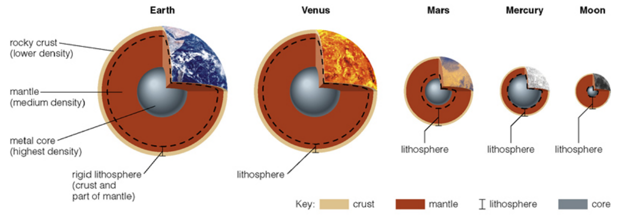
Terrestrial planets

1) Interiors
2) Vulcanism, plate tectonics
3) Surface temperatures
4) Atmospheres: densities, temperatures, composition
5) Optics: colours, clouds
6) What happened to Venus?

Interiors of the terrestrial planets

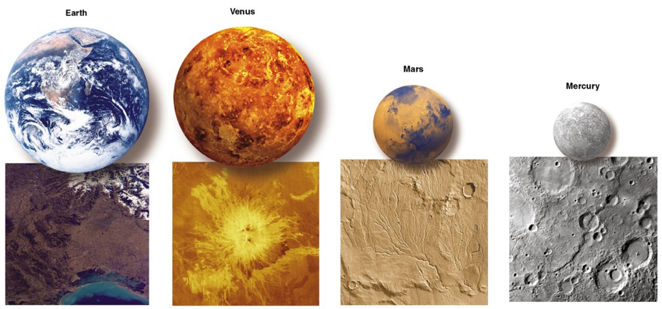
- Differentiated: dense, metallic core; inner part solid, outer fluid.
  lighter, mostly rocky mantle (*not* liquid, but can flow)
  even lighter rocky crust.
- Heat sources (other than residual heat): accretion
  differentiation/contraction
  radioactive decay
  tidal
- Heat flow: conduction in core
  convection in (outer) mantle ("rock creep"; ~100 Myr timescale)
  conduction through rigid lithosphere



Exteriors of the terrestrial planets

Shaped by four main processes:

- Impacts (many early on, now rare; can be used to "date" surfaces)
- Volcanism (Earth, Venus active; Mars maybe, maybe not; Mercury inactive)
- Plate tectonics (still active on Earth, not on Venus(?), Mars, Mercury)
- Erosion (wind, water, ...) (active on Earth, Mars; not on Venus, Mercury)



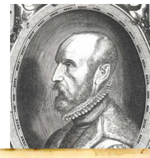
Earth has a variety of geological features visible in this photo from orbit.

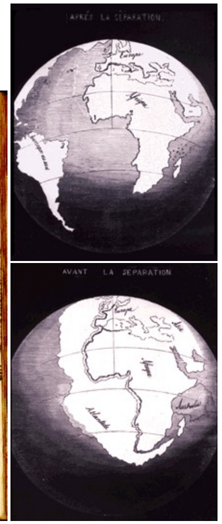
The central structure is a tall, twin-peaked volcano on Venus.

Mars has impact craters like the one near the upper right, but it also has features that look much like dried up riverbeds.

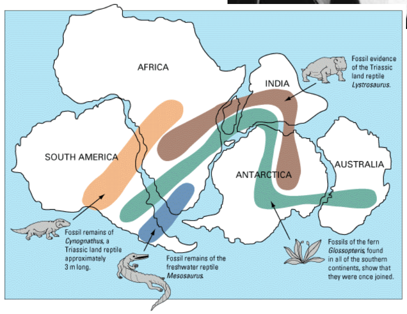
Mercury is heavily cratered, but also has long, steep cliffs—one is visible here as the long curve that passes through the center of the image.

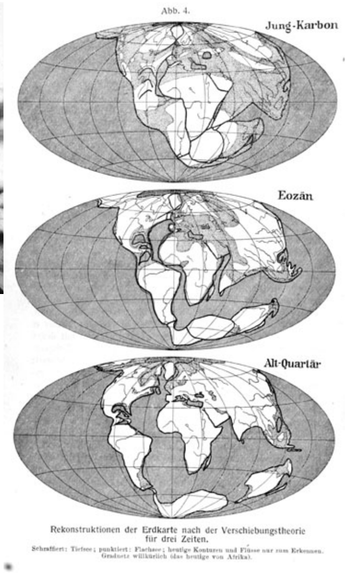
Continental Drift



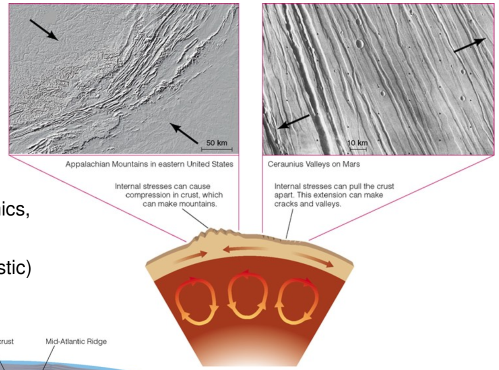


Continental Drift





Tectonics



Venus shows signs of tectonics,
but not plate tectonics.
Due to absence of water?
(water makes rock more plastic)

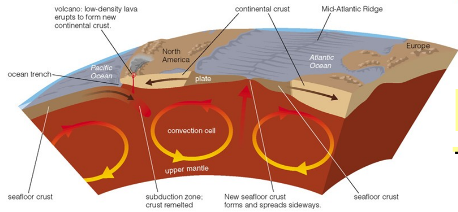
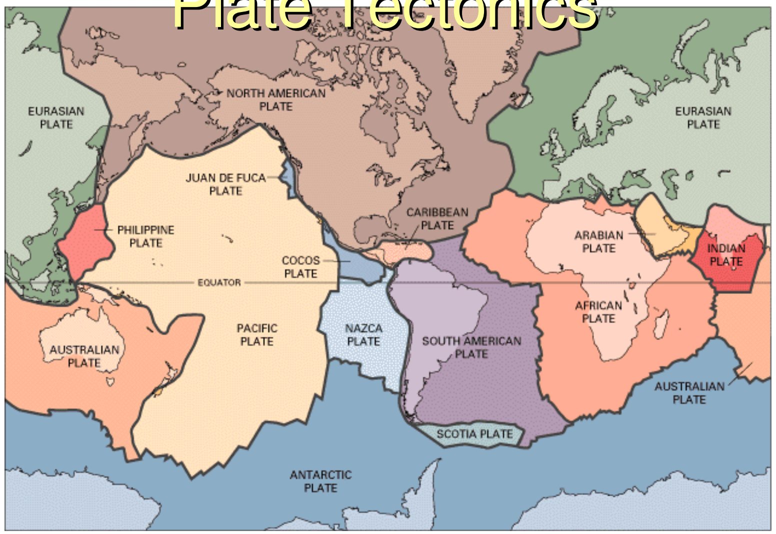
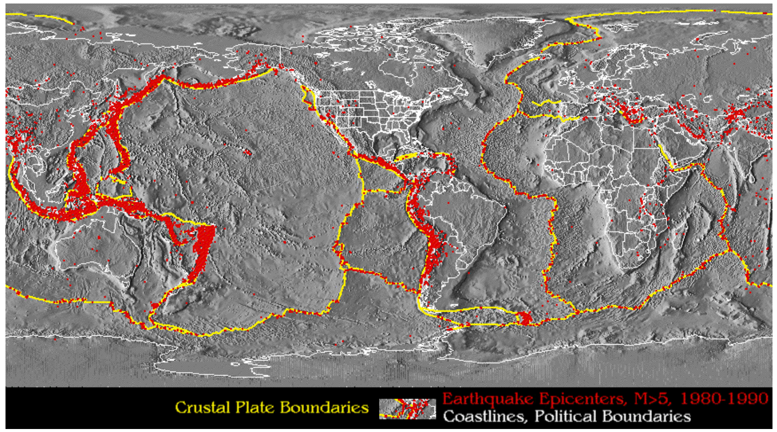


Plate Tectonics

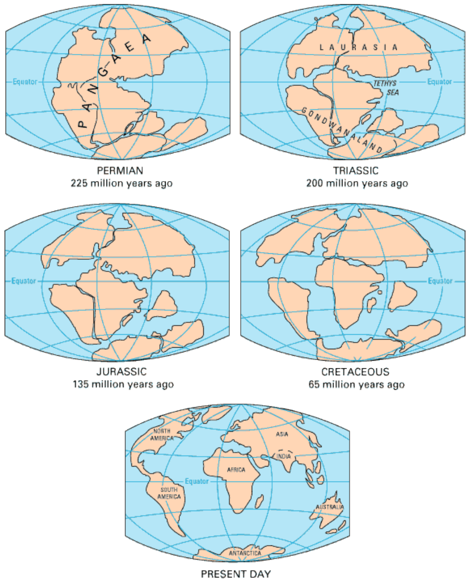
Plate Tectonics



Plates and Earthquakes



Long Term Effects



Passively Heated by the Sun *--- the further the cooler*

Typically we observe objects in reflected light, however, all objects emit re-processed thermal radiation which is observable at longer wavelengths.

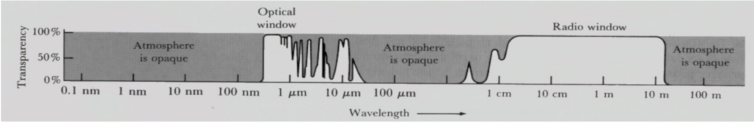
Blackbody temperature for a non-self-luminous spherical body at distance **a** away from the Sun (with albedo A -- reflectivity)

$$L_{abs} = (1-A)\frac{\pi R_p^2}{4\pi a^2} 4\pi R_s^2 \sigma T_s^4; \quad L_{em} = 4\pi R_p^2 \sigma T_p^4$$

$$\text{If } L_{abs}=L_{em}, \text{ then } \quad T_p = \left(\frac{R_o}{2a}\right)^{1/2} T_s (1-A)^{1/4}$$

	a (AU)	A	T_{pred}(K)	T_{act}(K)	
Mercury	0.4	0.06	422 K	100-725	(?)
Venus	0.7	0.77	230K	733	(?)
Earth	1	0.30	255K	288	(?)
Mars	1.5	0.25	218K	223	good

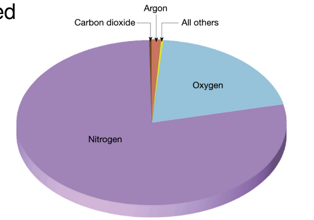
Greenhouse effect: optical radiation from the Sun reaches the ground, but the infrared radiation from the ground cannot easily escape.



Atmospheres: Terrestrial Planets

	Composition	surface pressure/T	
Mercury	--	< 10^{-12} bar	100-725 K
Venus	97% CO_2, 3% N_2	92 bar	733 K (460°C)
Earth	78% N_2, 21% O_2,1% Ar	1 bar	288 K (15°C)
Mars	95% CO_2,3% N_2,1.6% Ar	0.006 bar	223 K (-50°C)
Titan (@S)	95% N_2, few% CH_4,Ar	1.5 bar	93 K (-180°C)

Most atmospheres are reasonably well-mixed (no molecular weight separation)



Earth's atmospheric composition
From http://www.ux1.eiu.edu/~cfjps/1400/atmos_origin.html

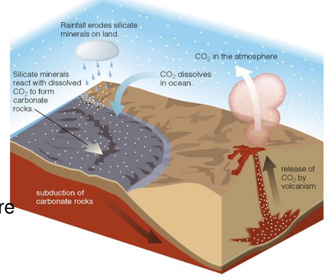
CO_2 cycle and Earth's Thermostat

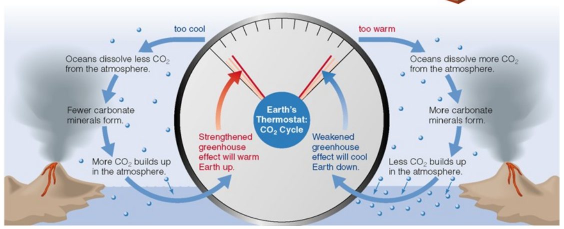
Venus has so much CO_2; where has it gone on Earth?

Sink: CO_2 dissolves in water, and reacts with silicates eroded by rain. Forms *carbonate rocks.*

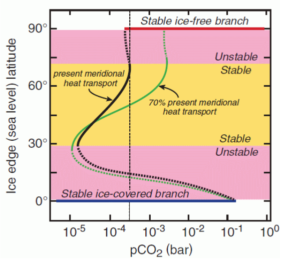
Source: volcanoes.

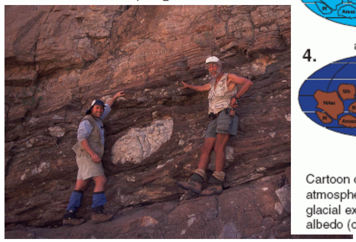
Earth's thermostat: Sink depends on temperature (source does not)



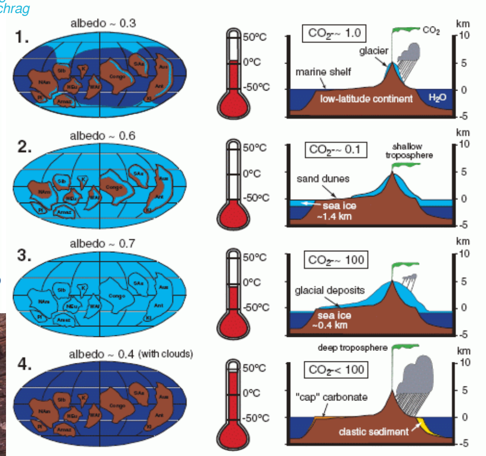


For details, see http://www.snowballearth.org/
Figures taken from a paper by Hoffman & Schrag
(the link to which has disappeared).





SNOWBALL FREEZE-FRY SCENARIO



Cartoon of one complete 'snowball' episode, showing variations in planetary albedo, atmospheric carbon dioxide, surface temperature, tropospheric depth, precipitation, glacial extent, and sea ice thickness. Stage 1. incipient glaciation; 2. runaway ice-albedo (onset of 'snowball'); 3. end of 'snowball'; 4. transient 'hothouse' aftermath.

Density & Temperature of our atmosphere

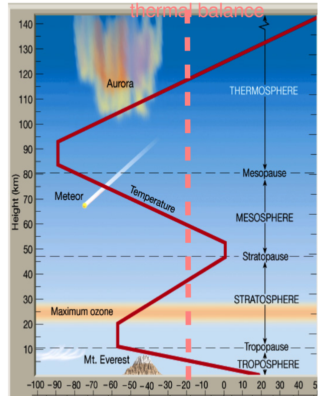
1) Temperature roughly **isothermal;**
   density decreases exponentially, H ~ 8 km

   Three local departures (T maxima)

   - Thermosphere absorbs X rays (~2000 K)
   - Stratosphere absorbs UV (O_3)
   - Ground absorbs whatever passes

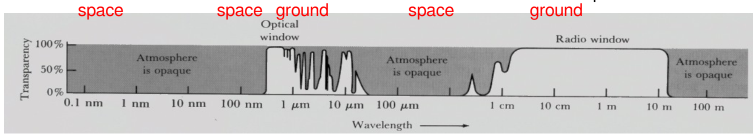
2) Atmosphere largely transparent in optical, but opaque in infrared → green-house effect

   - Troposphere heated by ground → turbulent → twinkling stars, planes fly @ ~10km
   - Astronomical observations: overcome turbulence & avoid absorption



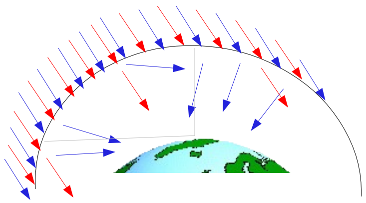
cold temperature hot

space space ground space ground



Atmospheric optics: I) Why is the sky blue on Earth? Rayleigh scattering

air molecules & other constituents (N_2, O_2, H_2O droplets, dust...) all have sizes smaller than optical λ, and they preferentially scatter short-λ photons: $\sigma \sim 1/\lambda^4$

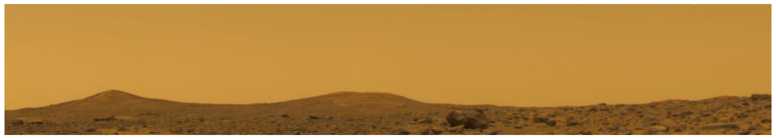


Earth: *sky is blue (--> ocean blue)*
sunset is red (reddened)
horizon whiter than zenith
Fall/Winter sky dark blue
UV is diffuse

Moon: *sky is black*

Mars: *sky is reddish yellow*
fine-dust (1-10μm) Mie scattering --> white
iron oxide mineral absorption in the blue --> reddish

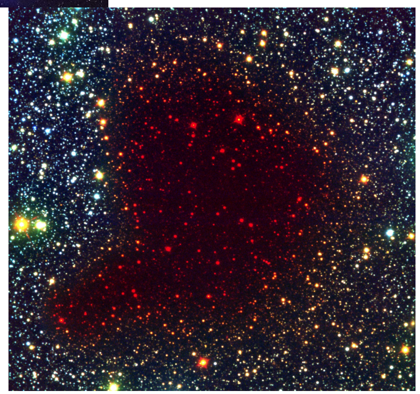
Mars Pathfinder true-color picture of Martian noon



Example of Rayleigh Scattering: *Interstellar Reddening*

1. interstellar space not empty
2. interstellar molecules & dust grains r < λ
3. scattered away – blue; transmitted – red

blue reflection nebula of Pleiades



Barnard 68

why is the Moon red during a lunar eclipse?

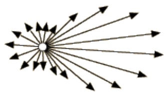
Atmospheric optics: II) Clouds

What are clouds? Aggregates of water or ice droplets suspended in air
In troposphere: low clouds-- water; high clouds-- ice

How do they form? 100% hum. + condensation nuclei (dust, cosmic-rays)
e.g., rising air that cools (--> humidity increases)

Why are clouds white? Water droplet colorless, solar light white
Mie scattering (droplets size r ~ 10μm > λ),
nearly geometric optics, no λ dependence
(at sunset, cloud is red)
soap foam: geometric scattering, also no λ dep.

Mie Scattering



Why don't clouds fall from the sky?
Tiny droplets, fall slowly; updraft mixing?
Fall and evaporate and form new ones?
Electrically charged clouds?

Origin of Earth's atmosphere

Our (& Venusian) atmosphere cannot be primordial

1) N_2, CO_2, H_2O are not condensed at 1AU from Sun, O_2 does not naturally occur
2) Earth too low in mass to accrete gas directly
3) Gas is unlikely to have been trapped in solids and dragged to Earth, since noble gases (Ne, Kr, Xe) are heavily depleted relative to solar abundance.
4) New-born Earth molten and hot (10^3K) --> most gases can escape thermally.

Some relief only in that in the early bombardment period (~ 700 Myr) water can be brought in by comets & asteroids.
(Note: D/H ratio in comets ~2 higher than ocean, so these cannot do it alone)

Origin of Earth's atmosphere (cont'd)

Our atmosphere is obtained gradually: volcanic outgassing & invaders

	1st atmosphere	2nd atmosphere	3rd atmosphere
	thermal escape	**outgassing/accretion**	**absorbing CO_2**
	H & He(?)	CO_2/NH_3 outgassed	most H_2O liquid
		H_2O accreted/outgassed	CO_2 got locked in
		(solid crust/ocean, 3.5Gyrs ago)	O_2 produced
P:	?	~100 bar (like Venus!)	~1 bar
T:	~10^3K	$0^oC < T < 100^oC$	~15^oC

sinks of CO_2: sedimentary rock via H_2O, life (carbon) via photon-synthesis
sources of CO_2: volcanic outgassing (+human activities)
sinks of H_2O: subducting plates
sources of H_2O: outgassing, comets/asteroids?

Currently sensitive balance reached, mild green-house
run-away green-house: too much CO_2, H_2O can all disappear
$\rightarrow$ sink disappears as well while outgassing produces yet more CO_2

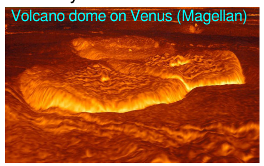
Venus: divergent evolution from Earth

	a(AU)	mass(M_E)	spin	atm. Pressure	T	plate tect.	ocean
Earth:	1	1	1 day	1bar	288 K	Yes	Yes
Venus:	0.7	0.8	243 day	92bar	770 K	No	No

1) 97% CO_2 in the atmosphere, ~ 700K, *no CO_2 sink due to dryness*

2) Why so dry? high D/H ratio indicates past large H_2O reserve
Green-house runaway and H_2O photo-evaporated

3) Cratering no older than ~0.8 Gyr $\rightarrow$ tectonics stopped recently


Volcano dome on Venus (Magellan)

A planet is a nonlinear system.
Strongly divergent evolution can occur.

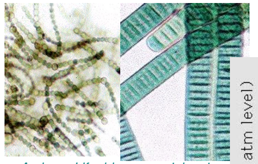
Cause & Effect?

1) Slightly closer to the Sun and got torched?
Or formation site had naturally less H_2O?

2) Too much CO_2 to start with and H_2O never condensed
(But: Initial Earth atm. ~100 bar, mostly CO_2 --> would require *fine tuning*?)

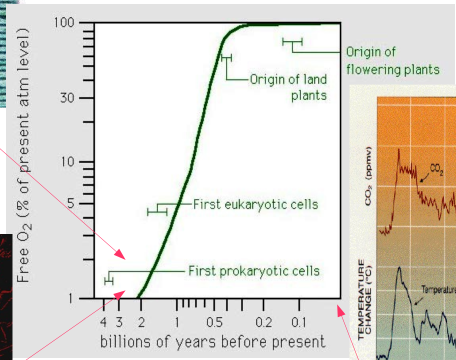
The Story for Mars: 2nd atmosphere gradually lost, no outgassing (tectonics)

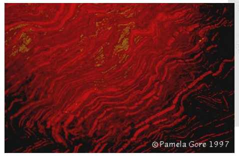
Origin of O_2 on Earth: photosynthesis; $CO_2 + H_2O + h\nu \rightarrow O_2$ + carbo-hydrate



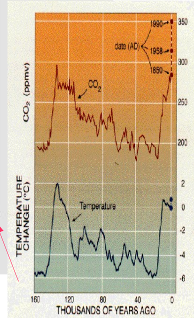
Archean Life: blue-green 'algae' or cyanobacteria (3.5-2.2 BYA) anerobic

From http://www.clas.ufl.edu/users/mrosenme/Oceanography





Red-banded un-oxidized iron-rich rocks, pre-cambrian, ~2.5BYA
http://www.dc.peachnet.edu/~pgore/geology/geo102/precamb.htm



CO_2 and atm. T correlation
(April 1989, Scientific. American)