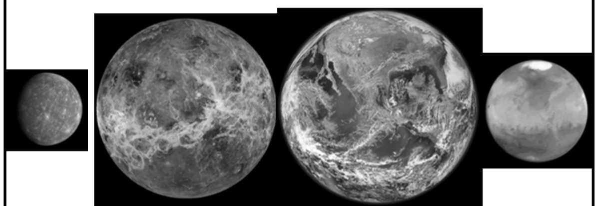
Lecture 23:

Terrestrial Worlds in Comparison



Astronomy 141 – Winter 2012

This lecture compares and contrasts the properties and evolution of the 5 main terrestrial bodies.

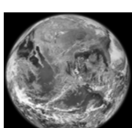
The small terrestrial planets have old surfaces and cold interiors.

The large terrestrial planets have young surfaces and hot interiors.

All terrestrial planets probably started with substantial atmospheres, but subsequent evolution was different.

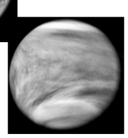
Atmosphere evolution is driven by a combination of the greenhouse effect, the presence or absence of liquid water, and the gravity of the planet.

The Terrestrial Planets



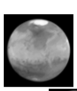
<u>Large Bodies</u>:

Earth (1 R_E, 1 M_E)



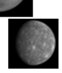
Venus (0.95 R_E, 0.82 M_E)

<u>Small Bodies</u>:



Mars (0.53 R_E, 0.11 M_E)

Mercury (0.38 R_E, 0.055 M_E)

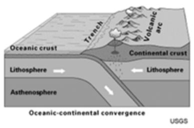


Moon (0.27 R_E, 0.012 M_E)

The evolution of planetary surfaces is driven by impact cratering, volcanism, and tectonism.

Impact cratering is only important during the first Gyr of the Solar System.

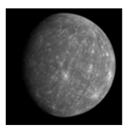
Volcanism & Tectonism are driven by the internal structure of the planets.



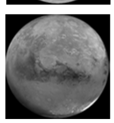
Is the interior hot enough to for tectonics or volcanism?

The surfaces of the small terrestrial planets were shaped primarily by impacts and early volcanism

Mars, Mercury & the Moon:
- Old, heavily cratered surfaces >3 Gyr old
- Single, continuous crust (no plates)
- Vertical Tectonism (stationary upwelling)

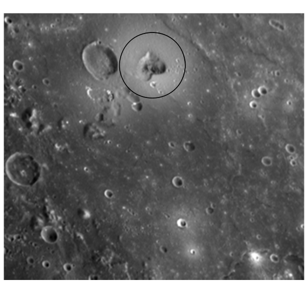


Crustal Shaping:
- Primary crust: shaped by impacts
- Secondary crust: shaped by volcanism

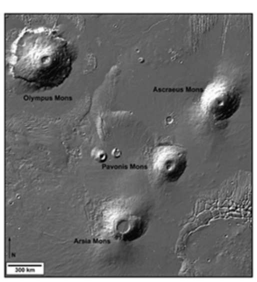


Lava plains (Maria) on the Moon
Lava plains and volcanic vents on Mercury
Hot-spot volcanoes on Mars

Evidence of past volcanism on Mercury and Mars

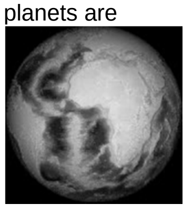


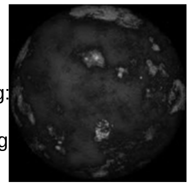
Volcanic vents on Mercury
[MESSENGER]



Hot Spot Shield Volcanoes on Mars
[NASA MGS]

The surfaces of the large terrestrial planets are young, with active tertiary crusts.





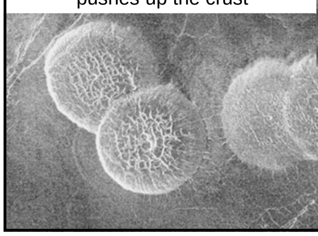
Earth's surface is ~100 Myr old

Venus' surface is ~500 Myr old

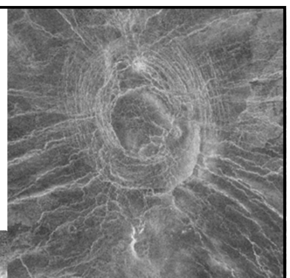
Earth: plate tectonics & lateral recycling: subduction, sea-floor spreading & Up-thrust constantly rebuild the crust.

Venus: one-plate crust & vertical recycling: volcanoes over mantle upwelling, compression over mantle down-welling

Vertical recycling tectonism on Venus

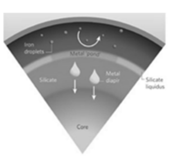


Pancake Domes
Magma upwelling
pushes up the crust



Corona
Magma down-welling
collapsing the crust

Internal heating & subsequent cooling drives the evolution of planetary interiors.



First Stage: Differentiation (heat of formation)

- Dense molten metals sink into the core.
- Lighter silicate rocks float to the crust.

Second stage: Volcanism

- Mantle still molten due to internal heating by radioactive decay and heavy impacts.
- Magmas rise to the surface as volcanoes

The cooling time of a terrestrial planet scales as the size of the planet.

Start with the total internal thermal energy:

$$Total\ Energy = const \times R^3 T$$

Cool by radiation losses from the surface:

$$Energy\ Loss\ Rate = 4\pi R^2 \sigma T^4$$

The Cooling Time is the ratio of the total energy to the loss rate:

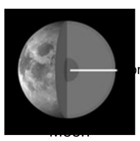
$$Cooling\ Time = const \times \frac{R}{T^3}$$

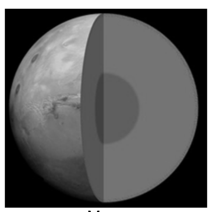
Hotter bodies cool faster than cooler bodies.
Larger bodies cool more slowly than small bodies.

The interiors of the small terrestrial planets cooled rapidly and have mostly solidified.

A solid mantle ends tectonic activity.

All have thick, cool, rigid crusts.





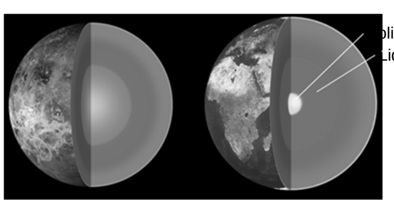
Mars

Mercury has signs of ancient volcanic vents.

Mars has large, extinct shield volcanoes.

The large terrestrial planets cool more slowly and are still hot.

Kept hotter longer by energy released from the decay of radioactive elements.



Convective motions in molten mantles drive tectonism and gives them active tertiary crusts.

The atmospheres of all of the terrestrial planets started out roughly similarly.

During formation, the terrestrial planets were molten from impacts with planetesimals:

- Fewer volatiles close to the proto Sun (too hot)
- Get more volatiles moving out into the Solar System (cooler)

Primordial Atmosphere Formation:

- Outgassing from volcanoes
- Comet impacts delivering frozen volatiles
- Primary gases are CO_2, H_2O, & N_2

All started with CO_2 , N_2, & H_2O atmospheres.

The evolution of Terrestrial Planet atmospheres is driven by three primary effects:

Greenhouse Effect:

- Solar heating & atmospheric cooling balance
- Helps determine if H_2O is liquid, ice, or vapor

Planetary Gravity:

- Determines a planet's ability to retain hot atoms & molecules.

Chemistry of CO_2 and H_2O:

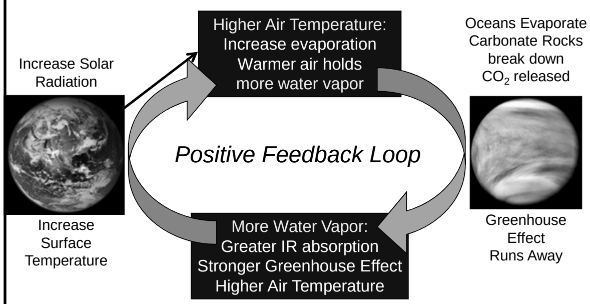
- CO_2 is easily dissolved in liquid H_2O
- Help determine the atmospheric CO_2 content, and its contribution to the Greenhouse Effect.

The Greenhouse Effect makes the temperature warmer than if there was no atmosphere.

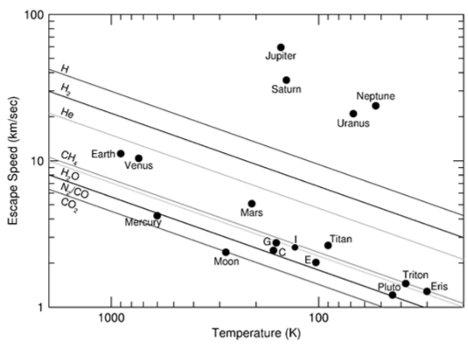
	Without Atmosphere	With Atmosphere	Water
Earth	255K	287K	Liquid
Venus	280 K	750 K	Vapor
Mars	214 K	220 K	Ice

But: It can be an unstable process…

Runaway Greenhouse Effect



The ability of a planet to retain atmospheric gasses depends on its mass and temperature.



Mercury is too hot for liquid water, and its gravity too weak to retain an atmosphere.

Lack of liquid water shutdown CO_2 and H_2O chemistry resulting in a *Runaway Greenhouse Effect*

Surface gravity was too weak to hold onto its hot atmosphere, so it lost all of its volatiles after ~1 Gyr

Result: *Mercury has no atmosphere today*

Venus' Atmosphere was also too hot for liquid water, but large enough to retain its atmosphere.

May have had early oceans that evaporated resulting in a *Runaway Greenhouse Effect.*

Gravity is strong enough to retain its atmosphere, so ended up with a hot, heavy CO_2 and N_2 atmosphere.

All of the H_2O lost to UV photolysis
H_2 escaped and the O reacted with other gasses.

Result: *Venus has a bone dry, hot, heavy CO_2 atmosphere*

Earth's Atmosphere was warm enough for abundant liquid water, and large enough to keep it.

The H_2O condensed into massive, deep oceans and setup a water cycle of evaporation and precipitation.

CO_2 chemistry in liquid water results in most of the CO_2 locked up in the oceans & carbonaceous rocks.

Plants thrive in liquid water, converting CO_2 into O_2
A mild Greenhouse Effect keeps water liquid.

Result: *Earth has a warm, moist N_2 & O_2 atmosphere*

Mars' Atmosphere may have been warm enough for liquid water during first Gyr, but too weak to keep it.

Some CO_2 locked into carbonaceous rocks??
Evidence of past water from the Mars Rovers.

As Mars cooled, the H_2O froze out (most may already have been frozen into saturated rocks).

Remaining CO_2 and N_2 escapes Mars' weak gravity, aided by the solar wind because of a weak magnetic field.

Result: *Mars has a cold, dry, thin CO_2 atmosphere today, but might have been hospitable in the past.*

The *present-day* terrestrial planet atmospheres are different outcomes of atmosphere evolution from similar starting points.

	Earth	Venus	Mars
CO_2	0.035%	96%	95%
N_2	77%	3.5%	2.7%
H_2O	1%	0.01%	0.007%
Ar	0.93%	0.007%	1.6%
O_2	21%	trace	trace
Temp	287K	750K	220K
	Habitable	Inhospitable Today	