Biogeochemical cycles - Overview

- This module looks at how the interplay between biology and geology steers the rich chemistry found on Earth
- Earth may well be the most chemically interesting planet we can ever visit
- The abundance of chemical elements available on Earth in conjunction with the interaction of biological systems has led to both the creation of incredibly complex molecular systems as well as to potentially catastrophic biologically-oriented events
- These include the development of photosynthesis, releasing vast quantities of oxygen into the atmosphere and the more recent overabundance of greenhouse gases into the atmosphere arising from human activities
- These topics will be examined in conjunction with a view on the extant geological footprint of the Earth
- The important factor that humans have the urge to measure and monitor their environment is kept to the fore in elucidating progress in terms of furthering our understanding of our environment and whether we can put the knowledge gained to good use for future generations

The interplay between biology and geology

- Compare chemistry of Mars and Venus with that of Earth and the reactions dealing with oxygen-containing molecules
- This will be explored in more detail later, but note that all 3 planets can be classified as “Type 10” meaning that they are theoretically suitably positioned in the solar system to support life
- The Earth has been labelled with the “Goldilocks syndrome” – the place most comfortable for life out of these 3 planets

Earth may well be the most chemically interesting planet we can ever visit

- Abundance of chemical elements across the universe compared with Earth. Evidence for complex molecules elsewhere
- Because of the size of the Universe it is difficult to judge its current composition – we are always looking back into history!
- Composition of the Solar System is easier
- We know that Earth has 92 naturally occurring elements and that we can produce artificial ones as well as unstable isotopes

Abundance of chemical elements available on Earth

- Periodic table so far highlighting the main elements, their electronegativities and those important in biology
- We can suppose that these elements also exist on the other planets since all apart from H, He (and Li) were formed through combinations of these via nuclear fusion as the solar system formed
- From our current perspective, the Universe is composed of 74 % H and 24 % He – but remember we are looking back in time

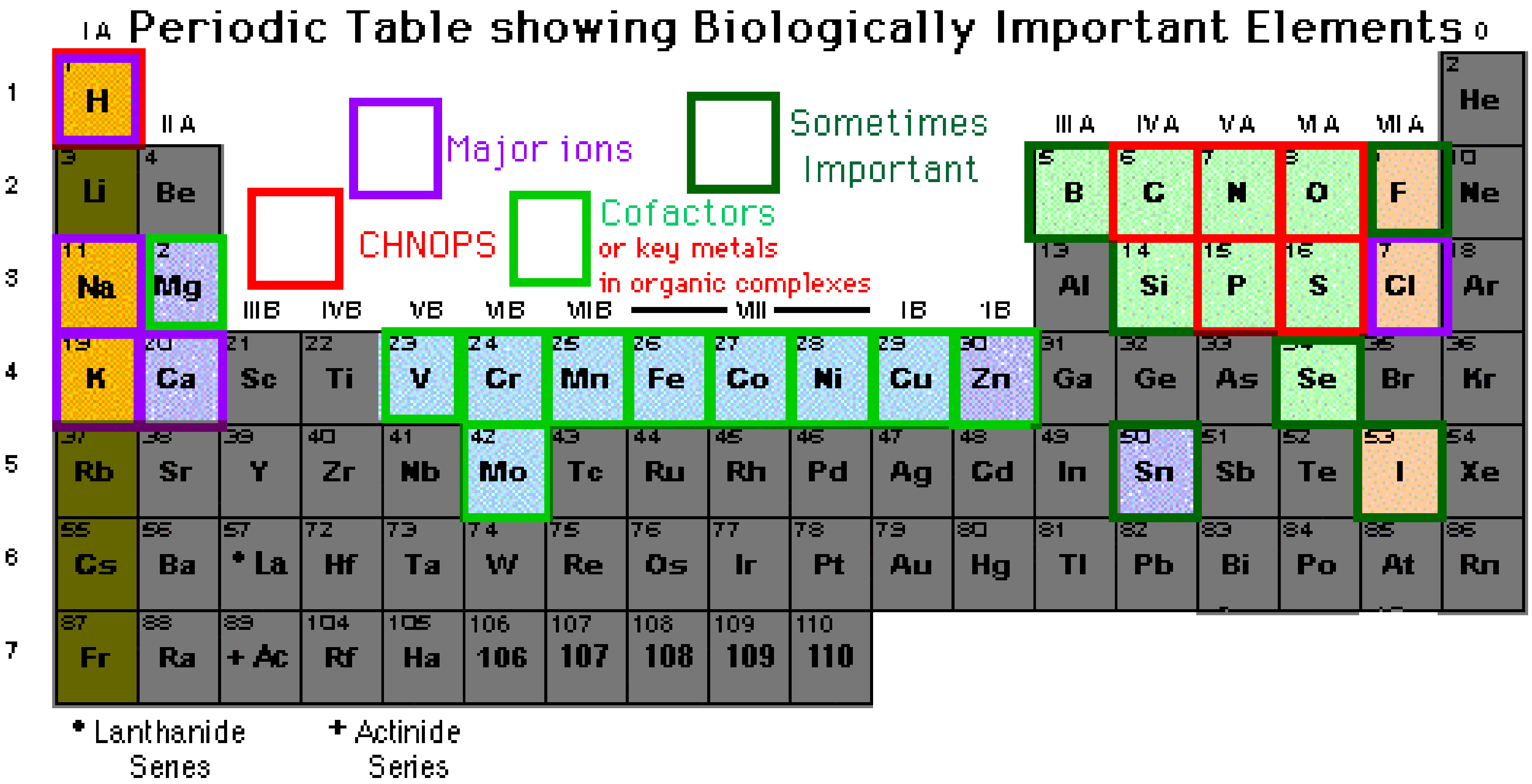
Periodic table according to element type

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 + Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

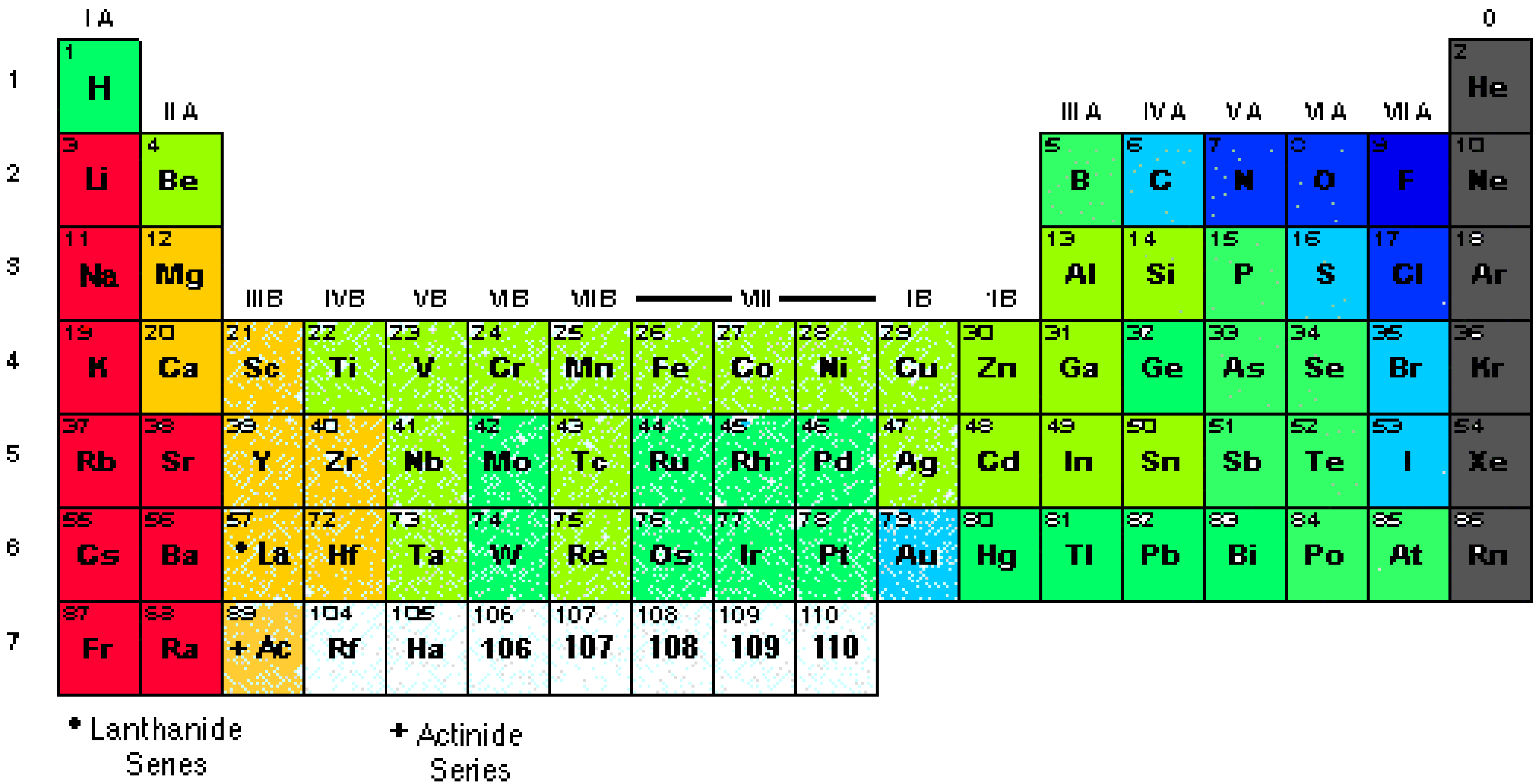
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Biologically Important Elements



26 elements are important to living things: the big six, C, H, N, O, P, S (CHNOPS) account for 99% of atoms by number (H most abundant) in the human body. In the remaining 1 % of so-called trace elements only 0.01 % come from the d-block.

Periodic Table Showing Electronegativities



Dark blue: highest electronegativity, red, lowest. Noble gases set at zero

Interaction of biological systems with available elements leads to the creation of incredibly complex molecular systems

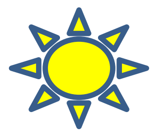
- Proteins, DNA, ATP, Carbohydrates, Polymers etc
- The use of carbon to build complex architectures is a special feature of chemistry on Earth. Although large C-C bonded structures can be found in interstellar media, molecules combining C, H, N, O plus others (P for ATP and DNA etc) may be a special marker for the presence of life.
- Initially these may have been formed by template reactions involving mineral fragments

Potentially catastrophic biologically-oriented events

- In general, biology affects its environment.
- Compare blood serum with seawater and simple things like chemical redistribution of P
- Chemical entropy – redistribution of elements
- N_2 fixation
- Photosynthesis
- CO_2 balance

Development of photosynthesis released vast quantities of oxygen into atmosphere

Overall reaction looks simple:



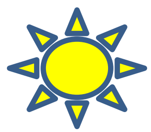
$$nCO_2 + nH_2O \longrightarrow \{CH_2O\}_n + nO_2$$

Simple combination of carbon dioxide and water gives carbohydrates plus oxygen. The dioxygen formed is a byproduct toxic to most forms of the extant bacteria (single-celled organisms) present when photosynthesis was first developed.

However, life evolved to meet the challenge of the presence of the toxic gas and now much of it depends on the presence of oxygen. In particular, the harmful uv-radiation was blocked from the atmosphere by reactions creating an ozone layer and the evolution of multicelled and land-based organisms was favoured.

One thing leads to another – aerobic respiration and CO_2 production

Photosynthesis:



$$nCO_2 + nH_2O \longrightarrow \{CH_2O\}_n + nO_2$$

Respiration and burning fossil fuels:

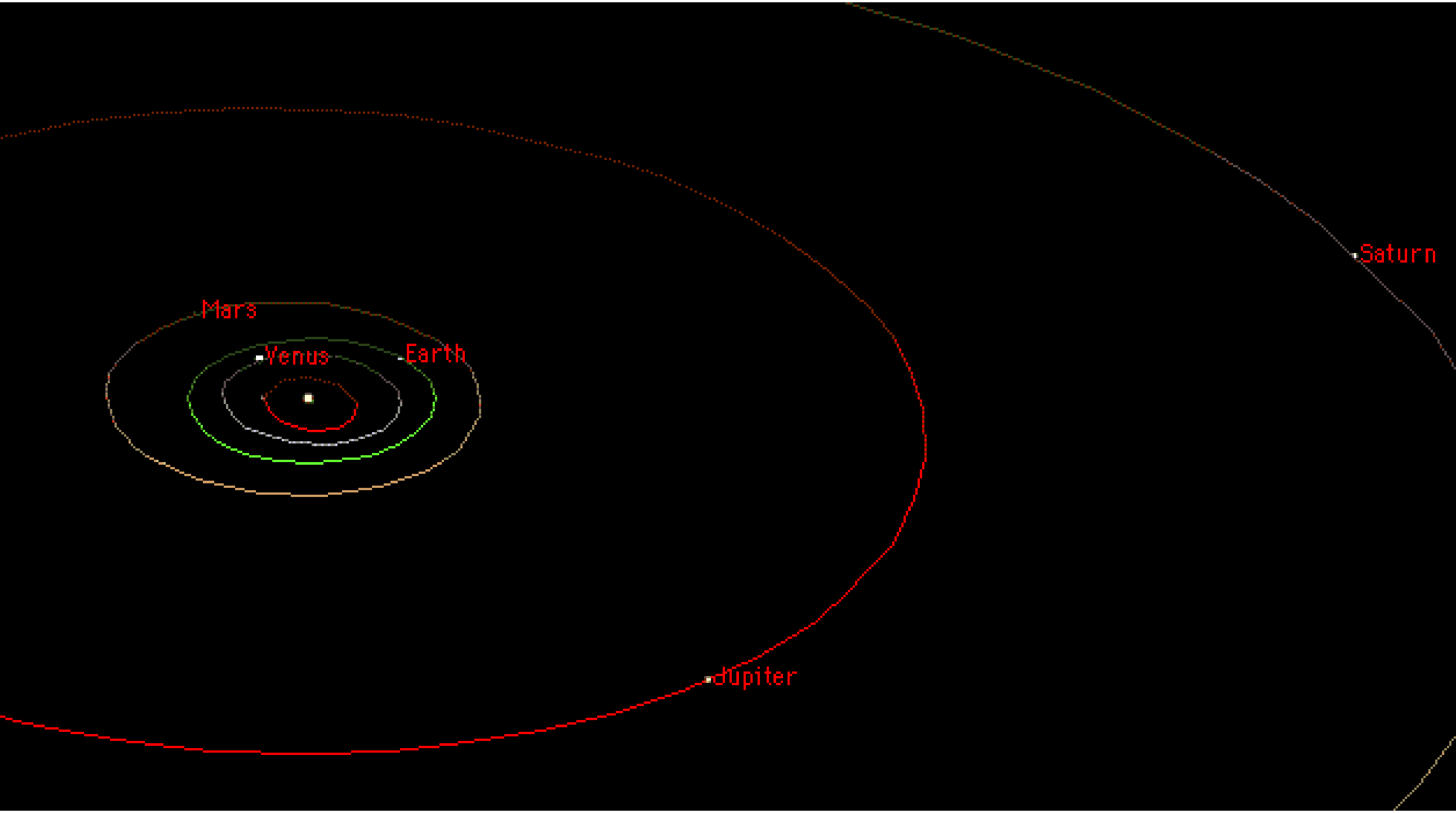
$$\{CH_2O\}_n + nO_2 \longrightarrow nCO_2 + nH_2O + ENERGY$$

Carbohydrates often reduced to hydrocarbons or carbon when in fossil fuels (but not in wood, for example). For organisms the original source is always floral or bacterial derived carbohydrate.

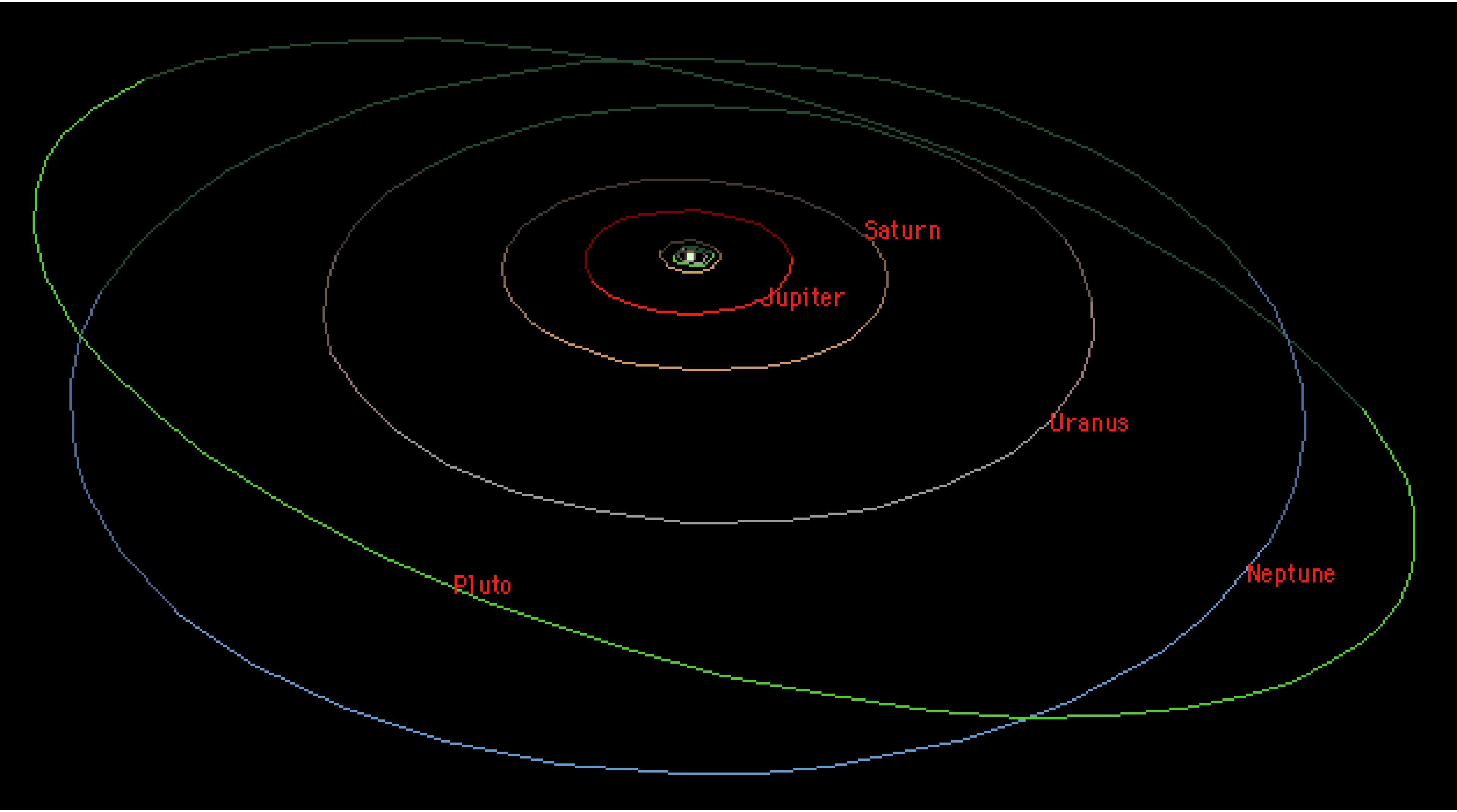
More recently excess greenhouse gases in atmosphere arising from human activities

- Although the greenhouse effect is an important way of keeping the surface temperature of a planet at comfortable levels, only tiny amounts of such gases are required – too much and things can go awry
- The vast majority of the atmosphere of the Earth is made up of nitrogen and oxygen with about 1 % argon and small amounts of other gases
- Contrast Venus and Mars

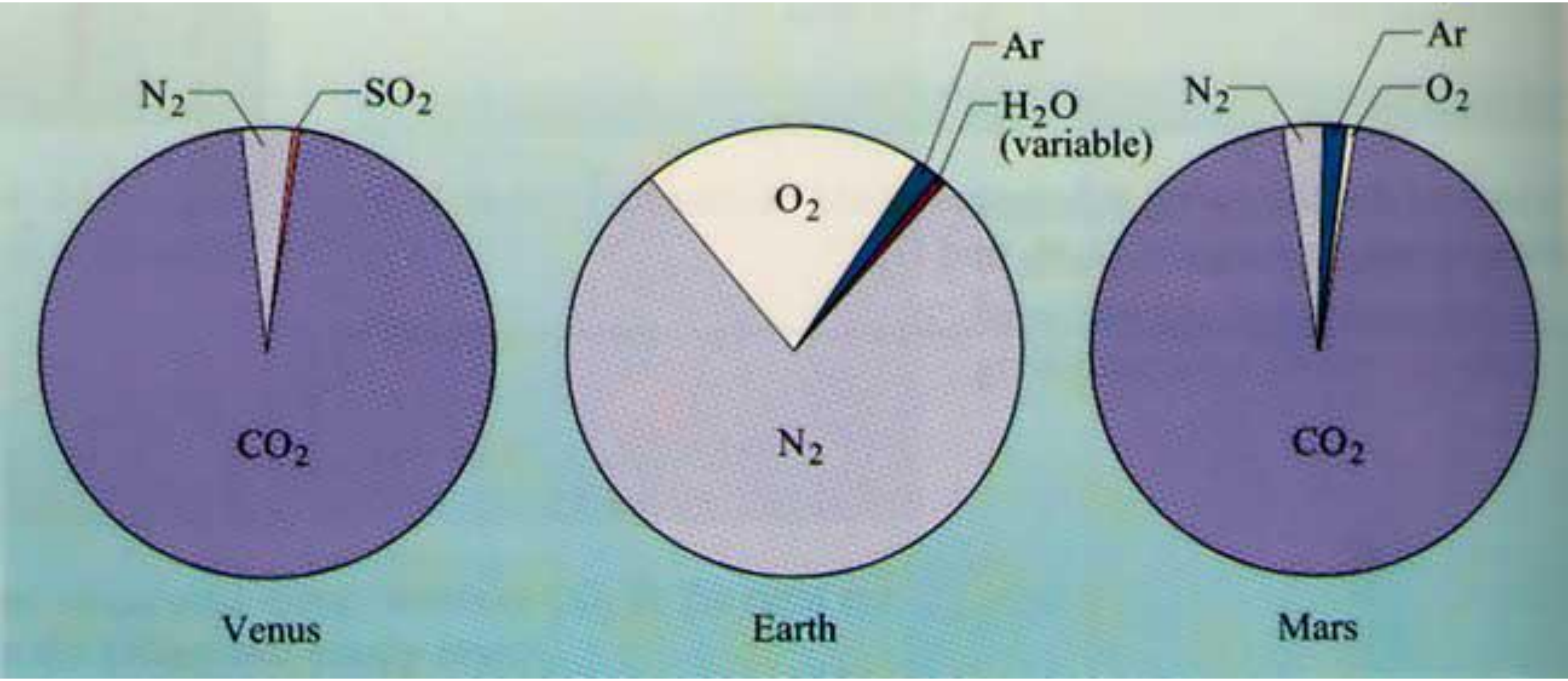
The Inner Solar System highlighting the Terrestrial Planets



Whole Solar System in Terms of the formerly accepted Nine Planets (i.e. with Pluto)

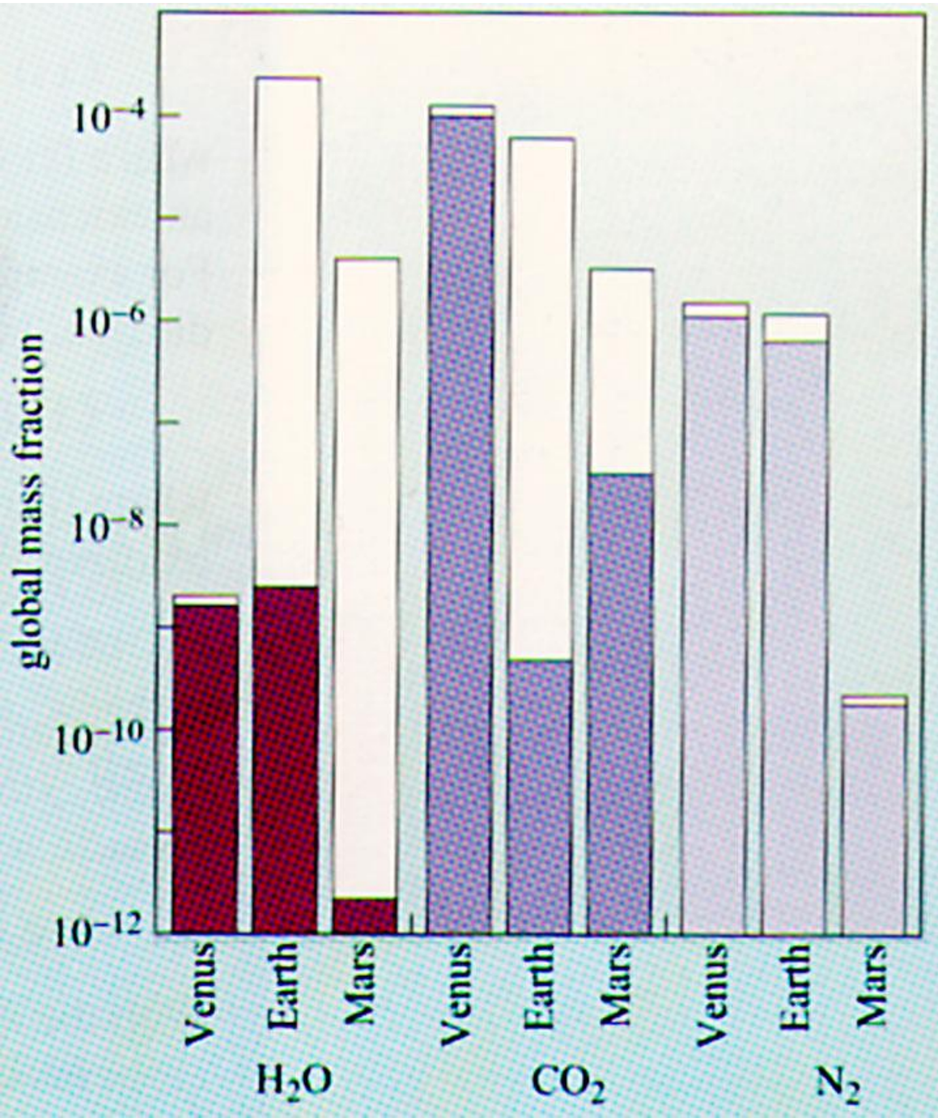


Compositions of the atmospheres of the terrestrial planets



The atmospheres of Venus and Mars have huge amounts of carbon dioxide and hardly any nitrogen – the opposite is true for the Earth

Current relative amounts of "Volatile gases" on Venus, Earth and Mars



These bar graphs show the amounts of total volatiles contained within the planets (to the top of the unshaded region) and those in the atmospheres of Venus Earth and Mars (shaded regions).

Three climatic scenarios can be recognised as resulting form the way in which the greenhouse effect has operated:

1. VENUS: Runaway Global Warming
2. EARTH: Ideal
3. MARS: Runaway Refrigeration

The detailed reasoning behind this will be discussed later

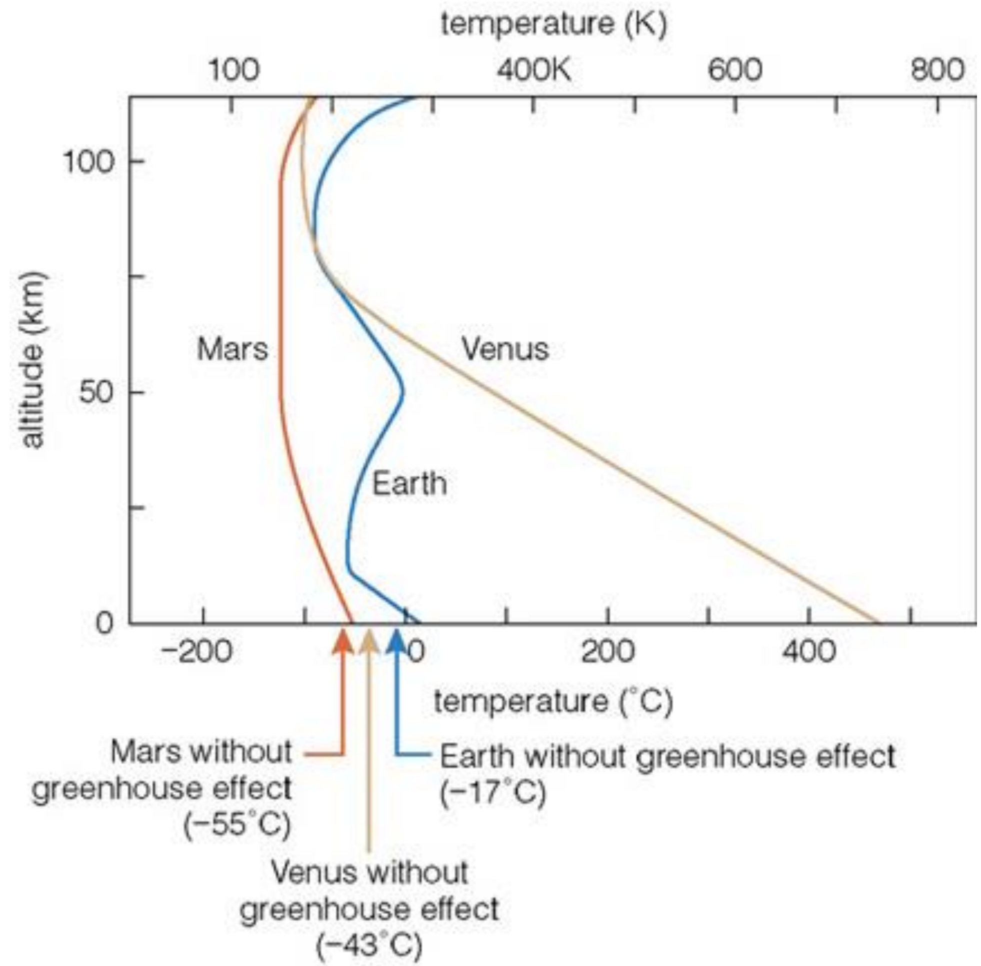
Outlook for terrestrial planets without influence of greenhouse effect

Without any greenhouse effect the terrestrial planets would be inhospitably cold at the surface.

The fact is, just the “right amount” of greenhouse effect is needed to make for ideal living conditions.

Indeed, periodically the Earth goes through a cooling phase (Ice Age) which is challenging for life. Overheating would be even more challenging!

The question is whether biological (human) activity can take the system over the “Tipping Point”



Some relevant aspects for terrestrial planets

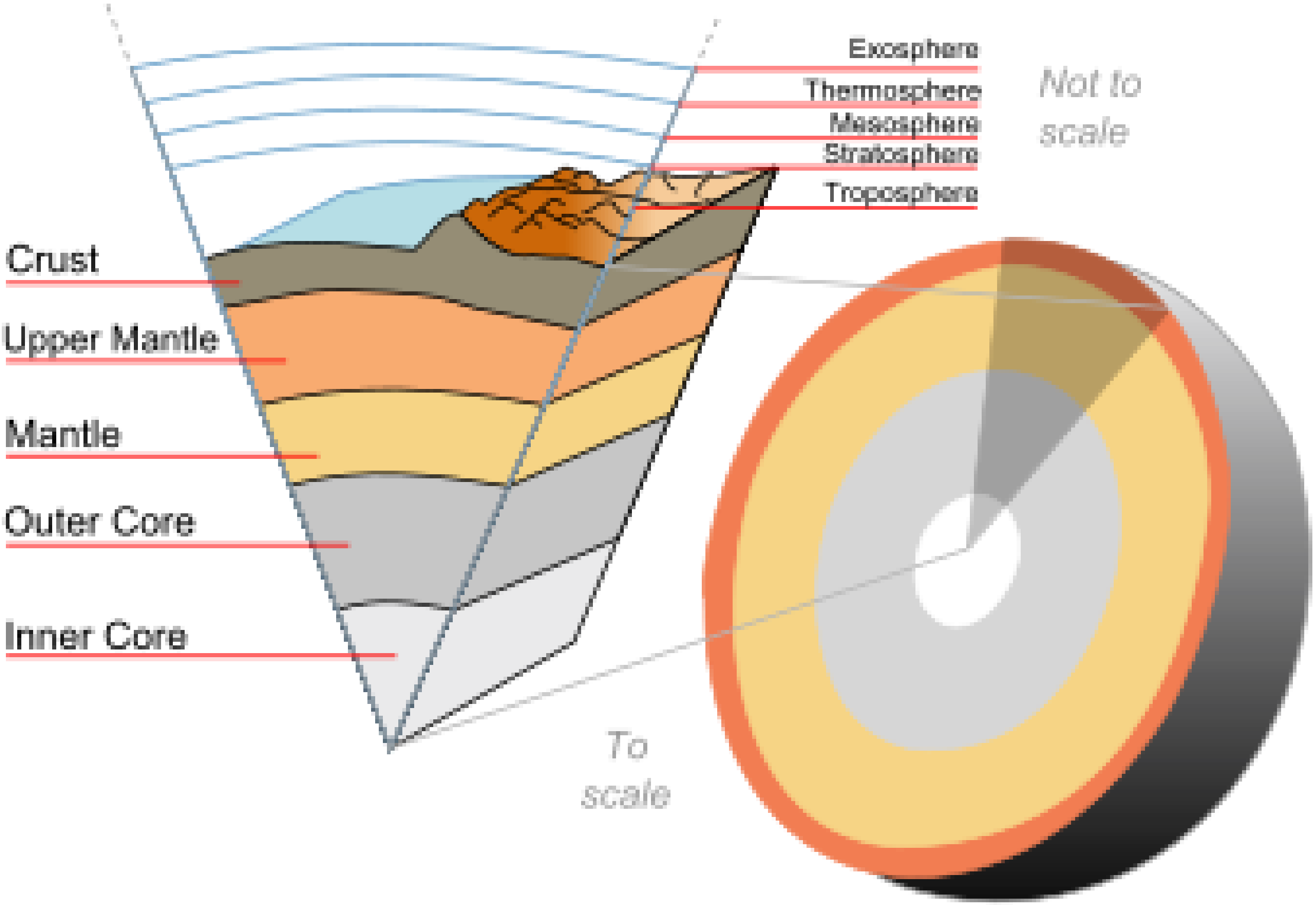
Table 11.1 Atmospheres of the Terrestrial Worlds

World	*Composition*	*Surface Pressure**	*Average Surface Temperature*	*Winds, Weather Patterns*	*Clouds, Hazes*
Mercury	helium, sodium, oxygen	10^{-14} bar	day: 425°C (797°F); night: −175°C (−283°F)	none: too little atmosphere	none
Venus	96% carbon dioxide (CO_2) 3.5% nitrogen (N_2)	90 bars	470°C (878°F)	slow winds, no violent storms, acid rain	sulfuric acid clouds
Earth	77% nitrogen (N_2) 21% oxygen (O_2) 1% argon H_2O (variable)	1 bar	15°C (59°F)	winds, hurricanes	H_2O clouds, pollution
Moon	helium, sodium, argon	10^{-14} bar	day: 125°C (257°F); night: −175°C (−283°F)	none: too little atmosphere	none
Mars	95% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 1.6% argon	0.007 bar	−50°C (−58°F)	winds, dust storms	H_2O and CO_2 clouds, dust

*1 bar ≈ the pressure at sea level on Earth.

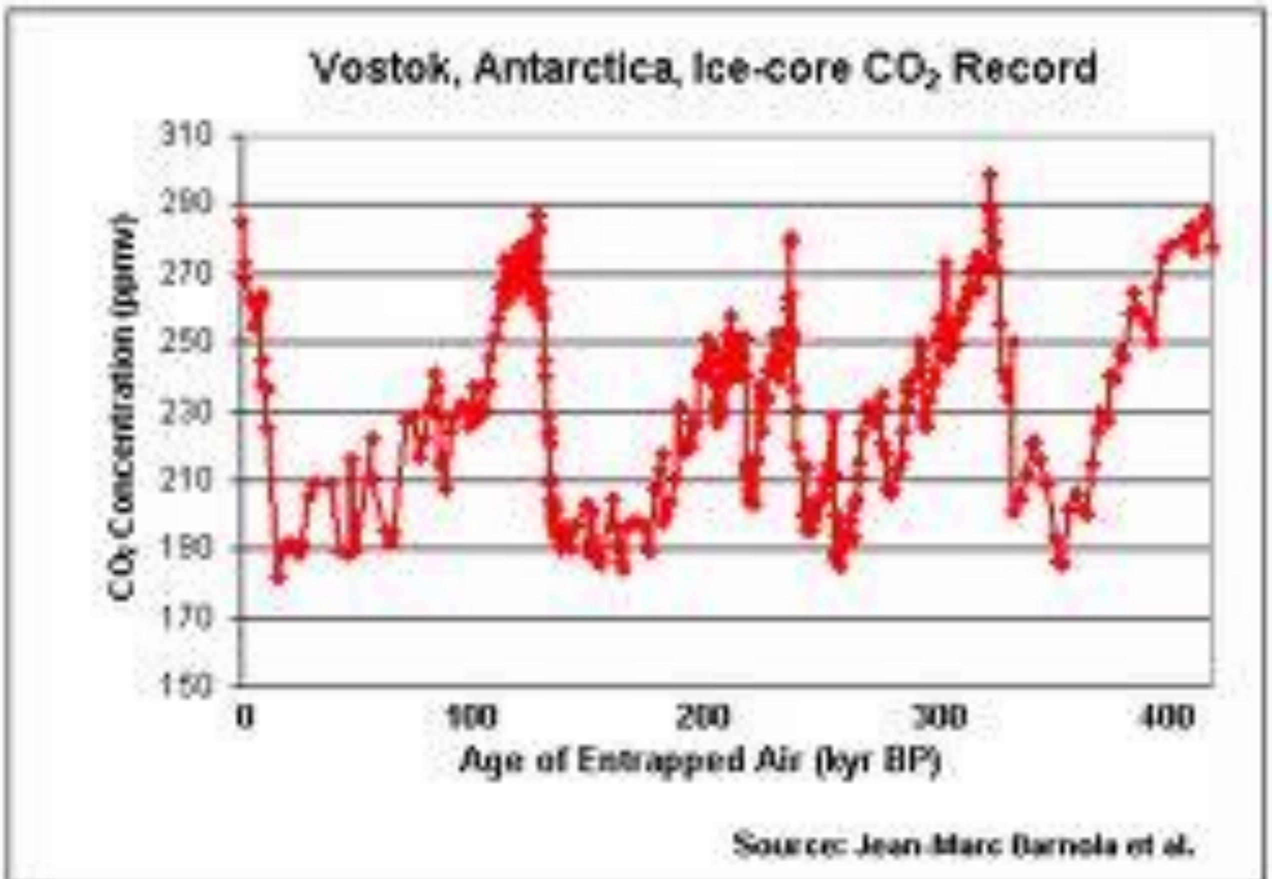
Note the relevance of clouds, weather in general and atmospheric composition. Two other very important features to be discussed later are the magnetic nature of the cores and the presence of water in controlling atmospheric carbon dioxide levels .

The core composition of the Earth might be a deciding feature for stabilising the environment



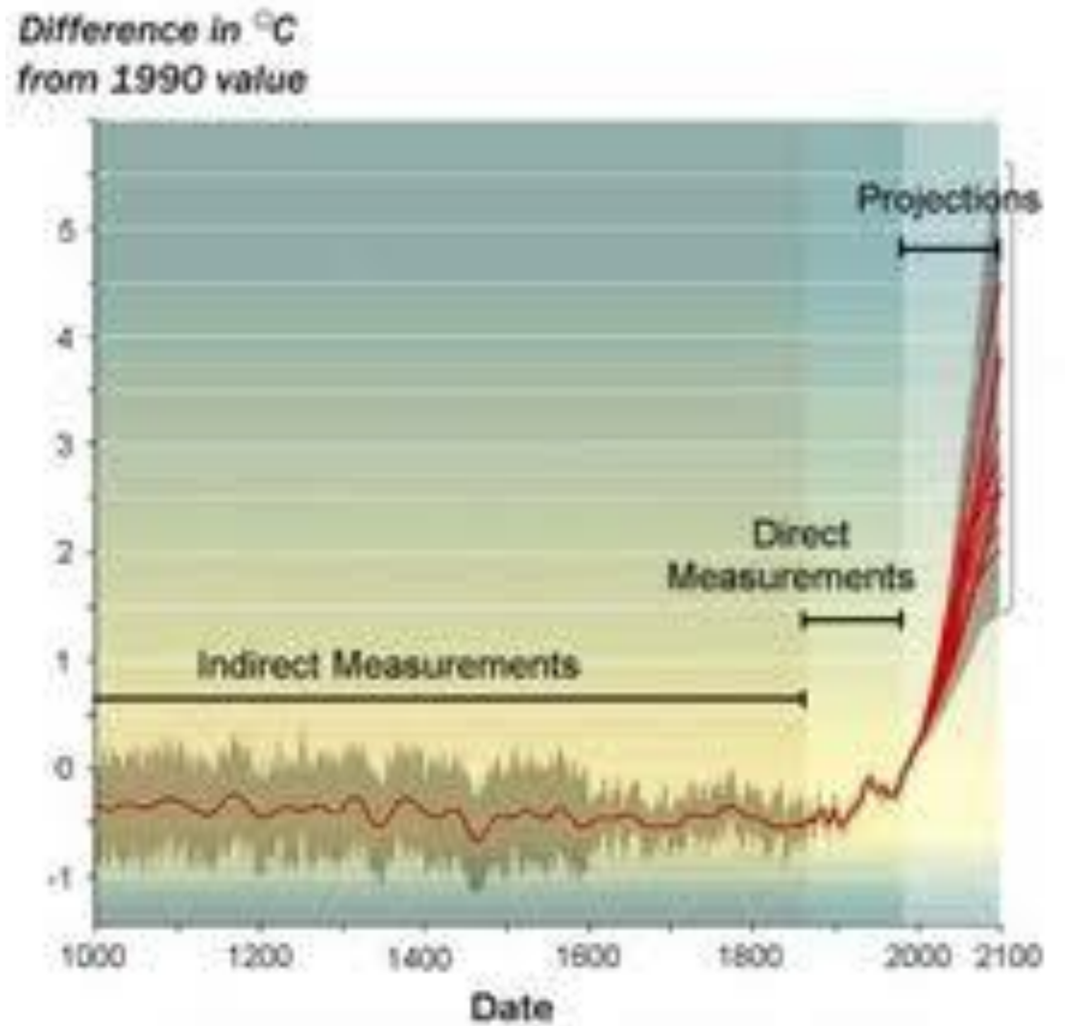
The magnetic core is important for protecting the surface from harmful solar wind - gamma and higher radiation – whilst the protective ozone layer blocks out the lower energy, but harmful to life, uv radiation

Is CO_2 really so bad? CO_2 levels on Earth from ice core sampling

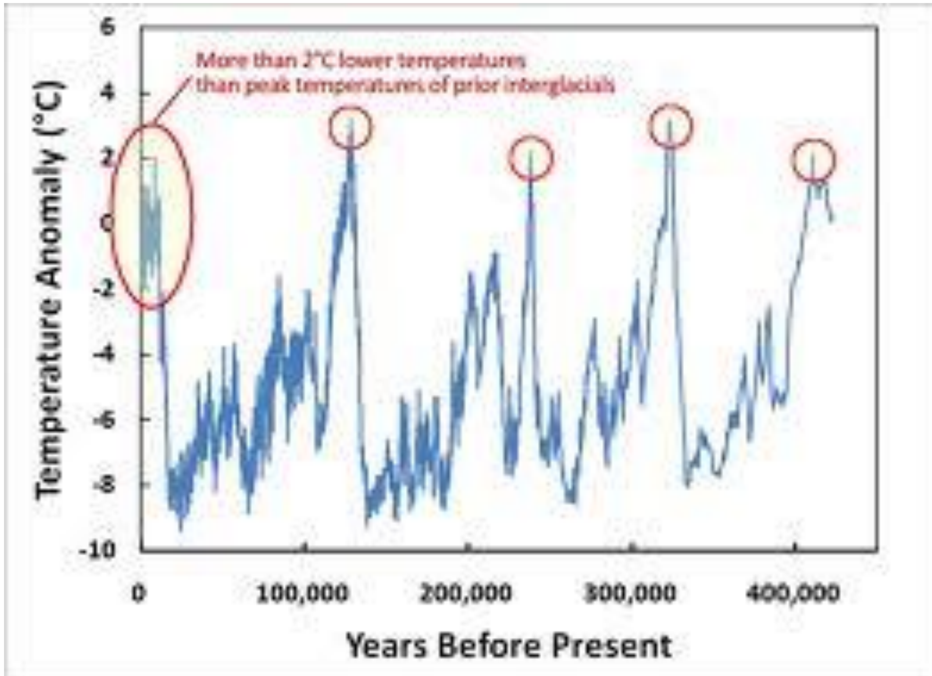


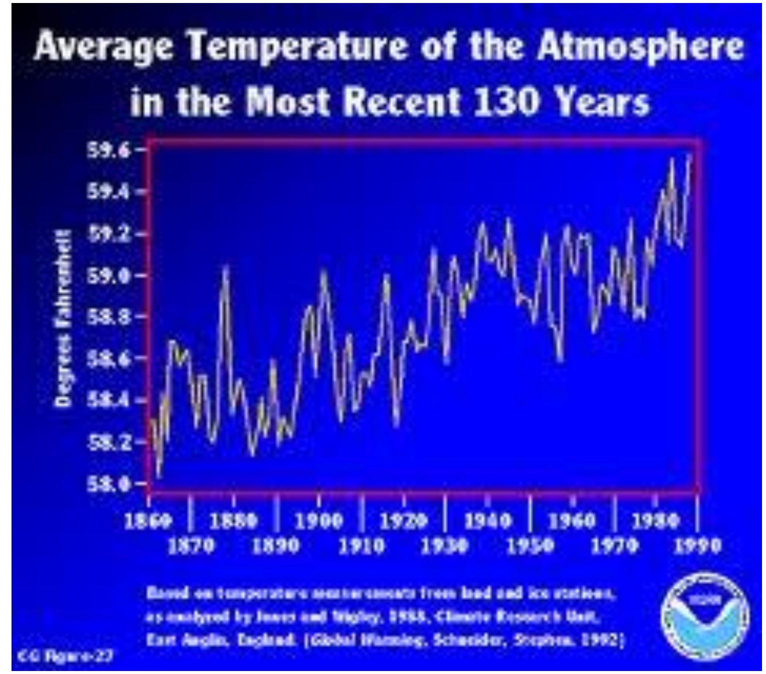
A search of the internet reveals any number of contradictory reports

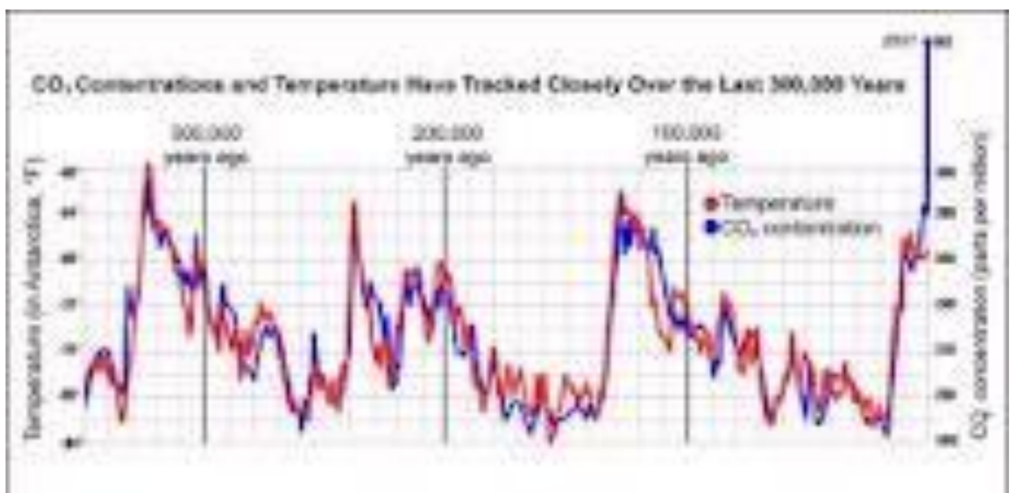
A scaremongering report suggesting a “Day after Tomorrow Scenario”.



Measured reports essentially showing the same results in different representations



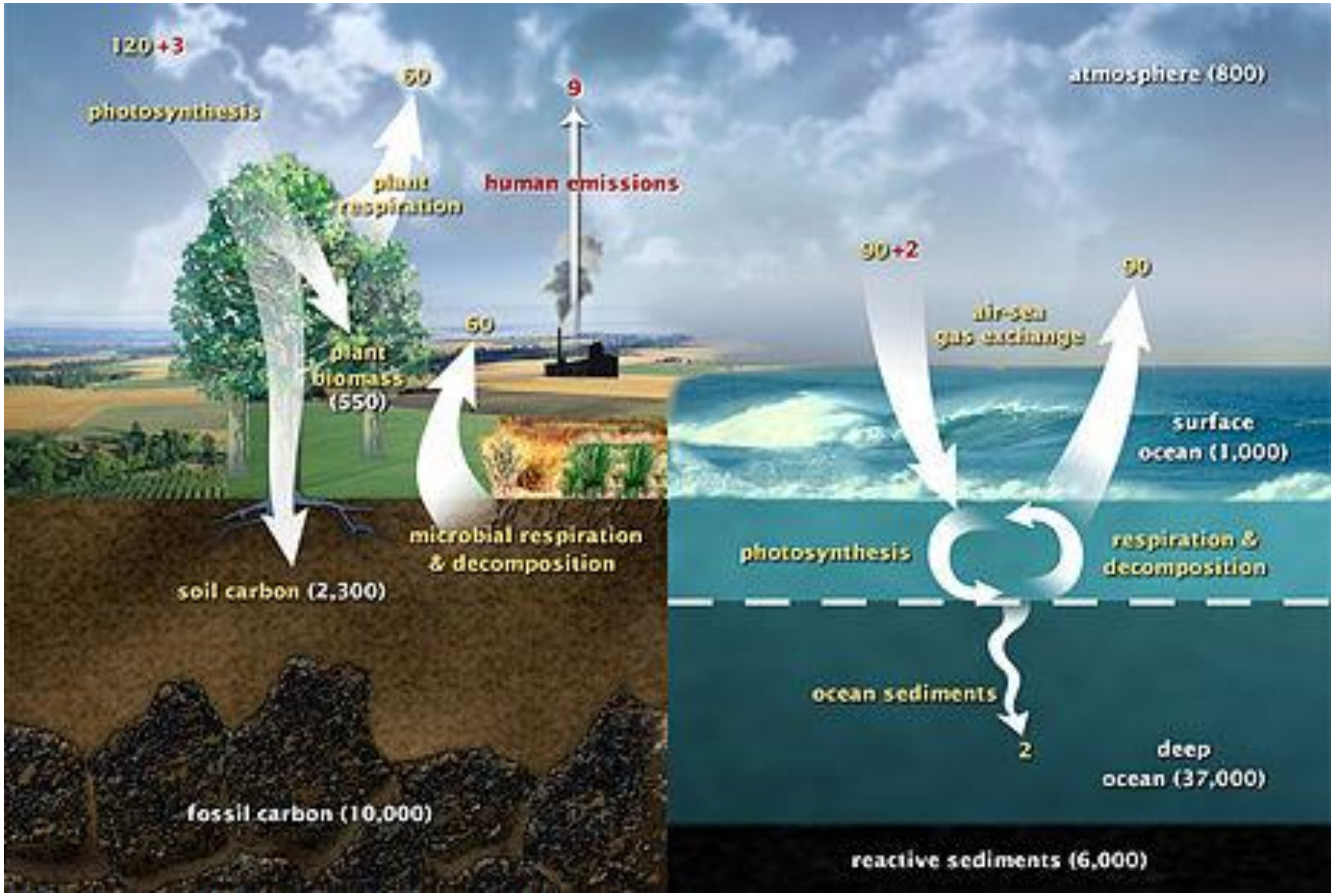




Perhaps the main problems lie in upsetting the natural biogeochemical cycling of CO_2

- Why is there so little CO_2 in the Earth's atmosphere compared with the levels on Venus and Mars?
- What trapped the water on Mars and Venus?
- Why is there so little nitrogen on Venus and Mars?
- Why does the Earth have a magnetic core?
- Did all the oxygen on Earth come from photosynthesis?
- Why is seawater a metastable solution?
- Why are rivers not salty?

The CO_2 Cycle

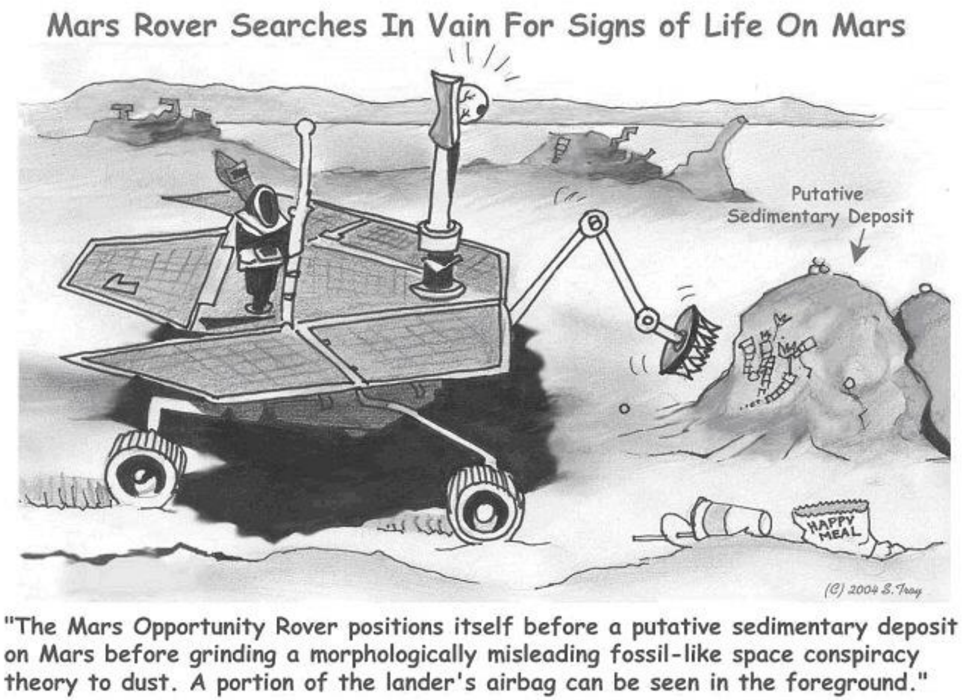


Important to contrast the land and marine interfaces for cycling of CO_2

Humans have the urge to measure and monitor their environment

- Humans seem to be unique in their desire to explore and quantify their surroundings and also in devising complicated experiments and building complex devices (as well as creating art and music)
- Understanding the processes of the natural world and the urge to discover how biological processes work as well to find ways of repairing damage to them through medical science is a central theme
- Because these processes run at the level of molecular science, chemistry – the science of atoms and the resulting molecules and the chemical bonds created by the interaction of the atoms’ electrons with each other – plays a central role
- The tools of the chemist – synthetic principles and methods, chemical analysis, physical property measurements, structure determinations, electrochemistry, supramolecular chemistry and electron structure descriptions – are all used in these studies

Is there life to be found on Mars?



The views from NASA/USA….

The moral: you have to know how to the measurements and look in the right places… and don't be fooled!