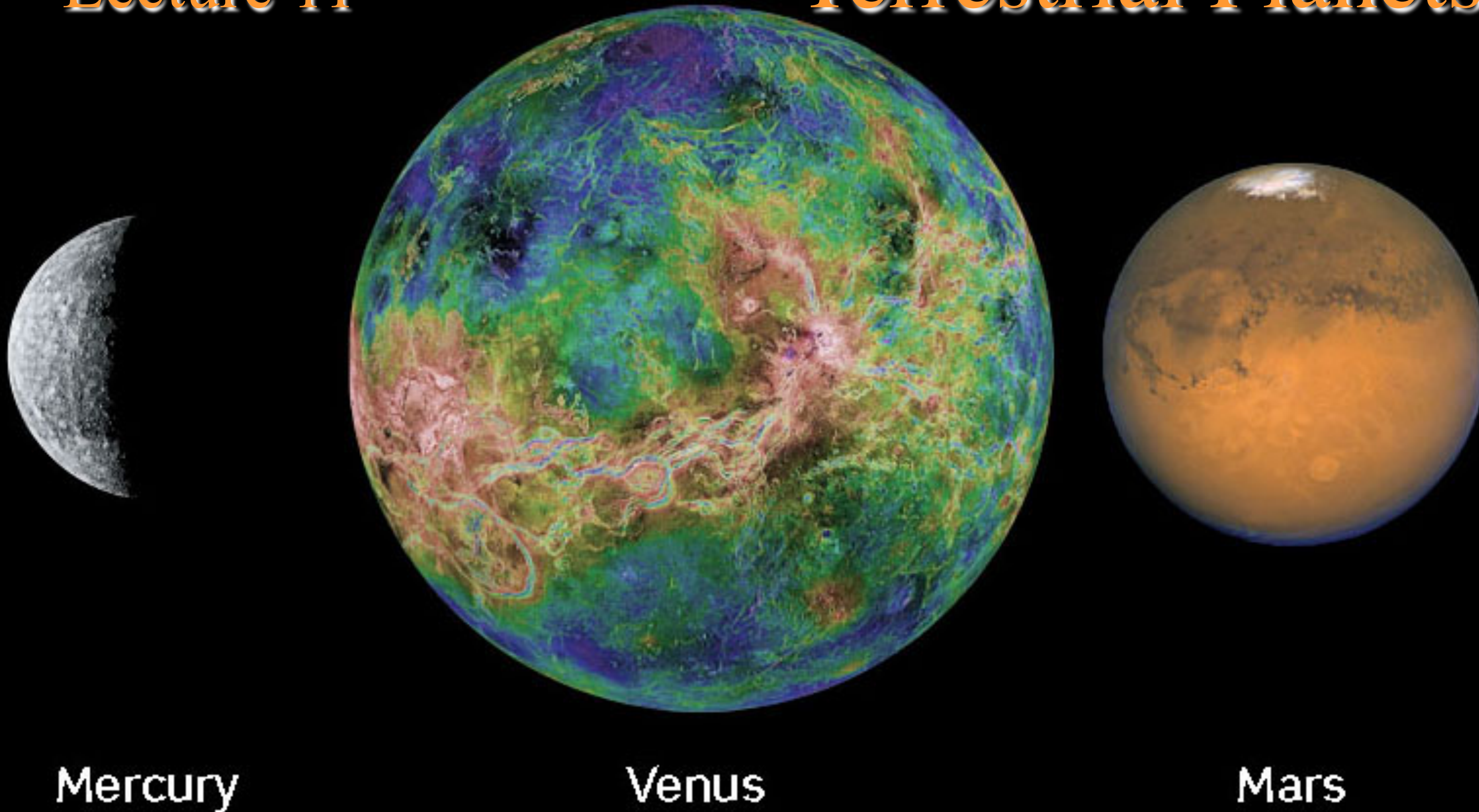
Lecture 11

Terrestrial Planets



Jiong Qiu, MSU Physics Department

Guiding Questions

1. What makes Mercury a difficult planet to see?
2. Why Venus is a bright morning and evening star?
3. What are special about orbital and rotation motions of Mercury?
4. What are special about orbital and rotation motions of Venus?
5. How and why atmosphere of Venus is drastically different from Earth's?
6. What effect does it have on the planet's temperature?
7. How do surface features and geological activities compare in terrestrial planets and the Moon?

11.1 Overview

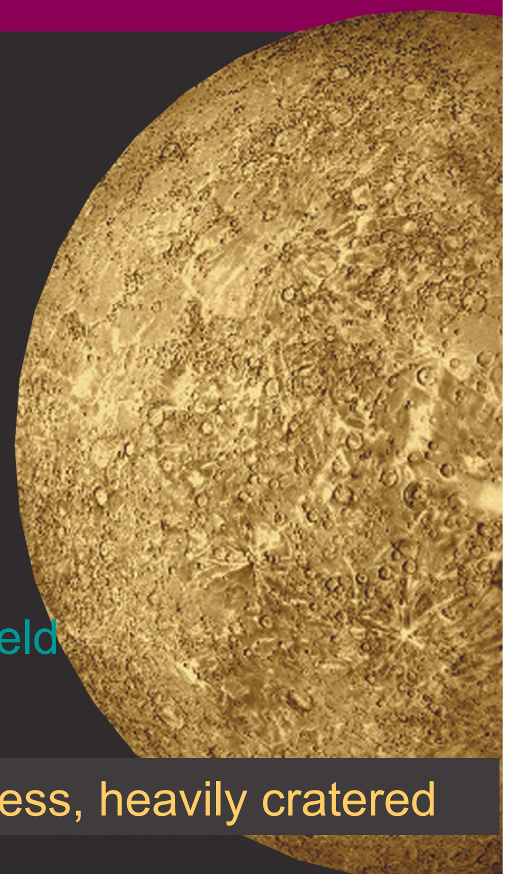
the terrestrial (inner) planet

	Mercury	Venus	Earth	Mars
Average distance from Sun (10^6 km)	57.9	108.2	149.6	227.9
Average distance from Sun (AU)	0.387	0.723	1.000	1.524
Orbital period (years)	0.241	0.615	1.000	1.88
Orbital eccentricity	0.206	0.007	0.017	0.093
Inclination of orbit to the ecliptic	7.00°	3.39°	0.00°	1.85°
Equatorial diameter (km)	4880	12,104	12,756	6794
Equatorial diameter (Earth = 1)	0.383	0.949	1.000	0.533
Mass (kg)	3.302×10^{23}	4.868×10^{24}	5.974×10^{24}	6.418×10^{23}
Mass (Earth = 1)	0.0553	0.8150	1.0000	0.1074
Average density (kg/m^3)	5430	5243	5515	3934

Mercury has a Moon-like surface but Earth-like interior. It also has its own unique properties.

Mercury Data

Average distance from Sun:	0.387 AU = 5.79×10^7 km
Maximum distance from Sun:	0.467 AU = 6.98×10^7 km
Minimum distance from Sun:	0.307 AU = 4.60×10^7 km
Eccentricity of orbit:	0.206
Average orbital speed:	47.9 km/s
Orbital period:	87.969 days
Rotation period:	58.646 days
Inclination of equator to orbit:	0.5°
Inclination of orbit to ecliptic:	7° 00′ 16″
Diameter (equatorial):	4880 km = 0.383 Earth diameter
Mass:	3.302×10^{23} kg = 0.0553 Earth mass
Average density:	5430 kg/m^3
Escape speed:	4.3 km/s
Surface gravity (Earth = 1):	0.38
Albedo:	0.12
Average surface temperatures:	Day: 350°C = 662°F = 623 K
	Night: −170°C = −274°F = 103 K
Atmosphere:	Essentially none



elliptical orbit
coupled spin-orbit

dense,
magnetic field

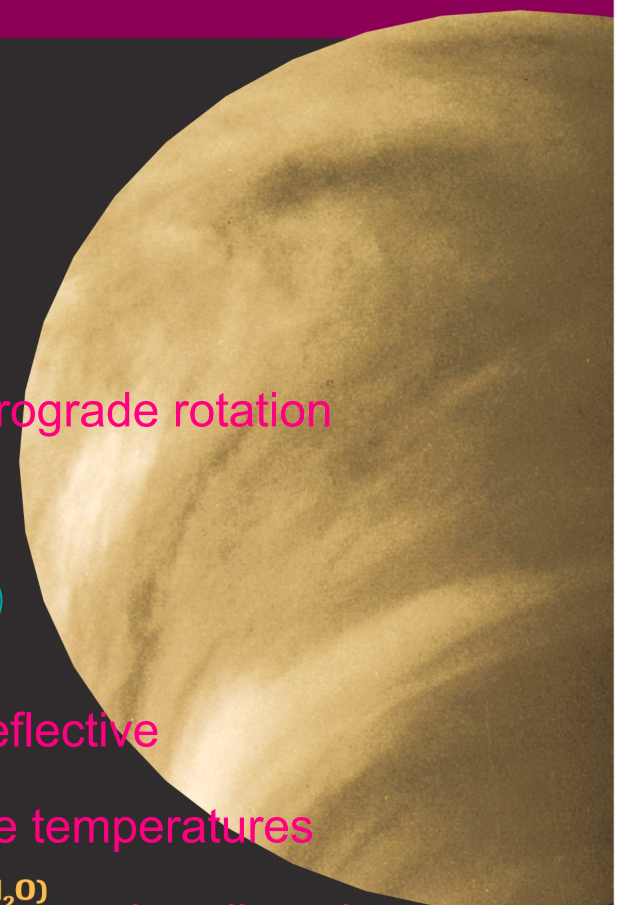
dry, airless, heavily cratered

Mercury is small and closest to the Sun.

Venus might be thought as the twin sister of the Earth with many similarities, yet differences abound.

Venus Data

Average distance from Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from Sun:	0.718 AU = 1.075×10^8 km
Eccentricity of orbit:	0.0068
Average orbital speed:	35.0 km/s
Orbital period:	224.70 days
Rotation period:	243.01 days (retrograde)
Inclination of equator to orbit:	177.4°
Inclination of orbit to ecliptic:	3.39°
Diameter (equatorial):	12,104 km = 0.949 Earth diameter
Mass:	4.868×10^{24} kg = 0.815 Earth mass
Average density:	5243 kg/m^3
Escape speed:	10.4 km/s
Surface gravity (Earth = 1):	0.91
Albedo:	0.59
Average surface temperature:	460°C = 860°F = 733 K
Atmospheric composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5% nitrogen (N_2), 0.003% water vapor (H_2O)



slow retrograde rotation

highly reflective

extreme temperatures

throttling air

Venus has a very thick atmosphere and is hotter than should.

- observation of terrestrial planets: their positions in the sky and their phases.
- orbital and rotation motions

  Kepler's third law: $a^3=P^2$

  spin-rotation coupling

role of gravitation

- atmospheres and energy balance

  greenhouse and icehouse effects

- surface, interior, geological activity, and magnetism

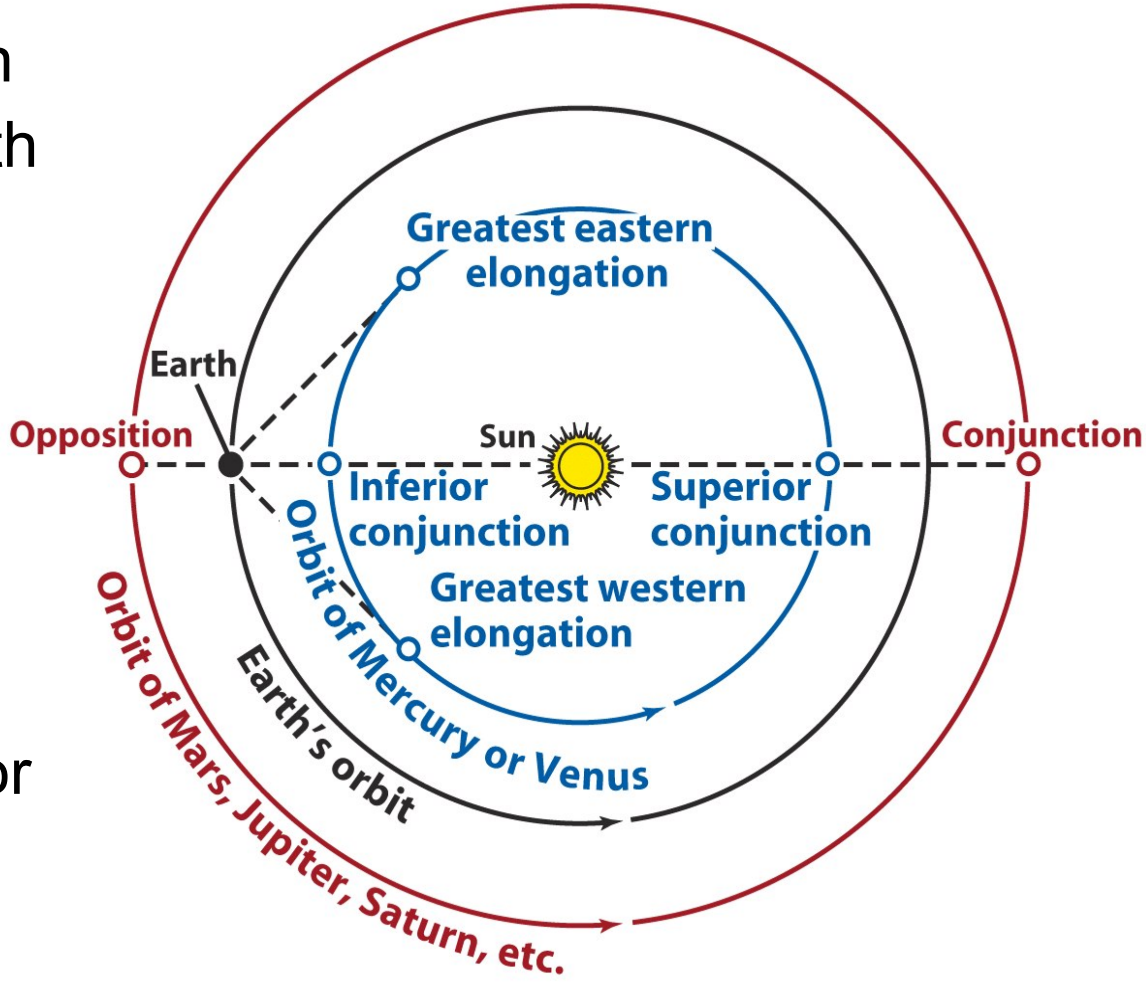
Gravity and distance to the Sun account for many important properties.

7.2 Position in the sky

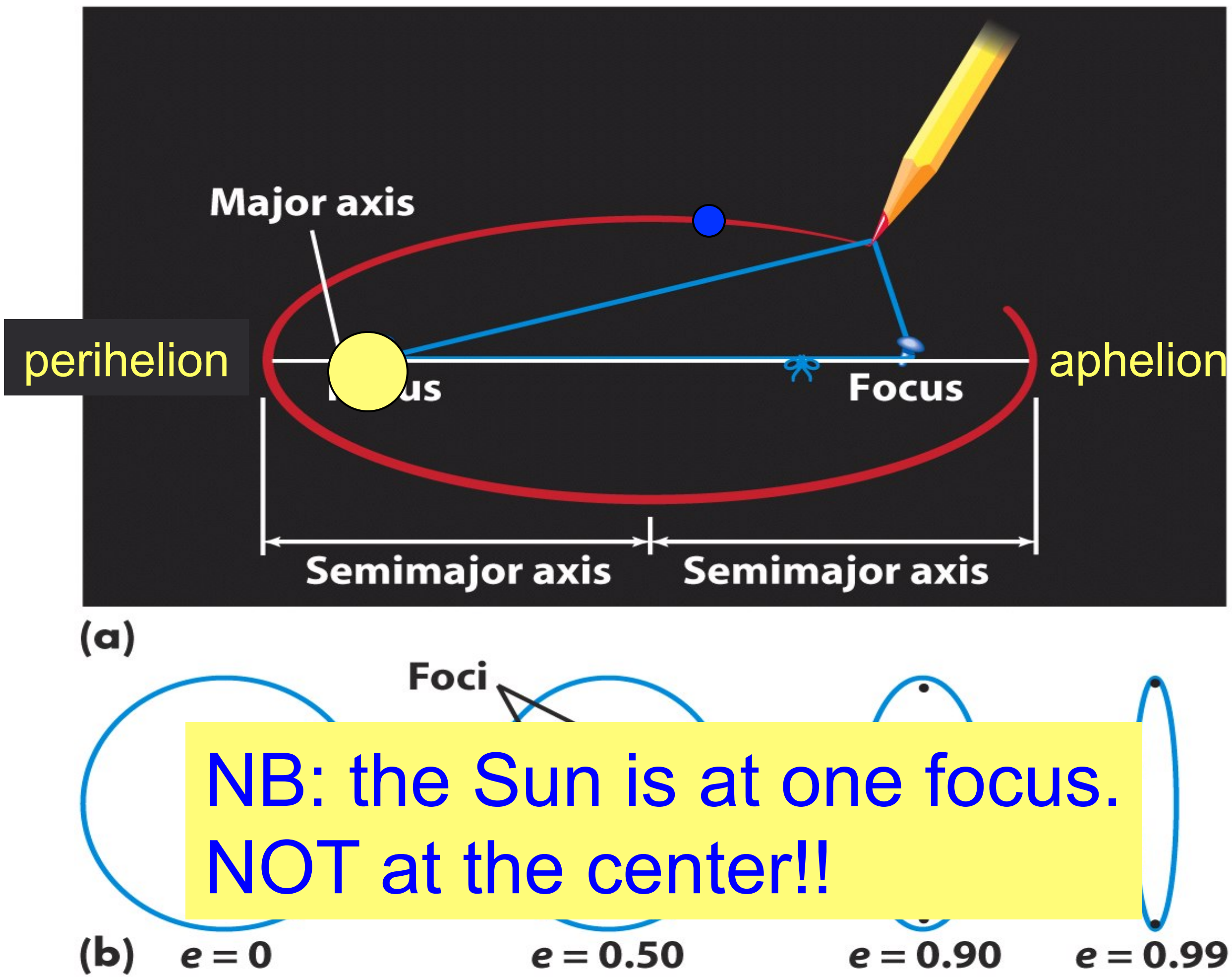
Mercury and Venus are **inferior planets** with smaller orbits than Earth's. They are always on the same side with the Sun and only seen in the daytime.

Mars, Jupiter, and Saturn are **superior planets** with larger orbits and may be observed both in the day and at night.

A planet is aligned with the Sun and the Earth at **conjunction** or **opposition** (only superior planets).



Kepler's First Law: the orbit of a planet is an ellipse with the Sun at one focus.



NB: the Sun is at one focus.
NOT at the center!!

Mercury: e = 0.206

Venus: e = 0.007

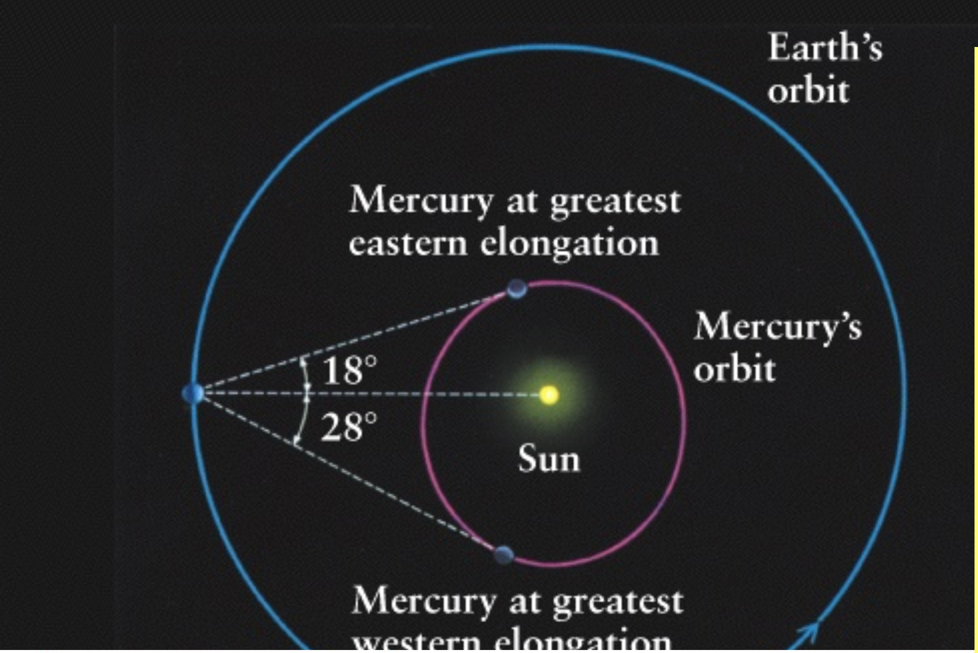
Earth: e = 0.017

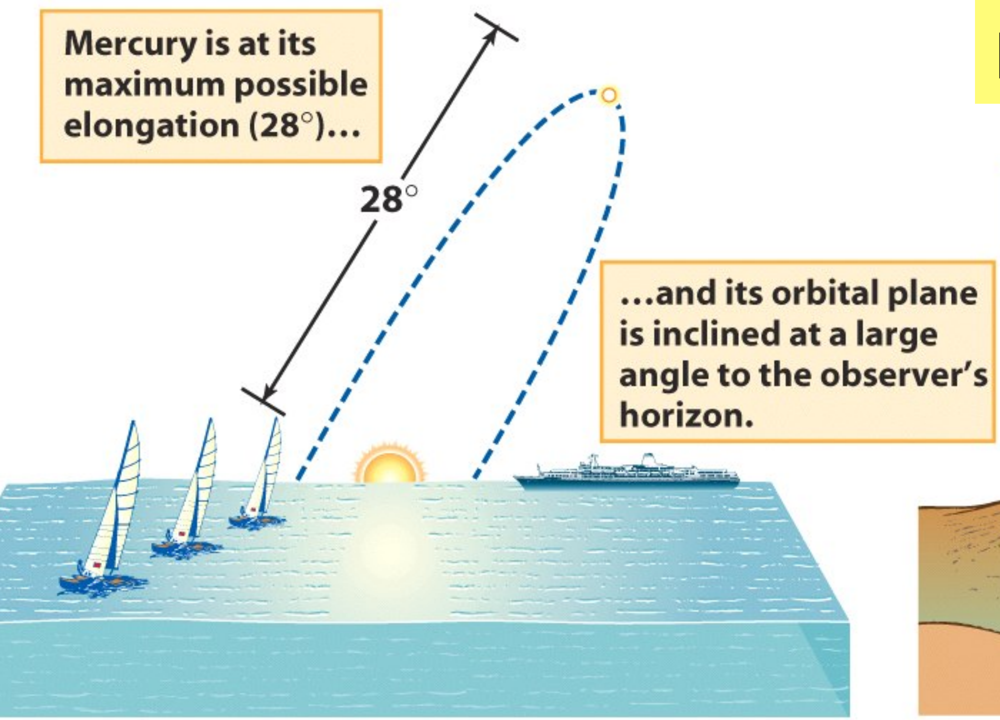
Mars: e = 0.093

(Moon: e = 0.055)

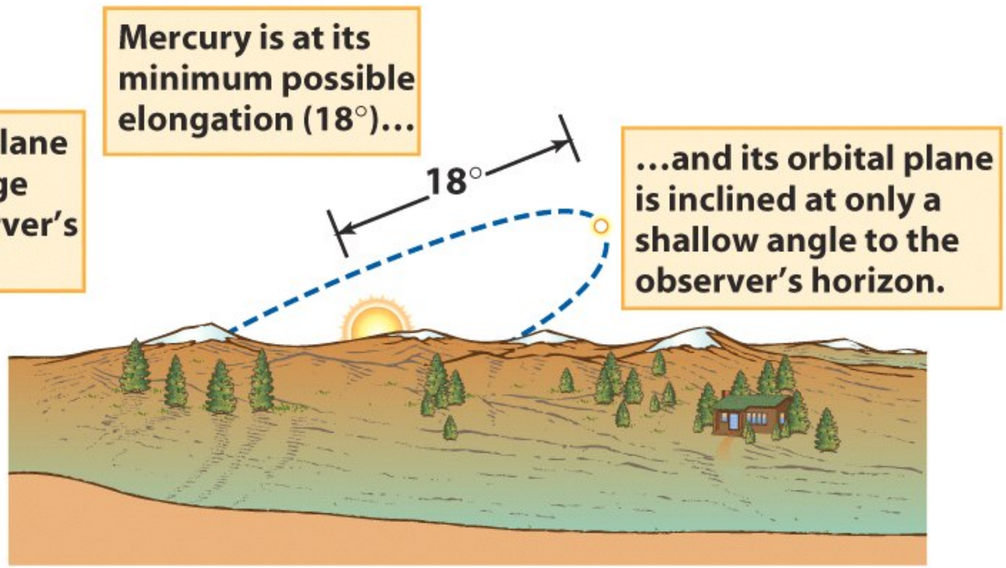
The smaller eccentricity, the more circular is the orbit.

Mercury may only be seen by optical telescopes on Earth **rising ~1-2hrs before Sunrise** at **greatest western elongation** or **setting ~1-2 hrs after sunset** at **greatest eastern elongation** (why?). Even so, it is difficult to see because of its inclined orbit.



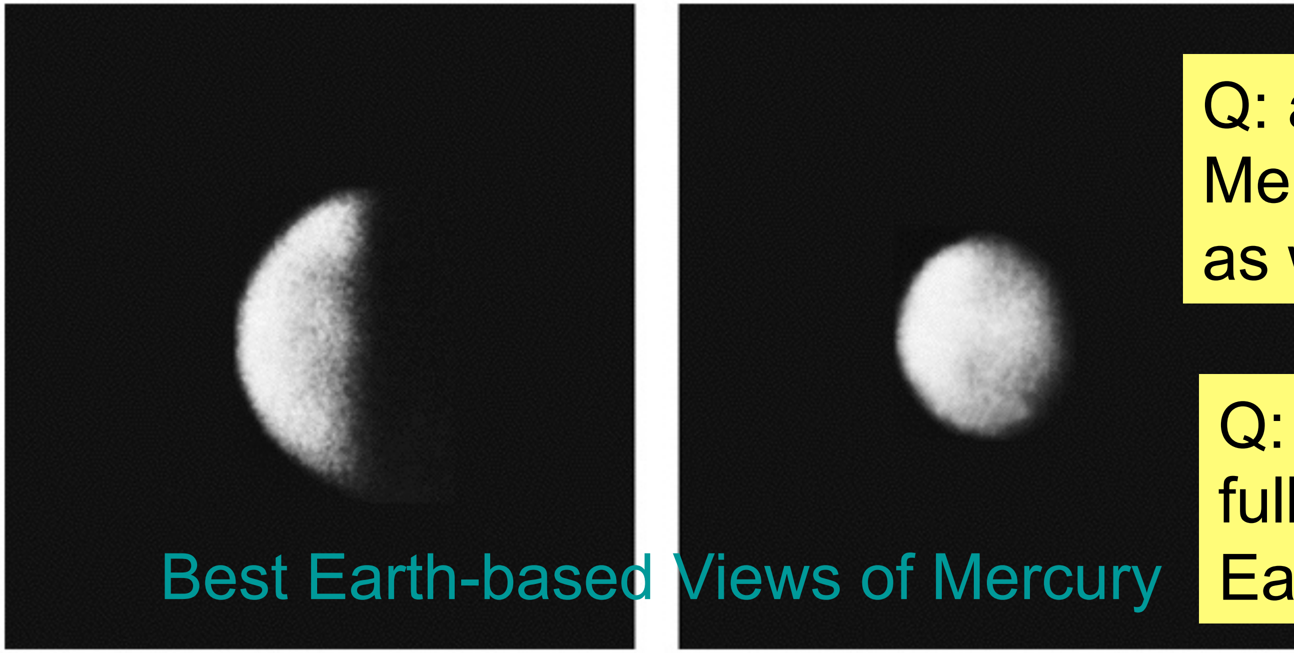


Favorable elongation



Unfavorable elongation

The very close distance of Mercury to the Sun (to the Earth as well) makes it very bright but also difficult to see its details.



Best Earth-based Views of Mercury

Q: at varying phases, Mercury changes size as well. Why so?

Q: can we ever see full Mercury from Earth?

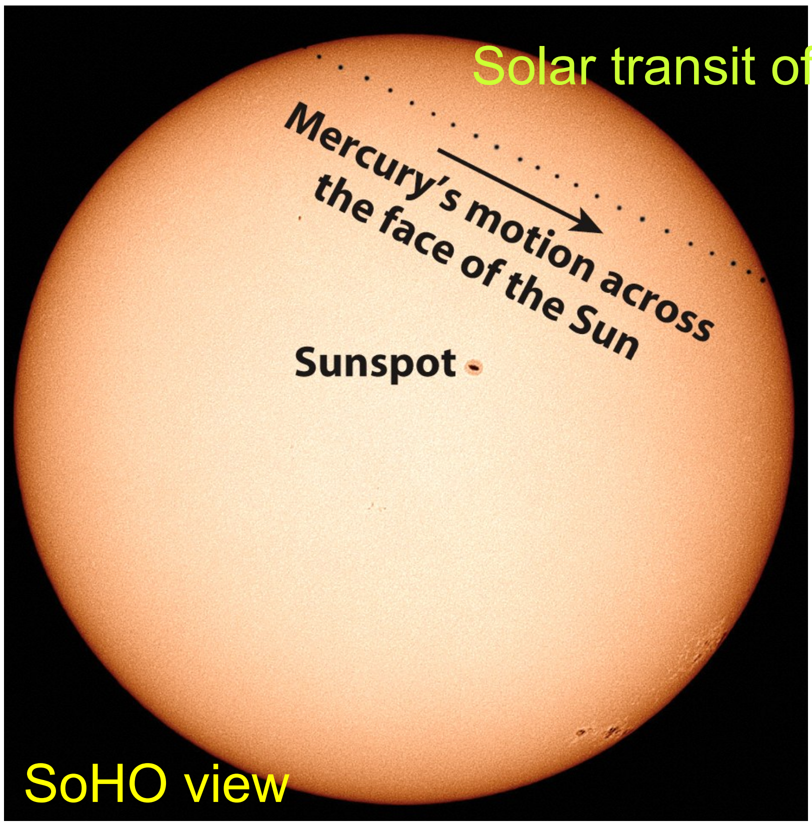
Mercury exhibits phases:

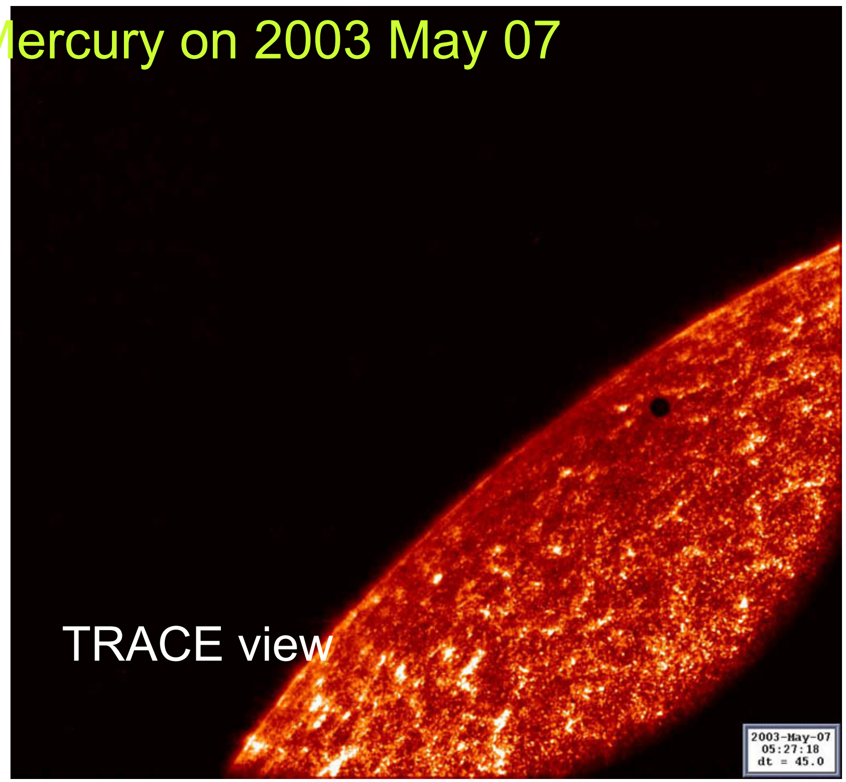
- Mercury shines by reflected sunlight.
- Mercury orbits around the Sun changing relative positions of Sun, Earth, and Mercury.
- Mercury (and Venus as well) appears largest around new phase at inferior conjunction.

The solar transit of Mercury occurs when Mercury is between the Earth and the Sun, similar to an annular solar eclipse.

Q: can we see Mars transit, Jupiter transit?

Solar transit of Mercury on 2003 May 07





Ex.1: Is the size of Mercury relative to the Sun the same as it appears in the above pictures? Why or why not?

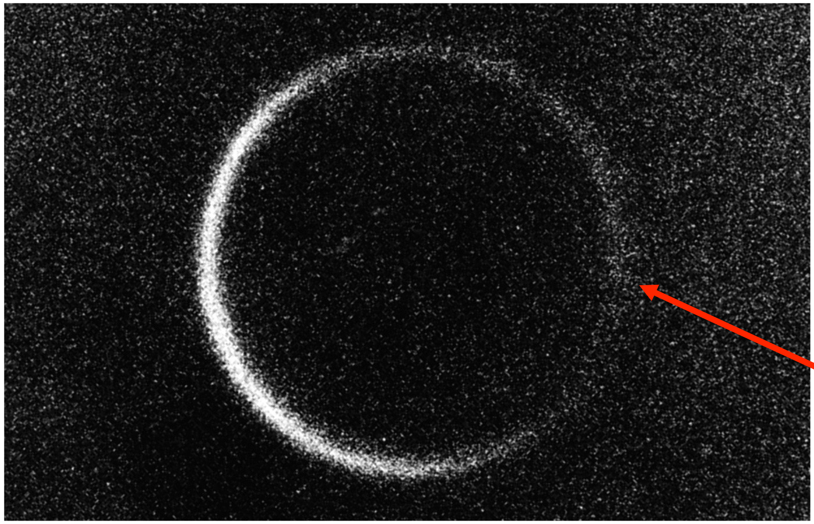
Venus is the brightest planet in the sky.

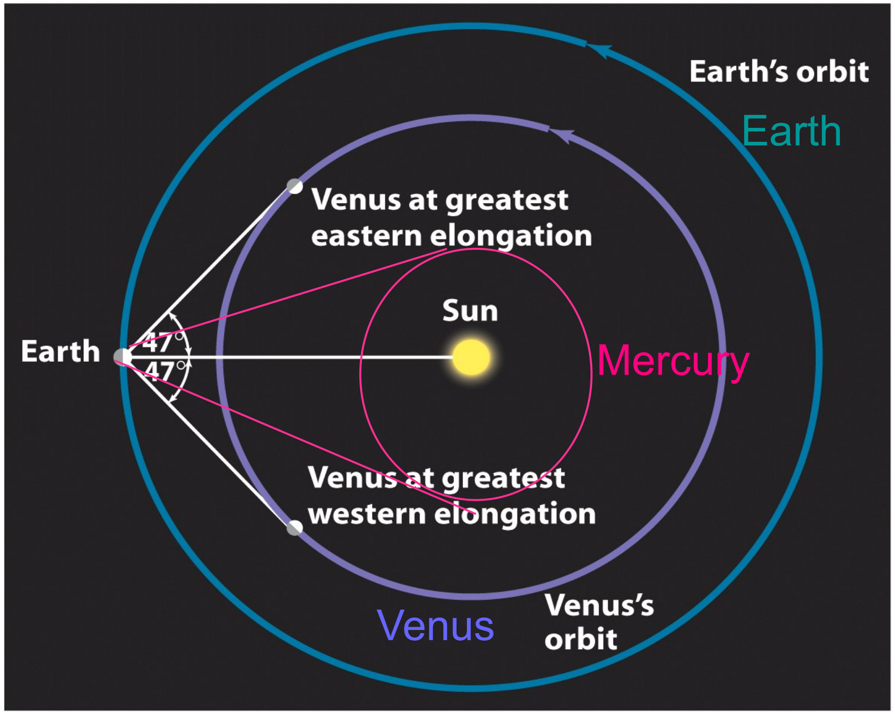
Ex.2: Why is Venus brighter than Mercury? How do we estimate the relative brightness?

Ex.3: Magnitude, or apparent brightness of Venus, Mercury, the Moon, and the Sun: brighter objects have smaller magnitudes!

	Sun	Moon	Venus	Mercury	Polaris
m	-27	-13	-4.5	0	2

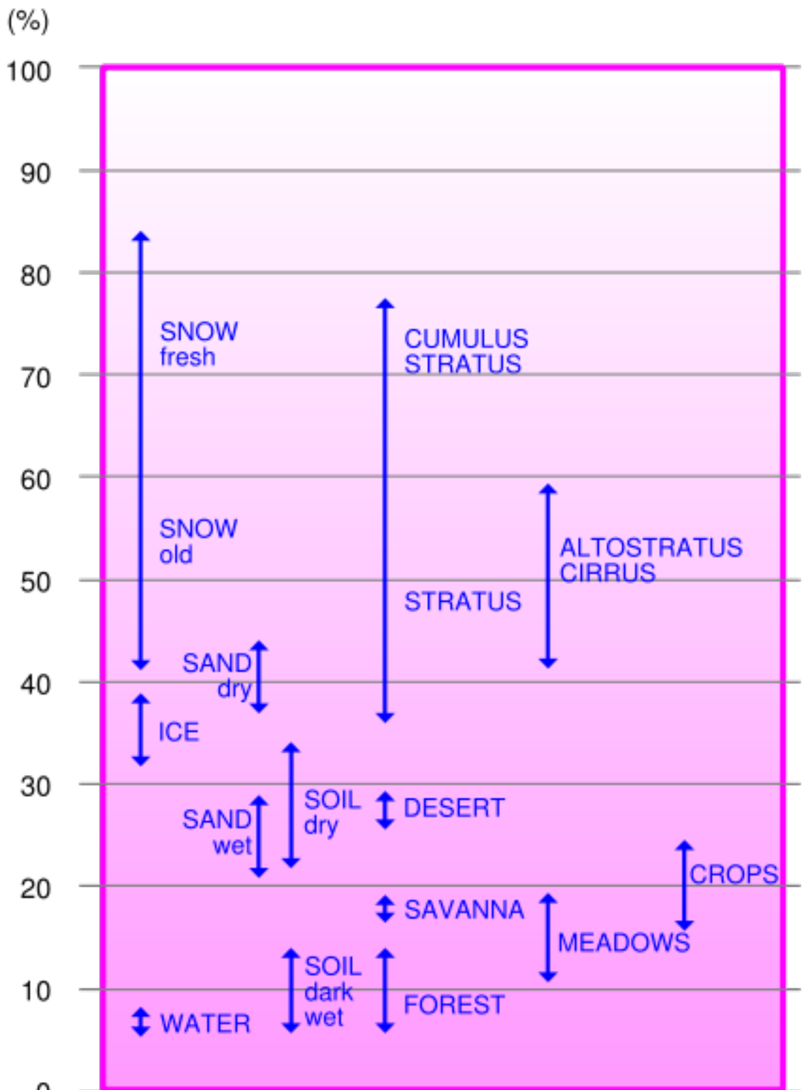
Venus at inferior conjunction (new Venus)





Cloud cover on Venus accounts for high reflectivity: **albedo** = 0.6

Ex.4: albedo of different surface features and clouds



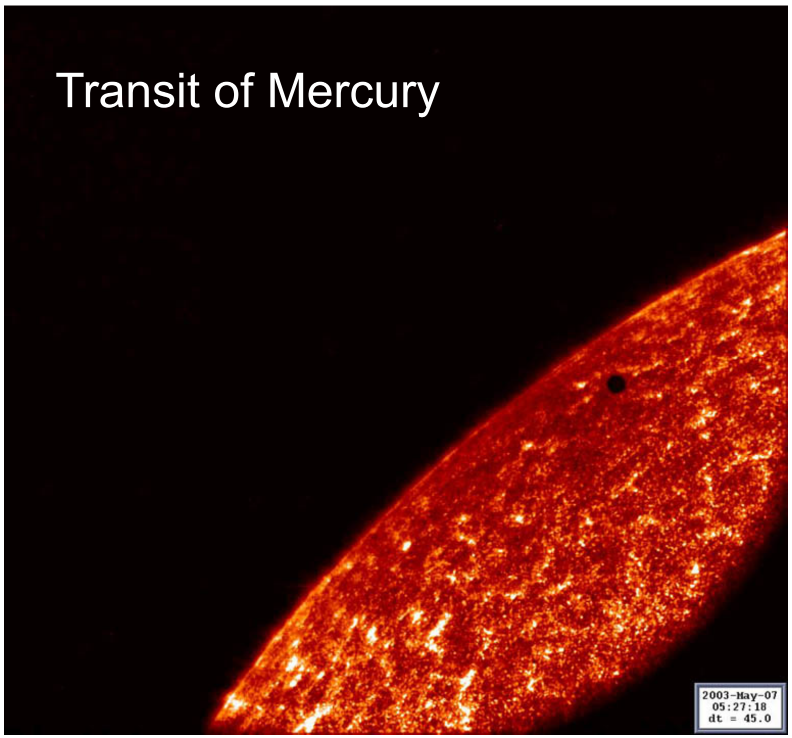
www.wikipedia.com

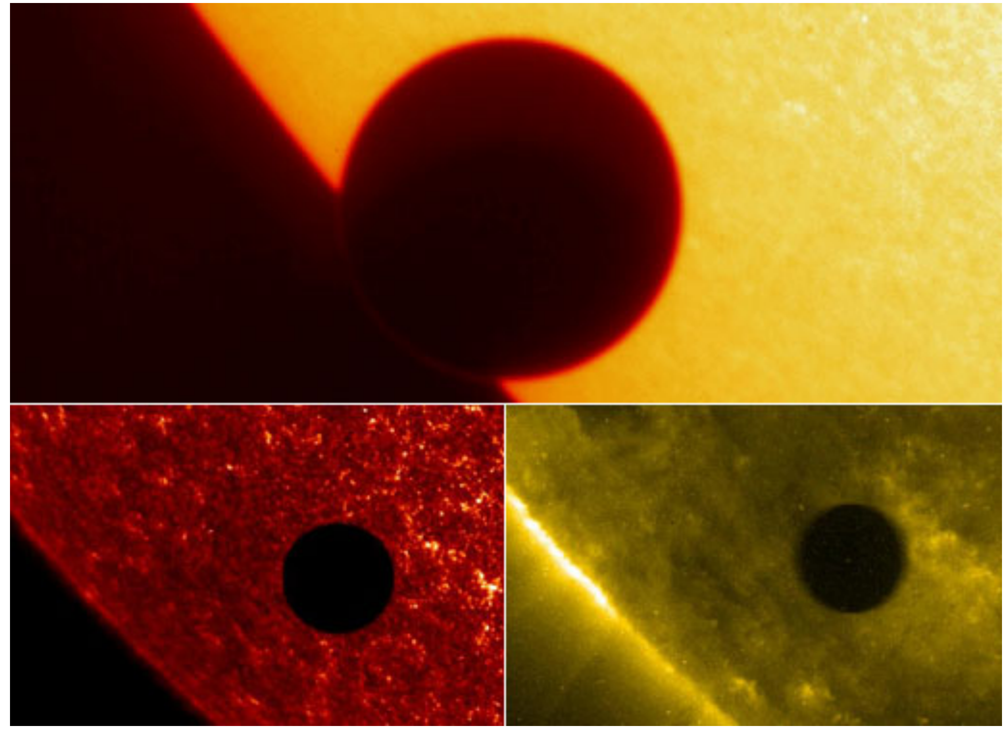
Surfaco	*albedo*
Snow	
fresh	0.80–0.95
old compacted/dirty	0.42–0.70
Ice	
glacier	0.20–0.40
Water	
calm, clear seawater	
solar elevation 60°	0.03
30°	0.06
10°	0.29
Soils	
dry, wind-blown sand	0.35–0.45
wet, wind-blown sand	0.20–0.30
silty loam (dry)	0.15–0.60
silty loam (wet)	0.07–0.28
peat	0.05–0.15
Plants	
short grass (0.02 m)	0.26
long grass (1.0 m)	0.16
heather	0.10
deciduous forest (in leaf)	0.20
deciduous forest (bare)	0.15
pine forest	0.14
field crops	0.15–0.30
sugar beet (spring)	0.17
sugar beet (early summer)	0.14

marine.rutgers.edu

Cloud-cover importantly determines the albedo, thus the energy balance, of a planet.

Solar transit of Venus, in comparison with transit of Mercury, reveals cloud cover on Venus.





Direct observation to trace the surface feature motion is difficult in both planets, but for different reasons.

Surface features of Venus can be observed at **radio** wavelengths - radio waves penetrate clouds!

7.3 Orbit and Rotation

- Orbits of the planets in the solar system are described by **Kepler's three laws**.

  1st law: elliptical orbit with Sun at one focus -- Mercury's orbit has the largest eccentricity

  2nd law: planet moves faster at perihelion than at aphelion

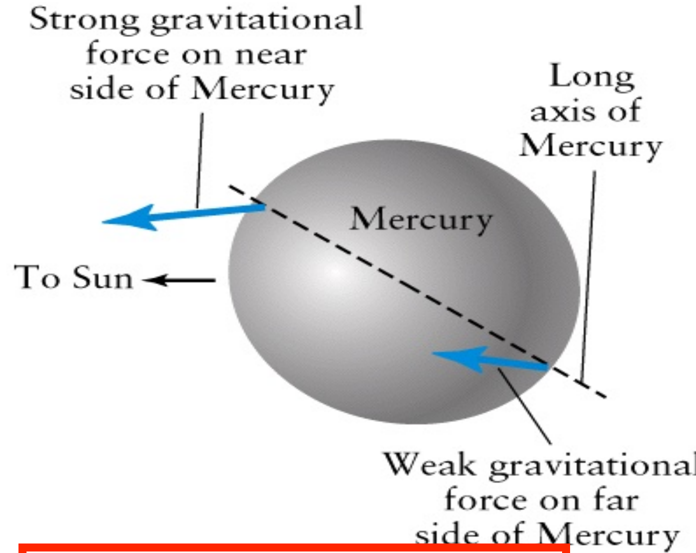
  3rd law: ***$a^3=P^2$*** a = 0.39, 0.72, 1.00, 1.5 AU
- Small inclination of orbits to ecliptic by 7^0, 3^0, 2^0 for Mercury, Venus, and Mars.
- Inclination between equator and orbit plane:

  Mercury: 0.5^0

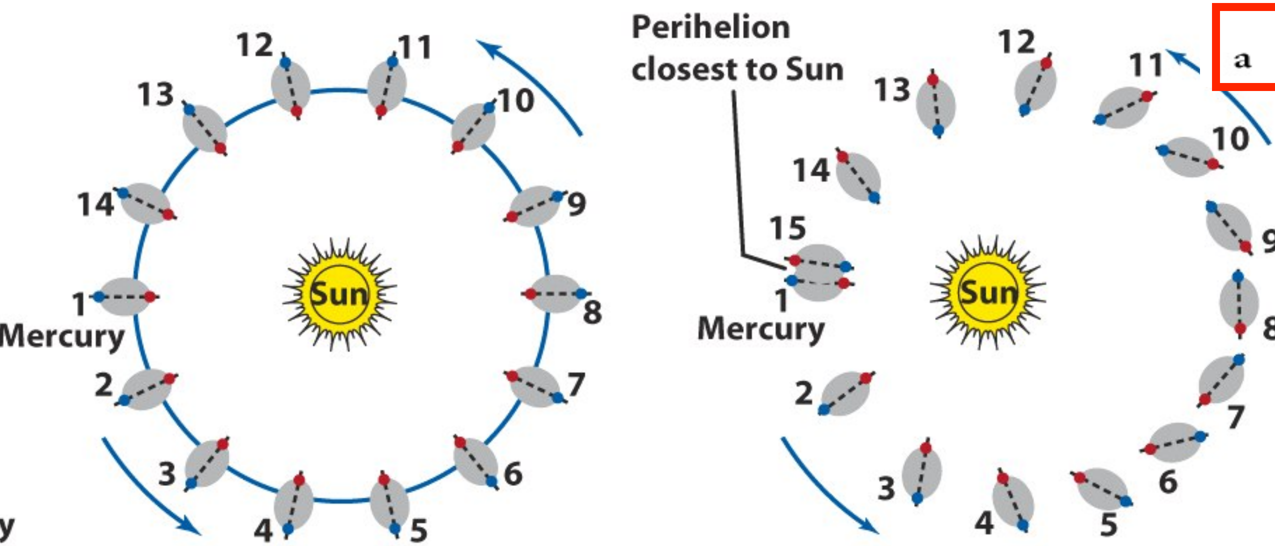
  Venus: 177.4^0 retrograde rotation!

  Earth 23^0 and Mars 25^0 seasons!
- Mercury and Venus are slow rotators; Earth and Mars rotate fast. Magnetic fields?

Mercury rotates slowly and has an unusual **3-to-2 spin-orbit coupling:** Mercury finishes 3 spins for 2 orbits - the only planet doing so. Why?



a Tidal forces on Mercury



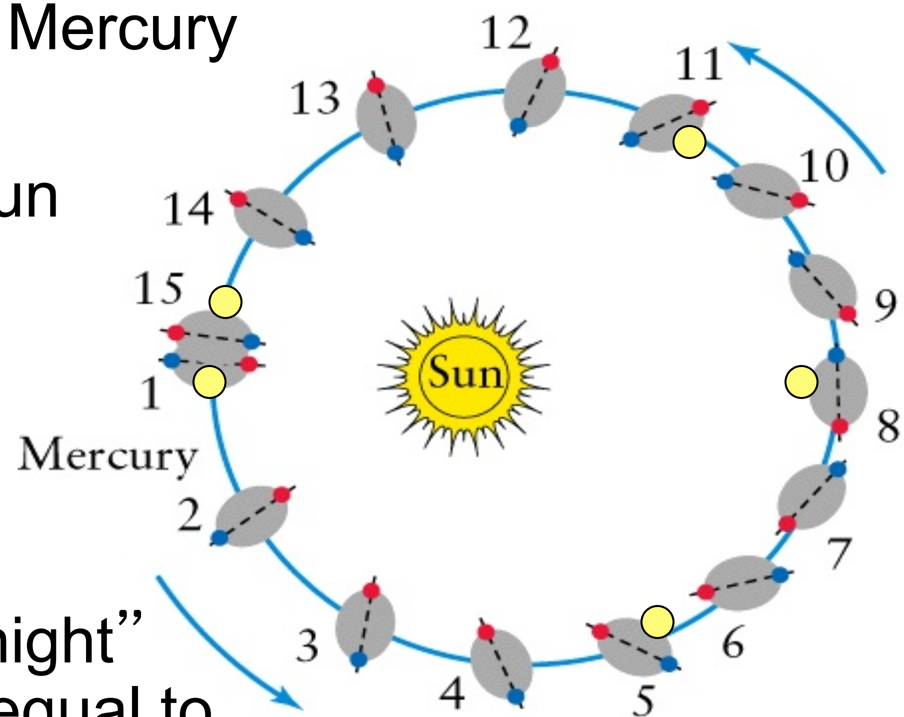
(b) If Mercury were in a circular orbit, its long axis would always point toward the Sun: Mercury would be in synchronous rotation (1-to-1 spin-orbit coupling).

(c) In fact Mercury is in an elliptical orbit, and its long axis only points toward the Sun at perihelion: Mercury spins on its axis 1½ times during each complete orbit (3-to-2 spin-orbit coupling).

Alternates sides of Mercury face the sun from one perihelion to the next.

The unique **3-to-2 spin-orbit** of Mercury is caused by:

- Strong **tidal force** from the Sun (close distance to the Sun).
- Its **elongated shape**
- Its **very eccentric orbit**



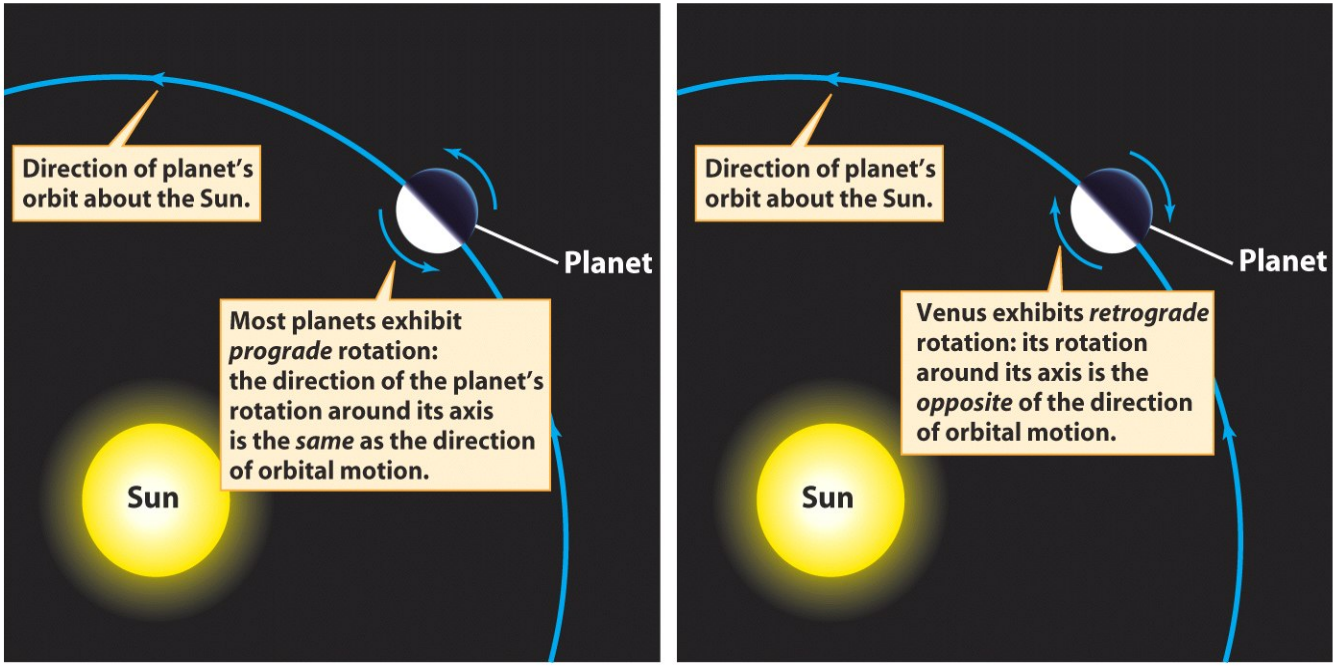
As the results:

- A "day" of solar light and a "night" in dark on Mercury would be equal to a Mercury year or 88 earth days -- in comparison: an Earth day is 1 day and an Earth year is 365 days.
- Extreme high and low temperatures in the daytime and at night.
- The Sun may sometimes appear to have a "retrograde"

Q: when would the Sun rise or set if Mercury's rotation were synchronous?

Venus's rotation is **slow** (243 Earth-days; 225 days orbit P) and **retrograde**, posing a challenge to nebula hypothesis.

Ex.8: right-hand rule vs. left-hand rule: orbits and rotations in the solar system are from west to east -- **prograde** and **right-hand rule** -- with a few exceptions.

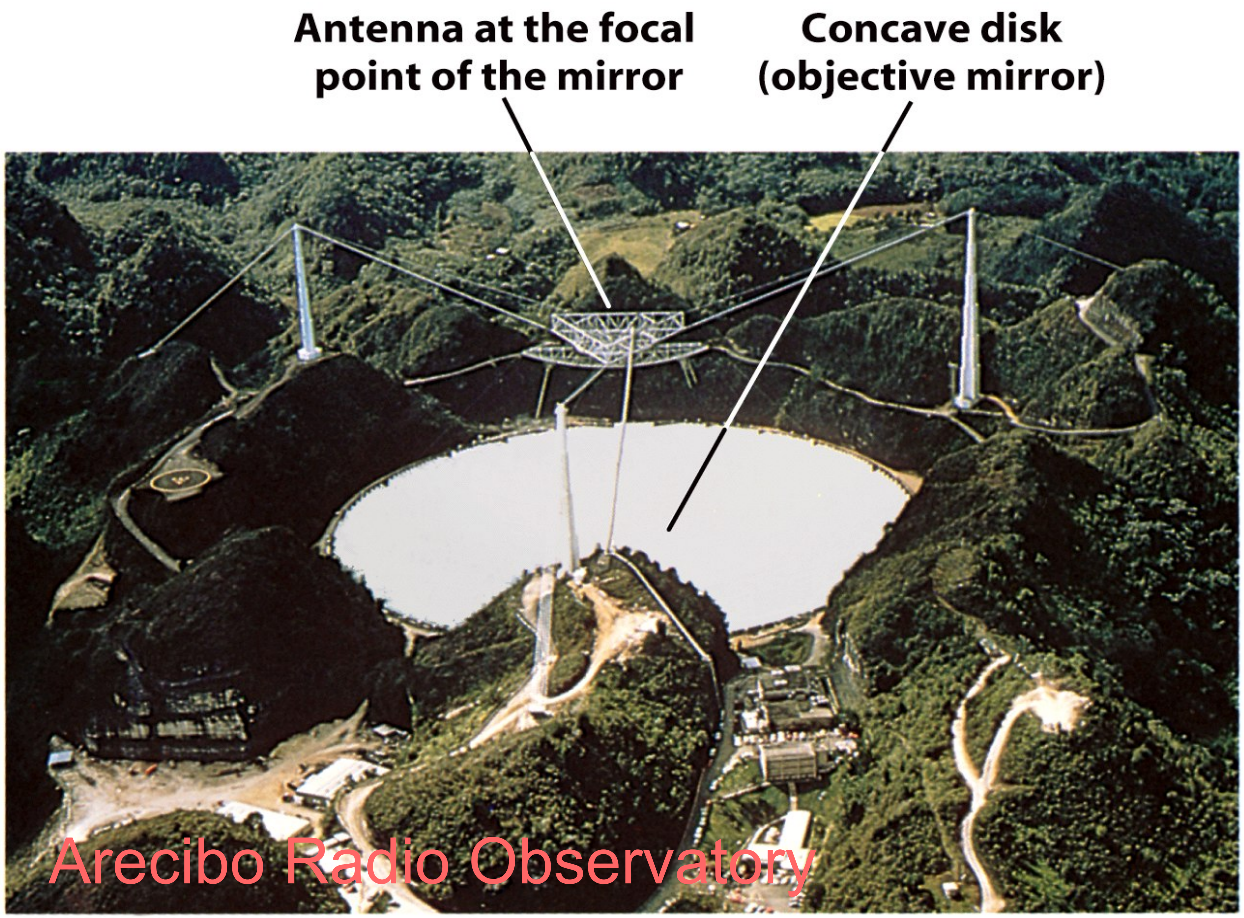


(a) Prograde rotation (b) Retrograde rotation

On Venus, the Sun rises every 117 Earth days and from the west!

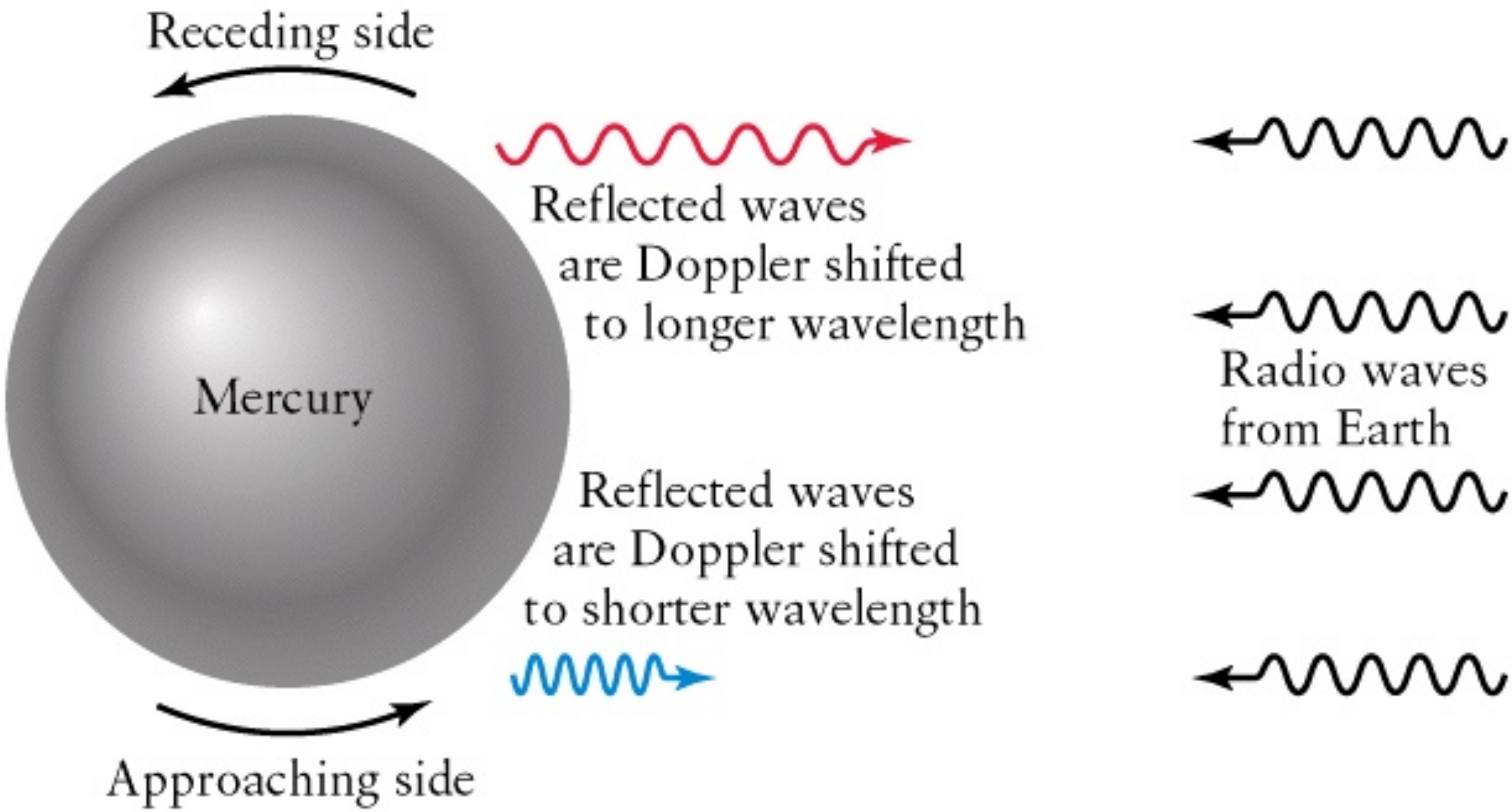
Q: what is the length of a solar day on a planet with (a) prograde rotation; (b) retrograde rotation; (c) synchronous rotation?

The non-synchronous rotation of Mercury is confirmed by radio observations from sites such as Arecibo.



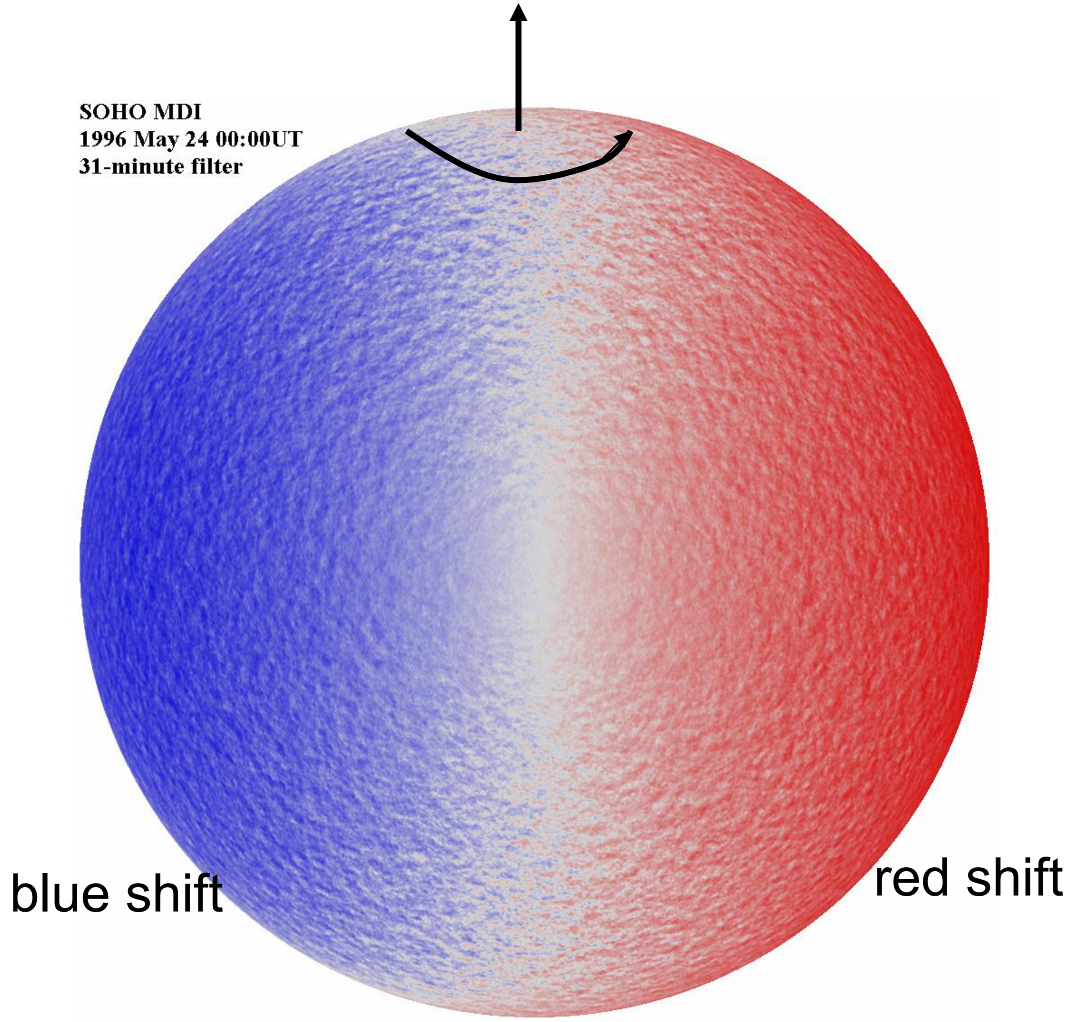
- The blackbody temperature from the radio spectrum is higher than expected of synchronous rotation.
- Doppler-shift measurements determine the rotation period.

Doppler shifts of reflected radio waves tell the rotation speed thus period of Mercury.



Ex.6: (a) how do we determine the rotation period of Mercury from Doppler-shift measurements? (b) how do we distinguish the rotation motion from other types of motion such as orbital motion?

Q: if we measure the Doppler shift along the equator, what does the profile look like?



Ex 7: Doppler shift measurements of the Sun's rotation (at equator)

$$V_d = V_r \sin\theta$$

V_d: = line of sight speed
V_r: = rotation speed
θ: = angle between radial and line of sight directions.

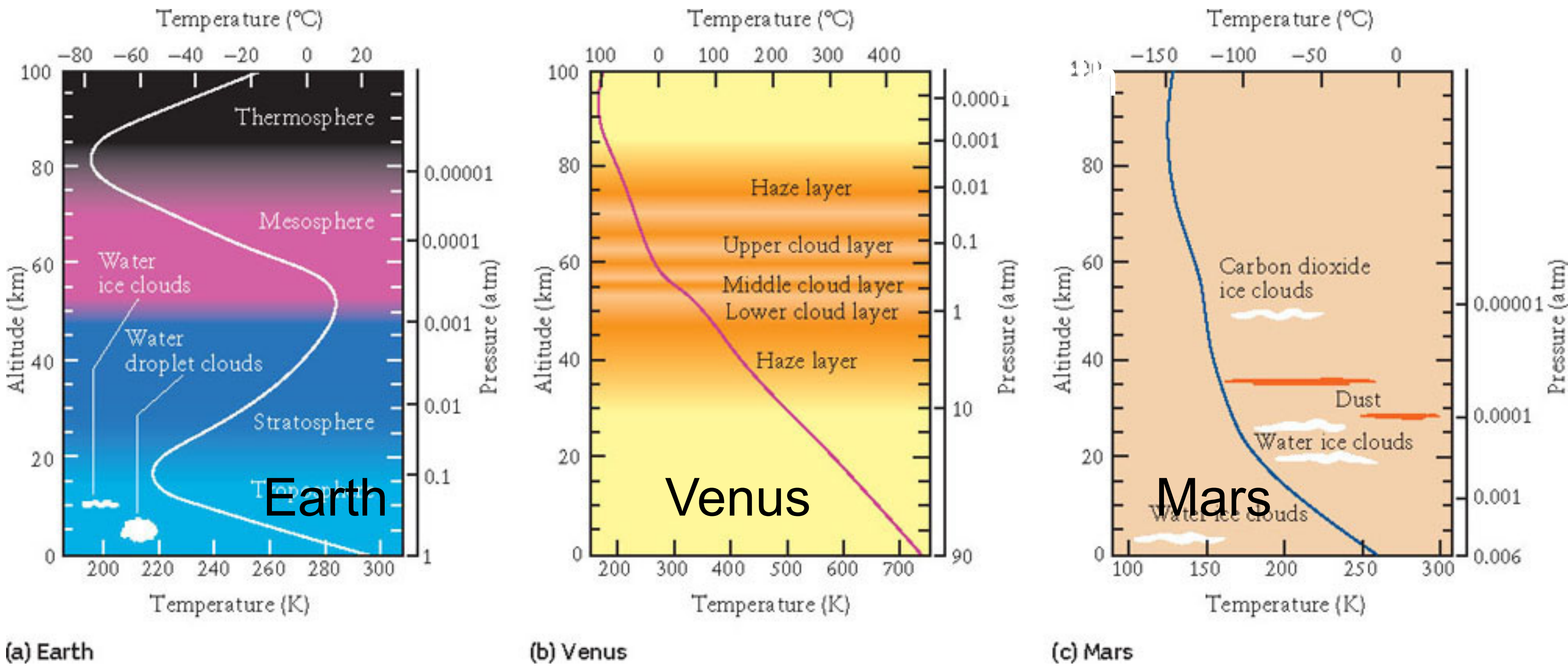
Q: astronauts placed a reflector on the moon for laser ranging from Earth. Where should they place it on the moon? Anywhere?

Q: we will send missions to land on Mercury. Instruments will use solar cells to provide power. If you are to design the capacity of the solar cells, for how long the solar cells should be able to provide energy in dark?

Q: we will send missions to land on Venus. Solar cells will face the sunlight during daytime to work most efficiently. How would you design to track the Sun in Venus' sky?

7.4 Atmosphere

- Venus: hot, dense; Mars: thin, cool. **Air pressure**: 0.01, 1, 90 *atmosphere* on Mars, Earth, and Venus.
- Venus and Mars: mostly made of CO_2; Earth: N_2 and O_2.



Temperature profiles in Venus, Mars, and Earth's atmospheres

table 9-4 Chemical Compositions of Three Planetary Atmospheres

	Venus	Earth	Mars
Nitrogen (N_2)	3.5%	78.08%	2.7%
Oxygen (O_2)	almost zero	20.95%	almost zero
Carbon dioxide (CO_2)	96.5%	0.035%	95.3%
Water vapor (H_2O)	0.003%	about 1%	0.03%
Other gases	almost zero	almost zero	2%

The chemical composition of the Earth's atmosphere is drastically different from that of other two terrestrial planets also possessing an atmosphere.

what leads to the difference in atmosphere composition if planets all formed from the same nebula?

They all started with the same composition, but the evolution took different paths as determined by the distance to the Sun and consequently the temperature (and mass as well).

Strong **greenhouse effect** raises Venus's temperature by over 400 K, and night is as warm as in daytime.

Ex.9: calculate the temperature of Venus if no greenhouse effect were present.

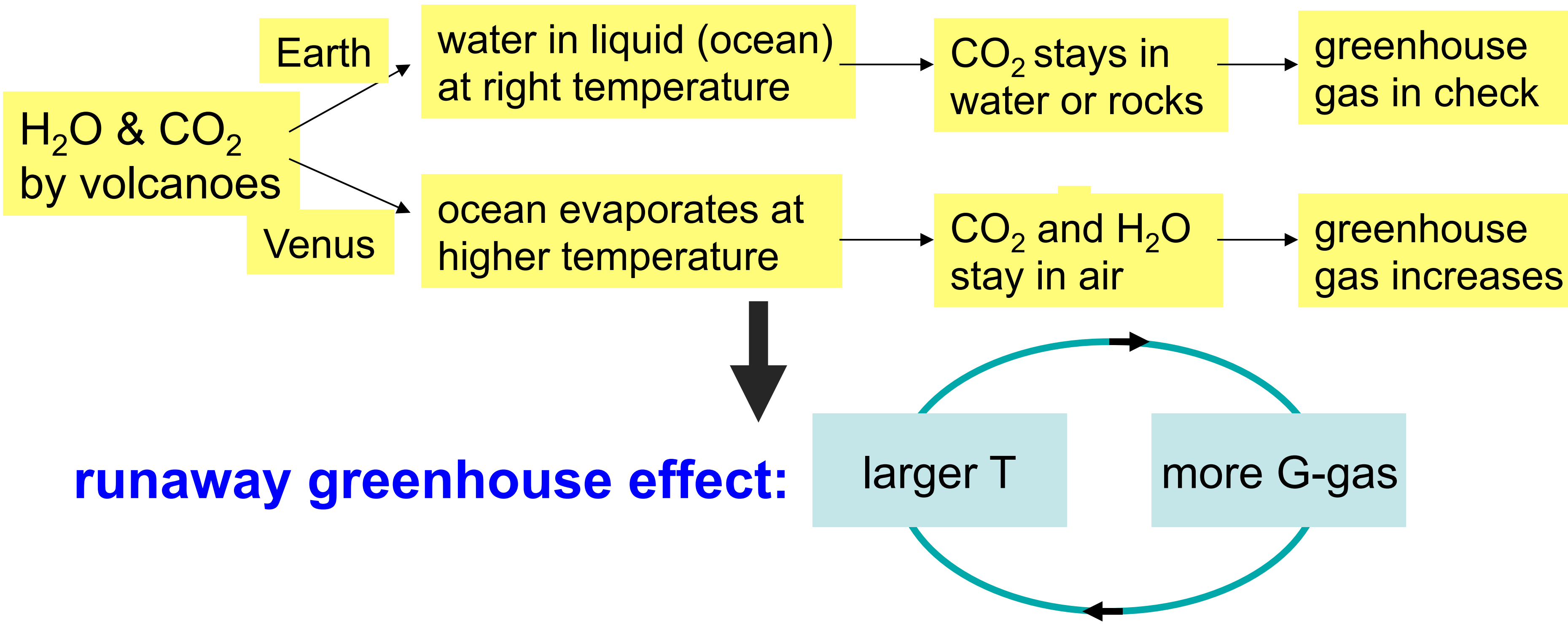
Using Stefan-Boltzman law to relate blackbody radiation and effective temperature, it can be shown that

$$T_p = \left(\frac{(1-a)R_s^{\,2}}{4d^2} \right)^{1/4} T_s$$

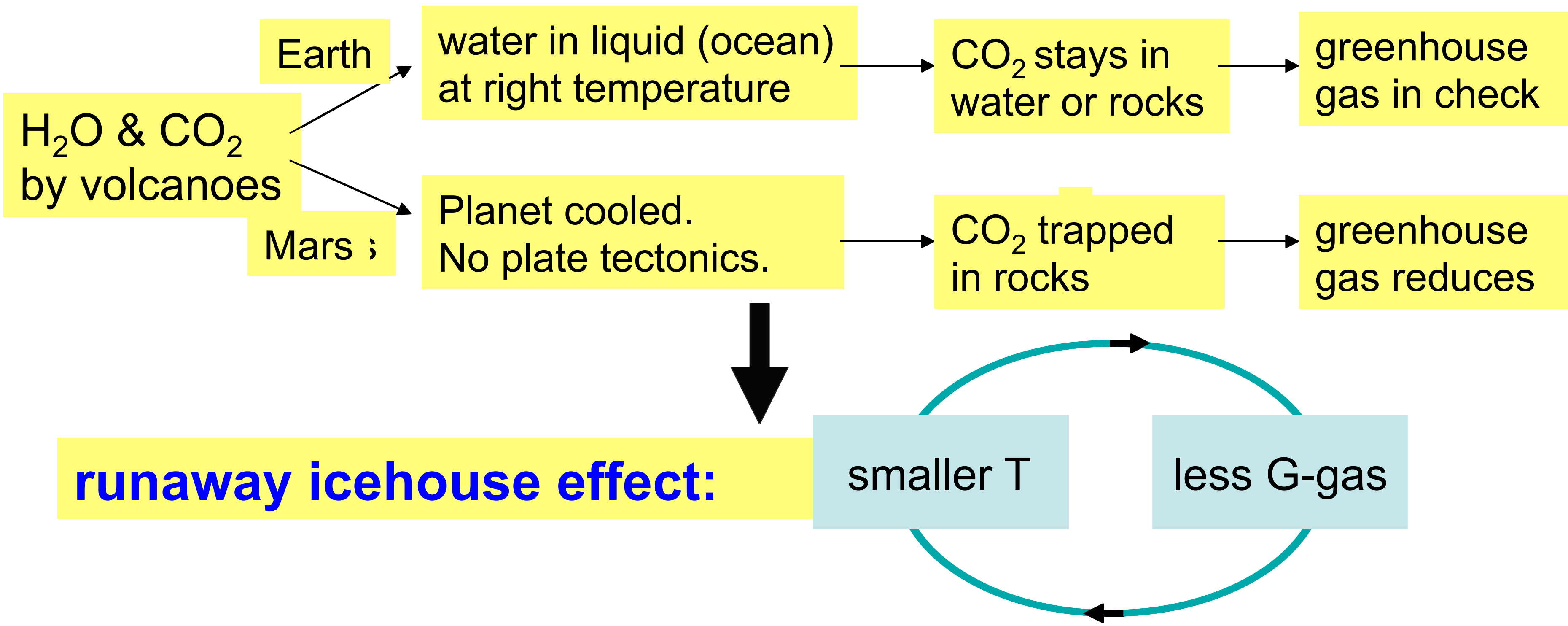
T_p = temperature of the planet (K degree)
T_s = temperature of the Sun (K degree)
R_s = radius of the Sun (m),
d = distance between the Sun and the planet (m)
a = albedo on the planet surface.

Without greenhouse effect, both Earth and Venus would have temperatures much lower than current values.

On Venus, Mars, and Earth, the atmosphere started with **water** (H_2O) and **carbon-dioxide** (CO_2). The evolution paths then departed.



The cycle ceased when all H_2O vapor were cracked by ultraviolet light and escaped, and all CO_2 were released from rocks.



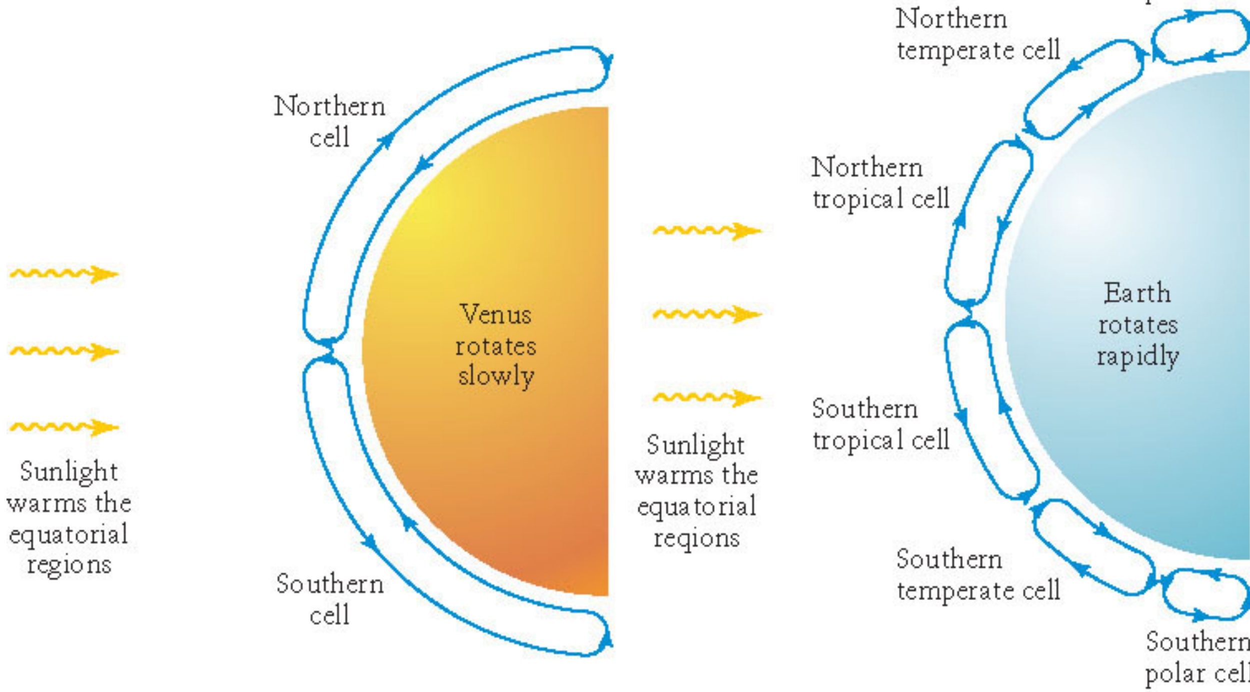
Earth: H_2O & CO_2 are **recycled** between air, ocean, and rocks.

Venus: runaway greenhouse effect ==> dense and hot

Mars: runaway icehouse effect ==> thin and cool

Q: what do you think is the key reason for these differences?

Motion in the atmosphere: convection

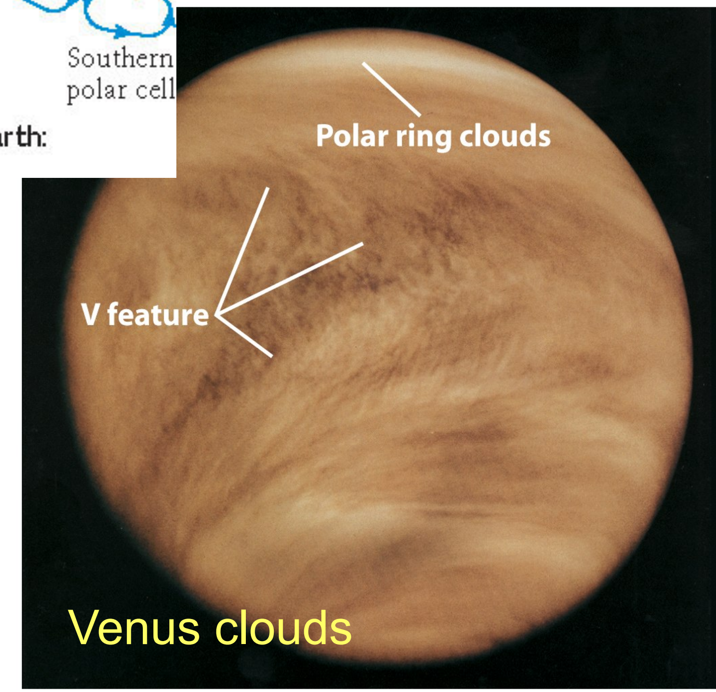


(a) Atmospheric circulation on Venus: two convection cells

(b) Atmospheric circulation on Earth: six convection cells

fast retrograde motion of Venus's cloud, as confirmed by Doppler-shift of spectral lines from sunlight.

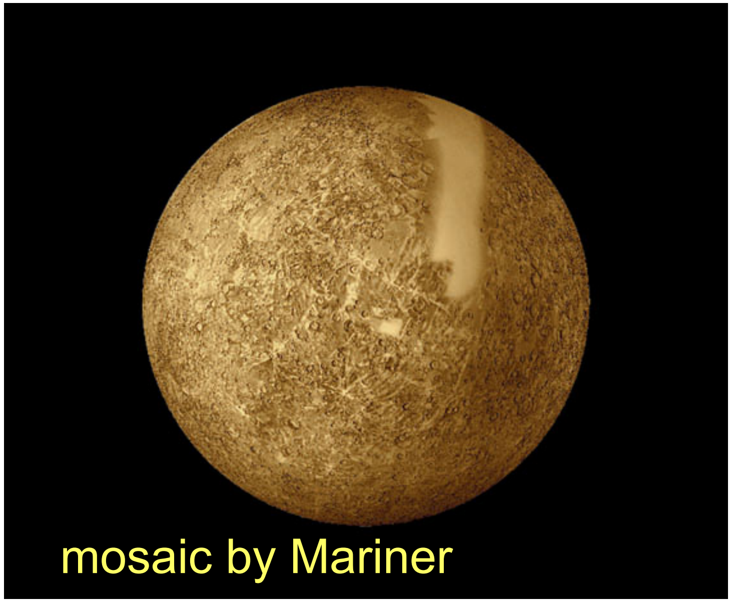
Only **one circulation (convection) cell** in each hemisphere of Venus because of its slow rotation.
(recall the case of Earth's atmosphere)

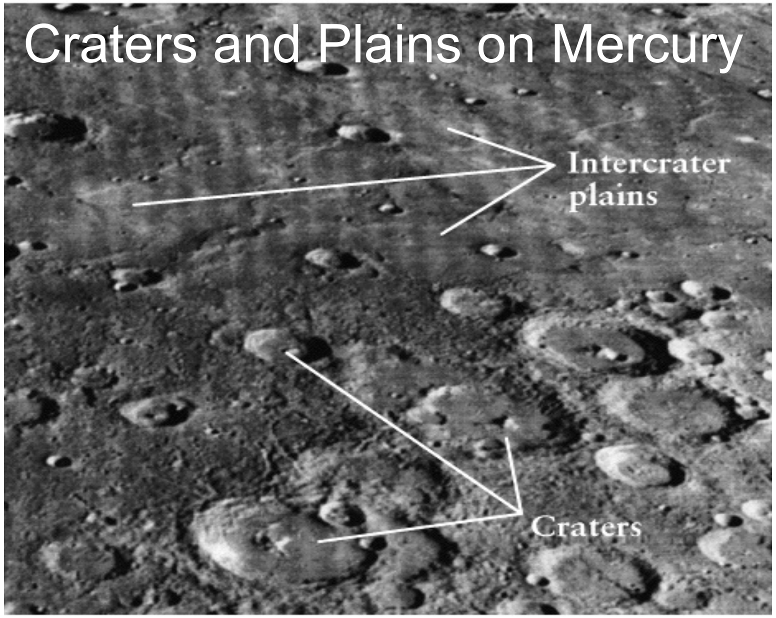


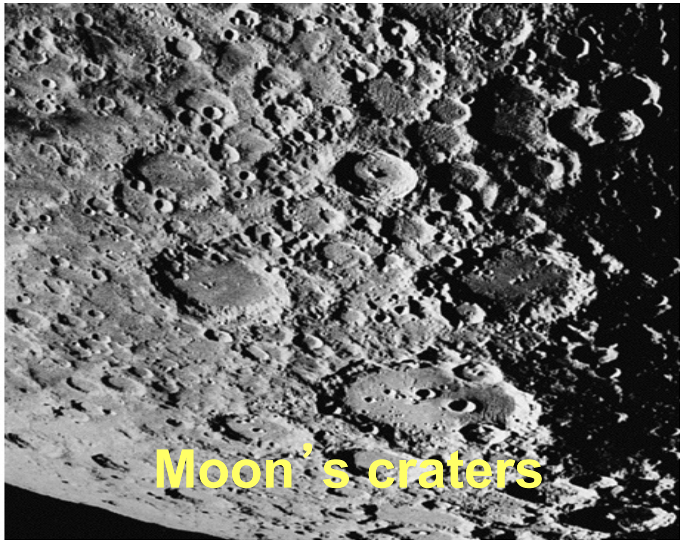
7.5 Surface and geological activities

Moon like Mercury. Volcanic Venus. Diverse Mars.
No plate tectonics

- **Cratering** is the telltale of the **age of a surface** (why?): Mercury is the most heavily cratered thus has an old surface, followed by Mars, Venus and Earth (note: in order of planet's size!).
- **Geological activities** empowered by **internal heat** (here comes the size dependence) renew the planet's surface.
  - -- **volcanoes**: still active on the Earth and perhaps Venus but not Mercury and Mars (why?)
  - -- **plate tectonics** are only found on the Earth: internal heat, molten interior, convection in aesthenosphere, thin and rigid crust, large body of water (ocean plates). How are all these not working on Mercury, Venus, and Mars?
  - -- **weathering** (wind & water erosion) and **life** activities: most evident on Earth, followed by Mars (in the past).

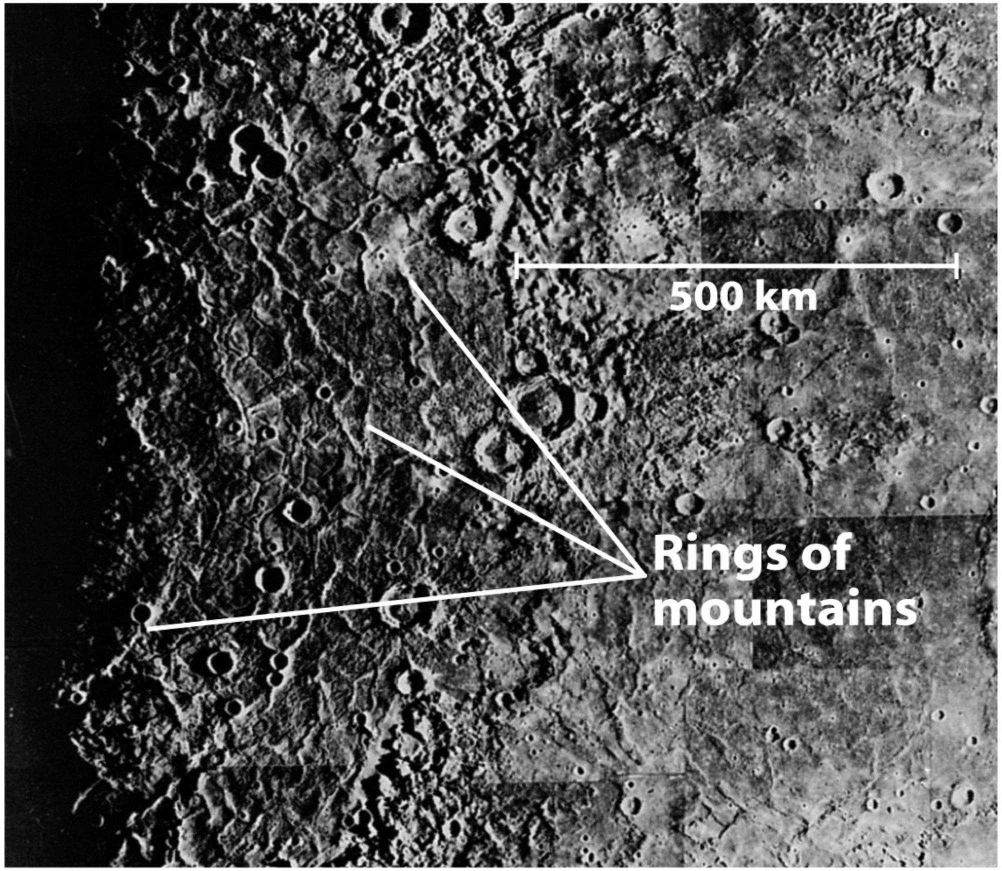






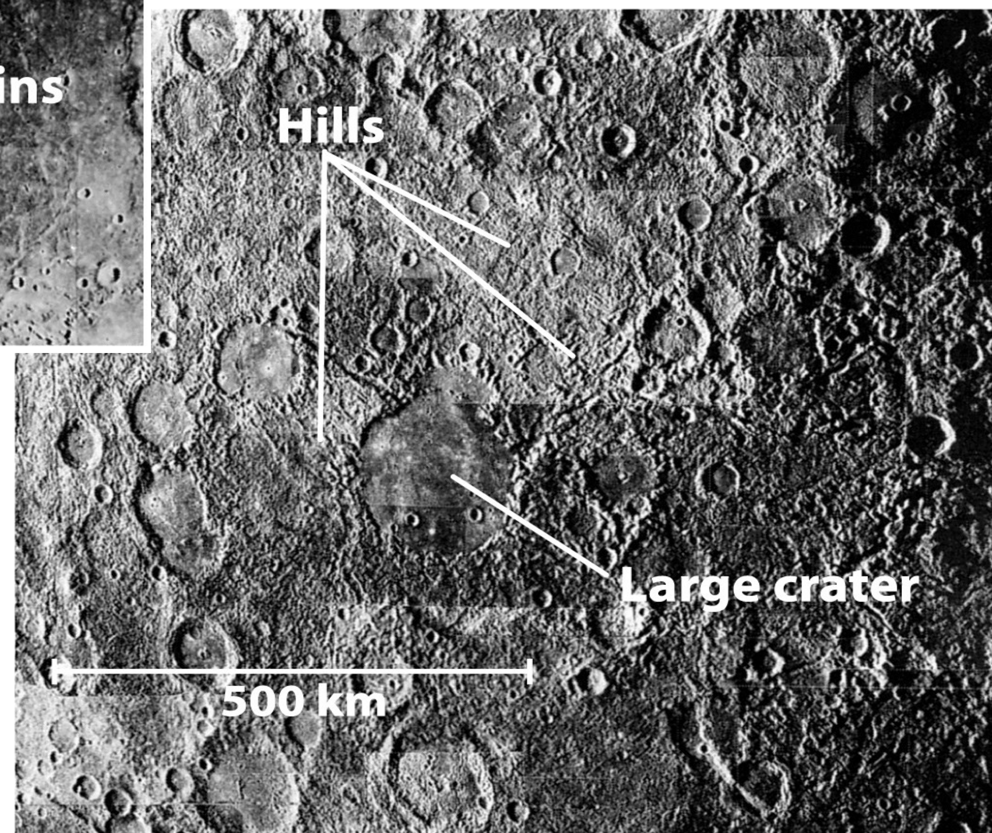
Mercury has a Moon-like, barren surface.

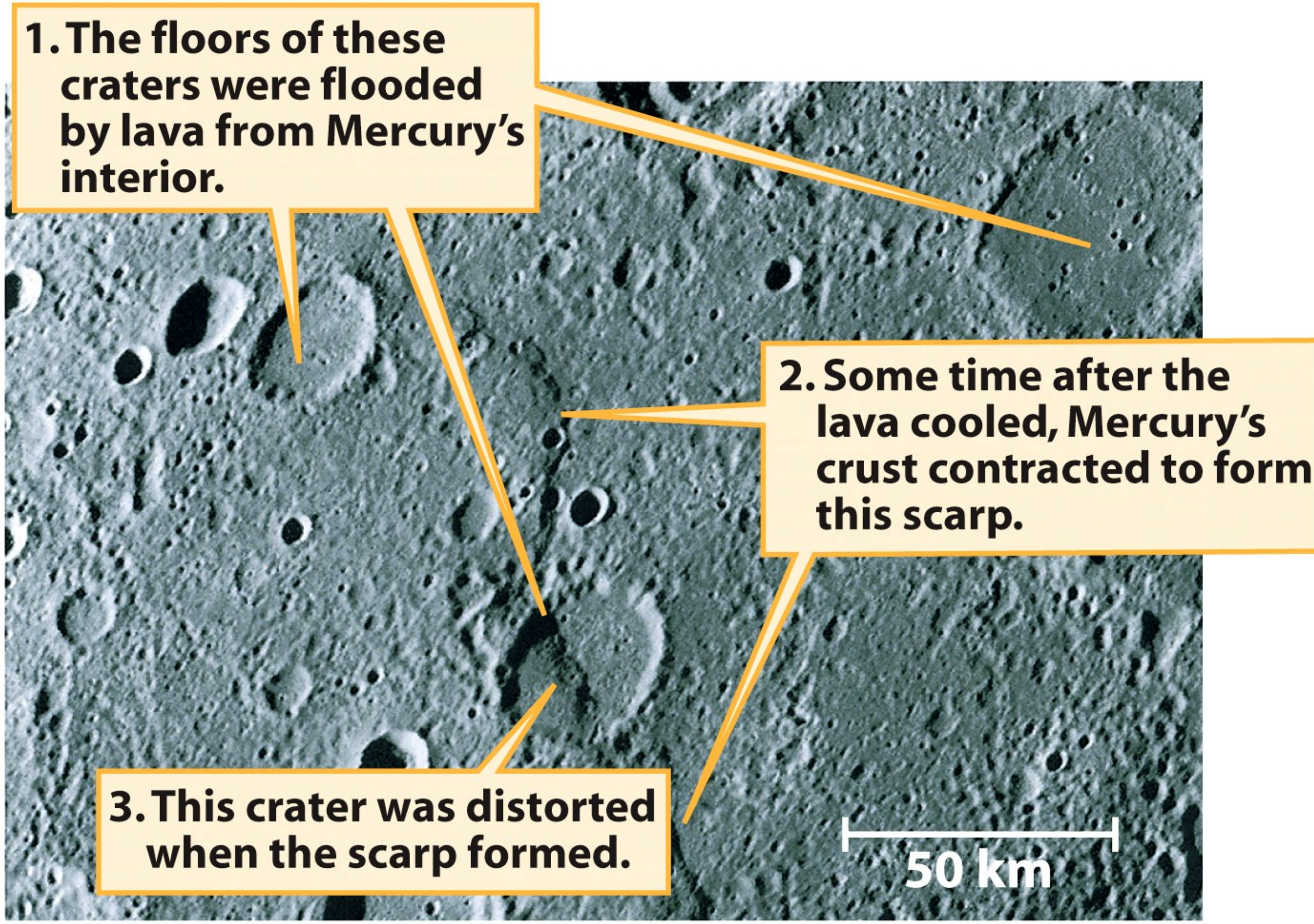
- Heavily cratered surface
- No evidence of tectonics or significant geological activity
- No atmosphere



The seismic waves from the impact that caused the Caloris Basin caused deformation on the opposite side of Mercury and created hills.

The Caloris **Basin** is evidence of a large impact (filled by lava flows), forming several concentric chains of mountains.

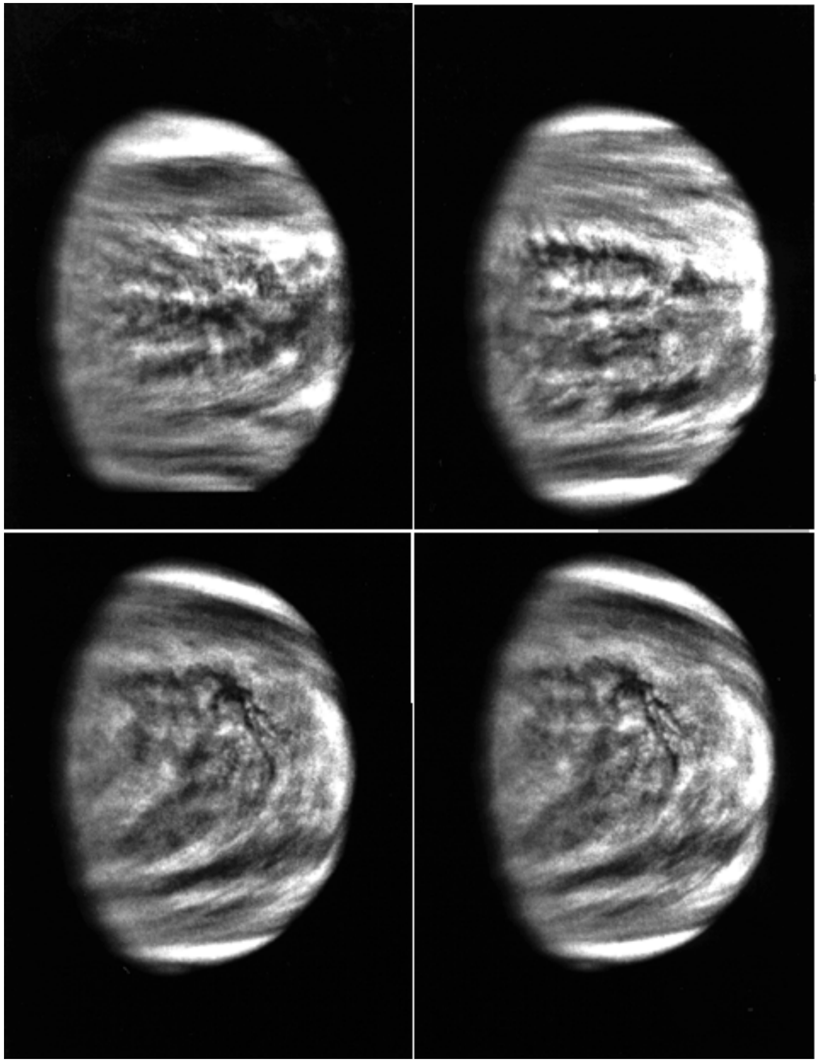




The overlap between features indicates the relative age of the feature. The Distorted Crater is 'older' than the Scarp.

Scarps are cliffs. They probably formed as the planet cooled and shrank.

The cloudy volcanic Venus

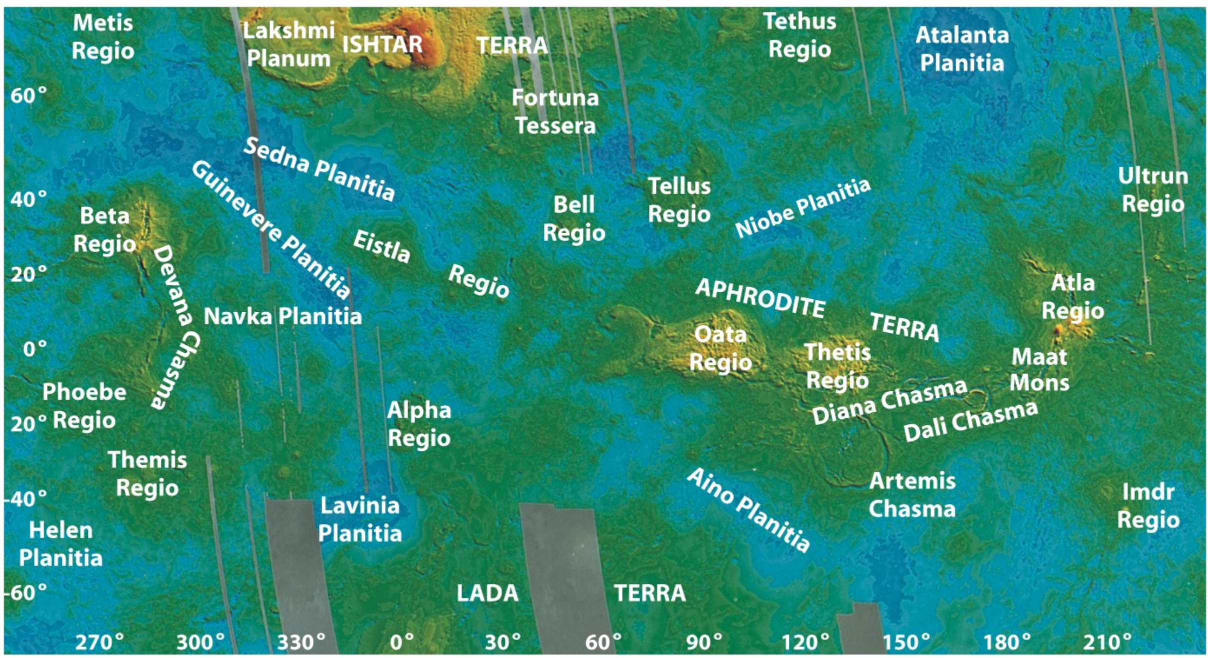


Venus' clouds by Galileo

Venus behind the veil: Magellan mapped 98% of Venus using radio observations. **Radar technique** maps the topography.

The topography of Venus

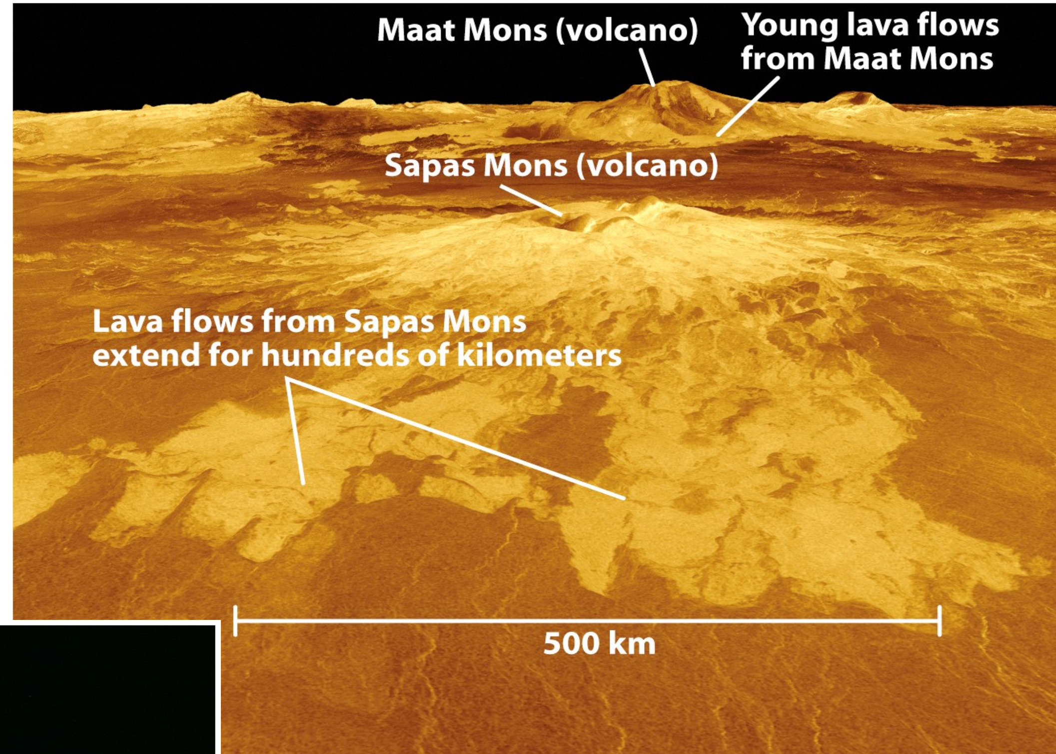
- surprisingly flat surface mostly covered with gently rolling hills, with a few highlands and large volcanoes.
- no evidence of plate tectonics, little weather erosion.

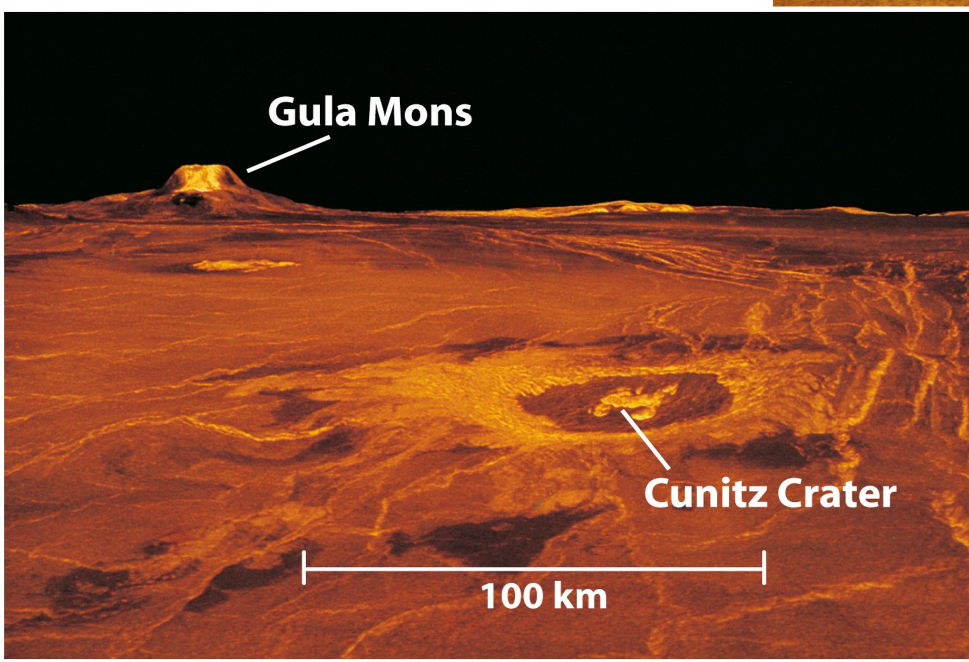


(http://www.jpl.nasa.gov/magellan)

Scientists suspect that, although Venus is very similar in size to Earth, its interior is probably different in major ways. In particular, Venus seems to lack an "asthenosphere," a buffer layer within Earth between the outer part of the planet and the mantle beneath. As a result, the gravity signature of features on Venus closely reflect surface topography, whereas on Earth such a correspondence does not always occur.

Volcanoes and **lava flows** all over the planet, producing a young planetary surface, about 500 millions yrs.

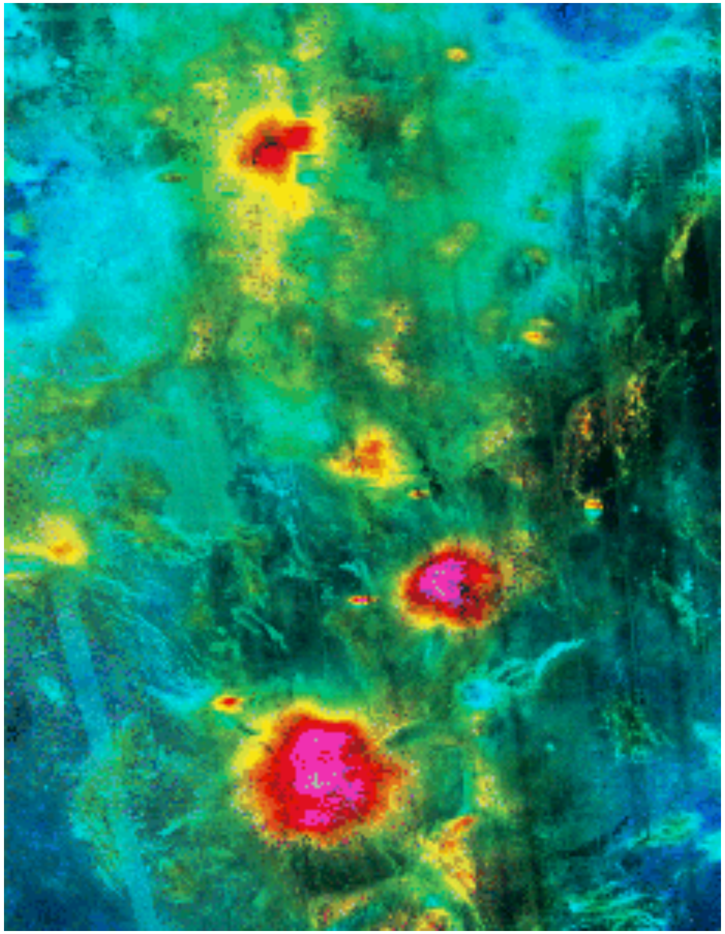


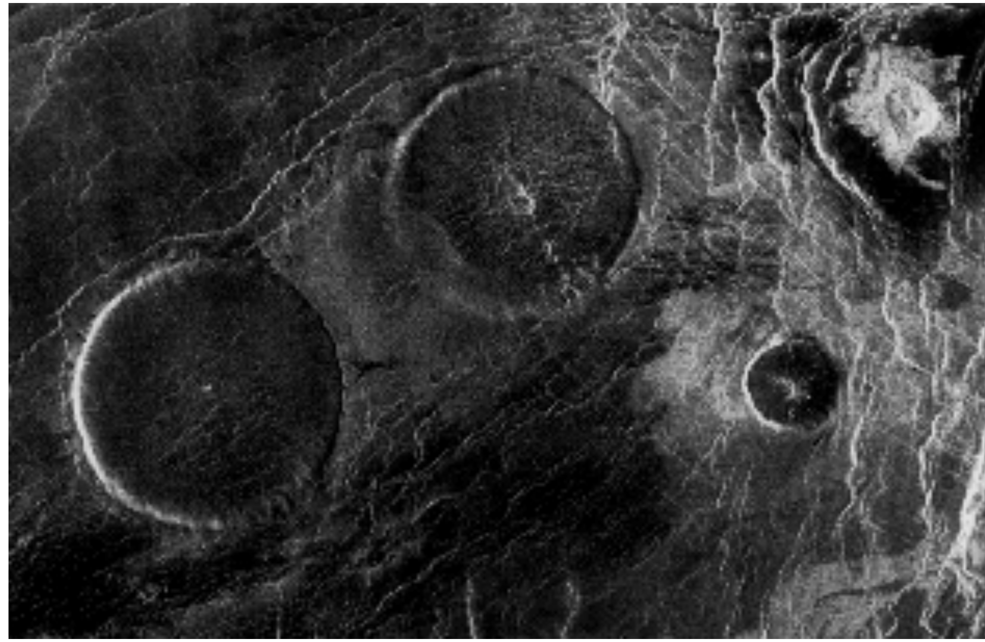


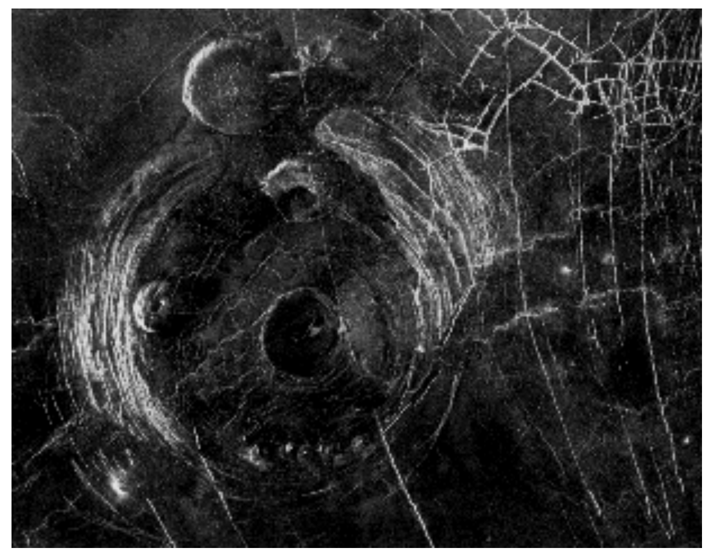
No plate tectonics.
No weather erosion.

Q: how does it compare with the Earth?

Pancake domes: unique features on Venus, formed by viscous (sticky) lava.

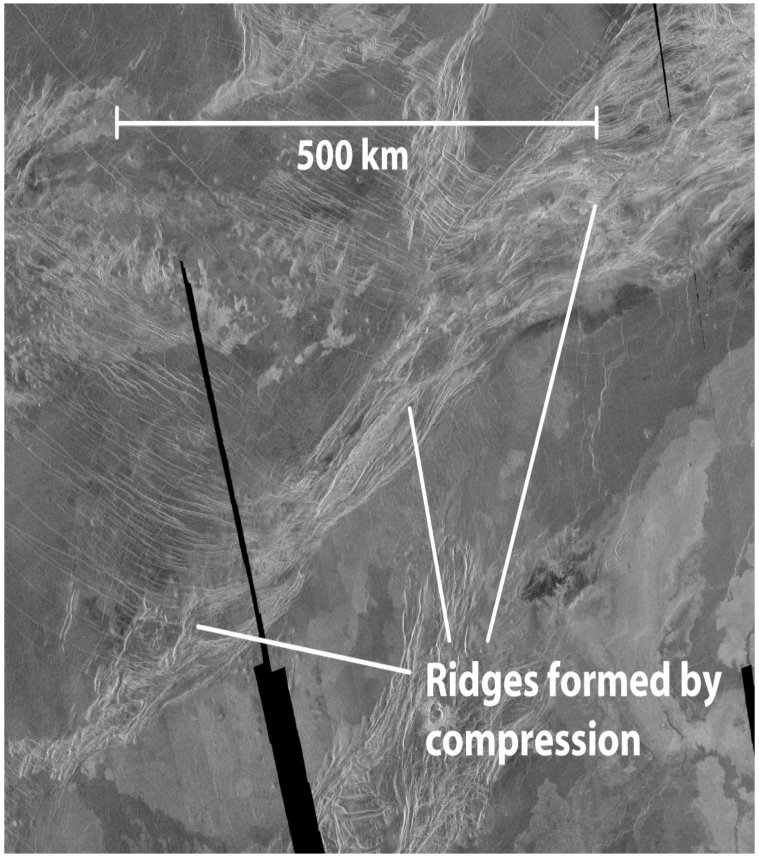


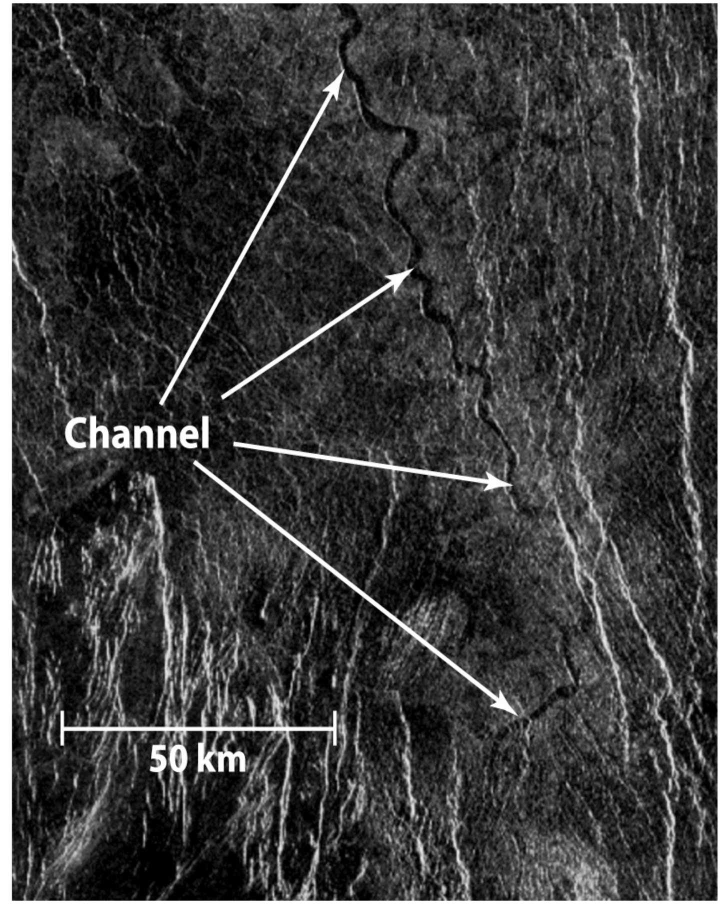




Hot spot volcanoes in a chain

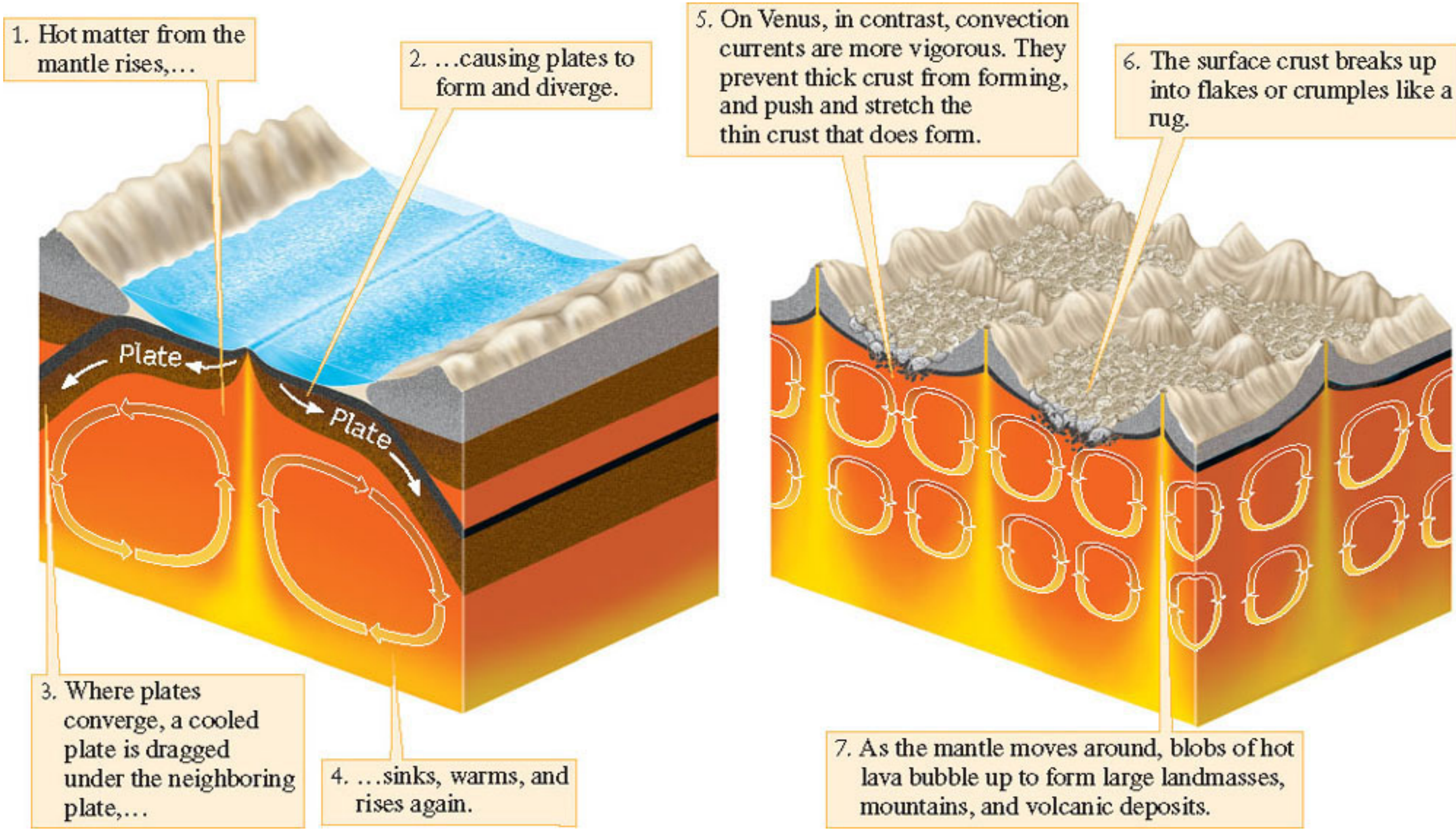
ridges and channels: lava channels





Scientists were also surprised to see huge channels thousands of kilometers long on Venus. These appear to be lava channels, and frequently show a fan of lava at their mouths.

Why no plate tectonics on Venus?

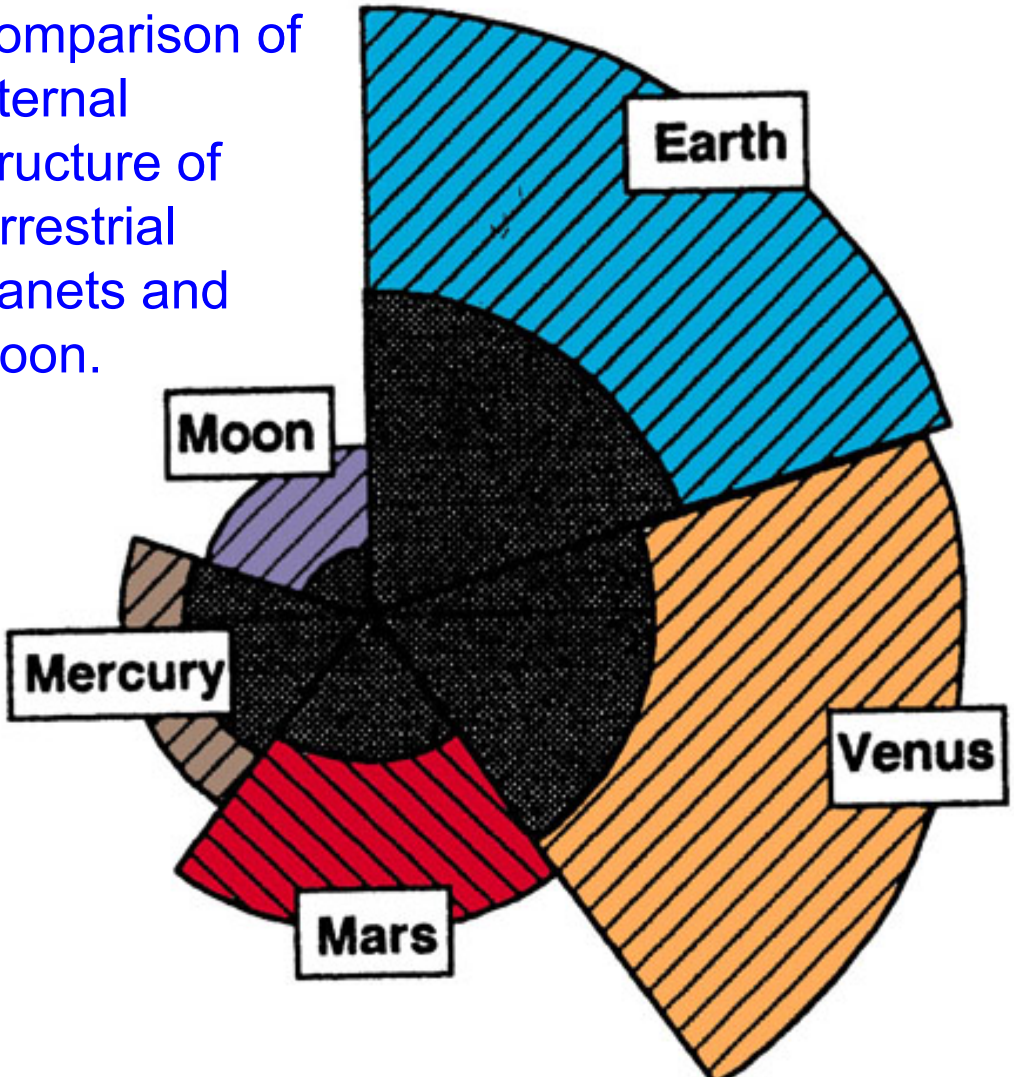


Earth: plate tectonics caused by internal heat and structure

Venus: too hot to form thick crust or plates

7.6 Interior and magnetic field

Comparison of internal structure of terrestrial planets and Moon.

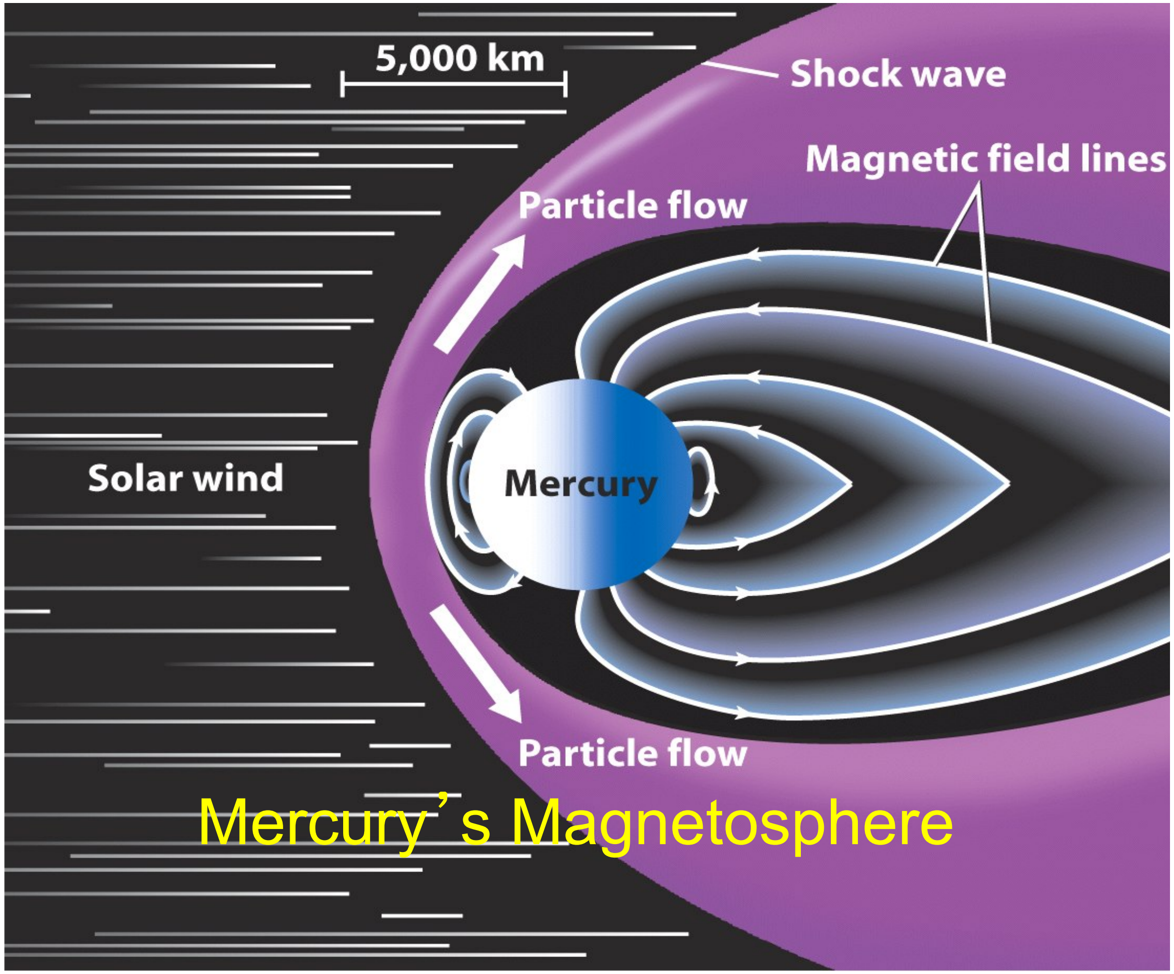


- The size of the metal (iron) core largely determines the density: Mars and Moon is less dense than Earth, Mercury, and Venus.
- Earth and Mercury have global magnetic field due to partially liquid iron core.
- Mars and Moon have solid cores, and Venus rotates too slowly, thus no global magnetic field.

(from http://quartz.ucdavis.edu/~gel36/comparison.html)

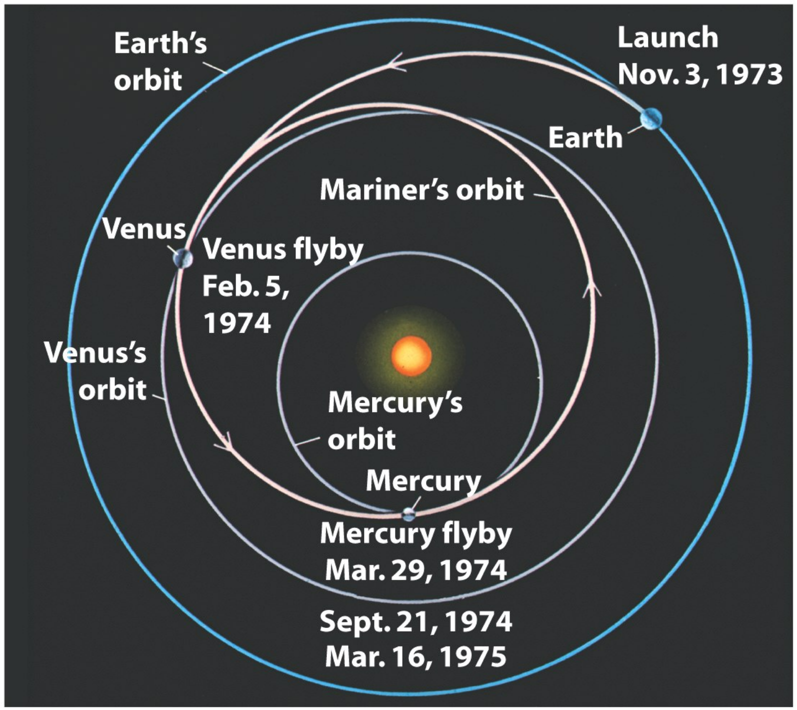
The magnetosphere blocks the solar wind from reaching the surface of the planet.

Mercury's magnetic field lacks the strength (only 1%? of the Earth's magnetic field) to trap the charged particles into radiation belts like the Van Allen radiation belts around the Earth.

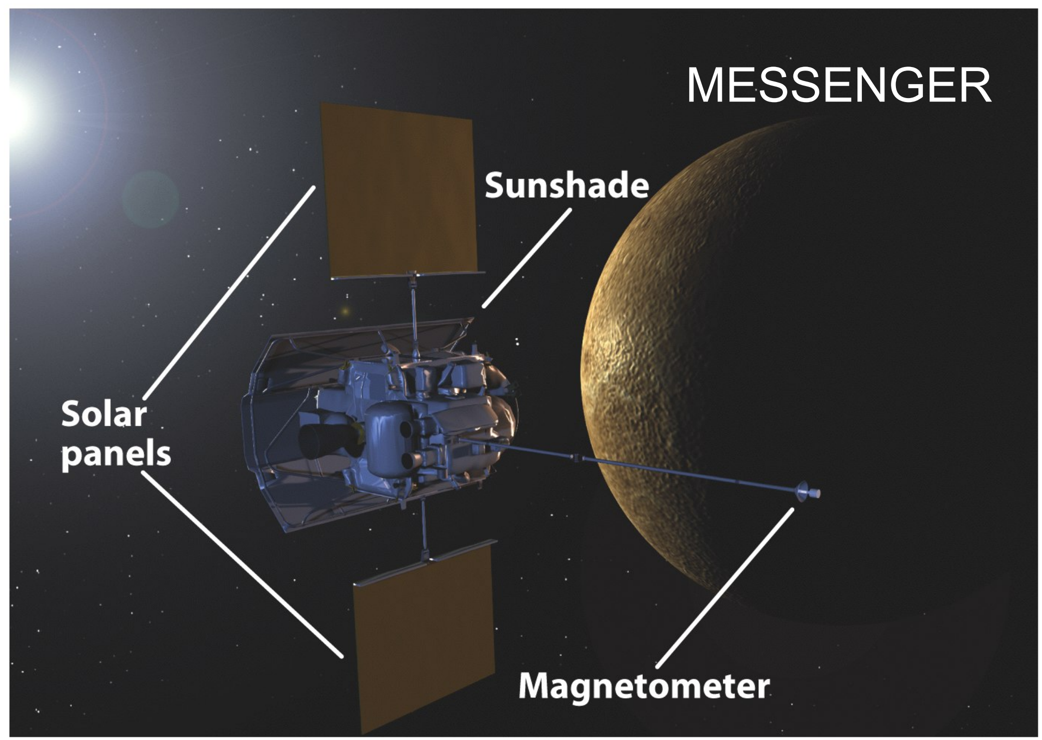


7.7 Past, current, and future missions

Most of our detailed information about Mercury's surface is from the fly-by [Mariner mission]in 1974/1975



MESSENGER arrived in Mercury orbit in 2011 and mapped the other side of Mercury.



Mariner only saw one side (45%) of Mercury's surface.

The largely unknown Mercury

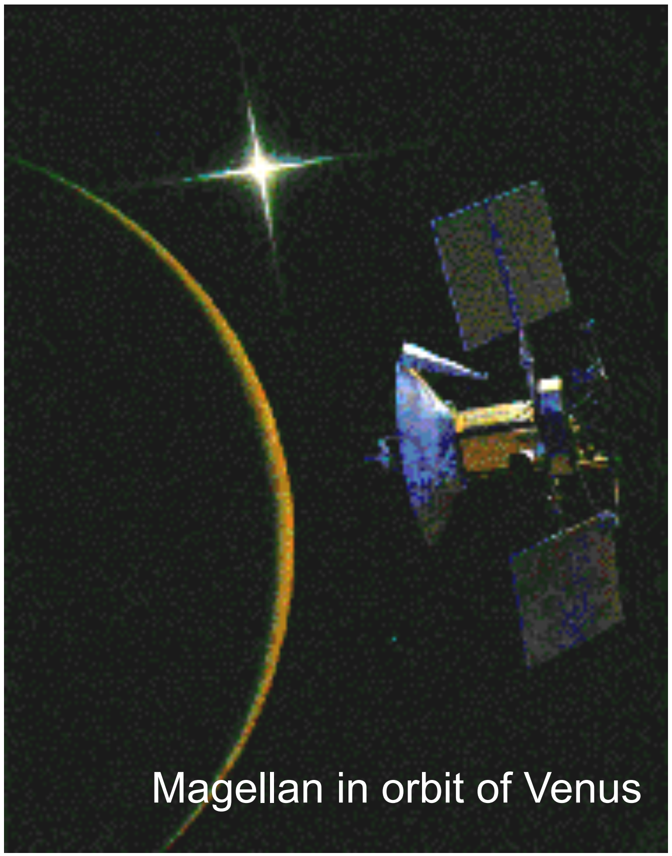
1: Why is Mercury so dense?
2: What is the geologic history of Mercury?
3: What is the nature of Mercury's magnetic field?
4: What is the structure of Mercury's core?
5: What are the unusual materials at Mercury's poles?
6: what volatiles are important at Mercury?

The MESSENGER is seeking answers to these questions.

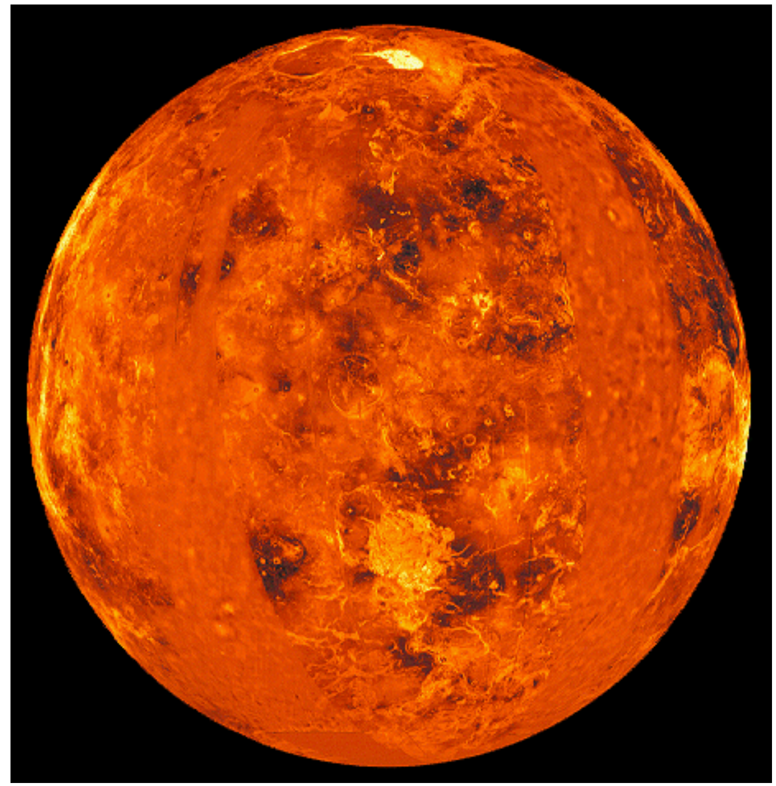
http://messenger.jhuapl.edu/

Missions to Venus

Mariner 2 was the first mission to Venus (1960-62), followed by Soviet **Venera** missions. **Magellan** (1990-1994) took back the most detailed images of Venus.



JPL/NASA



Magellan mapped 98% of Venus using radio observations.

Key Words

- 1-to-1 spin-orbit coupling
- 3-to-2 spin-orbit coupling
- conjunction
- crustal dichotomy
- eccentricity of orbit
- favorable opposition
- greatest eastern elongation
- greatest western elongation
- gullies
- hot spot volcanism
- inferior planets
- Kepler's three laws
- pancake domes
- polar cap
- prograde rotation
- retrograde rotation
- radar technique
- rift valley
- runaway greenhouse effect
- runaway icehouse effect
- scarp
- solar transit
- superior planets