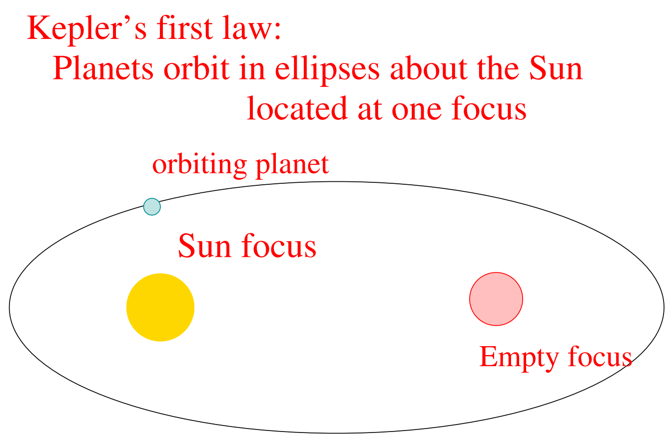
As the mass of the Sun is so enormous compared other masses in the Solar System, its "orbit" is not much affected by the gravitational forces of the much smaller planets. It is, thus, convenient to presume that the Sun's position is almost fixed at one focus of the elliptical orbits of each of the planets. Practically and more accurately, it would be well to consider the ***centre of mass*** of the Solar System of Sun and planets to be fixed and the Sun and all the planets in orbit about this centre of mass. The centre of mass of the Solar System, though, is so close to the centre of mass of the Sun itself that the heliocentric viewpoint serves well in revealing the dynamics of the Solar System most simply[189].

[189]The motion of a star in its orbit about the centre of mass of a planetary system is used in the search and discovery of ***exoplanets***: http://exoplanets.org/

6.1 Kepler's laws:

In 1596, **Johannes Kepler** (1571-1639) published a treatise in which he predicted the planetary orbits. He had been a student and collaborator, in Prague, of **Tycho Brahe** (1546-1601), the Danish astronomer, who had ammassed a very large data set of very accurate astronomical measurements of the positions of the then known planets during several decades. Based on these data, Kepler established three empirical, i.e. based on observations rather than more fundamental theory, laws.[190] [191]

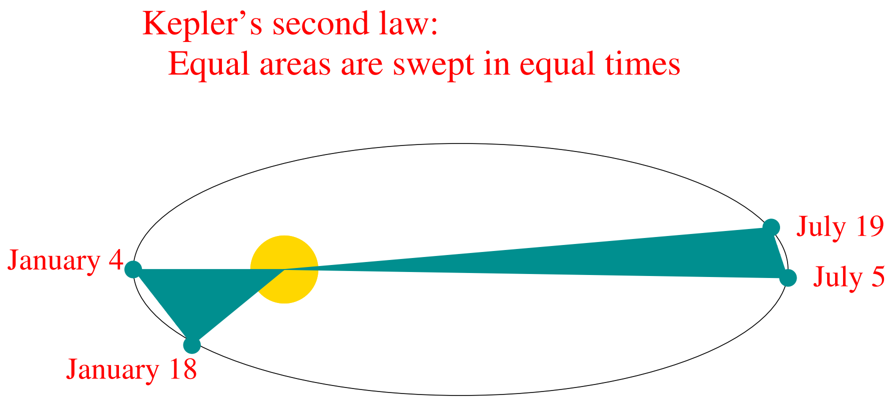
- **Kepler's first law:** *The orbit of a planet about the Sun is an ellipse with the Sun at one focus.*:



[190] Kepler's laws: I, II and III

[191] An ellipse is that path of all points which have a fixed sum of distance to two other points called the foci of ellipse. The fixed sum of distance, of course must be greater than the distance between the two foci and less than infinite. If the distance sum is just the distance between the foci, the ellipse has an eccentricity of $\mathbf{1}$; if the distance sum is infinite, the ellipse has an eccentricity of $\mathbf{0}$. An ellipse with an eccenticity, $\boldsymbol{e} = \sqrt{\mathbf{1} - \frac{\boldsymbol{b^2}}{\boldsymbol{a^2}}}$, of precisely $\mathbf{0}$ is as circle. In our description of an ellipse, $\boldsymbol{a}$ is 1/2 of the longest diameter through the ellipse – its semi-major axis – and $\boldsymbol{b}$ is 1/2 of the shortest diameter through the ellipse – its semi-minor axis.
Another measure of the eccentricity is obtained as $\boldsymbol{e = (\alpha - \pi)/(\alpha + \pi)}$ where $\boldsymbol{\alpha}$ is the farthest distance from to the gravitational centre of mass (equivalently, aphelion for the planets) and $\boldsymbol{\pi}$ is the closest approach (equivalently, perihelion for the planets).

- **Kepler's second law:** *A line joining a planet and the Sun sweeps out equal areas in equal intervals of time.*



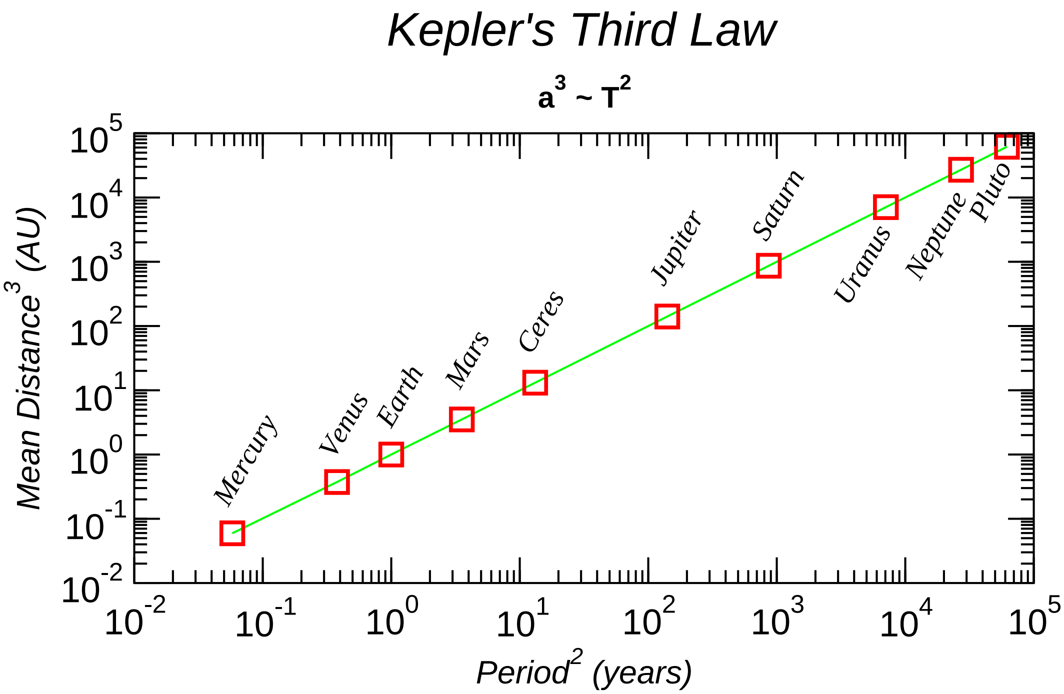
Note that Kepler's 2nd Law tells us that planets travel faster in their elliptical orbits when they are near the Sun than they do when they are far away. Earth is closest to the Sun on January 4 of each year at ***perihelion*** at $\mathbf{1.47 \times 10^8}$ ***km*** and farthest from the Sun on July 5 at ***aphelion*** at $\mathbf{1.52 \times 10^8}$ ***km***. Our orbital speed is, therefore higher on January 4 than it is on July 5. This variation in our speed in orbit about the Sun has an interesting effect on when the Sun appears to rise or set. In the northern hemisphere, the shortest day of the year is our ***winter solstice***, December 21, perhaps December 22 during the year preceding each leap year. But the shortest day is not due to the simultaneous latest sunrise and earliest sunset. Actually, the earliest sunset precedes the shortest day of the year by about two weeks and the latest sunrise follows the shortest day by about two weeks. Typically the latest sunrise is on the 4th or 5th of January depending upon where we are in the leap-year cycle. Similarly, the earliest sunrise precedes the ***summer solstice*** by about 1 week and the latest sunset follows by about 1 week.

The elliptical orbit of the Earth also has an effect on the local ***solar noon***, that time which would be measured as noon by a sundial. Depending on the time of year, the length of the solar day (i.e. from one solar noon to the next) as measured by a sundial and compared to uniform time varies. The variation in the length of day accumulates to a 17-minute advance at the beginning of November and to a 14-minute retardation in mid-February[192].

While the ellipticity of Earth's orbit has some important effect on the length of the solar day and the duration of daylight, it is the Earth's ***obliquity***, the inclination of its rotation axis from the normal to the orbital plane, that most contributes to the varying length of daylight and, thus, to the annual cycle of seasons[193].

[192] http://en.wikipedia.org/wiki/Analemma
[193] http://esminfo.prenhall.com/science/geoanimations/animations/01_EarthSun_E2.html

- **Kepler's third law:** *The square of a planet's siderial (referenced to the distant stars) period is proportional to the cube of the length of its orbit's semimajor axis. That is* $\boldsymbol{T^2 \propto a^3}$ *where* $\boldsymbol{T}$ *is the orbital period and* $\boldsymbol{a}$ *is the semi-major axis of the orbital ellipse.*



Question? Our average, Earth's speed in orbit about the Sun is $\boldsymbol{29.8\,km \cdot s^{-1}}$**. What is our orbital speed at perihelion and aphelion**[194]**?**

6.2 Newtonian mechanics allows us to "weigh" the Sun!

Kepler's Laws were studied by **Isaac Newton** (1642-1727) who recognized that a field of force which he called ***gravity*** was fundamentally responsible for the ordered, Keplerian, motion of the planets. In his ***Philosophae naturalis principia mathematica***, published in 1687, he showed how the force of gravity constrained planets into precisely Keplerian orbits.

[194] At perihelion: $\boldsymbol{30.3\,km \cdot s^{-1}}$; at aphelion: $\boldsymbol{29.3\,km \cdot s^{-1}}$.

- Newton theorized that the measurable force between two masses, say $M_\oplus$ and m_p obeyed an inverse square law of distance, r, scaled by some universal constant of gravity, G. That is:

$$\vec{F} = G\frac{M_\oplus m_p}{|\vec{r}|^3}\vec{r}.$$

  Properly, he didn't obtain a theory of gravity but rather showed how gravity influenced the attractive forces between masses. Properly, even now, we are only developing the theory of mass in terms of the ***Higg's field***.

- The scale factor, G, in this proportionality is the Newtonian constant of universal gravitation which was first measured in the laboratory by **Henry Cavendish** (1731-1810) in 1798:

$$G = 6.673 \pm 0.010 \times 10^{-11} N \cdot m^2 \cdot s^{-2}.$$

For a simple circular (i.e. $e = 0$) orbit, it is easy to obtain Kepler's Third Law from the Newtonian mechanics. We need only compare two forces: the one provided by the gravitational attraction of the Sun on a planet, the other, the "tension" required to maintain the planet along a circular path with the Sun at centre.

- The necessary tension is called the ***centipetal force*** and obeys a simple form as was shown by Newton:

$$\vec{F}_{centripetal} = m_p v_T^2 \frac{\vec{r}}{|\vec{r}|^2}.$$

  This is the force required to hold a planet of mass m_p moving along its orbit, tangentially, with speed v_T. The force acts on the planet towards the centre of revolution, the Sun.

- The Sun provides this centripetal force through its gravity and so

$$\vec{F}_{gravity} = G\frac{M_\oplus m_p}{|\vec{r}|^3}\vec{r} = \frac{m_p v_T^2}{|\vec{r}|^2}\vec{r} = \vec{F}_{centripetal}.$$

With a little cancelling of similar elements appearing on both sides of the equation and dropping the vector fussiness noting that $|\vec{r}| = r$,

$$GM_\oplus / r = v_T^2.$$

The tangential speed of the moving planet is easily seen to be the circumferential distance it travels around the Sun divided by the time it takes to do so: $2\pi r/T$. Here, T is the planet's its orbital ***period***. We obtain

$$GM_\oplus / r = 4\pi^2 r^2 / T^2$$

or

$$\boldsymbol{T^2 = \frac{4\pi^2}{GM_\oplus} r^3},$$

a statement of Kepler's 3 rd Law. Knowing $\boldsymbol{G}$, $\boldsymbol{\pi}$, measuring $\boldsymbol{T}$ and $\boldsymbol{r}$, we find:

$$\boldsymbol{M_\oplus = \frac{4\pi^2 r^3}{GT^2}}.$$

We can weigh[195] the Sun!

> **Question? The orbital period of the Earth about the Sun is 365.2425 days of length 86 400 seconds. Each day has $60 \times 60 \times 24$ seconds. The Earth orbits the Sun at an average measured distance of $r = 1.497 \times 10^{11}\ m$. Knowing G as given above, calculate the mass of the Sun[196].**

6.2.1 Is there a supermassive black hole at the centre of our Milky Way?

Andrea Ghez[197], of UCLA, has used a procedure, very similar to that described here for "weighing" the Sun, to measure the mass at our galactic centre. Having observed the orbits and periods of stars in the direction of the constellation Sagittarius where the galactic centre is known to be, she and her colleagues determine that there is an "invisible" supermassive gravitational centre, having a mass of almost $\boldsymbol{4 \times 10^6 M_\oplus}$, at the centre of our Milky Way.

6.2.2 Is there other unseen mass within our Milky Way?

If we were to look at the orbital velocities of stars within galaxies we could determine the mass distribution within them. This problem was much studied starting in the early 1970s with some surprising result; something seems to be wrong! **Vera Rubin**[198] looked at the orbital speeds of stars well outside the core zone of many galaxies. She studied the ***rotation curve***[199] to show that stars at distance from galactic centres were orbiting much faster than could be accounted for by the observable baryonic

[195] Well actually the Sun like all bodies orbiting about each other is in ***free fall*** with all forces in balance and so the Sun, like an astronaut in orbit, is properly ***weightless!***

[196] $\boldsymbol{M_\oplus = 1.989 \times 10^{30}\ kg}$.

[197] The acceleration of stars orbiting the Milky Way's central black hole
An animation of stellar orbits about the central black hole
TED-talk by Andrea Ghez

[198] Vera Rubin, astronomer! She showed that "Most of the Universe is Missing" (video)

[199] Rotation curves

matter of the galaxies. She could not account for the velocities at distance from the centre of galaxies if there wasn't some very large unseen mass distributed throughout the galaxy. Astronomers have called this unseen mass ***"dark matter"*** and there seems to be a lot of it! Orbiting at distance r about a spherically distributed central mass of M_c, a star would move, according to the Newtonian model above, with a tangential velocity of

$$v_T = \sqrt{\frac{GM_c}{r}}.$$

In all spiral galaxies that have been studied in detail, stars seem to move faster than this speed in the outer parts of galaxies. M_c must, therefore, be larger than that we can account for by the stars we see in the interior (to r) of the galaxy. If we were to know the tangential velocity, v_T, and the momentary radius of orbit of a star, r, we could determine the central attracting mass:

$$M_c = \frac{rv_T^2}{G}.$$

By most measurements of rotation curves of galaxies, M_c is over $4\times$ greater than we account for by observed star mass within galaxies. What is this mass? We don't know! It may be that 80% of what exists within galaxies and, even right here with us, is yet *undetected*.

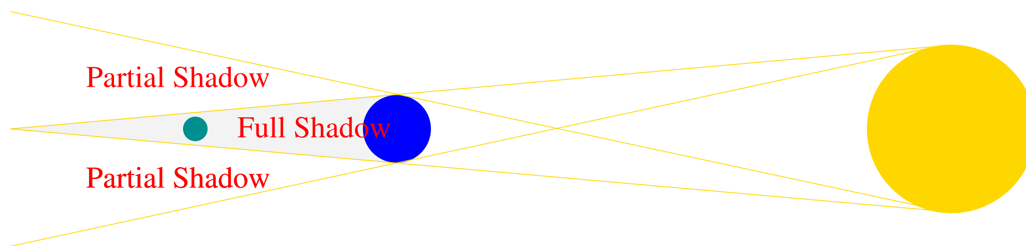
6.2.3 The orbit of Earth's Moon: weighing Earth

In principle, if we can accurately observe the orbit of the Moon about the Earth we can similarly "weigh" the Earth[200]. To measure the Moon's orbit is not a trivial matter, though. How do we observe one cycle of the Moon about the Earth?

- Once each lunar ***month***, the Moon comes to ***Full Moon*** phase. This happens during each month at the moment when the line from the Sun-to-Earth-to-Moon is most nearly a straight line.
  - The face of the Moon seen from Earth is fully lighted by the Sun at Full Moon. If the alignment is just right, the Earth casts a shadow over the face of the Moon. This is a ***lunar eclipse***.

[200] Remember that, technically, what we can find is the ***mass*** of the Earth, not its ***weight***. Properly, Earth is weightless!

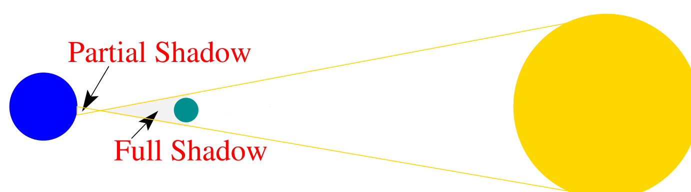
Lunar Eclipse Geometry



This occurs, on average, about twice per year. Lunar eclipses can be seen from anywhere on Earth that the Moon can be seen during the period of shadowing[201].

– The ***New Moon*** phase occurs at the moment when the line from Sun-to-Moon-to-Earth is most nearly a straight line. If the alignment is just so, one may observe a ***solar eclipse*** at New Moon. Solar eclipses, annular or total, occur about once per year but are only seen along narrow paths across Earth's surface.[202]

Solar Eclipse Geometry



Draw yourself simple diagrams to understand the geometry necessary in lunar and solar eclipses.

6.2.4 On Moon's orbit

- ***Lunar month:*** The period between phases of the Moon, say between Full Moons, is called the lunar month or sometimes ***synodic month***. Is this the period of orbit of the Moon about the Earth? No!

[201] On recent, current and future eclipses: http://eclipse.gsfc.nasa.gov/eclipse.html
[202] Next total solar eclipse visible from Montreal: April 8, 2024

As the Earth is orbiting the Sun and the Moon is orbiting the Earth in the same sense, it takes somewhat more than one orbital period for the Moon to cycle between successive Full Moon phases. The mean lunar month has a period of $\mathbf{29.531}$ days.

- ***Siderial month*** If we were to look at the interval between two successive times at which the Moon appeared in the same location relative to the distant stars in the night sky, we would measure a *siderial* (meaning relative to the fixed stars) period of revolution about the Earth. "month" is called the mean *siderial month*.

  It is a shorter time than the mean lunar month. How much shorter? Well during one year as the Earth orbits the Sun, the Moon orbits the Earth by one fewer lunar months than siderial months. In a year, there are $\mathbf{365.26/29.531}$ lunar months and $\mathbf{1+\frac{365.26}{29.531}}$ siderial months. While there are $\mathbf{12.3691}$ lunar months per year, there are $\mathbf{13.3691}$ siderial months in $\mathbf{365.26}$ days, each of $\mathbf{27.322}$ days.

  Interestingly, this is just the period of rotation of the Moon about its own axis; it is ***spin-orbit coupled*** to the Earth. It always shows us – to within $\pm\mathbf{6^o}$ of *libration*[203] in longitude and $\pm\mathbf{7^o}$ of libration in latitude – the same face!

- ***Draconitic month:*** Properly, the siderial month is not the orbital period of the Moon that we would seek in order to weigh the Earth.

  The Moon's orbit is inclined to Earth's equator by $\mathbf{18.3^o}$ to $\mathbf{28.58^o}$ depending upon the Earth's inclination and precesses about the Earth with a period of $\mathbf{18.6}$ years and so, month-by-month it doesn't return to exactly the same place in the night sky against the fixed stars each month. If we take into account this effect and measure the period between repeating maximum apparent latitude (projected from the Earth's geographical reference frame), we determine the mean *draconitic* month of $\mathbf{27.212}$ days.

- ***Tropic month*** The actual revolution period is that period between points fixed in ***declination*** which is the angle measured from the Earth's average rotation axis (and approximately fixed in the night sky by the "North Star", ***Polaris***, to the elevation of the Moon in the sky. The tropic month has a period of $\mathbf{27.331(582)}$ days.

  Can we use this month to determine the Earth's mass? Yes, but we have to correct for the fact that the while the Moon orbits the Earth, the Earth also co-orbits the Moon. The best fixed point for observing these orbits is the *centre of mass* of the Earth-Moon system which is displaced towards the Moon by $\mathbf{4636}\boldsymbol{km}$ from the Earth's own centre.

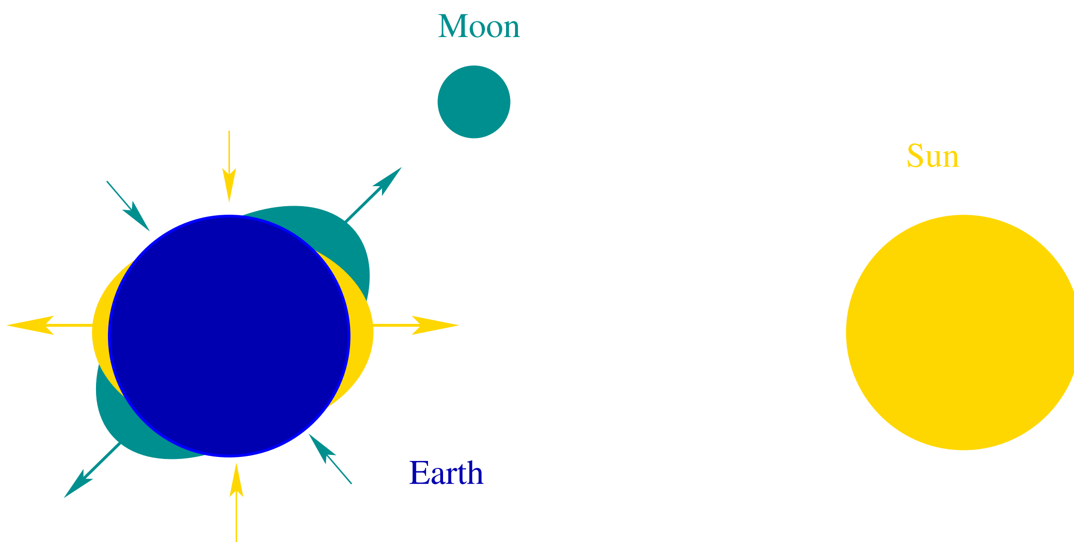
[203] A movie of the Moon's libration: http://www.nasa.gov/mov/214266main_Libration-Wobble_Movie_4_Web.mov

You could have waited until a small satellite was put into orbit about the Earth as was **Sputnik** in 1957 and then used its period of revolution about the Earth: $\boldsymbol{95'10''}$, $\boldsymbol{perigee = 170km}$, $\boldsymbol{apogee = 990km}$.

6.2.5 Tides

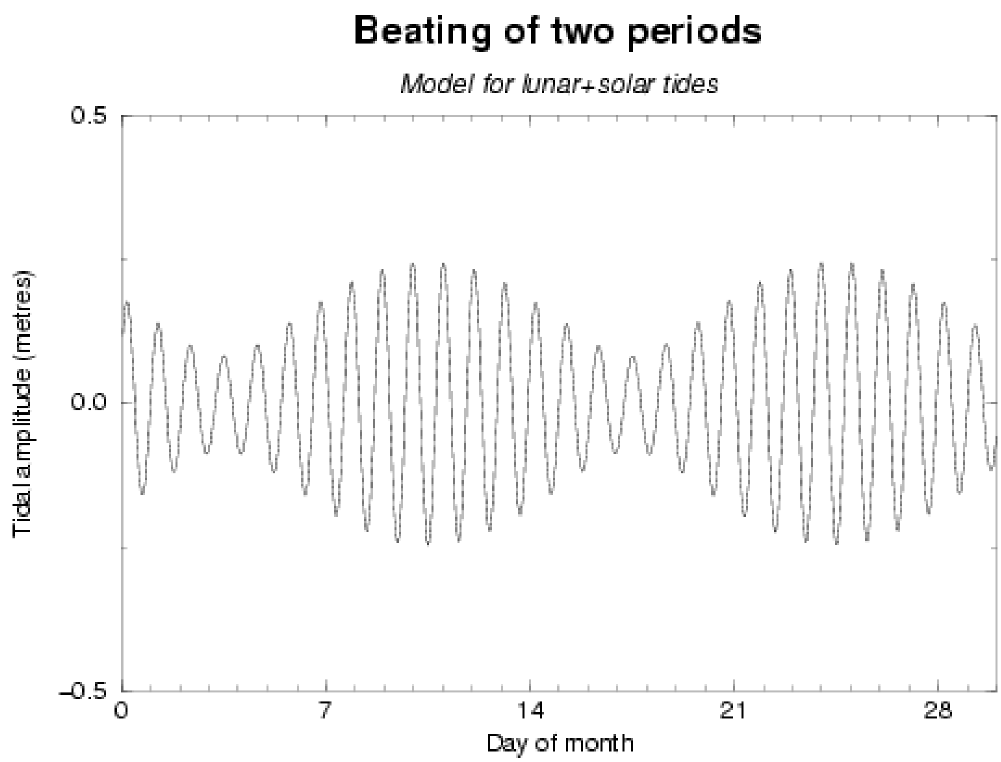
Differential gravitational forces on the Earth caused by the Sun and Moon raise ***tides***. Most people are familiar with the tides that are raised on the oceans but do not know that tides are also raised on the solid body of the Earth.

At Montreal, the surface of the Earth rises and falls by about $\boldsymbol{\pm 30cm}$ each day because of these ***earth tides*** or ***body tides***.

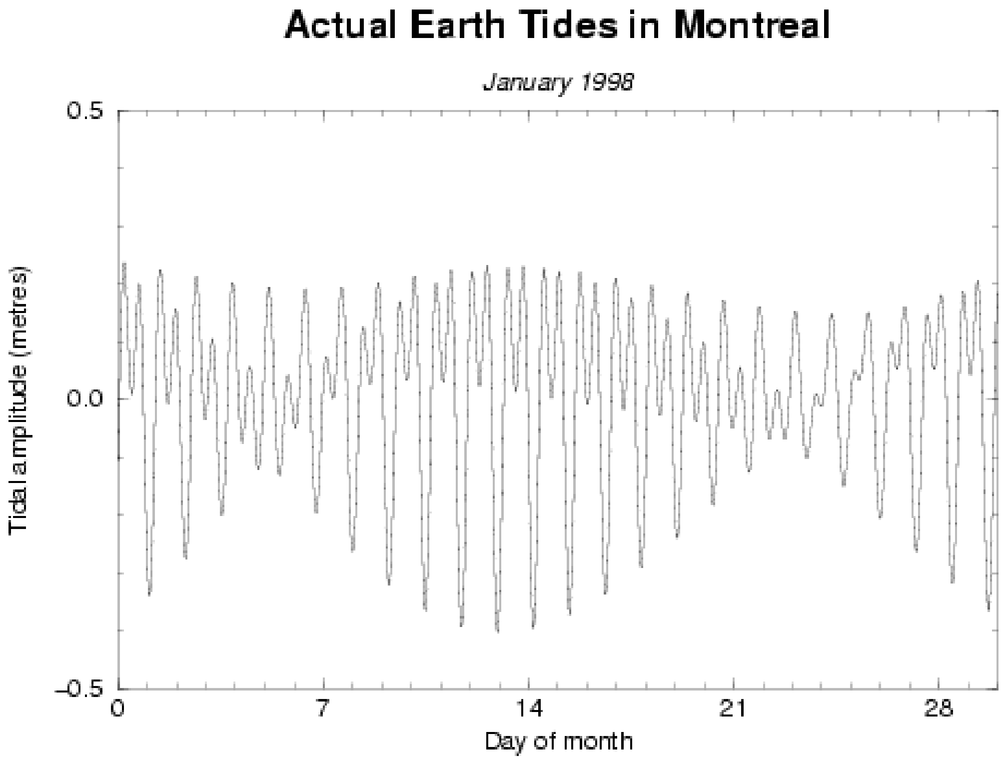


- ***Lunar tides:*** The Moon contributes to about **2/3** of the tidal distortion of the Earth. As the Earth turns once (relative to the Sun's position) in 24 hours, the Moon orbits in the same direction once in 29 days. This accounts for the $\boldsymbol{24 \times 29/28}$ hour $=$ **24** hour **51** minute full period of the lunar tide. Between successive "highs" or "lows" of the lunar tides, there are **12** hour **25** minutes.
- ***Solar tides:*** The Sun contributes to about **1/3** of the tidal distortion. The period of the solar tide is just **24** hours. Between successive solar "highs" and "lows", there are just **12** hours.
- ***Beating of the tidal periods:*** When the Sun and Moon are aligned (at New Moon and Full Moon phases), tidal amplitudes are highest as the solar and lunar tides conspire to add up in effect. When the Sun and Moon are most misaligned (at first quarter and last quarter phases), tidal amplitudes are lowest.

During a month, the tides beat against one another to produce a day-by-day variation of tidal amplitudes.



Because the tidal distortion is not symmetric about the Earth's centre as it rotates under the gravitational forcing of the Sun and Moon, tides actually look different from the beating of just two sinusoids.


Actual Earth Tides in Montreal
January 1998
0.5
0.0
–0.5
Tidal amplitude (metres)
0
7
14
21
28
Day of month

6 The space program: up close observations of planets and their moons

Much of what we have so-far dealt with was, or could have been, learned through Earth based, traditional astronomy. Following decades, if not centuries, of preparation, the contemporary age of space exploration really only began in the 1950s. In what is usually regarded as the "beginning" of space-based exploration, the Soviet Union launched the first Earth orbiting satellite, **Sputnik I**, in October, 1957. One month later they launched **Sputnik 2** with the first living cosmonaut, the dog, Laika. The *space race* was on. Within three months, the US successfully launched its first satellite, **Explorer I**. These small satellites gave us our first opportunity to map the body of the Earth, its gravity and magnetic fields, its atmosphere and its magnetosphere from above. By the end of the decade, dozens of satellite and deep space probes were launched and some successfully. The Soviet Union's **Luna I** missed its intended impact with the Moon in January, 1959; it still remains in heliocentric orbit. Later, in the summer of 1959, **Explorer 6** obtained the first photographs of the Earth from space. In September, **Luna II** impacted the Moon and while flags and pennants were dropped on its surface, the Soviet Union laid no claim to Moon. In October, **Luna 3** had given us the first photos of the backside of the Moon. The following summer, **Sputnik 5** returned the first animal cosmonauts back to Earth from orbit.

The decade of the 1960s was, probably, the high-point of efforts in space exploration as the Soviets and Americans continually and competively "one-upped" each other. In September 1962 with the launch of our first **Alouette I** satellite using a US launch vehicle, Canada entered into the age of space exploration. The two Alouette and subsequent **ISIS 1,2** satellites remain in orbit and are even partially, though passively, still operational. The ultimate prize, though, was to land humans on the Moon.

On April 12, 1961, Cosmonaut **Yuri Gagarin** completed the first manned orbit of Earth in the Soviet Union's Vostok spacecraft. **Valentina Tereshkova**, the first woman in space, orbited the Earth 48 times aboard Vostok 6 on 16 June 1963.

On May 21, 1961, newly elected US president, **John F. Kennedy**, responded to this success by committing to place men on the surface of the Moon before the end of the decade and to bring them home safely. This incredible goal was accomplished with the launch of **Apollo 11** on July 16, 1969 and the safe return of the trio of astronauts, Neil Armstrong, Buzz Aldrin and Michael Collins, 8 days later following the July 20, 1969 landing at 20:17:40 UTC on the Sea of Tranquility. During the decade of the '60s, many astronauts and cosmonauts had orbited Earth, we had impacted Mars and Venus and flown by both, we had soft-landed instruments on the Moon, we had orbited the Moon.

In the 1970s, both the US and Soviet Union withdrew from the challenge of manned space flight to distant bodies. Exploration beyond low-Earth orbit platforms was left to robotic probes. The Soviets soft-landed on Venus (**Venera 7**) in 1970, constructed the first space station (**Salyut 1**) in 1971, impacted, then soft-landed on Mars in late 1971 (**Mars 2, 3**), orbited and then landed on Venus again (**Venera 9**). The US orbited Mars (**Mariner 9**) in 1971, launched **Pioneer 10, 11** to the outer planets in 1972, flew by Mercury (**Mariner 10**) in 1974, placed two very elaborate landers on Mars (**Viking Landers**) in 1976, orbited Venus (**Pioneer Venus Orbiter**) in 1978 and launched **Voyager 1, 2** to explore the outer planets and their moons. These were heady days of space exploration.

In the 1980s, NASA concentrated on the reusable Shuttle Program[204] and its contribution to the International Space Station[205]. Because of the cost of these programs, NASA cut back on most deep-space exploration until the mid 1990s. The Soviet Union and Europe took up the challenge of catching up to the US in planetary exploration.

[204] The Shuttle
[205] ISS program

7 Rotational dynamics of the planets and their satellites

As well as orbiting about the Sun, all the planets rotate about their own axes. Also, the moons of the planets and our own Moon rotate about their own axes though most have rotation periods which are synchronous with their orbital revolution periods about their mother planet.

We shall learn that the actual rotational dynamics of planets and our Moon can be quite complicated. The Earth ***wobbles*** as it rotates. Part of this wobbling is forced by the seasonal movement of mass over the Earth, the 12-month ***seasonal wobble***. Part of the wobbling is a so-called ***free wobble*** called the ***Chandler wobble*** which has a 14-month period. As well, the Earth's rotation axis ***precesses*** with a 26 000 year period. The Moon ***librates*** as it orbits the Earth... it's all very complicated...

The planetary system:

rotational parameters

Planet	**Rotation Period**	**Inclination**
	(siderial in hours)	*(^{o} to orbital plane)*
Mercury	**1407.6**	**0.0**
Venus	**5832.0**	**178.0**
Earth	**23.934**	**23.4**
Mars	**24.623**	**25.2**
Jupiter	**9.842**	**3.1**
Saturn	**10.65**	**26.7**
Uranus	**17.2**	**97.9**
Neptune	**16.05**	**28.8**
Pluto	**153.36**	**119.0**
Moon	**655.73**	**6.7**

Note that three of the planets have their rotation axes inclined by more than $\mathbf{90^o}$ to their orbital plane. Venus is inclined by almost $\mathbf{180^o}$; Venus rotates backwards, in the opposite sense to its revolution about the Sun. Uranus and Pluto rotate with their axes lying almost in their orbital plane.

> **Venus rotates about its axis with a period of 243 days in an almost precisely opposite sense to its 225 day orbit about the Sun. Normally, and colloquially, we define the North direction according to what is called the "right hand rule": the thumb points in the North**

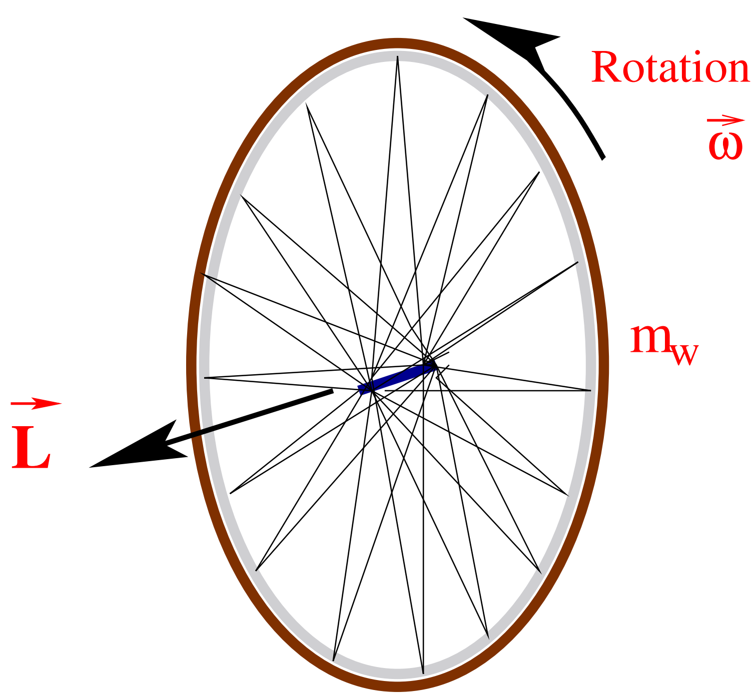
direction when the rotational direction is towards the tips of our right hand's fingers. Venus' North points in the almost precisely opposite direction to Earth's. Earth's North Star, Polaris, sits above Venus' southern pole. In this geographical convention, all planets rotate towards the East and so Sun rises in the East and sets in the West.

Question: With a series of diagrams, determine the length of the Venusian solar day, the period between successive "noons", the moment when the Sun is most nearly at "zenith"[206]

7.1 Moments of inertia of the planets

A rotating body tends to stay in rotation unless acted upon by an external ***torque***. A spinning bicycle wheel continues to rotate unless braked. Friction in the bearings of the wheel-axle does, of course, contribute to the slow braking of the spinning wheel.

Rotation and angular momentum

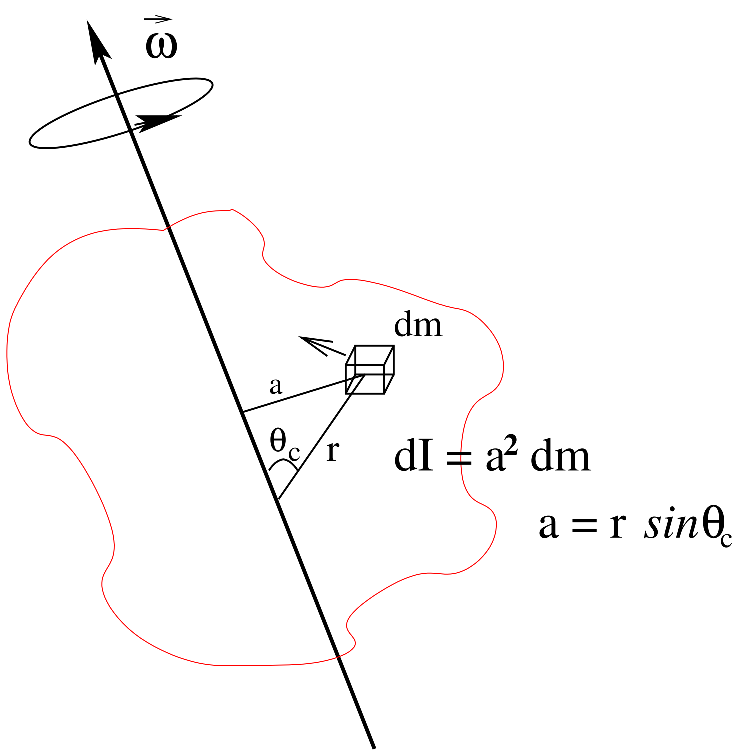


[206]Venusian solar day = **117** Earth days; Venusian siderial day (relative to the *fixed stars*) = **243** Earth days.

- The quality and quantity which determines the continuing tendancy to rotate is called ***angular momentum*** and is usually designated by a vector form $\vec{\mathbf{L}}$. The $^{\rightarrow}$direction of the vector is established by a convention called the ***right-hand rule***. If the fingers of the right hand are wrapped in the direction of rotation, the thumb points along the $^{\rightarrow}$direction of the angular momentum vector.

- The rate of rotation, $\tilde{\boldsymbol{\omega}}$, is determined as the number of turns – usually in ***radian*** measure – per unit time. It's $^{\rightarrow}$direction is also determined by the right-hand rule. Rotation rates are usually described in units of $\boldsymbol{rad \cdot s^{-1}}$. There are $\boldsymbol{2\pi}$ radians in one full cycle of $\boldsymbol{360^o}$ of rotation and so $\boldsymbol{1\, rad = 57.2957..\,^o}$.

Returning to the spinning bicycle wheel, we would find $\vec{\mathbf{L}} \propto \boldsymbol{m_w}$, where $\boldsymbol{m_w}$ is the mass of the tire + rim, $\vec{\mathbf{L}} \propto \boldsymbol{a^2}$, where $\boldsymbol{a}$ is the radius from the axle to the wheel rim and $\vec{\mathbf{L}} \propto \tilde{\boldsymbol{\omega}}$. The properties inherent to the wheel are assembled as $\mathbf{I} = \boldsymbol{m_w \cdot a^2}$, the ***moment of inertia*** of the wheel. The angular momentum of the spinning wheel is then $\vec{\mathbf{L}} = \mathbf{I}\,\vec{\boldsymbol{\omega}}$.



Let us look at a simpler model and then generalize it.

- If we were to have a small mass, $\boldsymbol{dm}$, rotating about an axis at distance $\boldsymbol{a}$ from that axis, it would determine a small element of moment of inertia, $\boldsymbol{d}\mathbf{I} = \boldsymbol{a^2\, dm}$.

- Allowing for varying density throughout the volume, let $\boldsymbol{dm = \rho(\vec{r})\, dv}$ where $\boldsymbol{\rho(\vec{r})}$ is the density at vector displacement $\boldsymbol{\vec{r}}$ from some chosen point along the axis and $\boldsymbol{dv}$ is a small element of volume at that place.

- $\boldsymbol{a = |\vec{r}| sin\, \theta_c}$ where $\boldsymbol{\theta_c}$ is the (colatitude) angle between the rotation axis and the vector $\boldsymbol{\vec{r}}$.

- $$\boldsymbol{d}\mathbf{I} = \boldsymbol{(|\vec{r}| sin\, \theta_c)^2\, \rho(\vec{r})\, dv}.$$

- If we sum, ***integrate***, over all such small volumes of mass forming the entire volume,
$$\mathbf{I} = \int_{\boldsymbol{volume}} \boldsymbol{(|\vec{r}| sin\, \theta_c)^2\, \rho(\vec{r})\, dv.}$$

- Note that **I** depends upon the axis of rotation.

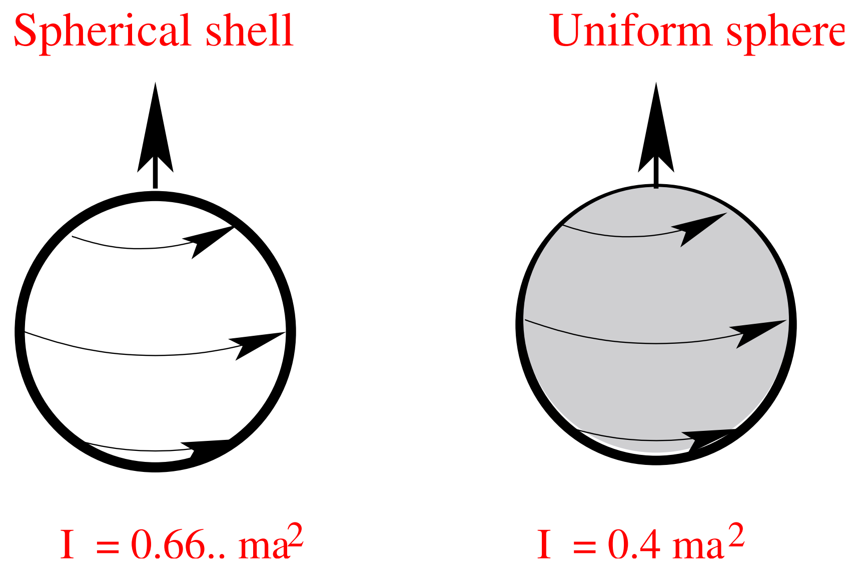
- If we can well determine **I** for a planet, we can learn something useful about how mass or density is distributed within.

Some examples of possible planets calculated according to the integral above:

- For a perfectly spherical planet of uniform density and radius, $\boldsymbol{a_p}$, such that its overall mass is $\boldsymbol{m_p = \frac{4}{3}\pi \rho\, a_p^3}$, rotating about a diameter (which obviously passes through its centre),
$$\mathbf{I} = \boldsymbol{\frac{2}{5} m_p\, a_p^2.}$$

- For a perfectly spherical planet, rotaing as above, with all its mass concentrated in a thin surface layer,
$$\mathbf{I} = \boldsymbol{\frac{2}{3} m_p\, a_p^2.}$$

- For a perfectly spherical planet with all its mass concentrated at its centre, i.e. with $\boldsymbol{\vec{r} = 0}$ for each element of mass,
$$\mathbf{I \equiv 0.}$$



What we should be able to recognize from these models is that when the mass is concentrated towards the centre of our possible planet, for the same given overall mass, $\boldsymbol{m_p}$, and radius, $\boldsymbol{a_p}$, its moment of inertia is lower than when mass is distributed at distance from the centre. A moment of inertia, $\mathbf{I} < \mathbf{0.4}\, \boldsymbol{m_p}\, \boldsymbol{a_p^2}$, determines that the planet's mass is relatively concentrated towards its centre. The lower the moment of inertia, the more mass is concentrated at depth.

7.2 Determining I by astronometric observations

We can neither brake nor accelerate the rotation of a planet in order to measure its moment of inertia. Still, the moment of inertia can be determined for some planets in response to astronomical forces and torques.

When a body spins on an axle its gyroscopic action maintains its angular momentum vector fixed in ***inertial space***. If, for example, a rapidly and continuously spinning bicycle wheel were suspended on long flexible fibres by its axle, its axis of rotation would appear to make one full circle in one day as the Earth rotated under it. Actually, the axis of rotation would remain fixed in inertial space while our point of reference on a non-inertial, rotating Earth changed during the daily cycle.

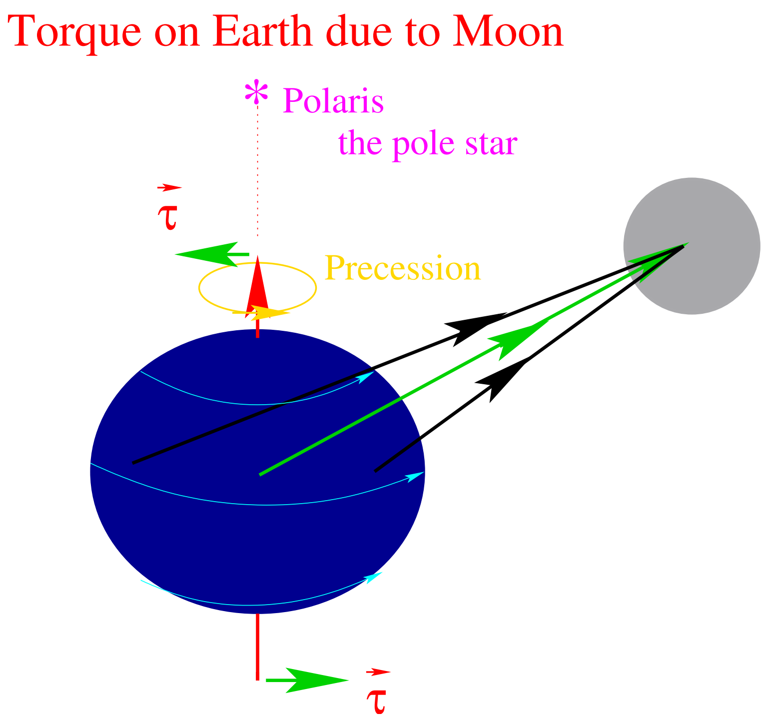
Returning the bicycle, holding the rapidly spinning front wheel off the ground with the handlebars as one twists a right-hand turn, the frame of the bicycle twists down towards the right. Try it! What is happening? When a torque is applied to the axle (on the rotation axis), a reactive torque exactly $\mathbf{90^o}$ to the applied torque results in maintaining torque balances.

The Moon applies such a twisting torque to the effective axle upon which the Earth rotates; the reaction torque causes the Earth's axis to move in a direction $\mathbf{90^o}$ to the applied torque. How does this arise?

The Earth is a slightly flattened ellipsoid of rotation. The ***flattening*** is determined by a measure

$$\boldsymbol{f = \frac{r_e - r_p}{r_e} \approx \frac{1}{300}}$$

where $\boldsymbol{r_p}$ is the polar radius and $\boldsymbol{r_e}$, the equatorial radius of the Earth. If the Moon's present location in its orbit about the Earth is not precisely aligned with the equator of the spinning flattened Earth, there is a greater gravitational attraction to the near side of the Earth than to the far side – from the Moon's perspective.



The Moon produces a torque on the axis of rotation and in reaction to this torque, the Earth ***precesses*** with a precessional rotation in the same sense as the spin. This precession is cyclical with a **26 000** year period and an average half-angle of about $\mathbf{23^o}$. Presently, Polaris, the North Star, is aligned with the rotation axis of the Earth above the northern hemisphere. In **12 000** years, it will be more nearly aligned with Vega which is presently more than $\mathbf{40^o}$ declined from the Polaris reference.

The rate of precession, $\vec{\boldsymbol{\omega}}_{\mathbf{p}}$ is proportional to the applied torque twisting the axle of rotation and inversely proportional to the angular momentum of the Earth's spin which, of course, is proportional to $\mathbf{I_z}$. As a top or dradle spins down and begins to topple over, it precesses with an ever increasing rate as its spin angular momentum decreases even though the applied torque is also increasing.

7.2.1 $\mathbf{I_z}$ for Earth

Physical analysis of the gravitational-force-induced torques on the Earth due to the Moon and our observation of the period or rate of precession allowed us, already in the 1800s, to determine the moment of inertia[207] (about the rotation axis) for the Earth. We know it to be $\mathbf{I_z = 0.3308} \boldsymbol{m_\circ a_\circ^2}$.

7.2.2 I for the other terrestrial planets

Only Earth has a substantially massive Moon to apply a significant torque on its rotation. Thus only for Earth was it relatively easy to obtain measures of its axial moment of inertia by this means.

- Mercury has no moon, nor does Venus. They also rotate very slowly and so the effects of twisting torques due to the proximity of Sun amd other nearby planets are small and produce only enormously long and unmeasurable precession periods. Moreover, the body of Venus is essentially invisible from the Earth because of the thick atmospheric covering clouds. We do not have good measures for the axial moments of inertia of these two planets.

- Mars rotates quickly, once in about **25** hours. It only has very small moons, Deimos and Phobos, which produce immeasurably small torques on the planet. Jupiter, though, is close enough from time-to-time to apply significant torques which do present a precession. Some measurements have recently been made of this precession as the position of the **Mars Pathfinder Lander** is monitored by high-precision interferometry from Earth and compared to the position of the **Viking Landers** measured in the 1970s.

- There is another way to determine **I**. By accurate measurements of the detail of the gravity field about a planet as can be obtained by observations of the orbital perturbations of artificial satellites in low orbit about it, we can obtain accurate measures of the planet's moment of inertia. Such has been accomplished, only recently, for Venus and Mars. This approach to measurement is more difficult for Venus than for Mars because Venus rotates so slowly that it is almost spherically symmetric in its gravity field.

  - Mars' axial moment of inertia is $\mathbf{I_z = 0.366} \boldsymbol{ma^2}$.
  - Venus', $\mathbf{I_z \approx 0.33} \boldsymbol{ma^2}$.

[207] The Earth is not spherically symmetric and so its moment of inertial depends upon the axle about which its spin is imposed. The moments of inertia are actually described by a 9-element symmetric tensor in which the diagonal elements are $\mathbf{I_z}$, $\mathbf{I_x}$ and $\mathbf{I_y}$.

- The Moon rotates slowly but is under the enormous gravitational torque applied by the Earth. Its ***libration*** best determines the axial moment of inertia: $\mathbf{I_z = 0.394} \boldsymbol{ma^2}$.

- For Mercury, we are just now mapping its gravity field with Mercury Messenger: current best estimate $\mathbf{I_z = 0.346(\pm 0.014)} \boldsymbol{ma^2}$[208]. This estimate accords with geochemical knowledge inferred from the spectral appearance (inferring the surface and interior geological materials) of Mercury.

7.2.3 What do these measurements of I tell us?

For the Earth, Moon and Mars, we have excellent evidence that the moments of inertia are less than those of a sphere of uniform density having equal size and mass. This tells us, unequivocally, that for these bodies, ***density increases towards their centres***. This agrees with our expectations for Earth for we believe we know that the Earth must contain about 35% of its mass in iron and that that amount of iron is not seen in the crust or in mantle materials which have been brought to the surface. The iron must be at depth. This supports our expectation that we have a fluid iron core, containing within a solid iron core, with a radius of about $\mathbf{1/2}$ the radius of the Earth. That the Moon's relative moment of inertia is somewhat less suggests that it contains much less iron and accords with its smaller size which would not allow as much compression to high density of interior materials at depth. Mars' moment of inertia supports an iron core to about $\mathbf{1/2}$ its radius as well. We shall learn later that this core must be frozen solid. We infer that Venus is very much Earth-like in its interior as we believe it formed nearby in the Solar System of materials similar to those which formed Earth. Still, again, we shall learn later that its lack of a magnetic field suggests that its iron core must be frozen (or perhaps entirely liquid without an inner core yet solidifying). We know from **Mariner** fly-bys of Mercury that the planet is very dense, almost as dense on average as Earth. Earth among all the planets has the greatest average density. Still, Mercury is very much smaller than Earth and so the compression of materials to high density at depth should be a much smaller factor in its average body density. The high density of Mercury suggests that it contains a very large core, perhaps accounting for 50% or more of its mass, of iron. All the terrestrial planets have geophysically and geochemically differentiated... on Earth the process of differentiation continues to the present.

[208] Soloman, *et al.*

8 Geophysical processes in planetary differentiation

The differentiation of the terrestrial planets and asteroids and also of the gas giants depends upon both geophysical and geochemical processes. Properly, ***geophysics*** refers to the *physics of the Earth, i.e. "geo-"* and ***geochemistry*** to the *chemistry of the Earth*. Applied to the planets and Solar System and the Universe as a whole, the science of chemistry is sometimes better called ***cosmochemistry***. Presently we don't use a similar term to describe a physics generalized to the description of processes on the planets. Some authors do use terms like, for example, ***selenophysics*** to describe the *physics of the Moon*.

- The geophysical processes involved in differentiation depend largely upon differential densities of materials which might be either inherent or dependent upon their temperature.
  - Bouyant materials rise and dense materials sink... The temperature caused bouyancy of ***mantle*** materials and ***fluid core*** is largely due to the slow freezing of the iron inner core and the release of the ***latent heat of fusion***.

8.1 The internal structure of Earth, Moon and the terrestrial planets

We know from the rotational dynamics of Earth, Moon and Mars that their internal density increases rapidly towards their centres. We infer the same for Venus and Mercury though we really haven't obtained accurate measures of their moments of inertia.

- The typical structure of a typical terrestrial planet (Earth as model) or our Moon comprises:
  - A thin outer crust of lighter silicates (largely granitic) where high standing and somewhat denser silicates (largely basaltic) where low standing.
  - A very deep mantle of silicates, ever denser with depth.
  - A core, largely composed of ***Fe***, ***Ni*** and some alloying lighter elements such as ***O*** and ***S***. The core may be frozen solid or, like Earth and Mercury, have an overlying melted shell.
  - If the planet's gravity is strong enough to hold volatiles against their evaporation into space, it may well have a substantial atmosphere. Earth has large oceans of liquid water.

The crustal skin and mantle of the planet has little ***Fe*** and ***Ni***. The crust is especially enriched in ***Ca***, ***Na***, ***K***, ***Al***, ***Si*** and ***O***. The ***Fe*** and ***Ni*** has mostly sunk into the core. In the table below, one might note that overall, the Earth comprises about 15% by mass ***Si*** but the crustal abundance[209] is about 28% ***Si***; take care with the meaning of the normalization to $\boldsymbol{Si = 1}$.

Estimated relative abundances by mass

Element	Solar photosphere	Av. meteorite	Earth (whole)	Earth (crust)
H	**803**	***little***	***little***	**0.0050**
He	**201**	***little***	***little***	**< 0.0006**
O	**8.8**	**1.95**	**2.1****	**1.69**
C	**4.0**	**−−**	**−−**	**0.0034**
Si	**1**	**1**	**1**	**1**
Mg	**0.77**	**0.82**	**0.93**	**0.075**
Fe	**1.41**	**1.69**	**2.2**	**0.18**
S	**0.41**	**0.12**	**0.03***	**0.0019**
Al	**0.071**	**0.065**	**0.071**	**0.29**
Ni	**0.089**	**0.099**	**0.17**	**0.0007**
Ca	**0.072**	**0.082**	**0.096**	**0.13**
Na	**0.035**	**0.040**	**0.025**	**0.10**
K	**0.0045**	**0.0060**	**0.00012***	**0.093**

*Notice, especially that ***S***, sulfur, and ***K***, potassium, seem to have significantly lower relative (to solar) abundance on Earth than do other elements in this list. It may well be that we do have more normal sulfur if most sulfur is dissolved into iron in the fluid outer core as is arguedby many geophysicists and geochemists. We know that there must be some lighter alloying element in the core; sulfur, oxygen and carbon are the possible candidates.

**Oxygen, like hydrogen and helium, all being quite volatile, were not easily contained to Earth its gravitational pull during the early evolution.

Structurally, the Earth is now well ***differentiated***.

- The thin ***crust*** is comprised of myriad minerals formed into hundreds of rock types. Overall, the crust is not nearly as rich in ***Fe*** and ***Mg***, especially, as is the Earth as a whole. The crust is much richer in lighter metals.

  The oceanic basaltic crust (∼71% of Earth's surface) as measured at mid-ocean ridges shows abundances by atom count: ***O*** (61%), ***Si*** (15%), ***Fe*** (3.1%),

[209] Crustal abundance

Mg (2.3%), ***Al*** (9.2%), ***Ca*** (3.4%), ***Na*** (1.6%) and ***K*** (1.0%). By mass contribution: ***O*** (44%), ***Si*** (21%), ***Fe*** (9.1%), ***Mg*** (2.7%), ***Al*** (12.5%), ***Ca*** (7.0%), ***Na*** (1.8%) and ***K*** (0.1%).

The continental crust is much more variable according to place: by relative mass composition, ***Fe*** (5%), ***Mg*** (2.1%), ***Al*** (∼8%), ***Ca*** (∼3.7%), ***Na*** (∼2.8%) and ***K*** (∼2.6%). ***O*** (47%) and ***Si*** (28%) are the most abundant elements.

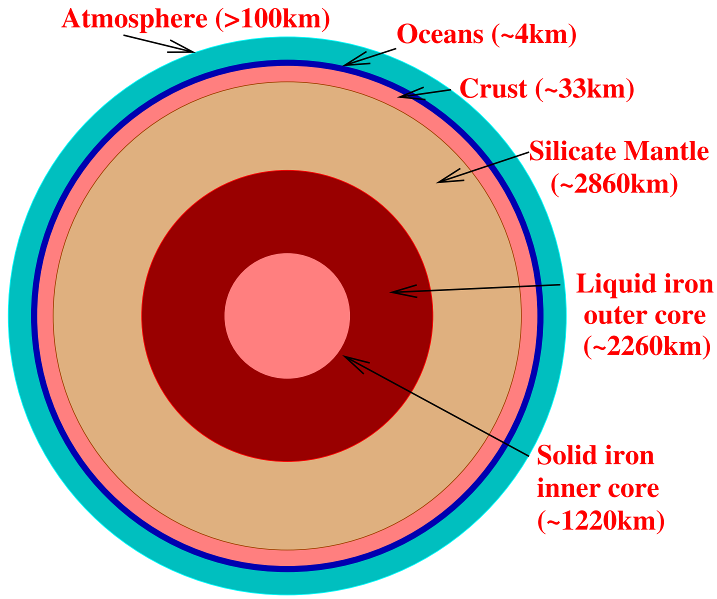
The crust extends from the surface to an average depth of about $\boldsymbol{33km}$.

- Below the crust, the ***mantle***[210] comprises $\boldsymbol{\approx 85\%}$ of the volume of Earth extending to a depth of $\boldsymbol{2900km}$ below the surface. At depths less than about $\boldsymbol{410km}$, the rocks are mostly formed of the minerals ***olivine***, various ***pyroxenes***, ***spinel*** and ***garnet***. It is composed mostly of silicates and metal oxides. Deeper, the most abundant minerals are thought to have a ***silicate perovskite***, structure like that of the common mineral ***perovskite*** but with stoichiometry, $\boldsymbol{[Fe, Mg]SiO_3}$ with and ***ferropericlase*** minerals with form $\boldsymbol{[Fe, Mg]O}$. There may be some trace minerals of the form $\boldsymbol{Al_2O_3}$, $\boldsymbol{CaO}$, $\boldsymbol{Na_2O}$.

- At about $\boldsymbol{2700km}$, the mineral structure perovskite reforms as ***post-perovskite***. In laboratory experiments, this is shown to happen at temperatures of about $\boldsymbol{2500K}$ and pressures of $\boldsymbol{125GPa}$ for stoichiometrically pure $\boldsymbol{MgSi0_3}$. Throughout the mantle, there is strong evidence that, by atom count, there is $\boldsymbol{9\times}$ as much ***Mg*** as ***Fe***. Iron is largely in the cores. Overall, by mass, its elemental composition is thought to be: $\boldsymbol{0}$ (44.8%), ***Mg*** (22.8%), ***Si*** (21.5%) and only 5.8% ***Fe***! The iron is in the core.

- Starting from the base of mantle at $\boldsymbol{2900km}$ depth and extending to the centre of the Earth, this last $\boldsymbol{1/8}$ volume of Earth is composed of ***Fe*** **(90%)**, ***Ni*** **(5%)** and a possible mix of ***C***, ***Si***, ***O***, ***S*** and ***H*** comprising less than **5%** by mass. **35%** of the total mass of Earth is in the core. The central, solid ***inner core*** is probably almost pure crystalline ***Fe***, perhaps even in a single crystal form; its radius is about $\boldsymbol{1290km}$.

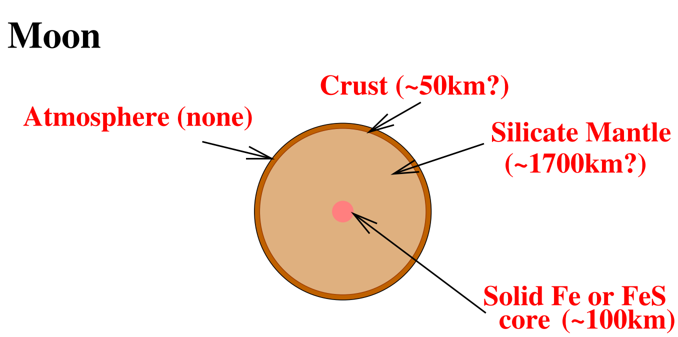
[210] Mineralogical composition of Earth's mantle



Model of an Earth-like planet

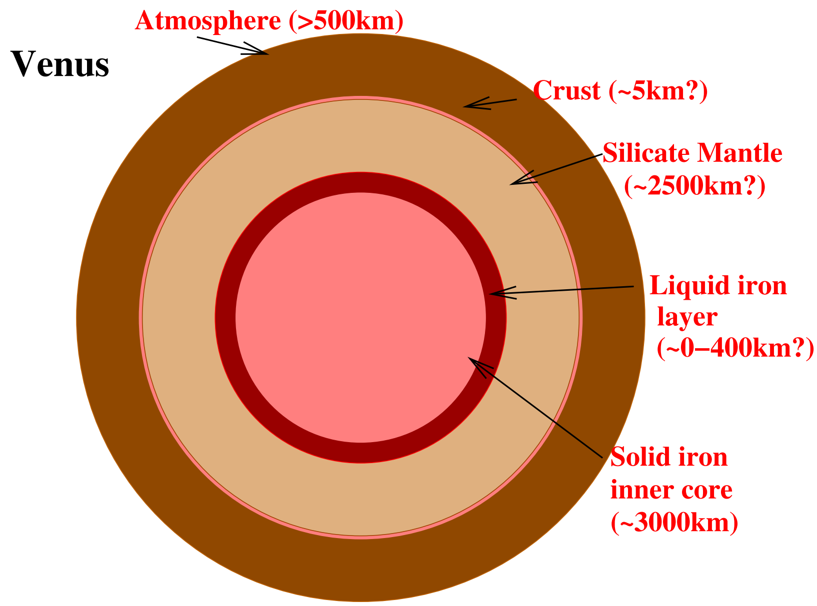
The Terrestrial Planets of the inner Solar System: The Moon and other terrestrial planets are probably very similarly differentiated, internally, with an iron core, a silicate mantle and low-density silicate crust.

- ***Moon***[211] We know, from its rotational dynamics, from its mass and from geochemical evidence that the Moon has less iron than Earth. It probably has only a very small iron core.



[211] Moon
GRAIL

- ***Venus***[212] formed near Earth in the Solar System and is of similar size. It is probably, at depth, similarly differentiated as Earth with an iron core contributing 35-40% to its overall mass. Its core is either entirely frozen or still completely liquid. We infer this because we know that Venus has no global (geodynamo-generated) magnetic field.



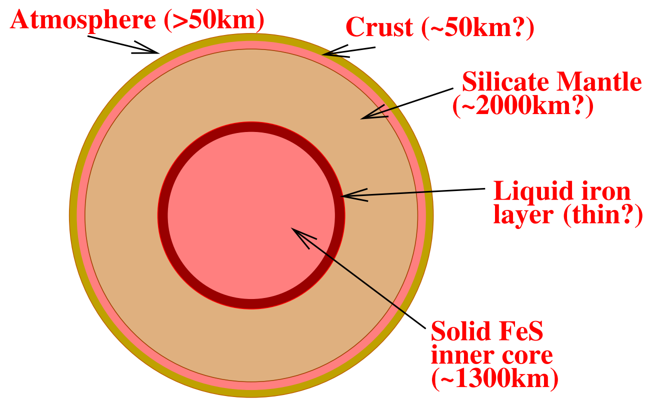
- ***Mars***[213] is thought to have an iron core comprising, perhaps 30% of its mass overlain by a silicate mantle. Mars' iron or iron sulphide core is probably either frozen or so viscous that it doesn't flow quickly enough to generate any magnetic field.

---

212 Venus

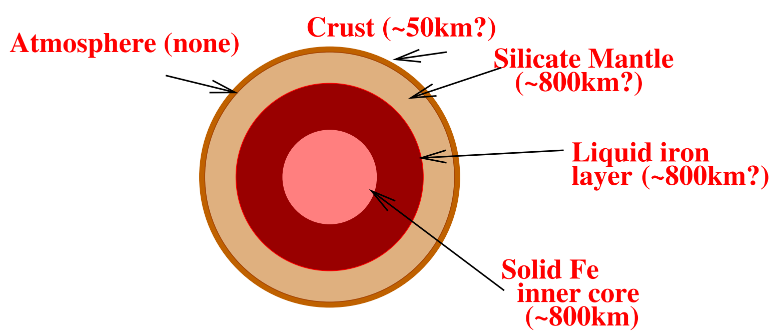
213 Mars
Curiosity: Mars Science Laboratory

Mars



- ***Mercury***[214], for its size, has a large mass. This argues for a larger ***Fe*** composition that the other terrestrial planets – probably ≈50%+ iron. The core is believed to be molten and in circulation because Mercury does have a global magnetic field.

Mercury

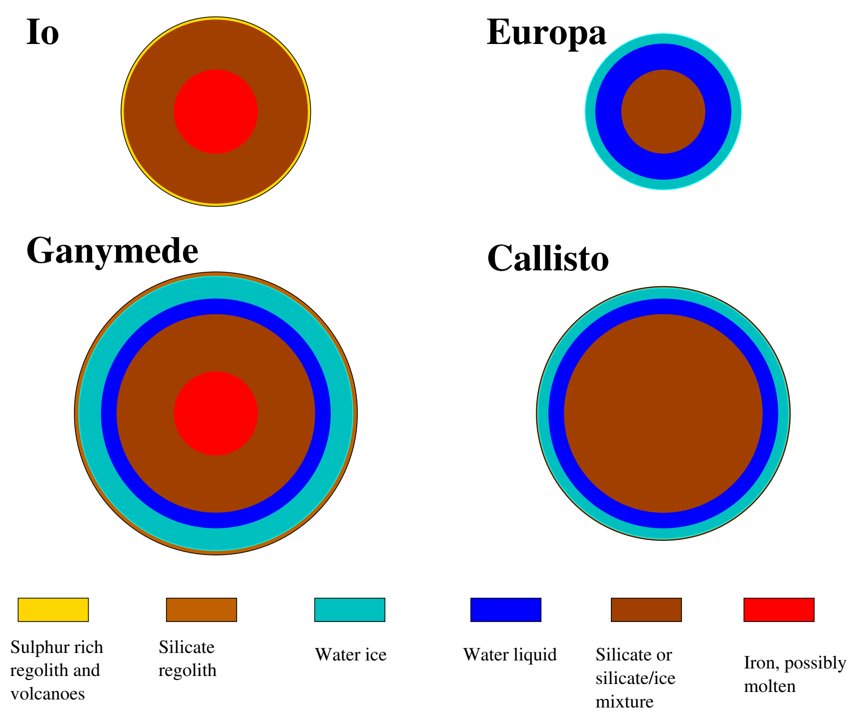


The outer reaches of the Solar System: The gas giants, Jupiter, Saturn, Uranus and Neptune are far enough from the heating Sun and massive enough to have high gravitational fields which have over eons contained the lightest elements of condensation.

[214] Mercury
Mercury Messenger Mission
Conversation with Maria Zuber, Mission Investigator

- ***Jupiter***[215] probably has a small core of rocky silicate-composition material and a deeper iron core just like Earth and perhaps of about the same size as Earth. Overlying this Earth-like centre we believe there is an ocean of exotic liquid metallic hydrogen more than $\boldsymbol{40\,000km}$ deep and which is again overlain by an ocean of liquid molecular $\boldsymbol{H_2}$-hydrogen $\boldsymbol{25\,000km}$ deep. Above that, there is a thick atmosphere of methane, $\boldsymbol{CH_4}$, $\boldsymbol{H_2}$ with possibly some water and $\boldsymbol{CO_2}$. More than 70% of the mass of the planet is hydrogen (≈90%+ by atom count). 25% of the mass of the planet is probably $\boldsymbol{He}$ like the Sun with the heavier elements contributing well less than another 5%.

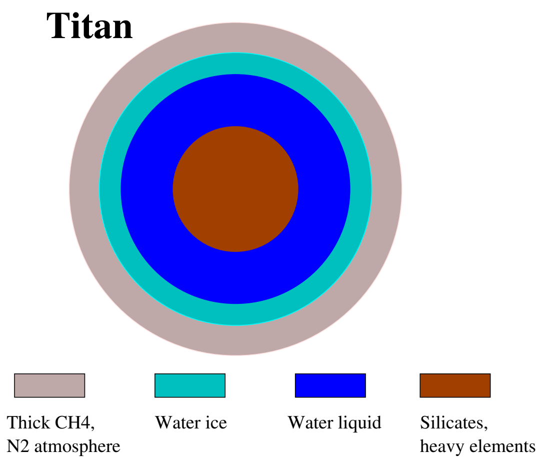
- ***Jupiter's Galilean moons:*** The Galilean moons of Jupiter (**Io**, **Europa**, **Ganymede** and **Callisto**) are very much like terrestrial planets in that they are hard-bodied and relatively dense suggesting that they comprise silicates and possibly iron.



- ***Saturn***[216] is similarly composed as Juptier over an Earth-like central zone. Saturn's largest moon, **Titan**, is interesting in that it has an extremely thick, thicker than Earth's, atmosphere composed mostly of $\boldsymbol{CH_4}$ and $\boldsymbol{N_2}$. It is

215 Galileo Mission
216 Cassini/Huygens
Cassini-Solstice

thought that this atmosphere is like that of the earliest stages of Earth's evolution.



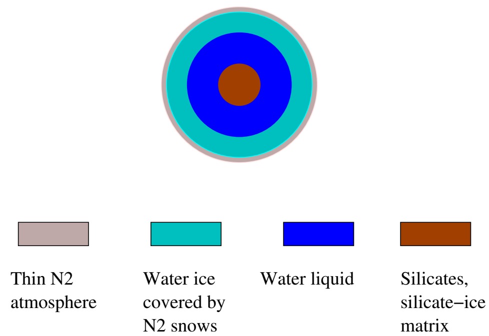
In January 2004, the Huygens probe landed on Titan, obtaining photos of its surface during descent and upon landing[217].

- ***Uranus and Neptune*** probably also have silicate cores overlain by volatiles though their volatiles comprise relatively much more water, H_2O, CH_4 and N_2 than Jupiter and Saturn. Neptune's largest moon, **Triton**, is known to be active with geysers of N_2 erupting from its surface and being sheared at $5 - 10\,km$ elevation by high winds in its thin, probably N_2 atmosphere.

- ***Pluto*** The surface and upper regions of its mantle are mostly ices of H_2O, CO_2, CO, N_2 and CH_4. According to its density, it probably has a substantial rocky core. Until the close approach to the Pluto system by the ***New Horizons***[218] deep space probe in the summer of 2015, we had little direct information about Pluto and its moons. We thought that what we knew of Triton probably also applied to Pluto. We have found that Pluto and its moons are exciting. Now the probe will continue into the Kuiper belt, hopefully to image new and so-far unseen objects.

[217] Titan's surface
[218] New Horizons mission website

Triton and Pluto



Earth among all planets has the highest ***density***, mass for its volume. Its high density is partially accounted for by the compression of overlying materials squeezing the deep iron core to high density. The iron core is somewhat less dense than one expects for the temperatures and pressures at depth so it must include somecomponent of lighter elements. The vigorous circulation of the fluid outer core layer produces Earth's strong magnetic field.

The crust of the Earth is differentiated laterally over the surface into continents and ocean basins.

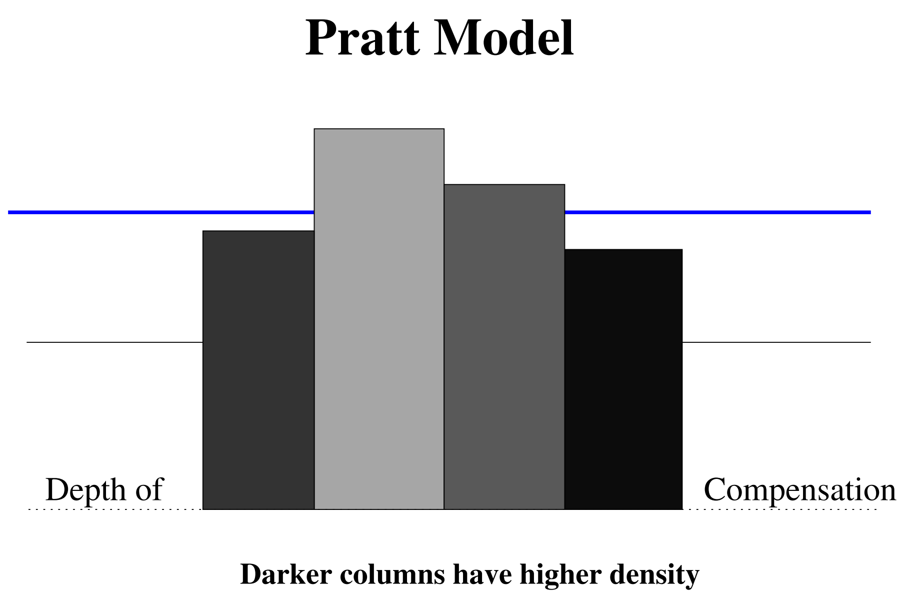
- The continents are high-standing, relatively low-density ***granitic*** materials. Granitic means *granite-like* rock which is a rock type very rich in $\boldsymbol{SiO_2}$ or *quartz* and without *olivine* mineral, $\boldsymbol{(Mg, Fe)_2SiO_4}$. Quartz is a relatively low density mineral – it is the most common type of sand and is the chemical composition of ordinary glass.
- The ocean basins are low-standing (and water filled) higher density ***basaltic*** materials. Basaltic or *basalt-like* rocks have essentially no free quartz mineral components, their $\boldsymbol{Si}$ and $\boldsymbol{O}$, being largely contained in olivine.
- Whereas average, uncompressed granitic rocks have a density of about $\boldsymbol{2.5gm/cm^3 = 2500kg \cdot m^{-3}}$, basaltic rocks have a density of about $\boldsymbol{3.3gm/cm^3}$.
  - Basaltic rocks seem to "float deeply", to the depths of the ocean basins when assembled into large masses on Earth. The average depth of the ocean floor, underlain by basaltic rock, is about $\boldsymbol{-4.5km}$.
  - Granitic rocks float high above the oceans, forming the continents. The average elevation of the granitic continents is about $\boldsymbol{0.9km}$.

How do we account for these large-scale differences in elevation?

8.2 Isostasy

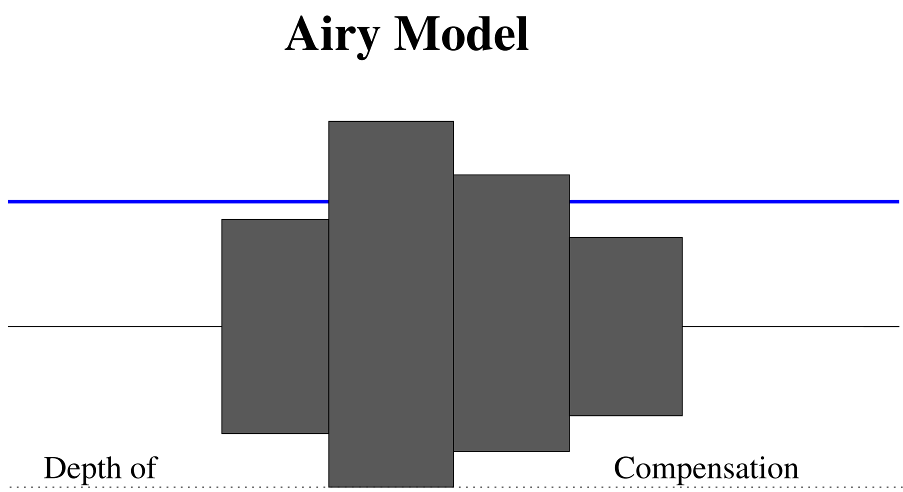
Isostasy largely explains differences of elevation on the Earth's surface. It especially well explains the reason for the depth of ocean floors and the generally high-standing continents.

- In 1855, archdeacon **J.H. Pratt** suggested that the reason for high elevations is that light materials "float" higher than do dense materials and that the rock of areas of high elevation are of low density.



  The effect is well known as we have determined that the density of mountain chain regions is lower than that of the lower floating continental cratons and much lower floating ocean basin basalts.

- **G.B. Airy** proposed another hypothesis: the high-standing regions are compensated by deeper roots but their densities are similar to those of low stands. The Airy hypothesis accounts, for example, for the height of icebergs. An iceberg that floats high has great root depth.



All columns have equal density

> The effect is well known as we have mapped the deep roots of the high mountain chains. The oceanic basin crust is quite thin ($\approx 7km$).

If the rocks of the crust of the Earth are floating, then they must be floating on a mantle which can adjust to the overlying mass and flow: a ***fluid mantle!***

8.2.1 Post-glacial rebound and isostatic adjustment

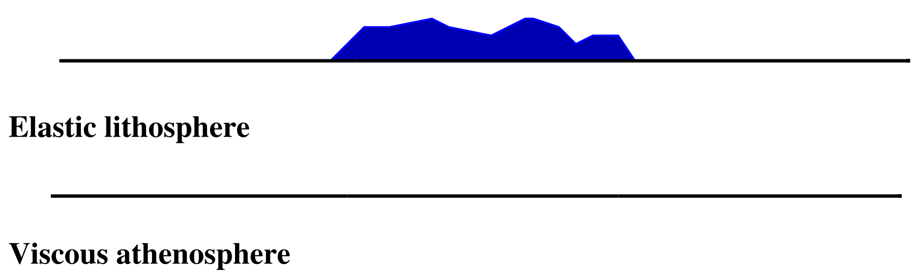
For centuries, tidal gauges along the coasts of Sweden and Finland in the Gulf of Bothnia and also along the states bordering the Baltic Sea, Latvia, Lithuania and Estonia, have been observed to show that these coasts are slowly rising relative to sea level. At the northern coast of the Gulf of Bothnia, tide gauges are showing land uplift rates of more than $1cm/year$. In the last $5\,000$ years, this coast of Sweden and Finland has risen by more than $100m$. What is causing this continuing rise of land? ***Post glacial rebound!***[219] Since the first ***geodetic*** satellites were launched in the late 1950s, we have monitored the ***geoid***[220] with ever increasing spatial and temporal resolution. The geoid is the surface of an ideal global ocean in the absence of tides and currents, shaped only by gravity; it is, colloquially, the surface of mean sea level. Since the launch of of the ***GRACE***[221] and ***GOCE***[222] satellites, we have been able to watch and measure the geoid to better than $1cm$ vertical precision over averaging areas of about $100km$ radius with time resolution of only weeks. The gravitational mass of a rainstorm that dumps $1cm$ of rain on a state the size of Nebraska can be

[219] Current uplift rates in mm/year
[220] A recent geoid ...a video of the rotating geoid
[221] NASA's GRACE mission
[222] ESA's GOCE mission

mapped. With a succession of such geodetic missions, we will be able to map the rate of post-glacial distortions of our Earth by satellite.

- Until about **7 000** years ago, this region was overlain by Fennoscandian icesheet to a depth of more than $\boldsymbol{3km}$ above the Gulf of Bothnia.[223]

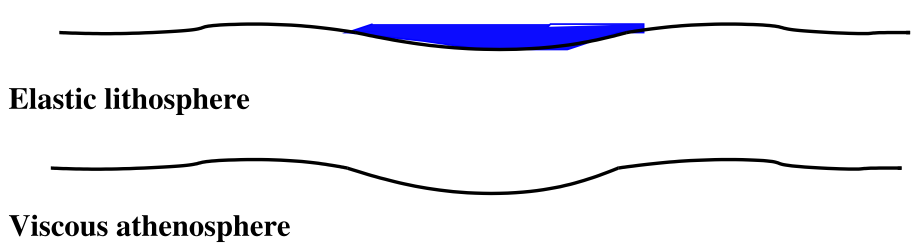
Glacial loading



- It had lain there for at least **30 000** years, depressing the Earth's lithosphere.

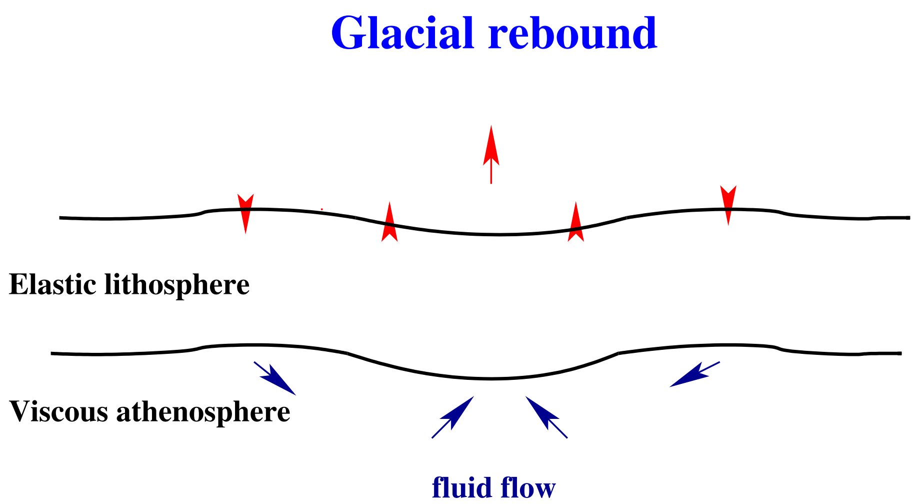
- Then about **10 000** years ago it began to melt quickly. The heavy load of the ice over time had depressed the underlying continent. The region had come into isostatic adjustment with the load.

Glacial melting



[223] Fennoscandian glaciation ...and rebound
Laurentian icesheet extent ...Laurentian uplift

- Relieved of the heavy ice load the whole continental region began to *rebound* – to bounce back up.



Glacial rebound is also observed at about the same rate, $\boldsymbol{1-2cm/yr}$, over James and Hudson's Bay in Canada. The Laurentian icesheet was larger and deeper than that of Fennoscandia.18 000 years ago, it covered almost all of Canada. It had depressed the Earth's surface even deeper below average sea-level. It had largely melted by about $\boldsymbol{6\,500}$ years ago and the land was rebounding. This is a very well studied phenomenon.

8.2.2 Viscosity of the fluid mantle

If the "fluid" upon which these depressed continental areas were floating could have moved very quickly, it would have infilled under the lowered load quickly. The fluid, though, flows extremely slowly; it has a very high ***viscosity***, usually represented by symbol, $\boldsymbol{\eta}$, a measure of its self-stickiness.

- Water has a viscosity of $\boldsymbol{\eta \approx 10^{-3} Pa \cdot s}$, maple syrup, $\boldsymbol{\eta \approx 2.5 Pa \cdot s}$ and red hot common glass, $\boldsymbol{\eta \approx 10^{12} Pa \cdot s}$.

- From the rate of rebound, we can calculate the viscosity of the slow moving, underlying mantle fluid!

  $\boldsymbol{\eta \approx 10^{20} - 10^{23} Pa \cdot s}$.

- It flows extremely slowly, so slowly in fact that we can't even recognize its fluid-like property over short times.

- Glass at normal temperatures is an amorphous solid – not crystalline. It behaves like a fluid.

  At room temperature $\boldsymbol{\eta \approx 10^{19} Pa \cdot s}$.

- The "fluid" mantle which underlies central Canada and Fennoscandia is even stickier than glass but, still, on time scales of hundreds or thousands of years, it looks like a fluid.

- On short time scales – and note that glass actually behaves like a very brittle solid when struck by a stone – the mantle is a very hard solid too! In fact, almost all regions of the mantle are "harder" and "stronger" than any known materials on the surface.

The fact of the fluid nature of the mantle allows for the ***convection*** process and the continuing geophysical differentiation of the planet.

8.3 Mantle convection

Geologists have known for more than 100 years that the continents move across the surface of the Earth.

Sir Francis Bacon in about 1620 recognized that the coastline of North America could be nicely fit against the coastlines of Europe and northern Africa. In 1799, **von Humboldt** noted that the same symmetry existed between the coastline of South America and that of central and southern Africa and that there were extensions of mountain ranges of South America on the African continent. It seemed as though the continents, separated by the Atlantic Ocean, had once been joined. This hypothesis was clearly stated by **A. Snider** in 1858 in France. In the early 1900s, the hypothesis took on some geological popularity as **F. Taylor**, **H.D. Baker** and then **Alfred Wegener** described theories of ***Continental Drift***[224] Geophysicists were slow to the accept the possibility because, as **Lord Rayleigh** argued, "Solid rock can't move through solid rock!". Some geophysicists held vainly to an alternate theory, the "Expanding Earth Hypothesis" which argued that Earth's volume had increased over geological time and that the earlier surface was no longer large enough in area to cover the surface of the greater volume. The Atlantic Ocean was seen to be an ever-widening crack on the surface of a growing Earth. In 1963, **J. Tuzo Wilson**, a physicist at the University of Toronto, wrote a famous article entitled "***Continental Drift***" which was published in the April issue of ***Scientific American*** magazine. He argued a mechanism which quickly found acceptance among geophysicists who finally joined their geological colleagues in this view of the tectonic process on Earth.

[224] On the history of the concept of Continental Drift

The theory of Continental Drift evolved and elaborated into the, now almost universally accepted theory, ***Plate Tectonics***[225].

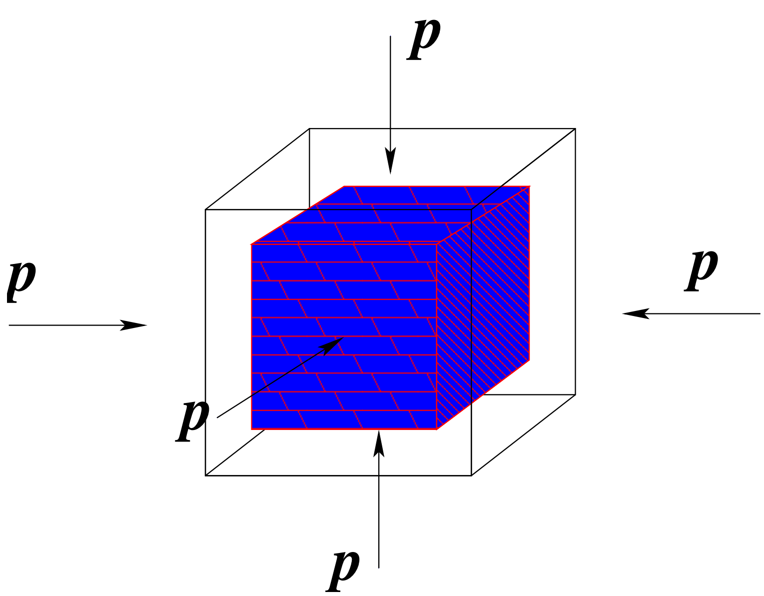
8.3.1 Earth's mantle is fluid!

If the Earth's mantle is fluid, it can be brought into circulation if the Earth's interior temperature is sufficiently hot.

- Post-glacial rebound suggests that the mantle is fluid on long timescales.
- If the mantle is a fluid and if there is a sufficiently steep temperature gradient from a hot base to a cool surface, it can efficiently transport heat from depth by a process called ***convection***. Convection drives the drift.

8.3.2 The adiabatic gradient

Suppose we have a small volume of material, say in the form of a cube. Suppose now that we apply a pressure to this cube. Recall that a pressure acts evenly in all directions and so each face of the cube feels the same squeezing force. The dimensions of the cube shorten; it responds to the pressure ***stress*** with a deforming ***strain***. If no energy is allowed to escape from the volume, the energy in the volume is also compressed. It becomes hotter!



[225] Plate tectonic theory – historical perspective

How much hotter?

If we compress our cube very quickly, it doesn't have time to come to thermal equilibrium; if we insulate it from its environment so that heat energy can neither flow in nor out of it, it cannot come to equilibrium. Such a compression is called ***adiabatic compression***; what is preserved in adiabatic compression is the ***entropy*** of the cube of material.

- From the physics of ***thermodynamics*** we know that

$$\begin{aligned} \Delta T &\propto \Delta P, \\ &\propto T, \\ &\propto 1/\rho. \end{aligned}$$

  where ρ is the density of the material of our cube.

What is the constant of proportionality?

If we were to heat the gas under constant pressure, it would want to expand as

$$\frac{\Delta V'}{V} = \alpha_P \cdot \Delta T',$$

but it has to expand against the confining pressure and so, effectively, it is being compressed by the confining pressure. It heats up just a little more than if there were no confining pressure by an amount:

$$\Delta T \propto \alpha_P$$

where α_P is the ***volumetric expansion ratio*** per K.

Depending on its capacity to hold heat, its ***heat capacity at constant pressure***, C_{H_P}, which determines what temperature increase would be caused by an inflow of heat, the material will more or less expand. For a material of very high C_{H_P}, it warms less and expands less. So when we compress the gas under some increase of pressure, ΔP, its temperature rise, ΔT, is greater according to its α_P and lesser according to $1/C_{H_P}$.

$$\Delta T \propto \frac{\alpha_P}{C_{H_P}}.$$

The constant in the equation relating an adiabatic temperature increase due to an increased pressure obtains as

$$\Delta T = \frac{\alpha_P}{C_{H_P}} \frac{T \, \Delta P}{\rho}.$$

The material of the Earth's mantle behaves accordingly.

Pressure within the Earth's mantle increases with depth as $\Delta P = |\vec{g}|\rho\Delta z$, where Δz is an increment of depth and $\vec{g}$ is the downwards oriented gravitational force on the material. As it turns out, for our Earth, $|\vec{g}| = g \approx 10 m \cdot s^{-2}$ throughout the mantle. It actually slowly increases from about $9.8 m \cdot s^{-2}$ at the surface to about $10.2 m \cdot s^{-2}$ at the base of the mantle. Within the mantle, then, the adiabatic temperature due to the varying pressure is

$$\Delta T = g \frac{\alpha_P}{C_{H_P}} T \Delta z,$$

and the ***adiabatic temperature gradient*** is

$$\frac{\Delta T}{\Delta z} = g \frac{\alpha_P}{C_{H_P}} T.$$

If the temperature profile in the mantle is adiabatic and we know the temperature at the top of the mantle, say T_{top}, we can calculate the temperature throughout. The previous equation determines a *differential equation* which can be solved given a known temperature somewhere in the profile. Letting the $\Delta T \rightarrow dT$ and $\Delta z \rightarrow dz$ become infinitesmal,

$$\frac{dT}{T} = g \frac{\alpha_P}{C_{H_P}} dz,$$

and if we *integrate* both sides of this equation, here shown step-by-step, we obtain

$$\int_{T_{top}}^{T(z)} \frac{dT}{T} = \int_{z_{top}}^{z} g \frac{\alpha_P}{C_{H_P}} dz,$$

$$ln\,(T(z)/T_{top}) = g \frac{\alpha_P}{C_{H_P}} (z - z_{top}),$$

$$T(z)/T_{top} = exp\,(g \frac{\alpha_P}{C_{H_P}} (z - z_{top})),$$

$$T(z) = T_{top}\, exp\,(g \frac{\alpha_P}{C_{H_P}} (z - z_{top})).$$

If we know the temperature at the top of the mantle and we know the thermodynamic constants appropriate to mantle material, we can determine the exponential adiabatic temperature profile to the base of the mantle. A reasonable temperature for the top of the mantle is suggested by the temperature of magmas which issue from great shield volcanos like that of Kilauea[226] in Hawaìi, about 1200^oC. For typical rock materials, $\alpha_P \approx 1.4 \times 10^{-5} K^{-1}$ and $C_{H_P} \approx 1.3 \times 10^3 J \cdot kg^{-1} \cdot K^{-1}$.

---

226 Recent/current eruption on Kilauea
Kilauea webcams

Calculate the adiabatic temperature at the core-mantle boundary at a depth of 2900 km, starting from a temperature of 1500 K at the top of the mantle, say at $z_{top} = 50\,km$.[227] **Note: $1J = 1kg \cdot m^2 \cdot s^{-2}$; $g \approx 10m \cdot s^{-2}$.**

We shall argue that because the mantle is fluid-like, the mantle is in constant convection and this brings the mantle temperature profile toward the adiabatic temperature profile. While fluids can be driven into convection if the temperature gradients through them are sufficiently high, solids cannot. Heat can be carried through fluids by convection but can only be carried through solids by conduction. The outer ***elastic*** shell of the Earth, its ***lithosphere*** which is typically about **50 km** thick, acts as a heat-conductive layer with a very poor heat conductivity. It acts like an insulation between the cold exterior of the Earth and its hot interior. The temperature gradient through this lithospheric shell is very steep, rising from about **300 K** on the surface to about **1500 K** at its typically **50 km**-base; the gradient near the surface is about **25 K/km**. If one were to drill just **4 km** into the Earth – and one does drill this deep for natural gas in the Alberta basin – one finds that the temperature is already well above the boiling point of water.

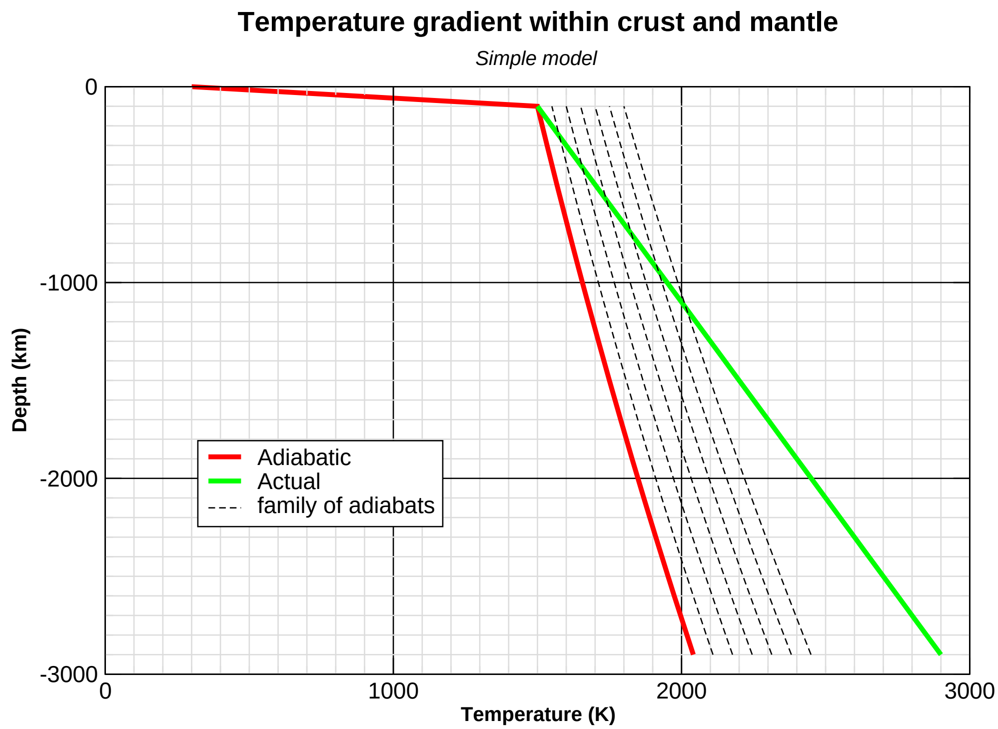
8.3.3 The adiabatic gradient and convection

Let us suppose the entire mantle follows the adiabatic temperature profile. This is the temperature profile that is in equilibrium with the pressure profile. The pressure and temperature within the mantle are related in a particular way that describes local equilibrium. In the real Earth mantle, at any pressure and depth, the temperature might well be somewhat different from this equilibrium temperature. If significantly different, the very material of the mantle, because it is fluid and mobile, adjusts toward finding that depth and hence pressure that accords with equilibrium.

If a volume of mantle material is moved along the adiabatic temperature profile, say we move a volume of material upwards to lower pressure, its temperature decreases as it expands to remain in exact temperature equilibrium with the lower local pressure. The mantle temperature follows the adiabatic gradient (in the figure, below, the red line)[228].

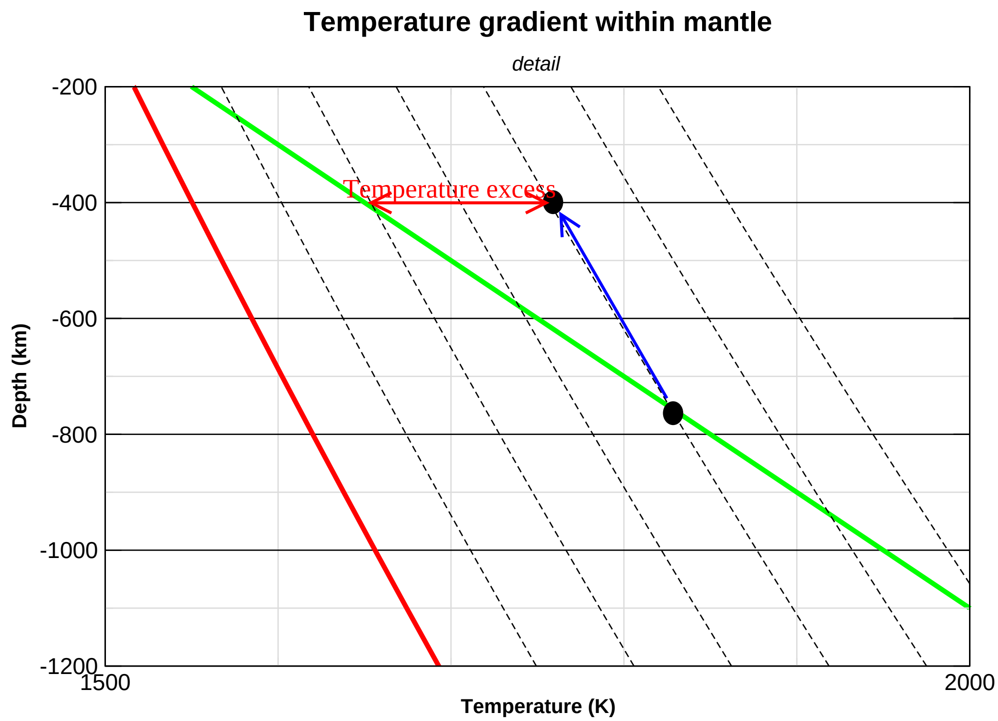
[227] Answer: **2039 K**. Because Earth's mantle is in such *vigorous convection*, we know that the temperature at the base of the mantle must be quite a lot higher than that accounted for by only the adiabatic gradient. Common estimates of the temperature at the core-mantle boundary are about **3500 K** with a very steep rise in the 200km just above the boundary. The temperature at the centre of Earth's core is at least **5100 K**.

[228] In the crust and that part of the upper mantle that comprises the *lithosphere*, the temperature gradient is much steeper than the adiabatic. Through this *insulating* zone, *conduction* transports heat.



Suppose now, that the actual temperature profile is a little steeper than the adiabatic temperature profile (in the figure, the green line). By "steeper", we mean that temperature increases more rapidly towards depth than would be predicted by the adiabatic gradient.

When a volume of material (black spot at temperature according to the green line) is moved upwards, it cools following the adiabatic gradient – it follows an ***adiabat***. But, in so cooling, it finds itself warmer than other material (its temperature on the green line) at its new lesser depth and lower pressure. Being warmer, it is somewhat expanded in comparison with local material and its density, therefore, is lower; it is relatively ***bouyant***. It would like to continue to rise even further under its own bouyancy. That is, if we even infinitesmally move a volume of material upwards through a temperature gradient which is steeper than the adiabatic, it wants to move even further upwards under bouyancy. The reverse is true for a volume of material displaced along a temperature gradient steeper than the adiabatic towards greater depth. It wants to continue sinking.



So, if there is any perturbation of material either upwards or downwards, it wants to accelerate away in the direction of the perturbation.

- This describes the process of mantle convection.
- The whole material of the mantle is set into continuing motion as heat is carried from depth towards the surface by the convecting fluid.
- The Earth's mantle is and has been convecting for the past **4.5** billion years. Core formation would seem to have already occurred by this time.
- The motion will eventually stop when the actual temperature profile cools to settle down to the adiabatic or cooler. That is, when there is no more excess heat anywhere in the deep interior maintaining a locally steep temperature gradient, convection will cease.
- The excess temperature can derive from bottom heating of the mantle (heat flowing in the mantle from the core) or from internal heating within the mantle (heating by decay of radionuclei, especially $^{40}\boldsymbol{K}$).
- Much of the heat emanating from the core to heat the base of the mantle is being released by the freezing of iron onto the inner core. The rest is the residual heat

from earlier decay of radionuclei and from the gravitational potential energy released as heat during the density stratification (differentiation) of the Earth.

- When the whole core is frozen and there is no significant amount of $^{40}\boldsymbol{K}$ left at depth, convection of the mantle will stop.

  We are probably billions of years from this eventuality on Earth. Presently, the Earth is in a very vigourous state of mantle convection.

It is probably the case that the mantles of Mercury, Mars and the Moon are no longer convecting though as we shall learn later, we have evidence that Venus' mantle was momentarily, at least, in very rapid convection as recently as **500** million years ago.

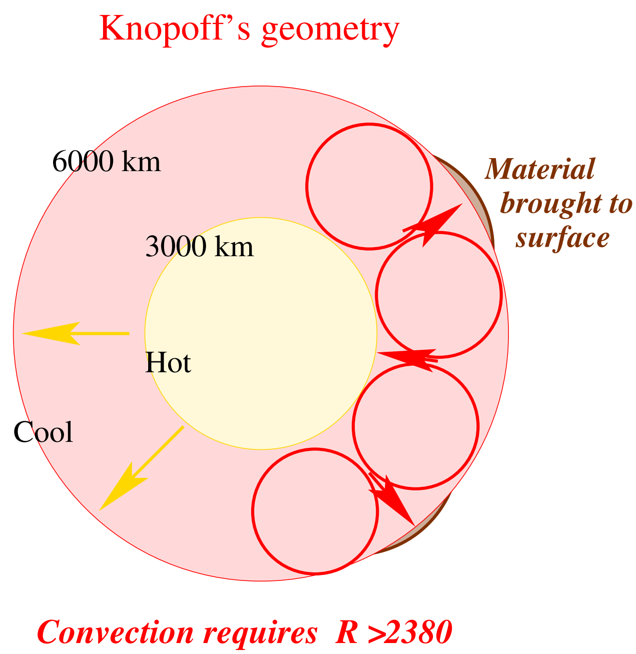
8.3.4 The Rayleigh number

The vigour of the convection is determined by a ratio of forces, the dimensionless ***Rayleigh Number***:

$$\mathrm{R} = \frac{\boldsymbol{bouyantforces}}{\boldsymbol{viscousforces}}.$$

The bouyant forces push the convection while the viscous forces retard it. Through fluid mechanical analysis, we can estimate just what this number must be for the Earth's mantle to remain convective.

In 1964, **Leon Knopoff** determined that for a spherical shell bounded below by a rigid surface contact with a spherical hot core and above by a rigid surface, with the inner radius being just $\mathbf{1/2}$ the outer, convection is maintained when $\mathbf{R} > \mathbf{2380}$. This model approximates the geometry of Earth's mantle. It seems that the relatively vigourous convection of the Earth's mantle would require $\mathbf{R} > \mathbf{10^5}$. The evidence for this is the very rapid motion of ***tectonic plates*** across the surface of the Earth that are being rafted about by the convection process. Because the motion is rapid, **R** must be very high and the bouyant forces must substantially dominate the viscous forces resisting convection. The bouyancy forces are high when the temperature gradient is high, that is, if the deep interior of the Earth is at temperatures much higher than could be accounted for by adiabatic compression. Whereas the temperature of the core-mantle boundary need only be about $\mathbf{2100}\,\boldsymbol{K}$ under a purely adaiabatic gradient, we believe the actual temperature to be much higher than this, $\sim \mathbf{2800} - \mathbf{3200}\,\boldsymbol{K}$. The Earth will surely convect for a very long time into the future.



Mantle convection within Earth.

8.4 Mantle convection and Plate Tectonics

Starting in the late 1960s, geologists and geophysicists started measuring the rates of motion of various ***plates*** floating over the Earth's surface[229] [230] [231] [232] [233] [234].

It was determined, for example, through observations of continuing offsets of roads and of lines of trees in orange orchards in California, that the San Andreas fault separated a plate to the west, now called the ***Pacific Plate***, from another to the east, the ***North American Plate*** and that the Pacific Plate was moving north-westward at about $\mathbf{4\,cm/yr}$ relative to the North American Plate[235]. It was also quickly noted that the Atlantic Ocean was spreading open, separating the Americas from Europe and Africa and that the rate of widening had averaged about $\mathbf{2.5\,cm/yr}$ during the past **200** million years[236].

[229] Motion of tectonic plates
[230] History of plate motions: http://www.ucmp.berkeley.edu/geology/tectonics.html
[231] Opening of the Atlantic ocean
[232] A detailed tectonic map of the Pacific basin
[233] A detailed tectonic map of North Polar Region
[234] A detailed tectonic map of South Polar Region
[235] Understanding plate motions: http://pubs.usgs.gov/publications/text/understanding.html
[236] http://research.utep.edu/Portals/73/PDF/ofr-02-0400.pdf See page 14.

8.4.1 Seismic and tectonic boundaries

Seismology, the geophysical science that is concerned with earthquakes and the radiating wave fields that earthquakes produce, and ***tectonics***, the geological science that is concerned with the large scale and continuing slow motions of the mantle and lithospheric plates, divide the Earth according to different layering structure.

- **The seismic boundaries**
  - ***Crust:*** This outer skin, typically about 30km thick, shows a relatively low velocity for seismic sound waves, the (***P-waves***). Its base is characterized by a sharp increase in the P-wave velocity to about $\boldsymbol{8km/s}$.
  - ***Mantle:*** Most of the volume ($\boldsymbol{\approx 87\%}$) of the Earth comprises the silicate, rocky mantle. The mantle has a layered structure that affects seismic wave velocities. The structure is caused by ***phase changes*** of the mantle minerals as they are compressed at depth into higher density forms.

    The most distinct boundaries are at $\boldsymbol{\approx 440km}$ where ***olivine***, $\boldsymbol{[Mg, Fe]_2SiO_4}$, becomes compressed into the ***spinel*** structure and then at $\boldsymbol{\approx 670km}$ where the spinel becomes further compressed into a mix of ***perovskite***, $\boldsymbol{[Mg, Fe]SiO_3}$, and ***ferro-periclase***, $\boldsymbol{[Fe, Mg]O}$. The lower mantle is thought to maintain this mix to the core-mantle boundary at $\boldsymbol{2970km}$ depth. At, perhaps $\boldsymbol{2770km}$ the pressure of $\boldsymbol{1.25GPa}$ allows for the perovskite mineral form to compress into the ***post-perovskite***. If this is the cause of the elastic discontinuity, $\boldsymbol{D''}$, observed by seismic experiments, the temperature there is established at about $\boldsymbol{2500K}$.
  - ***Outer core:*** The outer core is essentially a liquid mix of iron, $\boldsymbol{Fe}$, and nickel, $\boldsymbol{Ni}$, with some alloying lighter elements, probably, sulfur, $\boldsymbol{S}$, and possibly oxygen, $\boldsymbol{O}$, and even carbon, $\boldsymbol{C}$.
  - ***Inner core:*** At the centre of this liquid core is the frozen, crystalline probably almost pure iron (though perhaps with some $\boldsymbol{Ni}$ and $\boldsymbol{Co}$ and even traces $\boldsymbol{K}$) inner core. Its radius is $\boldsymbol{1222km}$.

    The outer core and inner core contain about $\boldsymbol{35\%}$ of the Earth's total mass in less than $\boldsymbol{1/8}$ of its volume.
- **The tectonic boundaries**
  - ***Lithosphere:*** This is the outer ***elastic*** shell of the Earth; it appears to be quite solid, even when watched over very long times. The lithospheric plates, typically between $\boldsymbol{0km}$ and $\boldsymbol{\approx 100km}$ are rafted around on the surface by the convective engine.

    This layer is elastic even when viewed on time scales of 100s of millions of years; the underlying ***asthenosphere*** is ***plastic*** on time scales as short as years.

- ***Asthenosphere:*** Viewed during long periods of time, this layer is the softest or most easily deformable and flowing region of the upper mantle. When viewed for very short periods of time, though, as with seismic waves, it appears to be extremely hard.
- ***Mesosphere:*** Below about $\mathbf{700}\boldsymbol{km}$, the mantle becomes much more viscous and less mobile – by a factor of about **100**.
- ***Core-mantle boundary zone:*** A mixed zone of varying thickness, $\mathbf{10-200}\boldsymbol{km}$ thick, lies at the base of the mantle. Rather than being a phase transition, this boundary may well be lithospheric materials that have been ***subducted*** to depth by convection – a ***subduction graveyard***. The much studied seismic $\boldsymbol{D''}$ layer that seems to correspond to these depths and possibly to such materials.

The ***rigid*** lithosphere is broken up into 11 major and several minor *plates*. They are all floating on the athensophere, driven into circulation by the convective heat engine.

8.4.2 Earthquakes, volcanoes and tectonics

Seismologists and volcanologists had long known that earthquakes and volcanoes seem to be assembled along lines around the world and especially rimming the Pacific Ocean, the so called "***Ring of Fire***". This ring characterizes boundaries between colliding and laterally sliding tectonic plates[237].

- **Plate margins**
  - ***Convergent margins:*** As the motions of the *tectonic plates* on the Earth's surface were initially being mapped in the 1960s, it became clear that this "Ring of Fire" followed zones where an oceanic plate was ***converging*** toward a continental plate and ***subducting***, or moving downwards under it.
    - Most of the largest earthquakes occur along the converging margins.
    - The west coast of British Columbia, Washington State and Oregon forms a ***subduction zone*** of convergence where the ***Juan de Fuca*** plate is being drawn down under the overlying ***North America*** plate on which the continent rides. Along this zone of convergence, on January 26, 1700, what might be the largest earthquake that we know of to have occurred on the Earth happened – the famous ***Cascadia megathrust event of 1700***[238] .

[237] Earthquake distribution: http://tasaclips.com/illustrations/Earthquake_Distribution.jpg http://esminfo.prenhall.com/science/geoanimations/animations/35_VolcanicAct.html

[238] http://www.earthquakescanada.nrcan.gc.ca/historic-historique/events/17000126-eng.php http://pubs.usgs.gov/gip/dynamic/magnetic.html

- * The volcanoes that ring the Pacific are mostly ones issuing ***andesitic*** magmas that form granitic (high silica) rocks characteristic of the continents. Eruptions are sometimes also explosive ashes and the mix of layers of andesitic magmas and ash layers form what are called ***stratovolcanoes***[239].

- ***Divergent margins, spreading ridges:*** The Atlantic Ocean was found to be opening as the Pacific Ocean was closing. The centre of spreading of the Atlantic Ocean – and there are also such spreading ridges in the Pacific and Indian Oceans and under some of the continents, too – formed a ridge called the ***Mid-Atlantic Ridge***. This ridge of relatively shallow ocean botton correlated with a line of volcanism and earthquake centres along the mid-zone of the Atlantic Ocean. Most spreading zones are found in the mid-oceans, though some, such as the ***East Africa Rise*** are spreading continents apart.
  * Earthquakes that occur along these spreading ridges tend to be smaller than those on convergent margins.
  * The volcanism of the ridges, that which is forming **Iceland**[240] at the moment for example, is of quite different character from that rimming the Pacific. The ridge volcanism is characterized by denser *basaltic* magmas which typically form the rock of the ocean basins.

- ***Transform margins:*** On a sphere, plates cannot simply spread apart on one boundary and come together on another. They have edges that somewhere must slip against each other.
  * The famous **San Andreas fault**[241] that runs northwest through California from the Gulf of California to Cape Mendocino is a ***dextral***[242] transform fault slipping laterally. Another such fault is the **Anatollian fault** that cuts across Northern Turkey[243].
  * What is probably the most famous earthquake to have occurred on Earth struck **San Francisco**[244] at 5:12 AM, April 18, 1906 as the San Andreas fault broke along a **900*km*** line from central California to Cape Mendocino.
  * Along the Anatollian fault through northern Turkey, a series of large earthquakes occurred, migrating from the far east in 1939 and culminating with one near Istanbul in 1944. Another similar series might

[239] Stratovolcano pictures
[240] Iceland sits on the mid-Atlantic ridge
[241] San Andreas fault – risk!
[242] As one looks across the fault, one sees a motion towards the “right”. A ***sinistral*** fault shows the reverse motion.
[243] Anatollian fault system
[244] Link to story of 1906 earthquake: http://earthquake.usgs.gov/regional/nca/1906/18april/index.php

have started in 1999.

    * Volcanoes such as Mt. Ararat in Turkey and the Mono Lake complex in California are associated with these transform fault zones.

- ***Hot spots:*** There are isolated volcanoes which are neither associated with ridges nor rims

    * ***Hawaìi.*** Hawaìi appears to be caused by a thin plume of mantle material rising from great depth and penetrating the surface of the Earth on Hawaìi's eastern side. That the Hawaìian Island chain continues northwestward from this plume and the rocks of the chain age towards the northwest indicate that the plume had penetrated through the surface to form the more northwestern islands of the chain in the past[245].
    * As the Pacific Plate moves over the hot-spot plume, fixed to depth in the mantle, the plume has periodically penetrated the surface forming volcanic islands. The aging of the islands towards the northwest can be explained. The northwestern islands were over the plume which is now erupting the large island of Hawaìi millions of years ago and they have since been carried off, floating on the Pacific Plate which is converging on Japan and the Kamchatka Penninsula of Russia.

All of these motions suggest that the underlying mantle is convecting. There is much debate over the scale-depth of convection of the Earth's mantle. More than just density variation due to temperature and pressure effects, there is a now well-understood variation of density within the mantle due to variations in the geochemisty and mineralogy of the mantle with depth. It may be that the mantle overturns as a whole. If this were to be the case and if **200** million years for a $\mathbf{5000}\,\boldsymbol{km}$ separation across the Atlantic has been required, this speed might be characteristic of the circulation. If a convective cell has a scale from the Mid-Atlantic Ridge to the centre of the North American continent, a distance of about $\mathbf{9000}\,\boldsymbol{km}$, and if it cycled through to the base of the mantle, it would have to circulate for about **800** million years to complete one full convective cycle.

The power driving the convective heat engine of Earth derives largely from the heat of fusion given up at the inner-core-outer-core boundary as the inner core freezes. In carrying this heat towards the surface, the mantle is forced into convective circulation. This circulation pushes the floating lithospheric plates across the Earth's surface.

[245] http://pubs.usgs.gov/publications/text/hotspots.html

8.4.3 Earthquakes, volcanoes and tectonics on other planets and moons

"***Quakes***" and volcanoes evidence tectonic activity. Seismometers, instruments designed to detect earthquakes, have been landed on Venus, Earth's Moon and Mars. The Russian Venera missions landed such instruments on Venus but in the short window of observation before the landers ceased their function due to the high temperature of Venus' surface, no "***venusquakes***" were observed. The Apollo missions to the Moon placed instruments on the surface which continued operation for many years. "***Moonquakes***" were observed due to shallow, near-surface, fractures that are thought to be due to residual stresses being relieved through faulting and also at depth, thought to be due to the monthly cycle of tidal stressing as the Moon's orbit about the Earth varies in distance. The moonquakes have been extensively studied in an effort to determine the internal mechanical structure of the Moon. The Viking landers of 1976[246], landed seismometers on Mars. One small possible event that has been interpreted as a possible "***marsquake***" was recorded. It is thought to have been caused by a fracture due to long-standing stresses in the crust of Mars, or, alternately to a landslide. While lunar seismic activity is well established, we have no evidence of quakes on Venus and only very equivocal evidence of any quakes on Mars. The lunar seismic activity does not suggest a classical tectonics on the body; there is no supporting seismic evidence of active tectonic processes on Mars.

Active volcanism is another measure of tectonic or geological activity on a planet or moon. Volcanic histories are clearly seen in the surface images of all the terrestrial planets and several of the moons of the Solar System (eg. Earth's Moon, Jupiter's moons **Io**, **Ganymede**, **Europa** and **Callisto**, Neptune's moon, **Triton** and possibly on Saturn's moon, **Titan**). Volcanic activity has only been *observed* on Earth, Io, Europa and Triton. Io is the most volcanically active body so-far discovered in our Solar System. Europa's surface of rafting water ice shows a plate-tectonic style of thousands of moving plates.

8.5 Measuring mantle circulation

In the early 1960s, geophysicists such as J.T. Wilson[247] had been brought to accept the fact of relative motions of the continents upon learning of the work of **Ted Irving**[248] of the Earth Physics Branch of the Geological Survey of Canada on paleomagnetic pole positions and then by that of **L. Morley** and **A. Larochelle** who, in 1962, recognized that a pattern of magnetic striping on the ocean floor southwest

[246] A summary of the Viking mission science: http://nssdc.gsfc.nasa.gov/planetary/viking.html
[247] http://pubs.usgs.gov/publications/text/Wilson.html
[248] http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=548532

of British Columbia showed a symmetry across the ridge between the Juan de Fuca and Explorer Plates. In 1963, **F. Vine** and **D. Matthews** published their landmark paper in ***Nature*** magazine re-iterating the Larochelle-Morley findings for "***Magnetic anomalies over ocean ridges***[249]". This provided the proof that convinced geophysicists that the Atlantic Ocean was spreading apart along the Mid-Atlantic Ridge.

8.5.1 Heat flow

The elastic lithosphere rides over the mobile, fluid asthenosphere. There is essentially no change of mineralogy from the base of the lithosphere into the upper asthenosphere. What distinguishes the layers is a temperature at which the viscosity of the mantle changes quite abruptly. The lithosphere appears elastic while the asthenosphere, liquid, when viewed with long tectonic time scales. The elastic properties, as seen by seismology, change very little and so their is no significant seismic discontinuity that can be mapped. The base of the elastic lithosphere is, therefore, determined indirectly according to data based upon heatflow from the Earth's interior and plate distortions caused by loads supported by the lithosphere.

- Under continents, the lithosphere is thick ($\boldsymbol{> 100km}$). Heatflow through the cores of continents is lessened by the thickness of this insulating layer.

  Heat flow is typically less than $\boldsymbol{50\,mW \cdot m^{-2}}$).

- Through the thinner lithosphere ($\boldsymbol{\approx 50km}$), average, underlying the ocean basins, heat flows more easily to the surface.

  Heat flow is typically about $\boldsymbol{100\,mW \cdot m^{-2}}$ in the deep basins.

The rate of heat flow can be used in determination of lithospheric thickness.

8.5.2 Loads on the lithosphere

When a line-load (a long line of mass) lies on the elastic lithosphere, the load depresses the lithosphere directly under the line load but allows it to bulge upwards at some distance lateral from the line load.

- ***Hawaíian Island chain*** The Hawaìian Islands offer a natural line load on the Pacific Plate. Analysis of the ocean floor's depression under the line load and its upward bulge at distances normal to the line load suggest that an elastic plate of about $\boldsymbol{60 - 90\,km}$ thickness floating on a low viscosity ($\boldsymbol{\eta = 10^{21} Pa \cdot s}$) athenosphere.

[249] Magnetic striping over Juan de Fuca Ridge: http://pubs.usgs.gov/publications/text/magnetic.html

8.5.3 Paleomagnetic evidence for plate motions

The Earth's magnetic field looks like one produced by an enormously strong (i.e. with large ***dipolar magnetic moment***) permanent magnet buried at great depth.

- On the surface of the Earth, the ***north-seeking pole: N*** of a compass needle tends to point geographically northwards. Actually, it is pointing along a direction towards the ***North Geomagnetic Pole*** which is now in the northern Arctic Islands of Canada.

- Note that the "***N***" pole of the compass needle is attracted towards a magnetic "***S***" pole. The North Geomagnetic Pole is an "S" pole, a ***south-seeking pole: S***.

- The compass needle really only shows us one component of the direction of the magnetic field. The closer we are to the geomagnetic pole, the more steeply the magnetic field vector is inclined.

  At Montreal, the magnetic field points about **8°** W-of-N geographical (its ***declination***) and is inclined steeply downwards from the horizontal by **71°** (its ***inclination***).

The Earth's ***geomagnetic field*** is generated by a ***magneto-hydrodynamic-dynamo*** called the *geodynamo*[250]. While magnetic poles are almost always nearly aligned with the rotation axis, their polarity changes irregularly. The last ***reversal*** [251] of the magnetic poles occurred about 730 000 years ago and the next-to-last about 900 000 years ago.

Magnetization of rocks:

When a hot rock cools through the ***Curie temperature*** of its comprising minerals, whatever natural magnetic field exists at that time and place is "frozen into the rock". They take on the magnetic field direction which holds at their time of freezing. When they cool to crystallize minerals, they establish their ***age***. We can, therefore determine a time and a direction of magnetization at rock cooling.

When sedimentary rocks assemble at water bottom, small grains of the mineral ***magnetite*** assemble into the rock. The grains of magnetite *tend* to align with the magnetic field as they assemble. Thus, sedimentary rocks can also show the direction of magnetization at the time of their sedimentation on the ocean or lake floor.

The polar orientation of the field is frozen into rocks as they cool or sediment.

[250] The core field: http://www.lbl.gov/Science-Articles/Archive/assets/images/2003/May-09-2003/Glatzmaier_field._small.jpg
[251] About reversals

- ***Polar wander:*** If we can map the direction towards the north geomagnetic pole in rocks as a function of age we can determine how the magnetic pole has *apparently* wandered over time.

  – The apparently different wander of the geomagnetic pole as seen in North American rocks during the past 550 million years as compared to those seen in Europe can be brought to show the same apparent wander path if Europe and North America were brought back together about 200 million years ago and then were separated at a relatively uniform rate since that time.

    Polar wander offered the first geophysical evidence for the relative separation of Europe and North America and the spreading open of the Atlantic Ocean.

- ***Magnetic "striping" of the ocean basins:*** When rocks issue from the interior of the Earth and solidify along the ocean ridge axes, they quickly cool and take on (freeze in) the momentary direction and intensity of the Earth's geomagnetic field.

  – As the ocean opens, the ridge spreads, more magma is brought to the surface along the ridge axis and freezes capturing the field's orientation [252] .

    For the past 730 000 years, rocks have frozen in a record of ***normal polarity*** with a compass needle's N-pole pointing, generally, nortwards.. For a period of 170 000 years previously, they froze in a record of ***reverse polarity***, one for which a north-seeking magnetic pole is found in the northern hemisphere.

  – The ancient paleomagnetic polarity record has been assembled back for 100s of millions of years by radio-dating layers of lava flows.

  – When we accord the distance from the spreading ridge of a reversal (of known time in the past) with its time, we determine an average spreading rate during that time.

  – We find that the spreading rates across the North Atlantic have been very regular at about $\mathbf{2.8}\,\boldsymbol{cm/yr}$ for the past several 10s of millions of years. The South Atlantic is spreading more rapidly, now, at about $\mathbf{4.0}\,\boldsymbol{cm/yr}$. Certain regions of the East-Pacific Rise west of Chile are spreading extremely rapidly at $\mathbf{18.3}\,\boldsymbol{cm/yr}$.

[252] Magnetic striping of ocean floor: http://pubs.usgs.gov/publications/text/stripes.html

8.5.4 Motion of plates over "*plumes*": "*Hotspot* volcanism"

At several places on the Earth, the lithosphere seems to be penetrated at hotspots[253] where magma issues to the surface from somewhere deep within the mantle. The hotspots are seemingly position fixed to the deep mantle. Where a plume penetrates the lithosphere, its magma forms great ***shield volcanoes*** such as that of ***Mauna Loa***[254] on the great island of Hawaìi. Similar shield volcanoes have been recognized on Venus[255], Mars[256] and on Jupiter's moon Io. The Hawaìian chain of islands is remnant of a long history of such volcanism occuring at one mantle fixed place as the Pacific Plate upon which the Hawaìian Islands rides was being carried northwestward. By dating the volcanism using the radioactivity clock or by paleomagnetism, it is found that the islands age towards the northwest. They age at a rate which suggest a nortwestward velocity of Hawaìi relative to the plume of about $9\,\boldsymbol{cm/yr}$. This accords nicely with the spreading rates across the Pacific Ocean from California to Japan and the Kamchatka Penninsula of Russia.

8.5.5 Age and depth of the ocean floor

By dating the rocks of the deep ocean floor using radiodecay clocks, we find that the ocean basins are, as expected, oldest when farthest from their generating ridge axis. In the deep abyssal plains of the North Atlantic offshore from Georgia, rock ages are about 180 million years. Symmetrically on the other side of the Atlantic off West Africa, ages are about the same. 180 million years ago, both of these places were sitting on the then very young Mid-Atlantic Ridge.

- ***Ocean depths:*** The deepest parts of the ocean basins are the oldest!
  - As the oceanic lithosphere ages and cools, it freezes ever thicker; the frozen lithosphere is denser than the magma and so it "floats" deeper in accord with isostatic adjustment.
  - Geophysical analysis of the freezing of the lithosphere shows that the ocean basins should deepen as

    $$\mathbf{depth} \propto \sqrt{\boldsymbol{age}};$$

    where $\boldsymbol{age} = \boldsymbol{distance\,from\,ridge/spreading\,rate}$.

    Actually, after about 100 million years, the ocean basins flatten out as the lithospheric freezing depth stabilizes under effect of other geophysical and tectonic processes.

253 Volcanoes of Hawaii: http://www.volcanolive.com/hawaii.html
254 Mauna Loa: http://www.volcanolive.com/maunaloa.html
255 Maat Mons Sif Mons
256 Olympus Mons

When measuring the age of the deep ocean basins, we come to a remarkable fact. Nowhere is there ocean basin older than 220 million years[257], that being the age of a region of the west Pacific Basin off Kamchatka Penninsula. The ocean basins subduct into the mantle at convergence.

8.5.6 Other measures of plate motions

Accurate geometric surveying over time can establish spreading and convergence rates. Several of these ***geodetic*** methods have been applied to the problem.

- ***Radio-interferometry:*** Starting in the 1970s, it was found that by looking at the most distant objects, the ***quasars***, known in the Universe with radio telescopes which are sitting on different tectonic plates, the baseline distance between the telescopes could be measured.

  We now measure to an accuracy of about $\pm 1\ cm$ over intercontinental distances.

- ***GPS:*** In the late 1970s, at the height of the *"Cold War"*, the United States, the Soviet Union and some European countries launched a series of satellites carrying extremely precise atomic clocks which allowed for precise geographical positioning or navigation for their navies. These ***Geographical Positioning Systems***, GPS, were immediately used by all kinds of scientists and laymen to determine their position with accuracy – and also to synchronize clocks – on the surface.

  With the best systems, $100\ km$ baselines can be measured to within $\pm 1\ cm$.

8.5.7 Continents and ocean basins

We have, so far, concentrated our interest on what happens at the spreading ridges, the divergent margins of the plates, and have tentatively avoided the geophysics and geology of the convergent and transform margins. In taking up the spreading from the ridges, the plates must somewhere come into collision and overlap for the Earth is not growning in size. Whereas the oceanic plates, floating deeply under their isostatic balance and leaving room for the waters of the ocean, are everywhere geologically "young", the continents are generally very old. The central cratons of the continents around which they coalesced billions of years ago have probably floated on the surface of the Earth, never having been recycled into the interior of the Earth, for the past 4 billion years. We know that there are zircons found in Australian sediments of 4.2 billion years of age. We know that there are rock masses in northern Canada and Greenland which show an age of 3.95 billion years. We are discovering evidence of life

[257] Map of the age of the ocean floor: http://www.ngdc.noaa.gov/mgg/image/crustageposter.gif

in rocks in Greenland from 3.85 billion years ago. Neither the minerals and rocks nor the life could have existed in these rocks if they were at those times at depths of more than about 50 ***km*** below the present surface for they would have been heated to reset the clocks and to kill the life. It is surely surprising that life seems to have found foothold on the Earth within 100 million years of there being a rock for foothold. The continentents, formed of light granitic materials, have been floating on the surface for eons.

The young ocean plates collide with the continents as the continents float out across the surface. Where these plates collide, the oceanic plate is driven down – or is pulled down under its own weight – into the mantle. The ocean basins are being continuously recycled through the Earth's interior.

8.5.8 Earthquakes and Seismotectonics

Very deep earthquakes occur at many places on Earth. Commonly they follow a trend to depth which makes an angle of about 45^{o} with the surface. These zones of deep-trending earthquakes were first recognized in the 1930s by **Hugo Benioff**, a famous seismologist, and are so called ***Benioff zones***. Plate tectonics, the science of the deformation and motion of Earth's surface plates, explains the phenomenon: *subduction*.

Earthquakes on subduction zones

Earthquakes in Benioff zones occur within a subducting (i.e. sinking or underthrusting) lithospheric plate.

- One such area where very deep-focus (the ***focus*** is the central point from which an earthquake starts faulting) earthquakes lies just to the west of the Tonga trench and beneath the Pacific island of Tonga.

  Along the Tonga trench, the Pacific Plate, moving generally westwards converges upon the Australian-Indian Plate upon which the continent of Australia floats.

  - The convergence rate is about ***8cm/yr.***
  - The underthrusting Pacific Plate is sinking at an angle of about **45°**.
  - A deep ***trench*** forms at the line of contact along the ocean bottom between the plates, here about ***7km*** deep.
  - Along this **45°** contact surface, very large earthquakes occur as the plates stick, then slip at irregular intervals of time.

- Another interesting Benioff zone occurs on the west coast of South America, under Peru, Bolivia and Chile. There, the **Nazca Plate** which is spreading away from the East Pacific Rise (a ridge) about 4000$\boldsymbol{km}$ to the west is subducting under the **South American Plate**.

- Along this convergent margin, the largest earthquake, in terms of its ***magnitude*** ever instrumentally recorded on Earth occurred along this convergent margin in 1960: $\mathbf{M_s \sim 9.5}$.

  Tidal waves (***Tsunami***[258]) spread away from that earthquake travelled across the Pacific to Japan, reflected from the Asian coastline and then travelled back across the Pacific again to South and North America.

The **Tonga Trench** defines a subduction zone where an ocean plate subducts beneath another oceanic plate. The westcoastal zone of South America defines a subduction zone where an ocean plate subducts beneath a continental one.

- ***The Cascadia Subduction Zone*** defines a convergent margin which extends along the offshore west coast from central Vancouver Island to about mid-Oregon. An earthquake which probably there faulted on January 26, 1700 at about 9:00AM may be the largest event known to have ever occured on Earth.
  - It is known to have occured there and then because the tidal wave, the tsunami, generated was observed in Japan just 6 hours later and the direction from which the tsunami arrived can be "back-continued" to a source off the west coast of BC, Washington and Oregon.
  - By some estimates, this event, sometimes called the ***great mega-thrust earthquake of 1700***[259], may have had a magnitude approaching $\mathbf{M_s \sim 10}$. Much evidence of the local effects of this event and similar ones which occurred earlier in prehistory has been collected by ***paleoseismologists***. The record they have now assembled suggests that such events have occured irregularly in the past with intervals of somewhere between 300 and 800 years. A similar event could happen any day.

Volcanism on subduction zones

As, the subduction zones are characterized by frequent and very large earthquakes, they are also characterized by volcanism. In a downdip direction along the subducting plate, light continental granitic materials which have slowly sedimented over eons on the ocean floor and which are carried down with the subducting plate to depth, eventually melt and break their way back to the surface causing volcanos.

[258] Tsunami travel across the deep oceans at a speed determined by a simple formula: $\mathbf{speed} = \sqrt{\boldsymbol{g \cdot d}}$ where $\boldsymbol{g} = \mathbf{9.8}\,\boldsymbol{m \cdot s^{-2}}$ is the gravitational acceleration on the Earth's surface. Across the deep ocean, $\boldsymbol{d} \approx \mathbf{5000}\,\boldsymbol{m}$, allowing a speed of about 790$\boldsymbol{km/hr}$.
Cascadia event tsunami model
Explanation of the Cascadia induced tsunami

[259] Giant megathrust earthquakes: Cascadia

- Tonga Island is formed of such volcanism.
- Such volcanos are generally not characterized by dense basaltic rock as are the Hawaìian shield volcanos and the volcanos of Iceland, but by granitic (andesitic and ***rhyolitic***) rocks – low density continental materials.
- The great volcanos of the west coast, Garibaldi, Mt. Baker, Mt. Ranier, Mt. St. Helens, Mt. Hood, Mt. Shasta and Lassen Peak are all such volcanos. They form a line about 300***km*** eastward from the convergence of the Explorer Plate with the North American Plate, the convergence being about 100***km*** offshore.
- Japan, Taiwan, Borneo, the Indonesian Islands are all Island Arcs volcanically formed near or along convergent margins.

Wherever you find volcanos issuing andesitic or rhyolytic rock and wherever you find earthquakes aligning along Benioff zones, we have convergent margins.

Earthquakes at continent-continent collisions

Earthquakes occur at zones of continent-continent convergence.

- About 70 million years ago the Indian subcontinent being rafted northwards on an oceanic plate that was subducting under the Eurasian plate collided with Asia.
  - The low density continental material of the Indian subcontinent could not be brought to sink into the mantle because it is so light and bouyant.
  - the Indian subcontinent plowed into the Asian and pushed up the Himalayan mountains and plateau. This is the highest elevation region on Earth. The roots of the Himalayas are among the deepest floating on Earth.
  - The motion of India northwards is still going on with convergence rates of about 5***cm/yr***; the Himalayas are still being pushed up and eroded down by the work of water and ice and such will probably continue for another 100 million years before India comes to a stop cemented onto southern Asia.
  - Large earthquakes occur, typically in the Indian subcontinent, as a consequence of this collision; recall the **Gujarat earthquake** of January 26, 2001[260].
- Western Iran is another region of continental-continental collision along the east coast of the Persian Gulf. Arabia is splitting off from Africa, along a ridge that

[260] Gujarat, January 26, 2001: http://cires.colorado.edu/ bilham/Gujarat2001.html

falls along the Red Sea. This spreading axis continues southward splitting into two other spreading ridges, one tending eastward just south of Yemen and the other passing through Djibouti and down through the Great Lakes region of East Africa. This ***rift zone*** is called the East African Rift Valley. Wherever mountains are being lifted, the Pyrenees, the Alps, the Anatolian, the Rockies, there are tectonic forces driven by the great heat engine of convection lifting them.

Earthquakes on Transform margins

While it might not be clear, when plates move in relatively straight-line directions over the surface of a spherical Earth, it is necessary that a style of faulting normal to the spreading axis of the ridges occurs. These are the ***transform faults***. Such faults often arise along long convergence margins.

- From offshore central Mexico, near Acapulco, through the Gulf of California, through California, through the penninsula upon which the city of San Francisco is established to Cape Mendicino near Eureka, a famous and highly active transform margin is known as the *San Andreas Fault*.
- Another, just as active and just as famous called the *Anatolian Fault* cuts across northern Turkey and right through Istanbul.
  - These are long fault lines of great shallow earthquake activity.
  - The 1906 Great San Francisco Earthquake[261] and the several great earthquakes along the Anatolian Fault[262] in the 1920s and 1930s are caused by the rapid release of strain built up over decades on the stuck faults. The faults irregularly release the strain and move one side to another by several metres all at once.
  - The San Andreas Fault has been stuck in the region near and north of San Francisco for almost 100 years. During that 100 years, the general motion of the Pacific Plate northwestward relative to the North American plate averaged about $4\boldsymbol{cm/yr}$. A deficit of motion in the San Francisco area of about $4\boldsymbol{m}$ has built up into strain along the fault. It will break again... and the Antolian fault will break again near Istanbul with a motion of 4 or $5\boldsymbol{m}$ within the next decades. These breakages will cause great earthquakes, probably of $\mathbf{M_s \sim 7 - 8}$.

[261] San Francisco – 1906: Brief story
[262] Anatolian events 1939-99 Izmit event of 1999

9 Seismology and the internal structure of Earth and planets

Except for the very deepest of deep-focus events, earthquakes are caused by a fracturing or faulting of the elastic rock of the lithosphere. It may be that some very deep earthquakes are caused by extremely rapid mineralogical changes of phase; that is, they may be caused by a near-instant, pressure-driven phase change of olivine mineral into a more compact polymorph, spinel, over a large volume within a subducting plate.

- ***Focus:*** The point at which an earthquake starts to fracture or at which mineralogical phase begins to change is called the *focus*.
- ***Epicentre:*** The place on the surface directly above the focus is called the earthquake's *epicentre*.
- ***Fault plane:*** The surface over which the fracture occurs is called the *fault plane*.
- ***Seismic waves:*** By measuring the field of seismic waves that issue from an earthquake, seismologists can determine the plane of faulting, the amount and direction of slip along that fault plane and the amount of energy released in the event and so understand the mechanism and tectonic stresses involved in precipitating an earthquake.

9.1 Seismic waves

Much of our knowledge about Earth's deep interior has been obtained by studying the wavefields generated by earthquakes[263] as they travel out through the interior and across the surface. Several types of waves are excited by earthquakes. Seismic waves are detected by *seismographs*[264]; the records of earthquake waves are called *seismograms*. We use the travel times of seismic waves through the interior of the Earth to determine its internal structure[265].

- ***P-waves:***[266] Those waves which travel most rapidly from an earthquake source to a distant seismograph receiver are called *P-waves* or primary waves.

[263] Global distribution of earthquakes
Earthquakes: when? and where?: http://earthquake.usgs.gov/

[264] Current seismograms: http://quake.geo.berkeley.edu/bdsn/quicklook.html
http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm#P_S_R_L_Animations

[265] IRIS (Incorporated Research Institutions for Seismology) – animated descriptions

[266] P-wave animation

The seismograph is an instrument which is extremely sensitive to low frequency vibration of the ground.

- P-waves are actually sound waves which travel through the body of the Earth (and are so called ***body waves***) with a velocity which is determined according to a well known relationship,

$$\boldsymbol{\alpha = \sqrt{\frac{k + 4/3\mu}{\rho}}}$$

  where $\boldsymbol{k}$ is the bulk modulus of incompressibility of the rock, $\boldsymbol{\mu}$, its modulus of rigidity and $\boldsymbol{\rho}$ its density.

  * The bulk modulus of incompressibility is a measure of a material's resistance to compression under pressure. Gases have low resistance to compression and fluids and solids, generally, high resistance.
  * The ***modulus of rigidity*** is determined by a material's resistance to shearing. Gases and liquids have a strictly zero modulus of rigidity; i.e. $\boldsymbol{\mu_{liquid} = \mu_{gas} = 0.}$ Solid rock can present a very high modulus of rigidity. The P-wave is equivalent to a simple simple ***sound wave*** in air.

• ***S-waves:***[267] A slower travelling body wave type is also generated by earthquakes. It follows the P-wave along a path through the interior of the Earth. This *S-wave* or secondary wave carries a motion which is oscillatory normal (at $\boldsymbol{90°}$) to the direction of travel. It is a ***shear wave***.

- It's velocity, too, is determined by a simple form,

$$\boldsymbol{\beta = \sqrt{\frac{\mu}{\rho}}.}$$

  * Clearly, for fluids (i.e., liquids and gases) for which $\boldsymbol{\mu = 0}$, the S-wave velocity is $\boldsymbol{0}$ which really means that the wavetype cannot pass through such materials at all. S-waves do not travel through liquids!
  * This fact led seismologists before 1920 to the very important discovery that Earth's outer core is liquid. In 1930, **Mme. Inge Lehmann**, a Danish seismologist discovered, though, that deep within the fluid core, there was a zone in which such wavetypes again existed. This proved that the inner core of Earth is solid.

Using these *body waves* and by measuring their travel times from distant earthquakes to recording seismographs, one can obtain a measure of the average velocity along the path taken by the waves.

[267] S-wave animation

An analysis of long accumulated set of such data, typcially assembled into *travel-time* graphs[268] allowed seismologists to determine the variation in seismic P-wave and S-wave velocities with depth in the Earth. The body waves that travel from an earthquake to a very nearby seismograph don't travel very deeply into the Earth. Waves that travel through the interior of the Earth to greater distance travel deeper and so sample the velocities of material at greater depth within the Earth. By inverting such accumulations of data from hundreds of thousands of pairs of earthquake sources and ***seismograph*** receivers, seismologists had obtained a pretty good "image" of the elastic properties of the interior of the Earth by about 1935.

- ***Surface waves:*** Earthquakes also produce disturbances on the surface which cause waves to travel out over the surface of the Earth.
  - ***Rayleigh waves:***[269] These waves, named in honour of John William Strutt, Lord Rayleigh who in 1885 obtained a mathematical/physical description for them, travel out over the surface like ripples travel across the surface of water. But, because elastic forces rather than gravity forces dominate in the "springing" of the Rayleigh wave, its ripple motion is a little different from that of water ripples which are sometimes called gravity waves.
    - What forces a water gravity wave to oscillate is its disequilibrium with the flat surface of equilibrium. The crests of the wave are being pulled down to this surface while the troughs are being pushed up by slight differential pressure.
    - For Rayleigh waves travelling across solid surfaces, gravity forces do come into play but it is the elastic forces which dominate, especially the solid's property of rigidity. The wave represents an elastic distortion of the surface which is restored by the elastic strengths of the material.
    - Rayleigh wave velocities are typically about the same as the average S-wave velocity throughout the crust.

    About motion on the surface

    - ***Gravity waves on water:*** The overall result is that the motions of the surface in a water wave are in the forward direction of travel of the wave at crest and in the reverse direction in troughs.
    - ***Rayleigh waves:*** Just the opposite is the case for Rayleigh waves: the surface of the crests is actually moving backwards as the wave moves under it and the surface of the troughs moves forward. While this is difficult to notice by eye or by sensation during an earthquake,

[268] Explanation of travel-time graphs Earthquake-to-seismograph travel times
[269] Rayleigh wave animation

it is an effect well measured by seismographs, the instruments which measure the motions of the surface of the ground caused by earthquakes.

Next time you are sitting by the sea watching water waves, carefully note the motion of some small piece of flotsam in the water. Notice that when it is lifted by a wave passing across the water, it moves forward with the wave at crest and then when it drops into a trough, it moves backwards. If you could sit and watch Rayleigh waves travel across the ground surface, you would see just the reverse effect.

Rayleigh wave are the dominant surface wavetype which brings the surface to have an up-and-down oscillation. As noted above, they also produce an oscillation in the horizontal direction along the direction of wave travel over the surface.

– ***Love waves:***[270] These waves, named after A.E.H. Love who first obtained a mathematical/physical description of them in 1911, produce often-strong horizontal motions of the surface.

  * The horizontal motions are mostly in a sense normal (i.e. to right and left) of the direction of travel of the wave.
  * Love waves are really S-waves which have become trapped or "guided" by the layered structure of the Earth near the surface.
  * Love wave velocities are typically somewhat faster than Rayleigh wave velocities.

Surface waves, particularly the Rayleigh waves, are scaled in their amplitudes according to the size or strength of an earthquake. You know that by throwing a large rock into water one generates a higher amplitude wavefield emanating from the splash than if you were to throw in a small pebble. A large earthquake typically causes larger amplitude Rayleigh waves than does a small earthquake. Still, earthquakes are more complex than simple splashes. They may occur at great depth and when they do, they disturb the surface less than they would if they had occurred right near the surface. So the ripples that travel out from an earthquake depend not only on the size of the earthquake but also on its depth.

– When one observes water waves travelling out from a splash in a quiet pond, one see that the wave amplitude decreases with distance from the splash. Energy from the wave is slowly absorbed into the water, the wave-train disperses and becomes broader and broader with time and distance, but the dominant effect is that of the ever greater wavefront circumference.

[270] Love wave animation

- The wave spreading its energy over an ever-increasing circular wavefront causes the amplitude to decrease with a $\boldsymbol{1/r}$ dependence; $\boldsymbol{r}$ is the distance from the source splash, dependence.
- If we were to try to guess the size of the rock which caused the splash by observing the wave height as it passed by us at distance, we would have to know how far away the spash occured (cf. earthquake epicentre) to correct for the $\boldsymbol{1/r}$ fall-off of amplitude with distance from source.

9.2 Magnitude scales for earthquakes

From what we have learned of surface waves, we can construct something of a scale for determining the size of their causing splash or earthquake. The size relates directly to the amplitude of the wave, inversely to the distance from the source to the point of observation and somehow it is lessened in amplitude for an earthquake source which is deep.

- ***The "Richter Scale":*** In the 1930s, Richter studied earthquakes in California and developed for their size classification his famous *Richter Scale* of earthquake magnitudes.

  Generalized for use worldwide, the scale is now computed according to a formula:
  $$\mathbf{M_s} = \mathbf{log_{10}} \frac{\boldsymbol{A}}{\boldsymbol{T}} + \boldsymbol{f_{correction}(\Delta, h)}$$
  where $\boldsymbol{A}$ is the amplitude of the largest Rayleigh wave motion measured in milli-microns $\boldsymbol{m\mu}$ or better, in nanometres $\boldsymbol{nm}$, $\boldsymbol{T}$ is the period of this largest amplitude Rayleigh wave (typically about 20 seconds).

  The correction function, usually obtained from tables based upon empirical data, takes care of the adjustment for distance measured in great-circle degrees, $\boldsymbol{\Delta}$, and also for the depth to focus or ***hypocentre*** of the event.

- Richter's scale is logarithmic, base-10. That means that for every increase in $\mathbf{M_s}$ by one point, the amplitude must increase by 10×.
  - The energy carried by a wave is proportional to $\boldsymbol{(A/T)^2}$ and so the surface wave energy generated by an earthquake is actually about 100× greater for an event of $\mathbf{M_s = 8}$, for example, than for one of $\mathbf{M_s = 7}$.
  - As earthquakes become larger, though, they spread their energy over and ever broader range of frequencies. The largest earthquakes can cause the Earth to ring like a bell with a gravest period of 54 minutes.

- As large earthquakes are relatively more efficient at generating long period surface waves than are small ones, the wavefield energy doesn't correspond in direct proportion to the energy released in the event.
- The source energy actually increases by $\boldsymbol{\approx 63\times}$ for each Richter magnitude step.
- An earthquake of Richter magnitude $\mathbf{M_s = 8.1}$ like the 1906 San Francisco event releases about $4000\times$ the energy of one of $\mathbf{M_s = 6.1}$ like the **1989 Chicoutimi earthquake** which is the largest to have occurred in Quebec in the past 25 years. That earthquake caused some damage here in Montreal.
- Seismologists now normally use a more physically-based scale called the *"moment magnitude scale"*, $\mathbf{M_w}$.

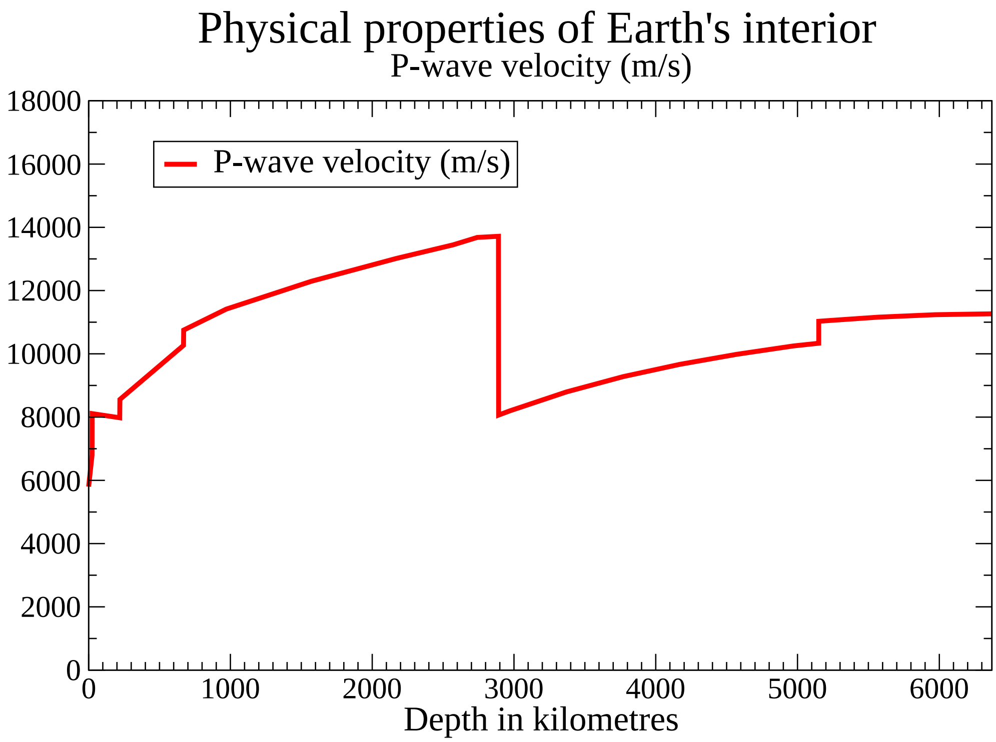
9.3 Elastic properties of Earth's interior

Having accumulated a century-long data set of the travel times from earthquake source to the recording seismograph for the four basic wavetypes described above, we can use these data to *invert* for the velocities as a function of place and depth within the Earth and from these velocities, determine the elastic properties as a function of place and depth.

Below we summarize what we know of the elastic properties of the interior as derived from that accumulated data set:

- P-wave velocity ($\boldsymbol{\alpha = \sqrt{(k + \frac{4}{3}\mu)/\rho}}$): The P-wave velocity generally increases with depth in the Earth.

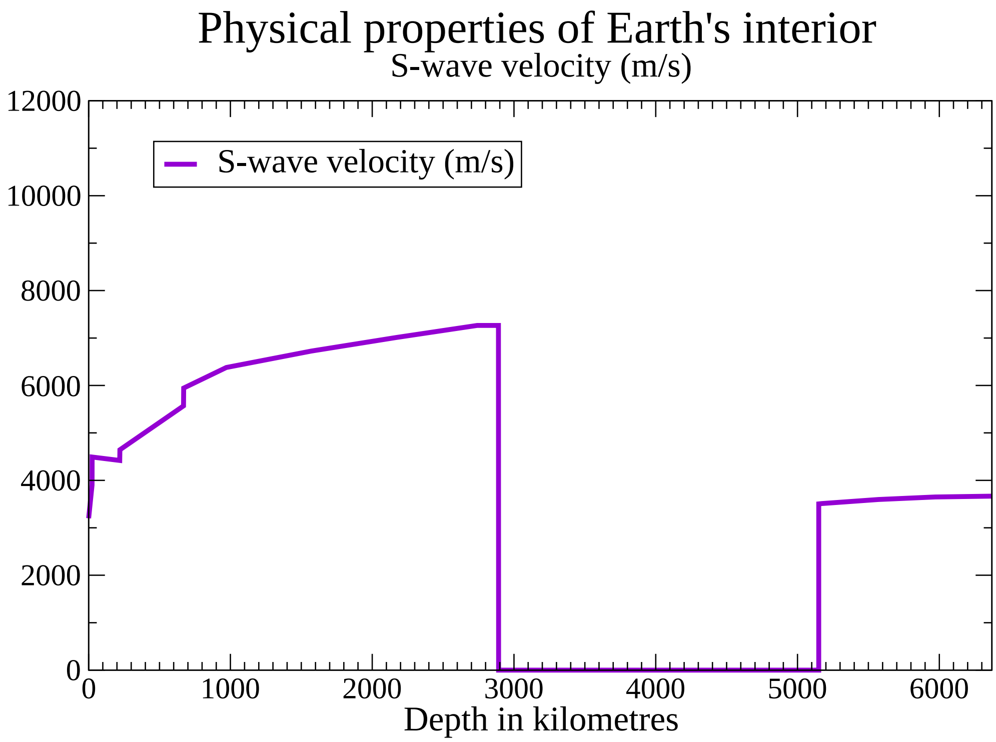
  - In more detail, it increases rapidly from a value of about $\boldsymbol{3 - 7km/s}$ in the crust (generally higher velocities deeper in the crust) to $\boldsymbol{9 - 10km/s}$ in the asthenophere.
  - Below a depth of about $\boldsymbol{670km}$, the phase change from *spinel* into *perovskite* and *periclase* brings the velocity up to about $\boldsymbol{11km/s}$ because these minerals are more "incompressible" and "rigid" than spinel.
  - It generally increases towards the base of the mantle at $\boldsymbol{2900km}$ depth to $\boldsymbol{13km/s}$ as the compressed materials of the mantle become increasingly rigid and incompressible.
  - Then, precipitously, at the core-mantle boundary, the velocity drops to only $\boldsymbol{8km/s}$ due to the outer core's non-rigidity. That is $\boldsymbol{\mu = 0}$ in the outer core.



– It continues again rising to about $\boldsymbol{10km/s}$ at the base of the outer core and then, because the solid inner core again contributes some rigidity, it jumps to about $\boldsymbol{11km/s}$.

- S-wave velocity ($\boldsymbol{\beta = \sqrt{\mu/\rho}}$): S-wave velocities are perhaps more interesting as they depend only upon the rigidity, $\boldsymbol{\mu}$, and density, $\boldsymbol{\rho}$ of the medium through which they travel. For a fluid, $\boldsymbol{\mu = 0}$.

  – Rising from about $\boldsymbol{2 - 4km/s}$ in the crust to $\boldsymbol{5 - 6km/s}$ through the asthenosphere, we note that *at seismic wave frequencies*, the asthenosphere is much more rigid (by a factor of about 10) than are the crustal rocks! At the period of seismic waves, the asthenosphere is seen to be very "hard".
  – Recall that at periods of tectonic processes (100s to millions of years), the asthenosphere is "fluid" with $\boldsymbol{\mu \approx 0}$.
  – Below the 670km discontinuity, the S-wave velocity rises to about $\boldsymbol{7km/s}$ at the base of the mantle.
  – In the outer core, it precipitously falls to $\boldsymbol{\beta = 0}$. Recalling that $\boldsymbol{\beta = \sqrt{\mu/\rho}}$, the reason must be that $\boldsymbol{\mu = 0}$.



– The work of Inge Lehmann in the 1930s showed that there were S-waves travelling through a deep part of the core. That there are S-waves means that this region has rigidity and is, therefore, not liquid, but solid. Madame Lehmann discovered the Earth's solid inner core.

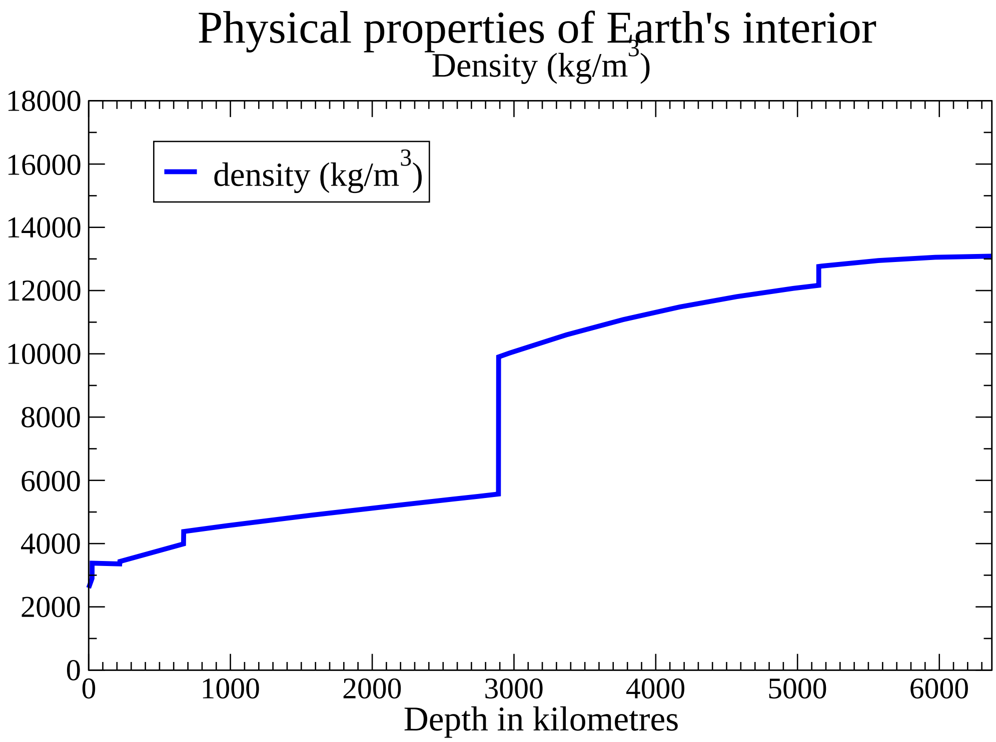
– Some researchers believe that they have discovered something of an "inner-inner core" though for the moment, most seismologists discount this claim.

• Density (ρ): While seismology by itself does not determine density, seismology with a knowledge of the Earth's moment of inertia does. Both P-waves and S-waves show velocities which are inversely proportional to the square-root of local material density.

– Density is found to increase from about $\mathbf{3600}\,\boldsymbol{kg \cdot m^{-3}}$ at the base of the crust smoothly to about $\mathbf{5800}\,\boldsymbol{kg \cdot m^{-3}}$ at the base of the mantle at a depth of $\mathbf{2900}\,\boldsymbol{km}$.

– At the core-mantle boundary, it jumps discontinuously as we move into the metallic iron core to about $\mathbf{10\,500}\,\boldsymbol{kg \cdot m^{-3}}$.

– The liquid core must be in a state of very rapid convection and so one expects its temperature profile to hold near the adiabatic. The density

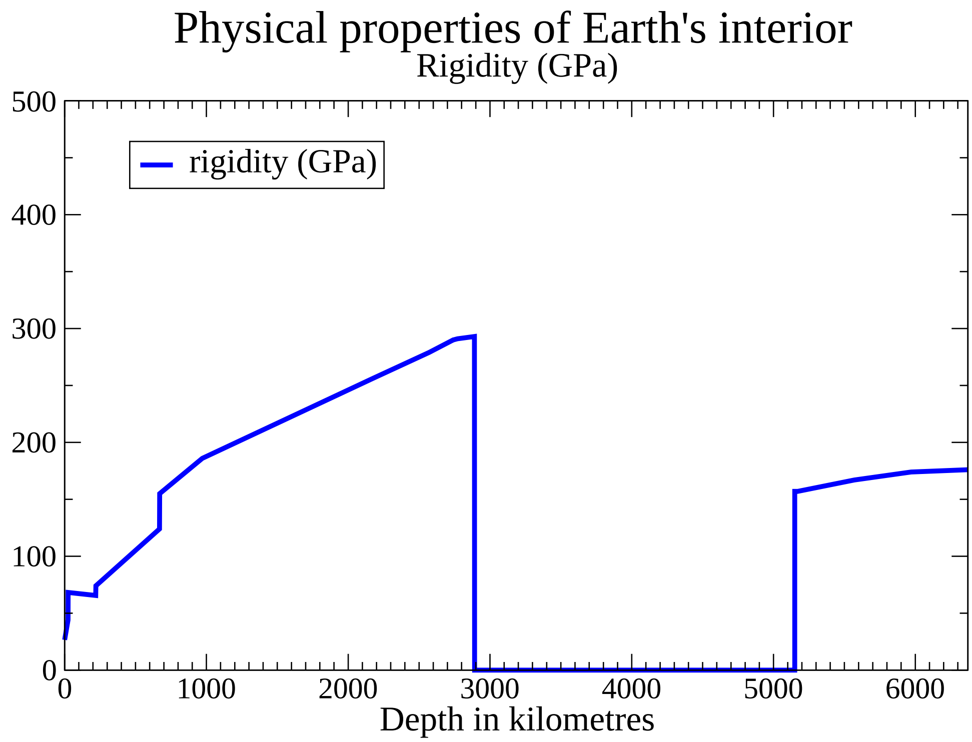


increases with pressure and inversely with temperature, smoothly to about $\mathbf{12\,500}\, \boldsymbol{kg \cdot m^{-3}}$ at the surface of the solid inner core.

– The density jump across the this boundary is not well established but most estimates suggest that at the outer boundary of the inner core, the density is $> \mathbf{13\,000}\, \boldsymbol{kg \cdot m^{-3}}$ rising to about $> \mathbf{13\,500}\, \boldsymbol{kg \cdot m^{-3}}$ at the Earth's centre.

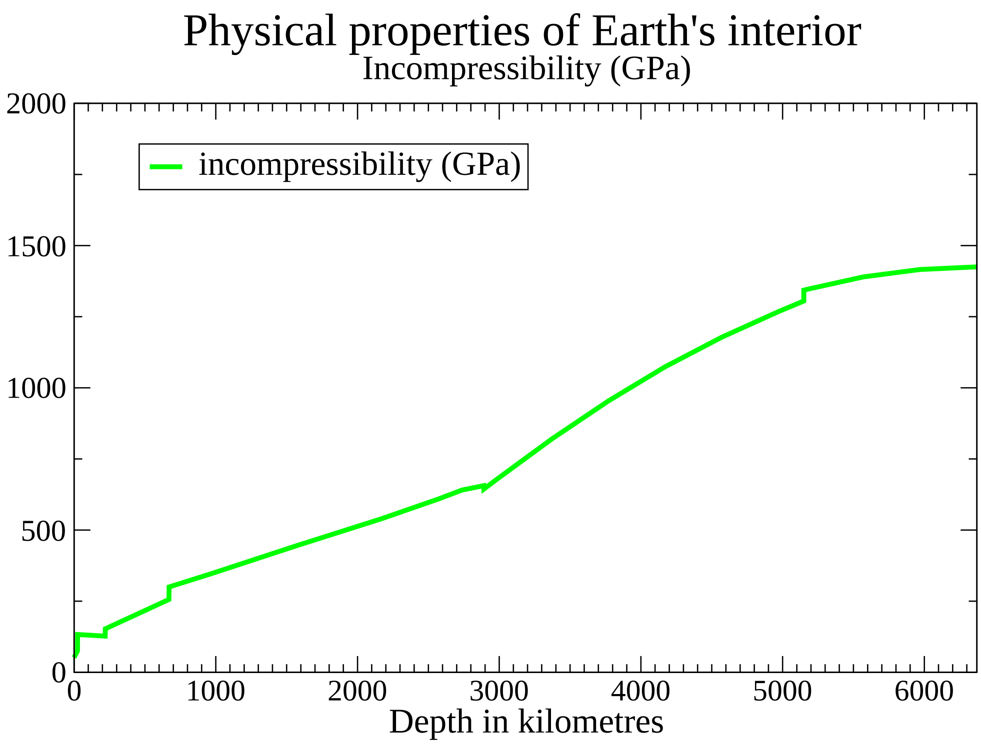
- Rigidity ($\boldsymbol{\mu}$) or shear modulus: Rocks are solid and clearly resistant to shearing stresses. Rigidity is properly a measure of ***hardness***. Liquids have no resistance to shearing stresses which are sufficiently slowly imposed. The extremely high viscosity of the mantle brings the mantle to respond with the nature of a solid to seismic shear waves which pass through it. That is, the mantle does show real rigidity to seismic shear waves for which the stress variations are characterized by time scales of only a few seconds. Stress variations imposed with time scales of hundreds of years would see the mantle as a fluid.

  – The hardest of rocks and minerals we know on the surface show rigidities (or ***shear moduli***) of $\boldsymbol{\mu} \approx \mathbf{80}\, \boldsymbol{GPa}$; for diamond, the hardest of all minerals. $\boldsymbol{\mu} \approx \mathbf{100}\, \boldsymbol{GPa}$.



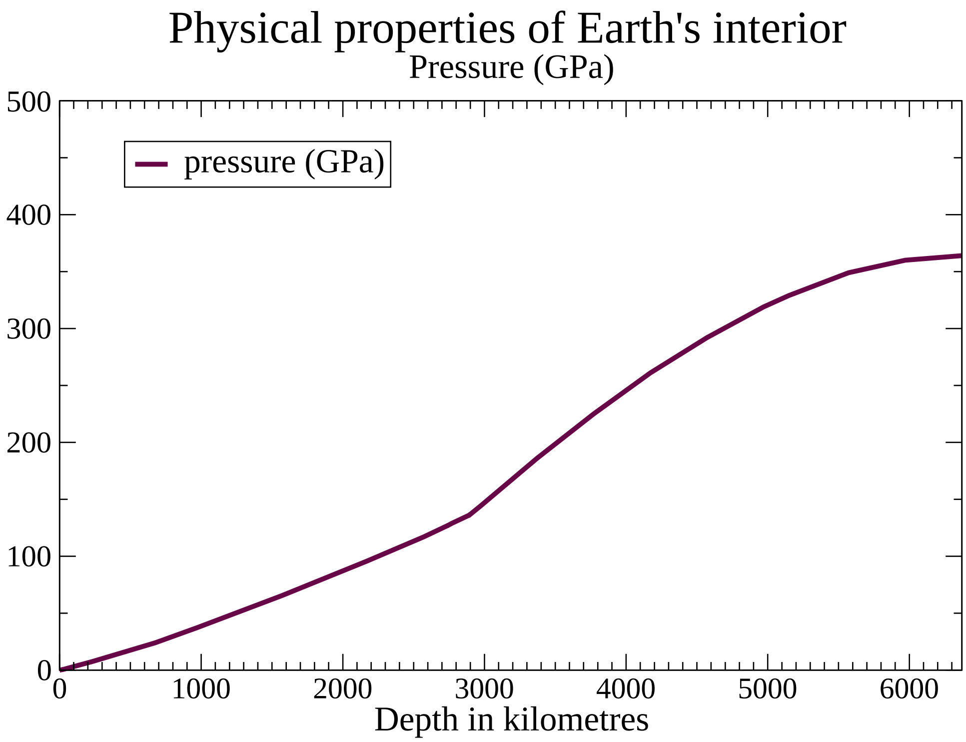
- As we move from the base of the lithosphere into the asthenosphere at about $\mathbf{100}$ km depth, the rigidity seems to decrease marginally (*soften*) from $\boldsymbol{\mu = 75\,GPa}$ to $\boldsymbol{\mu = 70\,GPa}$. Even here, in this most "fluid" region of the mantle, the rigidity is almost as great as that of diamond.
- Rigidity rises relatively smoothly through to the asthenosphere to about $\boldsymbol{\mu = 120\,GPa}$ at $\boldsymbol{670\,km}$ depth where it jumps to $\boldsymbol{\mu = 150\,GPa}$ before rising smoothly again to $\boldsymbol{\mu \approx 290\,GPa}$ at the base of the mantle.
- Rock deep in the mantle is very much more rigid than is rock we know on the surface – and, still, when observed over long times, it appears to be fluid.
- As we move across the core-mantle boundary into the iron outer core, the rigidity drops to $\boldsymbol{\mu = 0!}$. The outer core is such a low viscosity fluid that even short period seismic shear waves see it to possess no rigidity at all. It is because shear waves cannot travel through a fluid that we know that the outer core is fluid.
- The inner core is solid. We know that seismic shear waves, those which impose only shearing stresses in travelling through a solid material, do have velocity in the inner core. That proves its solidity. The inner core is not very rigid, however, with $\boldsymbol{\mu \approx 1.8 - 2.1 \times 10^{11}\,Pa}$ throughout.

- Incompressibility ($\boldsymbol{k}$) or bulk modulus: Incompressibility is a measure of a material's resistance to changing its volume under pressure.



  - Gases are very compressible ($\boldsymbol{k}$ small) while minerals such as diamond have high incompressibility, ($\boldsymbol{k = 443\,GPa}$). Strangely, it has just been discovered that the soft metal, osmium, has an even higher incompressibility than diamond: $\boldsymbol{k_{Os} = 462\,GPa}$. Osmium has much lower rigidity and does not appear as "hard"; diamond scratches or indents osmium easily.
  - The hardest rocks of our experience on the surface show a bulk modulus of incompressibility of about $\boldsymbol{k = 100\,GPa}$. The rapid increase of P-wave velocity with depth in the upper regions of the mantle takes this to about $\boldsymbol{k = 300\,GPa}$ at the transition boundary at 670 $\boldsymbol{km}$ depth and then linearly to about $\boldsymbol{k \approx 1500\,GPa}$ in the central inner core.

- Pressure: Pressure increases from $\boldsymbol{1\,bar = 101.3\,kPa}$ at the base of the atmosphere on the Earth's solid surface to $\boldsymbol{360\,GPa}$, or $\boldsymbol{3.6 \times 10^6\,bar}$, at Earth's centre.



9.3.1 Seismic tomography

One can perform the equivalent of a CAT-Scan on the Earth using seismic waves. In fact, seismic tomography is an older science than is medical tomography. By looking to the localized anomalies in the seismic wave velocities according to places within the Earth, we can actually track the history of descending tectonic plates and upwellings beneath spreading ridges. As the science evolves and as ever more data are obtained, we are producing a detailed picture of Earth's interior[271].

9.3.2 Normal modes of Earth's oscillations

Just as violin or guitar string oscillates with many overtones or modes, the Earth, when excited can also oscillate with its so-called *free modes*[272]. These are the equivalent of the *standing waves* that are produced as the sum-total of all the waves travelling through the interior. The relative amplitudes of all these modes is determined by the source excitation and the interior structure. We can look into the Earth through the

[271] Tomographic "slice" through Earth
Tomographic image across Tonga trench
[272] Free oscillations of Earth

very tones of its "*ringing*".

9.4 Other bodies in the Solar System and beyond

We have carefully unravelled in the Earth's interior mechanical properties during more than 100 years of seismic observation and analysis. Seismology is, perhaps, the best of all tools for discovering the condition of planetary interiors – and even the interior properties of the Sun and stars. Unfortunately, seismic experiments have not yielded very much information about the interior of the planets and moons of the Solar System.

On July 29th, 1969, the Apollo 11 mission placed magnetometers and seismographs on the Moon[273]. These were the first seismographs installed on a body beyond Earth. These instruments and subsequent instruments installed by following Apollo mission have given us a fairly good picture of the Moon's interior mechanical properties. The Soviet Union's Luna mission also attempted to install seismographs on the Moon but it is not clear that useful seismic measurements were obtained. The geophysical instruments installed by the Apollo astronauts were shut down in 1978.

NASA's Viking I and II missions to Mars landed seismograph system on its surface in 1976. Viking I's seismograph instruments failed and Viking II's only recorded one possible ***marsquake***; this single record provided no useful information about the solid or fluid mechanical properties of the planet.

The Soviet Union's Venera missions to Venus managed to land two seismographs on the surface of the planet. In the incredible heat of Venus' surface, both landers failed within about 1/2 hour and during that interval, no seismic activity was recorded.

Just as an earthquake, moonquake or marsquake might sets off a train of seismic waves that travel through the body, explosions on the Sun set off trains of "seismic" waves through the Sun. ***Helioseismology***[274] is a well developed extension of terrestrial seismology. By observing the oscillations over the surface of the Sun, helioseismologists have been able to invert their measurements for a model of the Sun's interior. The Canadian **MOST** satellite[275] employs ***asteroseismology*** to obtain structural models of some large nearby stars. One of its first observations of ***Procyon*** discovered that it does not pulsate as was expected and as does our active Sun.

---

[273] Apollo Apollo ALESP: http://rst.gsfc.nasa.gov/Sect19/Sect19_6a.html
[274] Helioseismology: http://soi.stanford.edu/results/heliowhat.html
[275] MOST:http://wombat.astro.ubc.ca/MOST/

10 Mineralogy and geological history of the terrestrial planets

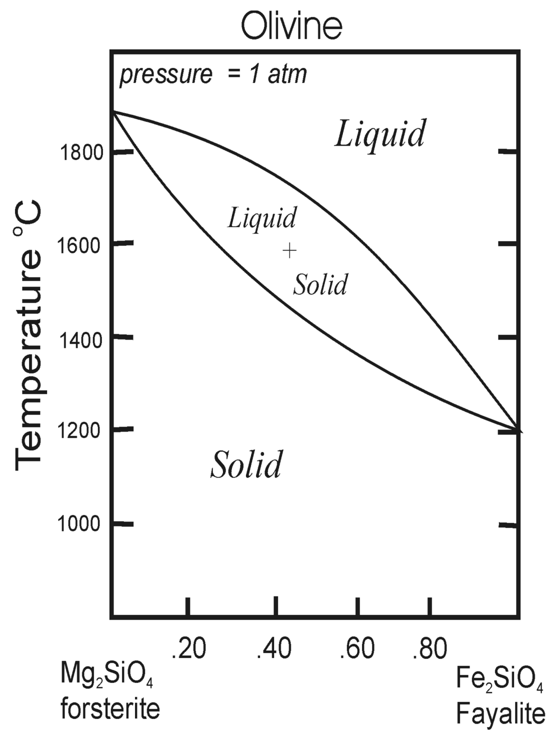
10.1 Mineralogy and minerals

The chemical elements can combine into molecules and minerals. We normally regard molecules, such as simple water, $\boldsymbol{H_2O}$, as having stoichiometrically precise relative composition of elements – in this case 2 atoms of hydrogen for each atom of oxygen. While water might be regarded as a mineral in liquid form with ice, one of its crystalline forms, many minerals do not follow a precise stoichiometry. Rather minerals may be regarded as structural edifices into which certain atoms can be easily secured. Most minerals can exist in liquid state though we are normally most interested in their solid, typically crystalline state. Rock salt with chemical formula $\boldsymbol{NaCl}$ exists as a typically white crystal. Common table salt, though, is not pure $\boldsymbol{NaCl}$ as iodine is added as $\boldsymbol{NaI}$ for health reasons. Both $\boldsymbol{Cl}$, chlorine, atoms and $\boldsymbol{I}$, iodine, atoms might well exist within a single crystalline piece of salt. Similarly, the *cation* $\boldsymbol{K^+}$ might be substituted for the $\boldsymbol{Na^+}$ cation in a crystal with either the $\boldsymbol{Cl^-}$ or $\boldsymbol{I^-}$ *anion*. The cation is an atom or group of atoms which tends to want to yield one or more electrons and so becomes positively charged. The anion is an atom or group of atoms which tends to take on one or more electrons and thus become negatively charged. The negatively charged anions are thus attracted to and complement cations. Much of the study of elementary inorganic chemistry relates to the stable molecules and crystals which can be formed of assemblages of various anions and cations.

Here, above, we have roughly described the mineral *halite*. It is not typically pure $\boldsymbol{NaCl}$ as atoms similar in property to sodium, $\boldsymbol{Na}$ can substitute for the sodium role and atoms similar in property to those of chlorine, $\boldsymbol{Cl}$, can substitute for it. Minerals typically have a range of compositions which is allowed for by such substitutions. Halite is one of the simplest of minerals.

The minerals which compose rocks in the Earth's crust and mantle are more complex. They are typically *silicates*, *oxides* and *sulfides* complemented with various metallic cations such as magnesium, $\boldsymbol{Mg}$, iron, $\boldsymbol{Fe}$, sodium, $\boldsymbol{Na}$, etc.. The silicates and oxides form *lithophile* minerals which means that they "like to be" rock. Certain metals form *siderophile* alloys. Certain metallic elements easily combine with sulphur; these are called *chalcophile* elements, iron, zinc and lead being among the common ones.

Among the most important of minerals in the solar system is *olivine* which has a chemical composition ranging between $\boldsymbol{Mg_2SiO_4}$ and $\boldsymbol{Fe_2SiO_4}$. Sometimes we note the generic range as $\boldsymbol{(Mg, Fe)_2SiO_4}$ allowing for any possible mixed composition of magnesium and iron. Magnesium and iron can take on different silicate compositions too. *Orthopyroxene* has a generic composition $\boldsymbol{(Mg, Fe)_2Si_2O_6}$. Relatively, the chemistry suggests that a $\boldsymbol{Si}$ atom takes on a role of an $\boldsymbol{O}$ atom in olivine. The minerals are brought to important difference in this "substitution". The very structure of the crystalline forms of the two minerals are very different from each other. Depending on the $\boldsymbol{Mg/Fe}$ ratio in olivine crystals, the physical properties such as its melting temperature vary.

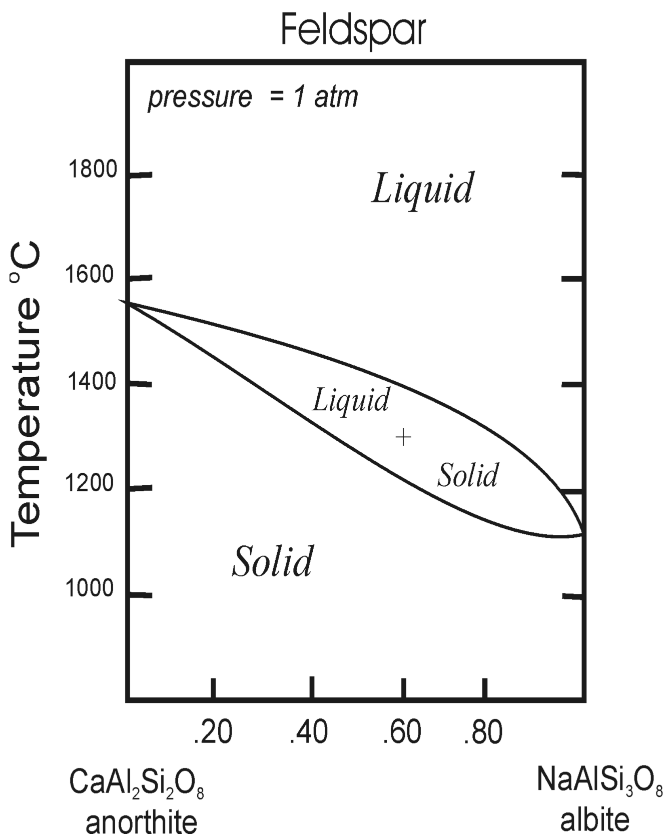


A simple phase diagram for the $[\mathbf{Mg,Fe}]_{\mathbf{2}}\mathbf{SiO}_{\mathbf{4}}$ olivine.

The magnesium rich form of of olivine, *forsterite*, freezes at very much higher temperature than does the iron rich form, *fayalite*. Mixed composition allows for a range of temperature over which both solidified (the magnesium rich components) and liquid (the iron rich olivine) coexist in a slurry. The history of the cooling of an olivine rich magma is recorded in its solid mineral phase. "*Xenoliths*", rocks brought to the surface along with erupting magmas, of olivine from Hawaiian volcanos have $\boldsymbol{Mg/Fe \approx 9}$.

Similarly, the mineral feldspar which is an important component of granitic rocks ranges from *anorthite*, $\boldsymbol{CaAl_2Si_2O_6}$, to a lower melting form, *albite*, $\boldsymbol{NaAlSi_3O_8}$. By studying the details of rocks derived from the freezing of granitic magmas, mineralogists can infer much about the conditions which held during the solidification.

Quartz is a very important simply composed mineral which is a common constituent of rocks. Quartz is $\boldsymbol{SiO_2}$ which in pure form is a colourless crystal. Quartz though



A simple phase diagram for the mineral feldspar.

can take on colour. Amethysts are quartz and often grading from colourless to deep purple. Citrine is quartz but it is amber-brown in colour. Citrine colouration can be obtained from purple amethyst by heating the quartz. The colour is a consequence of traces of metallic elements in the quartz. The crystal structure may be nearly perfect but with metallic cations substituting here and there for silicon. Quartz is a characteristic mineral in continental crustal rocks like granite. Granite is an *igneous*, meaning that it formed in cooling and freezing of *magma*, rock type which comprises a mix of minerals such as quartz, feldspar, mica, amphibole, and magnetite. It is typically relatively large grained because it cooled slowly under an insulating layer of rock into what is called a *pluton*. The same chemistry, cooling rapidly on the surface of the Earth as an extruded lava, produces a different rock type such as *andesite* or *rhyolite*. The minerals which form in quick cooling can be quite different from those which form under slow cooling even though the overall chemistry is little different. Basalts form of magmas having a composition like that of the Earth's mantle, below its continental crust. The ocean basins are basaltic. The great shield volcanoes of Hawaii are basaltic rock. The west-coast volcanoes, such as Mt. Rainier, are andesitic, of continental material. Basaltic rocks are denser than granitic rocks such as andesite. Their high density accounts for their low-lying in ocean basins, though, here and there on Earth, large basaltic flows (e.g. Hawaii and Iceland) are lifted to quite high elevation. Basalts have little or no quartz mineralization as crystals even though their overall elemental composition is not importantly different from granites. Their mineral compositions are quite different.

10.1.1 Condensation of minerals in the primordial solar nebula

As the Solar System was condensing into a disk with a proto-sun as the gravitational centre, heat from the newly igniting proto-sun warmed the disk which would spawn the terrestrial and other planets. Near the proto-sun in the interior regions of the nebula, the temperature of the cloud of chemical elements and dust increased. In the interior, only the *high temperature refractory* minerals[276] such as perovskite, with composition $\boldsymbol{CaTiO_3}$[277] and spinel, with composition $\boldsymbol{MgAl_2O_4}$[278] condensed into mineral at temperatures of probably more than 1400K. The inner regions of the nebula became, therefore, relatively richer in such minerals as other minerals could not form and their chemical components were swept farther out into the solar nebula by the thermal radiation and proto-solar wind. In regions of the cloud where temperatures were a little cooler, 800K to 1400K, iron and nickel condensed in metallic crystals, olivine crystallized as did pyroxenes, feldspars and silica. Only where temperatures were lower did minerals like troilite, wustite, spinel and the hydrated (i.e. with water) clays and serpentines form. And only where temperatures fell below about 300K, could mineral ices of water, carbon dioxide and methane assemble. These lighter, volatile, minerals and molecules are most common in the distant regions of the now condensed Solar System. The terrestrial planets are largely composed of the refractory minerals, metals and high temperature silicates.

The mineralogy of the inner terrestrial planets is important to our understanding of their evolution and geological/planetological processes.

10.2 Composition of the terrestrial planets

Geologists have long and well studied the mineralogy of Earth. In 1969, man landed on the Moon and the Apollo 11 astronauts returned rocks from the Moon allowing

[276] Note that minerals are properly structural crystaline forms that can be assembled with different chemical elements.

[277] Recall that the mineral perovskite in the mantle has composition $\boldsymbol{[Mg, Fe]SiO_3}$.

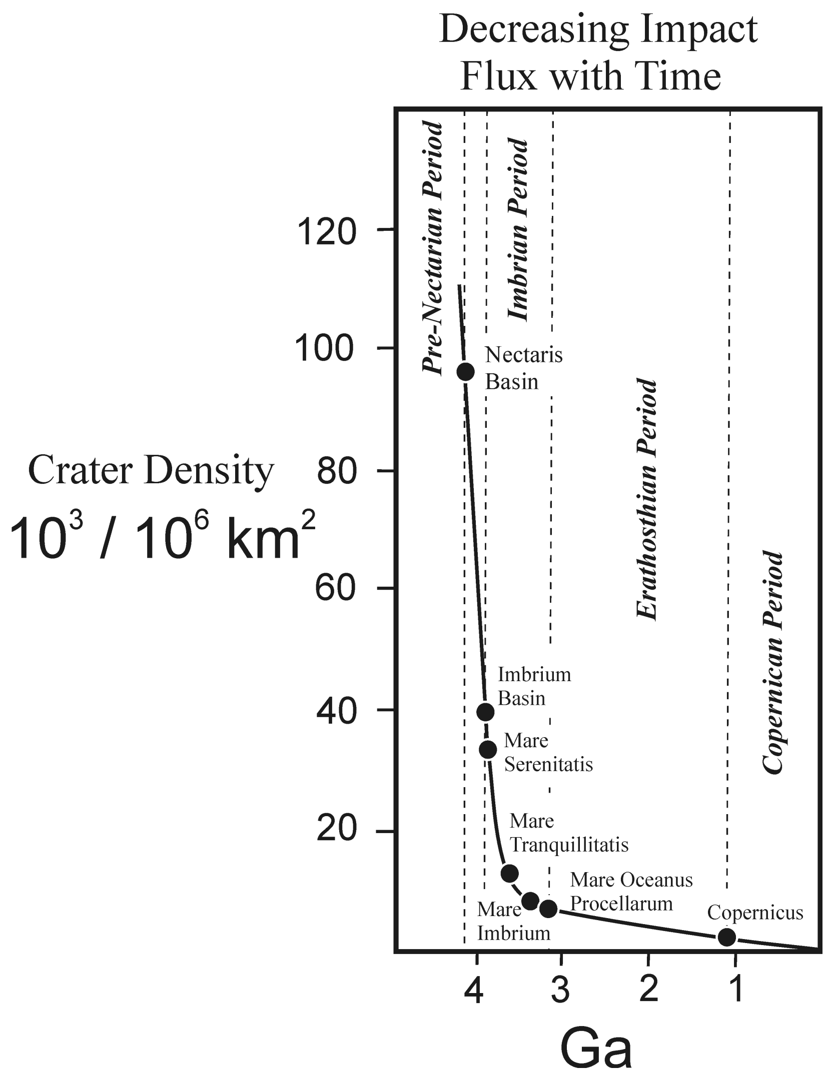
[278] A spinel polymorph, ringwoodite, with composition $\boldsymbol{[Fe, Mg]_2SiO_4}$ is a major component of the mantle at depths of between 520 and 660km. That is the olivine structure with $\boldsymbol{[Fe, Mg]_2SiO_4}$ composition undergoes a phase transition to a spinel structure at about 520km depth.

geologists for the first time to study the geology (or properly selenology) of another body in the Solar System. Moon rocks were found to be quite like Earth rocks but not identical. For example, Moon basalts were found to be less rich in $\boldsymbol{SiO_2}$ than basalts on Earth. Those returned from the *mare basins* were found to contain twice as much $\boldsymbol{FeO}$ as terrestrial basalts. The Moon was found to be not identical in composition to Earth, at least on its surface. Its compositional difference tells us something about its long geological past. The higher iron content in its crustal rocks is consistent with a model of a Moon splashed up in a giant collision of the proto-Earth with a Mars-sized body. Very early in the Earth history, at least 4.44 billion years ago, its mantle and crust had not yet been largely purged of iron which through the process of differentiation since that time has continued to be collected in the core. The Moon, being small, quickly froze and with little internal heat generation except from radioactive decay, did not manage to express an Earth-like mantle convection in bringing about further differentiation. The iron was not much further purged from the outer regions of the Moon into its small core.

Spectral surveying of Mercury by the Mariner 10 probe reveals that its surface is apparently less iron rich than crustal rocks on Earth. This suggests a more complete and early differentiation of that planet. While Mercury shows no evidence of active tectonics, it does possess a magnetic field indicating that its iron core is in circulation. This further suggests that an inner core might still be freezing out within Mercury, releasing a latent heat of fusion which drives the fluid circulations generating the magnetic field. As that heat is transported through the Mercurian mantle to the surface, it is possible that small scale convection becomes established allowing for further differentiation of its mantle. Still, there is no evidence that the crust of Mercury has been resurfaced or recycled into its interior in the past 3.9 billion years. The density of craters on the surface of Mercury give us a good estimate of the age of its crust.

10.3 The crater-density clock

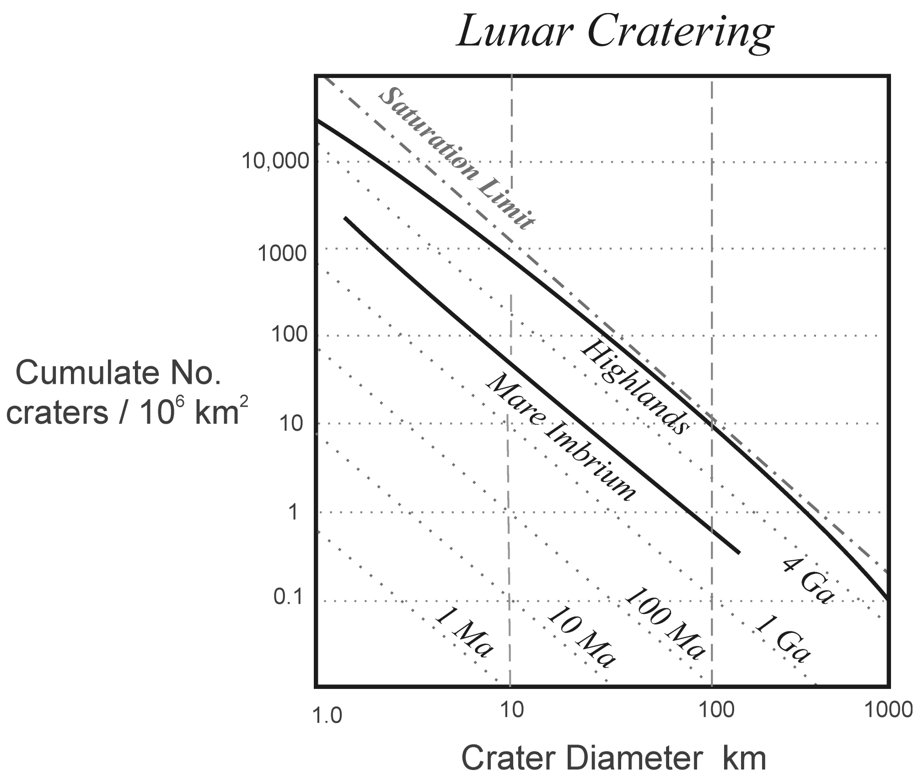
During the Apollo missions to the Moon, the astronauts returned rock samples to Earth. Those basaltic rocks obtained from the Mare Tranquillatus by Apollo 11 were determined through radioisotope dating to be between 3.7 and 3.9 billion years old. Rocks no younger than 3.3 billion years were returned by any of the subsequent missions which landed in maria basins.



Lunar cratering and age of the Moon's surface features
(after D. Francis, Earth & Planetary Sciences, McGill)

The later expeditions were directed towards the highlands. Granitic rocks returned by Apollo 16 from a highland region were found to be much older at 4.44 billion years. This is the probable age of solidification of the Moon's crust. Subsequent flooding of basalts consequent to great impacts by large asteroids filled the shallow maria basins with younger and more dense rock.

The highlands are seen to be very heavily cratered while the maria basins are much less so. Careful analyses of cratering can obtain something of an "order" to the cratering process. That is, a small crater which is seen to be within another larger crater had to have been caused by an impact subsequent to that which caused the larger one. By ordering craters and then by calibrating their "age" with the radioisotope determinations of actual age for rocks from them, we can calibrate a "*crater-density* *clock*". We find that early in the Solar System's history, the rate of impacts was much higher than it is now. Moreover, there were also relatively more large impacts than have occurred in more recent times. A simple diagram which relates the number of craters per million square kilometers to their diameters and to time is shown below. The *saturation limit* is the expected line for 4.567 billion years, the age of the planets. Superimposed on the calibrated lunar clock diagram, the crater cumulate density/size

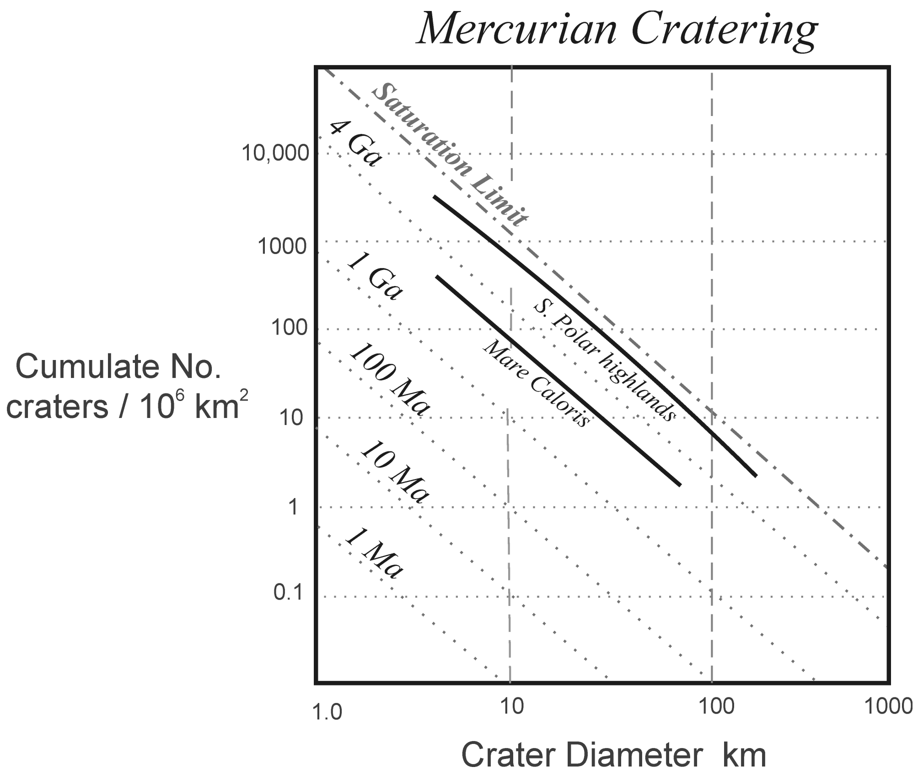


Lunar cratering and age of the Moon's surface features

(after D. Francis, Earth & Planetary Sciences, McGill)

relationship for the lunar maria and the lunar highlands is shown. We can so measure the "age" of these surface regions. We see that the highlands are very old while the surface of Mare Imbrium, the basin within the largest obvious crater on the Moon, is only about 1.8 billion years old. The Moon's surface has not been substantially renewed anywhere since that time. This might be regarded as the youngest area on the Moon's surface. The Moon has been geologically inactive for the past 1.8 billion years.

Returning to Mercury, we may apply this clock based on crater density to determine age of its surface. We assume that Mercury, like the Moon, Earth, Venus and Mars all faced about the same impact history and that what distinguishes, then, their surfaces is the actual age since regions of their surfaces solidified or were resurfaced by other processes such as erosion. We discover that Mercury's southern polar highland region

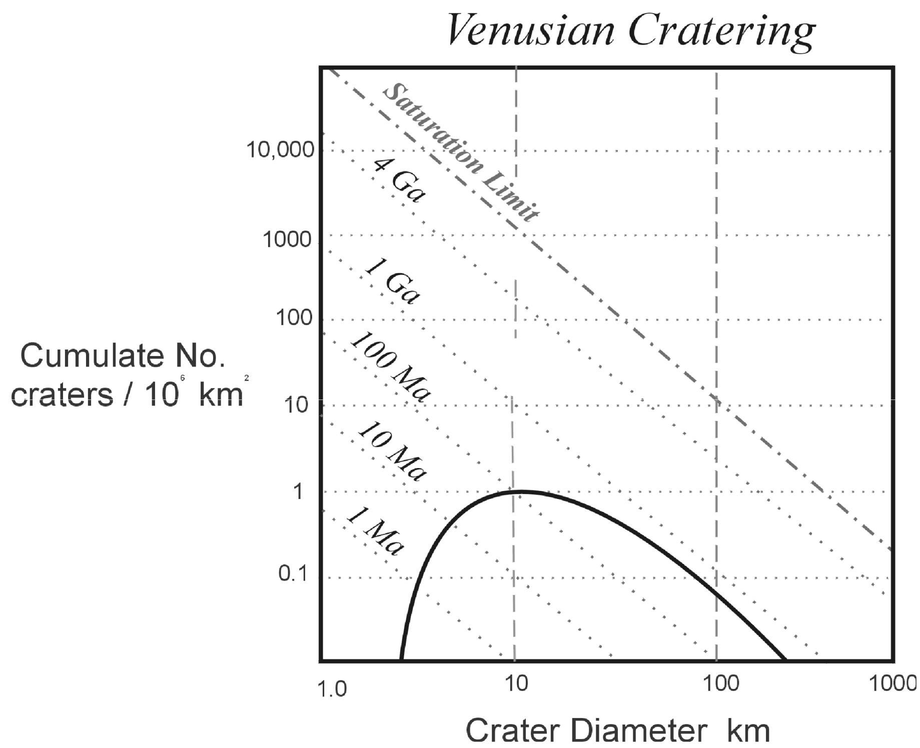


The age of Mercury's surface

(after D. Francis, Earth & Planetary Sciences, McGill)

is very, very old, more than 4 billion years while its Mare Caloris is well less than 3 billion years old. Again, the maria basins have been flooded with basalts subsequent to the impacts which produced them.

The Magellan orbiter mapped the surface of Venus using a *synthetic aperture radar*, SAR, system which could penetrate the planet's thick cloud cover. Analyses of the image compiled of the planet's surface tell us that its surface is actually very young at about 400 million to 700 million years. Moreover, we note that there is a lack of relatively small craters on the surface as indicated by the drop-off of the line on the lower left of the diagram above. This is due to the fact that Venus' very dense atmosphere, 90 times denser than Earth's, protects its surface from being hit by small impactors. The same holds for Earth, especially over the ocean covered basins. The young age of Venus' surface proves that it has been completely resurfaced by flooding basalts in relative recent geological time. We know that the ocean basins of Earth have all been completely renewed in the past 210 million years. The average age of the ocean basins is, thus, about 100 million years. The ocean basins cover 71% of Earth's surface. These basins are analogous to the basins on the other terrestrial planets

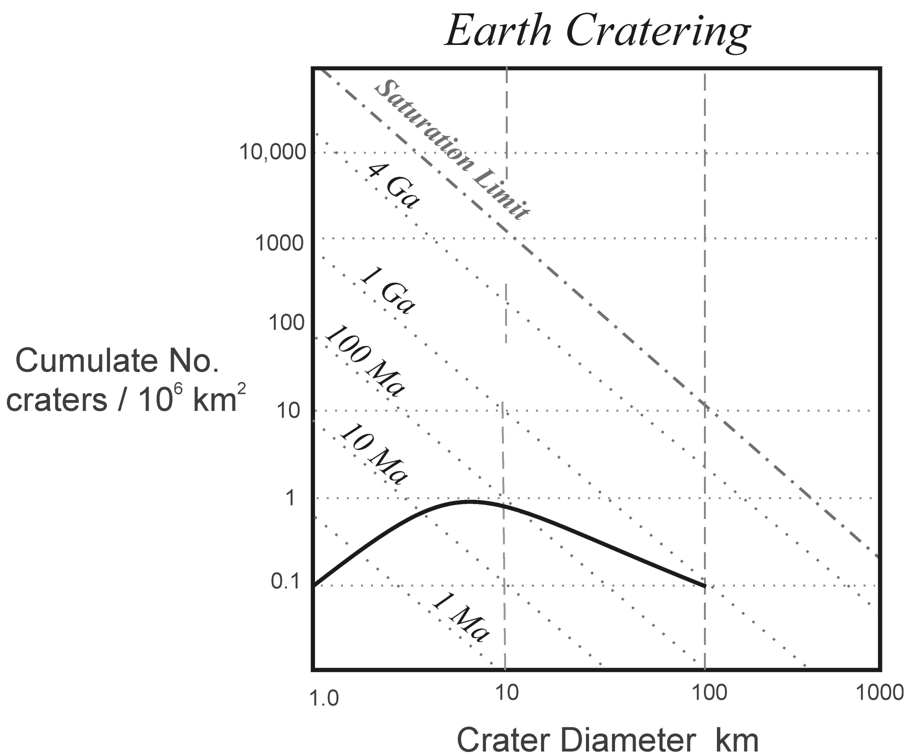


The age of Venus' surface

(after D. Francis, Earth & Planetary Sciences, McGill)

though, because the Earth is so continually geologically active, they are younger than the basaltic basins of the other planets. 29% of Earth's surface is continental highland. We know that the highlands are older. There are large provinces of rock on the surface of the Earth that are more than 3.5 billion years old. Much of central Canada's *Canadian Shield* is over 2 billion years old. Still the cratering clock does not show the degree of cratering that a 2 billion year old surface would show on the Moon, for example. Why? The continents on Earth are under continuing attack by erosional process of water, glaciation, plant life and wind. The continental surfaces are being continually carved back by these processes and as a consequence, the record of cratering, except for the very largest and deepest craters is lost.

The line of crater density - crater diameter for Earth shows a sharp decrease for craters smaller than about 8$\boldsymbol{km}$ in diameter. This is partially due to the "shielding effect" of the atmosphere for the smallest of imapactors and the same effect by the ocean water over 71% of the surface. The smallest meteorites, asteroids and comets do not get through the protective atmosphere and water to produce craters on the rocky surface. Another feature of the cratering line for Earth is that the line does not become parallel to the age lines even for craters as large as 100$\boldsymbol{km}$ in diameter. This is largely the effect of erosion of the continental craters as, on Earth, only continental

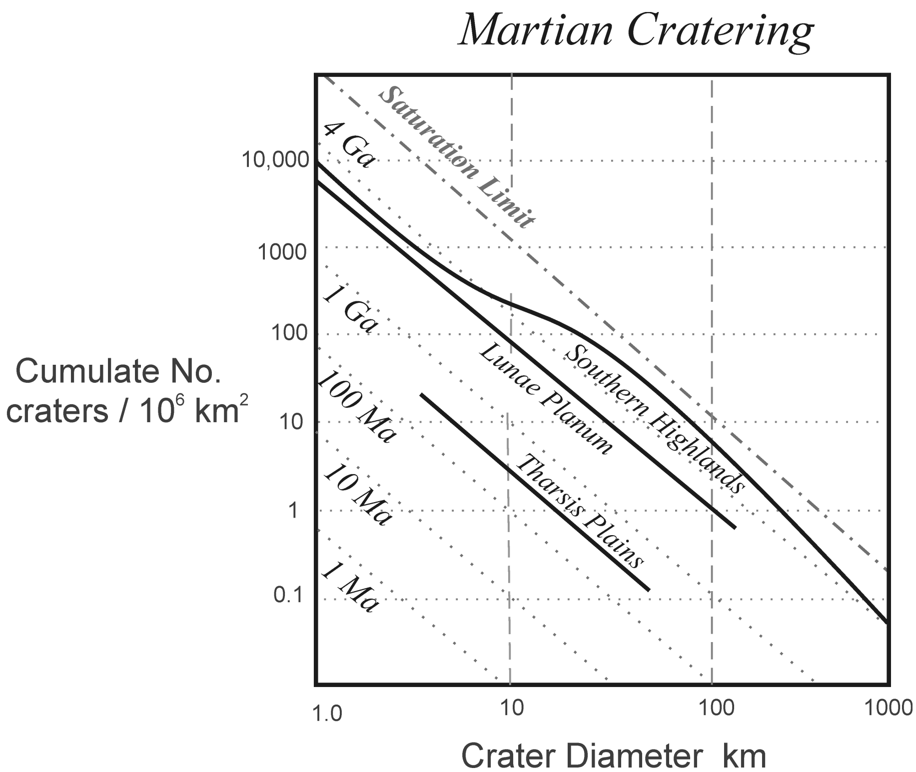


The *apparent* age of Earth's' surface

(after D. Francis, Earth & Planetary Sciences, McGill)

surfaces are older than 200 million years. The lack of such craters is a lack of such craters on the continents. Earth is the most geologically active of the terrestrial planets; geological activity erases the cratering record. There is increasing evidence that Mars was very geologically active in its early evolution. There is evidence that there is still erosion caused by water and wind on Mars. The highland regions of Mars, however, have not been much affected by these erosional processes and the cratering record is good evidence for highland age. Interestingly, the Southern Highlands show one apparent age for large craters and another, younger, for small. That is, there appear to be fewer small craters than would be expected given the age determined by large craters. The large crater age is over 4 billion years. The small crater age about 3 billion years. The lower-than-expected density of small craters might represent a 4 billion year age but with some atmospheric protection from impacts by smaller meteroids and asteroids. That atmosphere, if once there, is now lost to Mars.

The *Linae Planium* age is about 2 billion years. This large region of Mars' northern hemisphere might well have been an ocean basin until 2 billion years ago when the possible oceans finally evaporated from the surface of Mars. Mars gravity is so much less than Earth's that warm volatile water cannot be gravitationally bound against

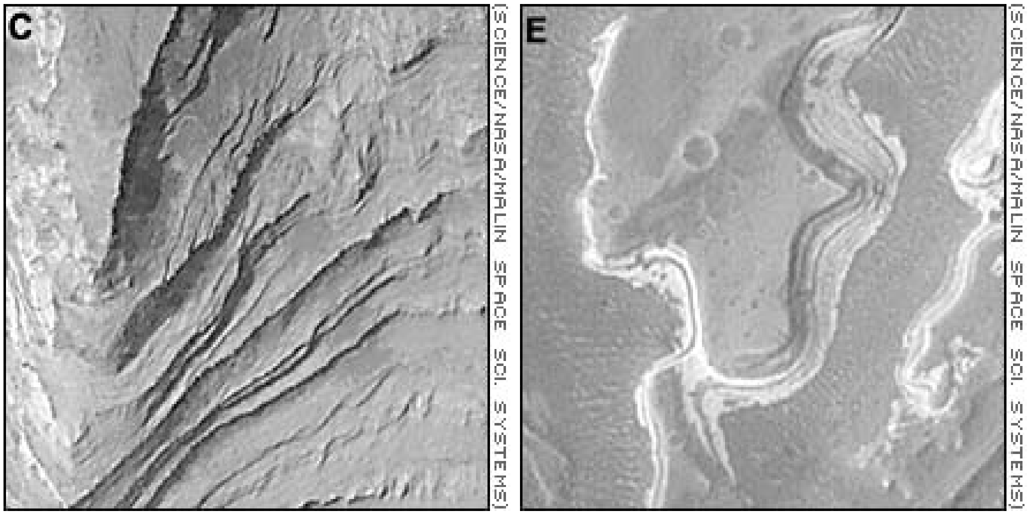


The cratering age of Mars' surface

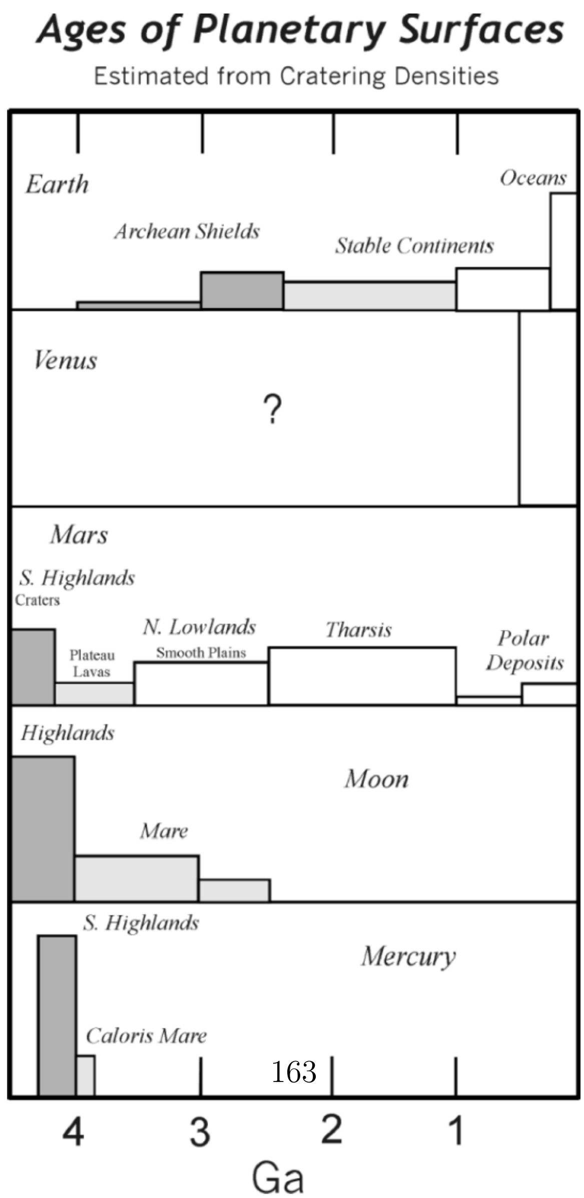
(after D. Francis, Earth & Planetary Sciences, McGill)

slow evaporation into space. It may well be that until about 4 billion years ago, Mars had a substantial atmosphere, perhaps even denser than that of present-day Earth and until 2 billion years ago, water covering much of the surface of the northern hemisphere. In fact evidence of lakes and oceans has recently been found in high resolution images obtained from the Mars Surveyor satellite.

We can now assemble something of a *histogram* of surface ages for the terrestrial planets. We find that, generally, Mercury and Moon have the oldest surfaces and Earth and Venus the youngest with Mars somewhere in between. The highlands of all the terrestrial planets might be regarded as the long-term, high-standing granitic-like crustal masses and the lowlands, probably denser basaltic masses. Earth, being most geologically active among the terrestrial planets, shows the youngest age of its basins. Also, Earth, being that terrestrial planet with the most water, glacial and wind erosion, shows most erasure of the geological record of cratering on its continental highlands.



High resolution images of Mars' surface showing possible beaches and shorelines of ancient lakes and oceans (From NASA [free-for-use copyright], Malin SSS)



A histogram of surface ages for each of the terrestrial planets and Earth's Moon
(after D. Francis, Earth & Planetary Sciences, McGill)

10.4 This concludes the lecture notes as transcribed for the term...

Thank you and good luck on the final exam....