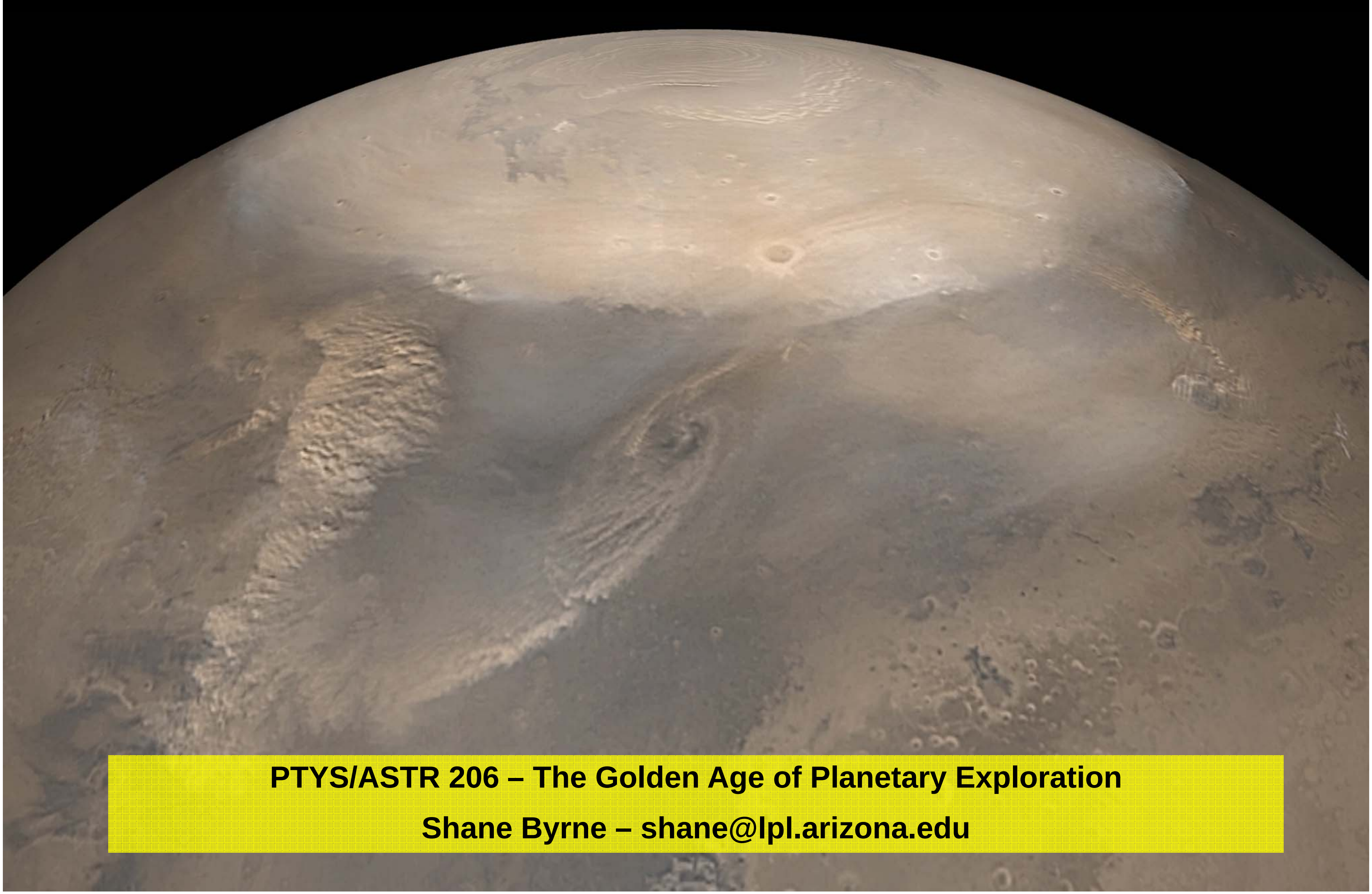
- **Announcements**
  - **HW 2**
  - **Mid-term results**

  - **Mid-term went very well**

- **Results**

87.5 – 100%	17
70-87.5%	37
62.5-70%	29
50-62.5%	19
<50%	21

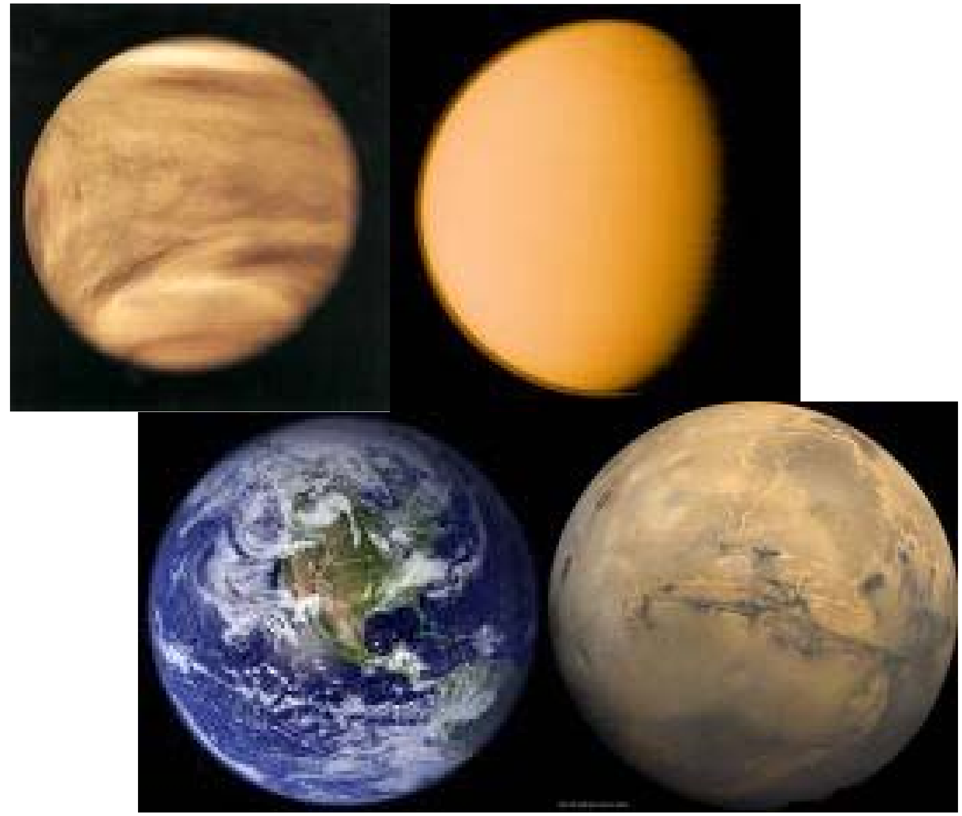
Terrestrial planet atmospheres



PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

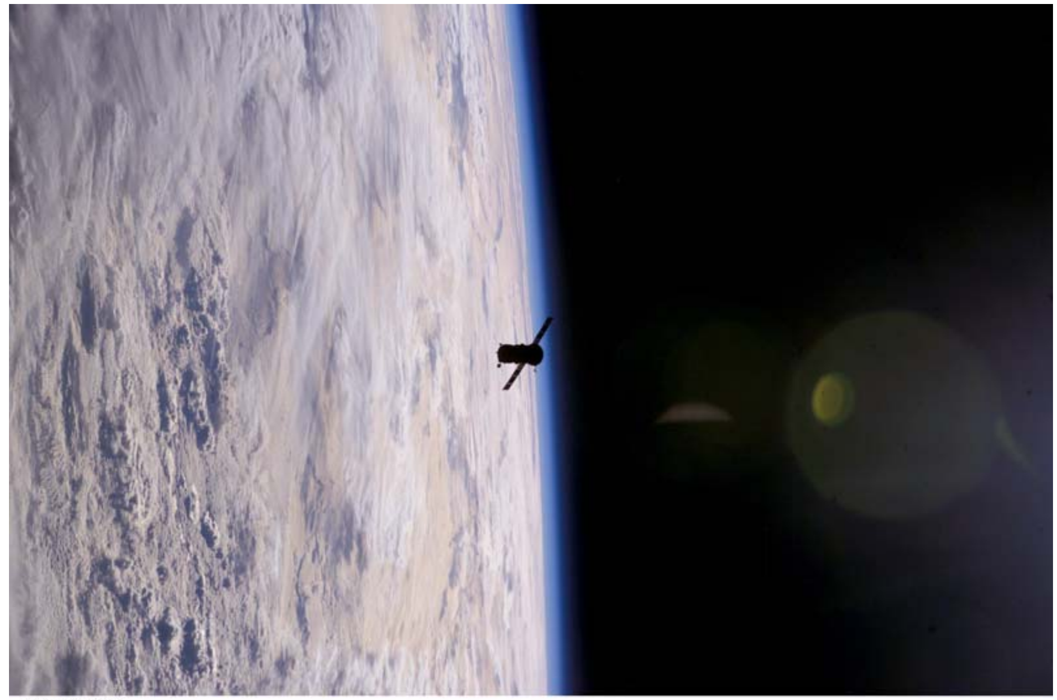
In this lecture…



- **Introduction to atmospheres**
  - **Pressure and Temperature**
  - **Scale height**
  - **Comparing planetary atmospheres**
- **Radiation and atmospheres**
  - **Clouds**
  - **Greenhouse effect**
- **Circulation**
  - **Why is Tucson a Desert?**
  - **What's El Nino**
- **Surface features from the atmosphere**
  - **Sand dunes and how they work**
  - **Eolian erosion**
- **'Atmospheres' of Moon and Mercury**
  - **Ice in polar craters**

Introduction

- **What's the atmosphere?**
  - **A thin gas layer**
  - **Gas molecules moving around at high-velocities**
  - **Held down with gravity**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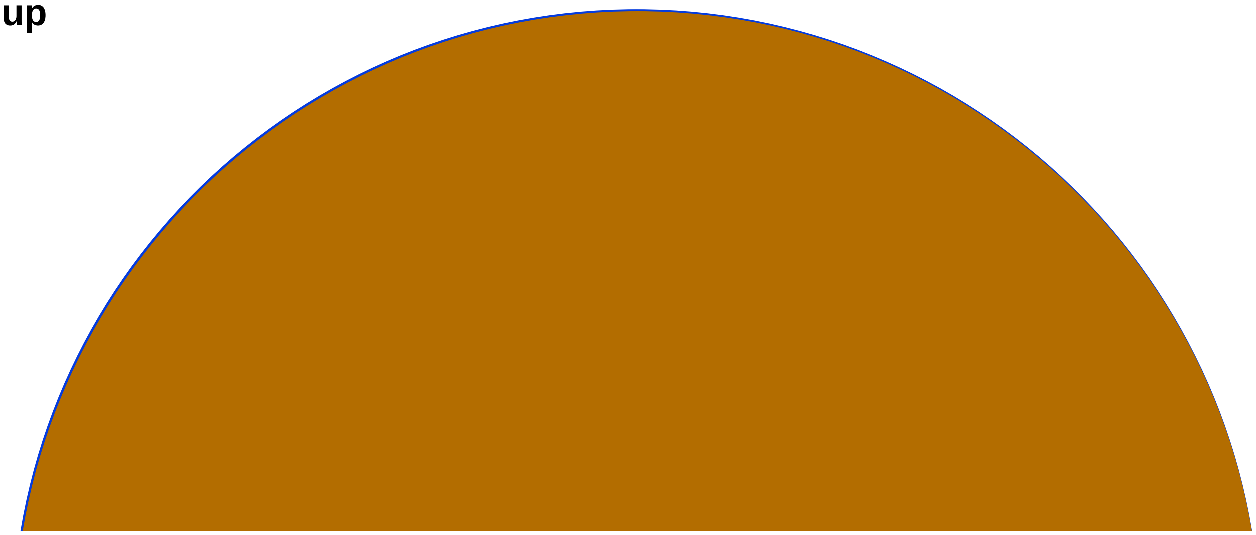
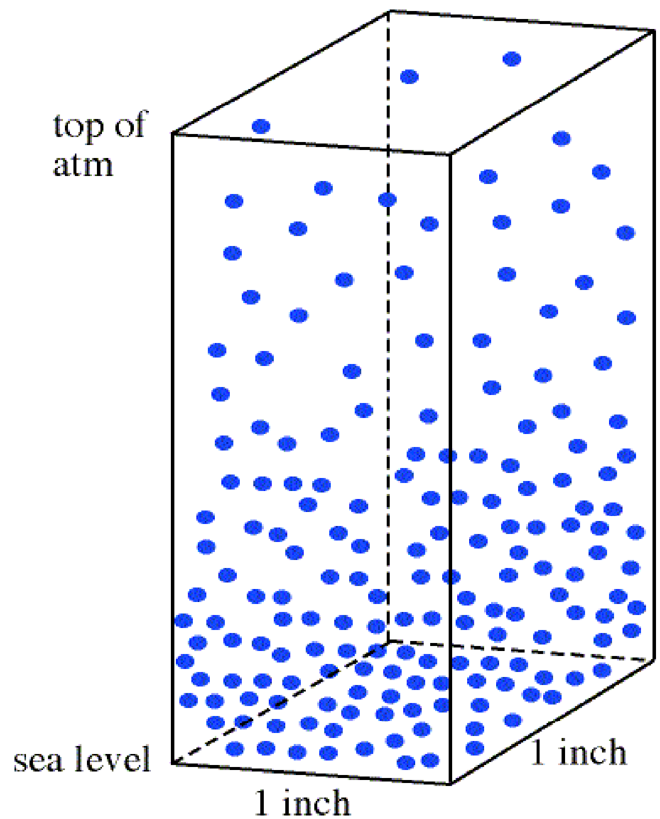
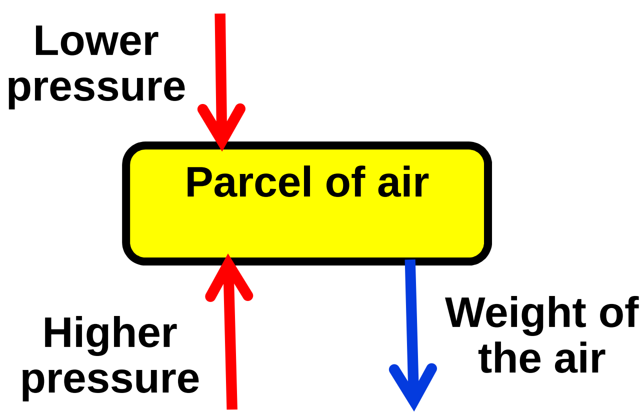
- **The "edge" of the atmosphere**
  - **Thins gradually with altitude**
  - **Karman line**
    - **Based on aeronautics**
    - **~100km up**



- Gravity squeezes the atmosphere
  - High pressure at the bottom
  - 10^5 Pascals (Newtons per square meter)
  - ~10,000 Kg of mass above each square meter
  - So why aren't we squashed flat?
- The atmosphere is supported by pressure
  - Pressure = a * density * temperature
    - 'a' depends on the type of gas
  - A cold dense atmosphere (e.g. Titan) can have the same pressure as a hot less-dense atmosphere (e.g. Earth)

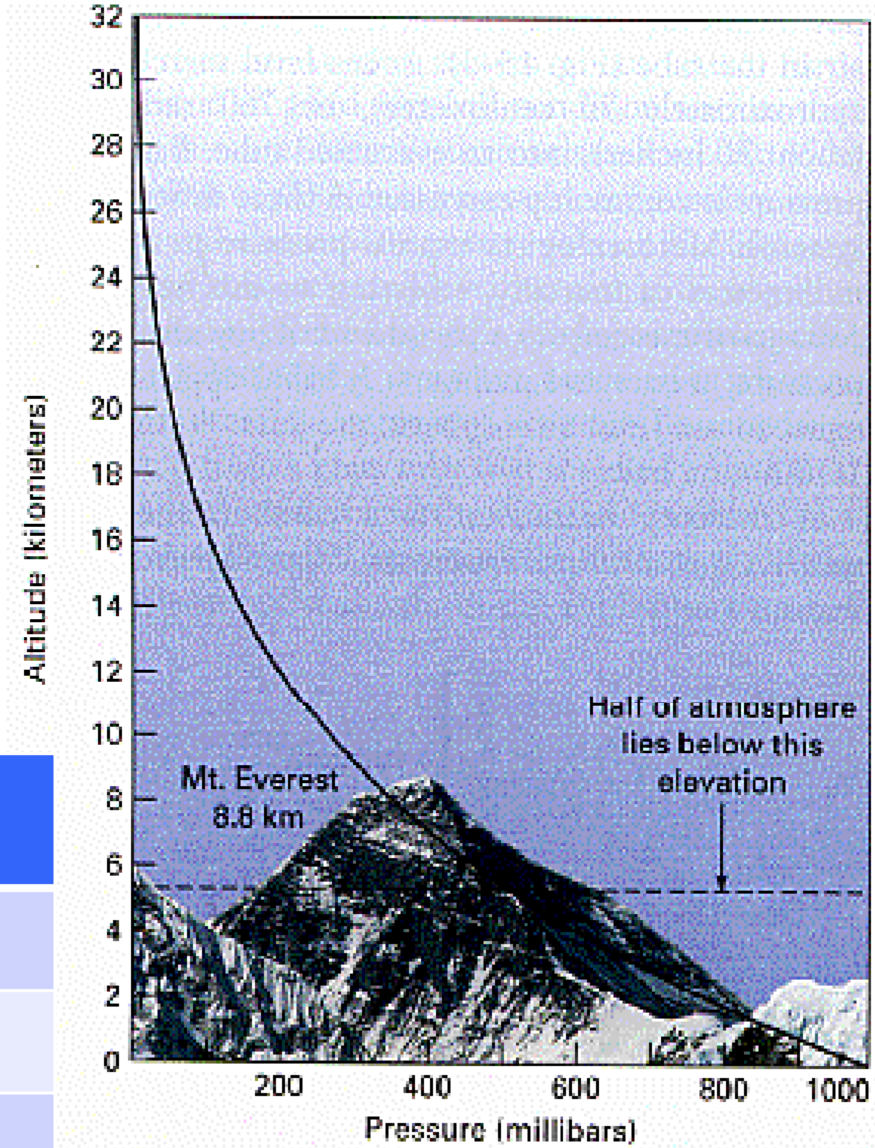




This is "hydrostatic equilibrium"
Makes the atmosphere (mostly) stable

- **Pressure drops with height**
- **The 'scale height' measures the thickness of the atmosphere**
  - **At the scale height the pressure is 1/e times the surface pressure.**
  - **e is a special number in math**
  - **1/e = 37%**
  - **Earth's scale height is ~8km**
- **Scale height tells you how compact the atmosphere is**

Scale height	Elevation	Atm. Pressure
1	8km	37% $=(1/e)^1$
2	16km	14% $=(1/e)^2$
3	24km	5% $=(1/e)^3$



- Earth's atmosphere has many sections
- All our surface features (even the highest mountains) are in the troposphere

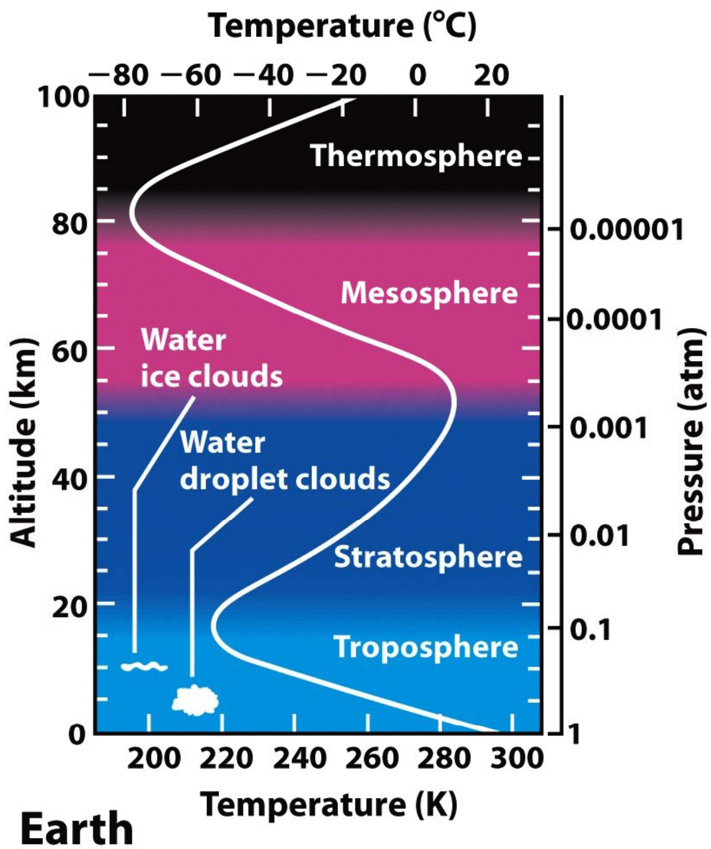
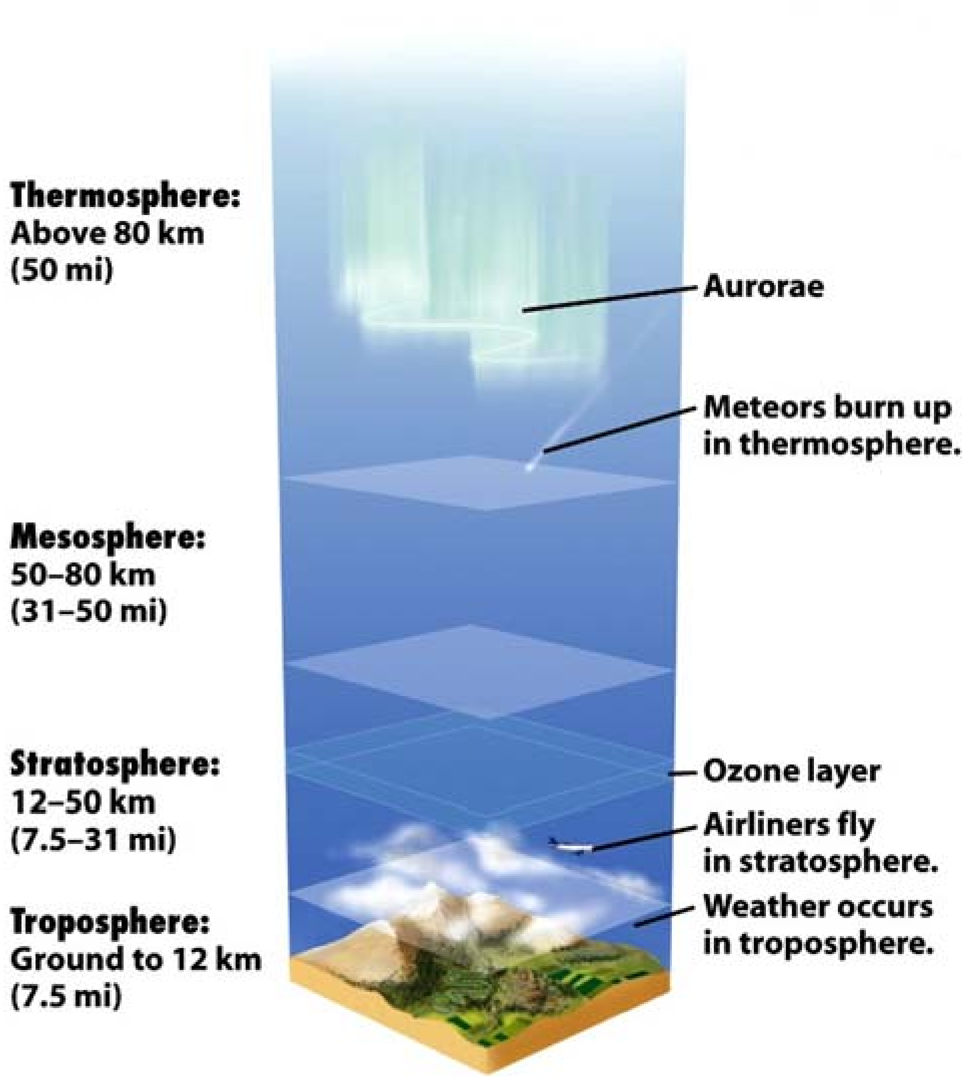


Figure 11-27a
Universe, Eighth Edition



Structure of Earth's Atmosphere

- **Here's a problem**
  - **What's the atmospheric pressure at the Karman line – 100km elevation**
  - **100km is 12.5 scale heights (i.e. 100km / 8km)**

  - **The pressure is $(1/e)^{12.5}$**
  - **Remember 1/e is 0.37 (or 37%).**

  - **So $(0.37)^{12.5}$ is 0.000004**
  - **The atmospheric pressure at 100km (the 'edge' of space) is 4 millionths that at sea-level**

- **Different planets have different gases, temperatures and gravities**
  - **If gravity goes up?**
  - **If temperature goes up?**
  - **What if the atmospheric gases were more massive? E.g. CO_2 vs. N_2**

- **Different planets have different gases, temperatures and gravities**
  - **If gravity goes up?**
    - **Higher gravity makes the atmosphere more compact**
    - **Smaller scale height**
  - **If temperature goes up?**
  - **What if the atmospheric gases were more massive? E.g. CO_2 vs. N_2**




- Different planets have different gases, temperatures and gravities
  - If gravity goes up?
    - Higher gravity makes the atmosphere more compact
    - Smaller scale height
  - If temperature goes up?
    - Higher temperatures makes the atmosphere less compact
    - Larger scale height
  - What if the atmospheric gases were more massive? E.g. CO_2 vs. N_2




- Different planets have different gases, temperatures and gravities
  - If gravity goes up?
    - Higher gravity makes the atmosphere more compact
    - Smaller scale height
  - If temperature goes up?
    - Higher temperatures makes the atmosphere less compact
    - Larger scale height
  - What if the atmospheric gases were more massive? E.g. CO_2 vs. N_2
    - Heavier gases make the atmosphere more compact
    - Smaller scale height




- **Comparing planetary atmospheres**
- **Compositions are very different**

Table 9-4 Chemical Compositions of Three Planetary Atmospheres

	Venus	Earth	Mars	Titan
Nitrogen (N_2)	3.5%	78.08%	2.7%	95%
Oxygen (O_2)	almost zero	20.95%	almost zero	Zero
Carbon dioxide (CO_2)	96.5%	0.035%	95.3%	Zero
Water vapor (H_2O)	0.003%	about 1%	0.03%	Zero
Other gases	almost zero	almost zero	2%	5% methane

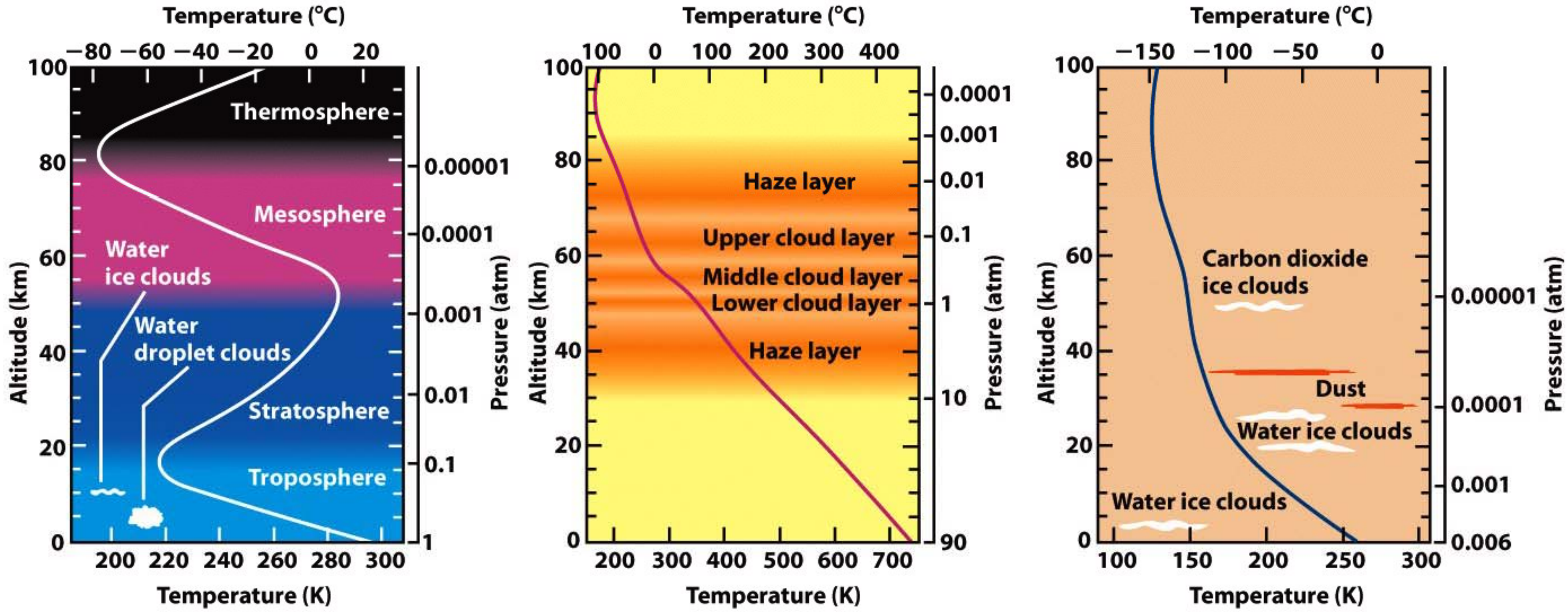



- **Carbon dioxide very common for the inner planets**
  - **Not on Titan or other outer solar system bodies**
  - **Any guesses why?**
  - **Not on Earth…**
  - **Any guesses why?**

- Carbon dioxide very common for the inner planets
  - Not on Titan or other outer solar system bodies
  - Any guesses why?
  - Too cold! Carbon dioxide is frozen solid in the outer solar system

  - Not on Earth…
  - Any guesses why?
  - Carbon dioxide used to dominate Earth's atmosphere
  - Removed by plants

- **Comparing the amounts of atmosphere…**
- **Venus, Earth and Mars are hugely different**
  - **Earths surface has a pressure of (10^5 Pa) or 1 bar or 1 atmosphere**
  - **Venus surface is about 90 bars**
  - **Mars surface is about 0.006 bars**



(a) Earth (b) Venus (c) Mars

Figure 11-27
Universe, Eighth Edition

Radiation and atmospheres

- Three major effects
  - Reflection from clouds
    - Water on Earth
    - Sulfuric acid on Venus
    - Cools the surface
  - Greenhouse effect
    - Warms the surface
    - CO_2 on Earth, Mars and Venus
  - Transports heat to cold areas
    - Polar night on Earth and Mars
    - Night on Venus

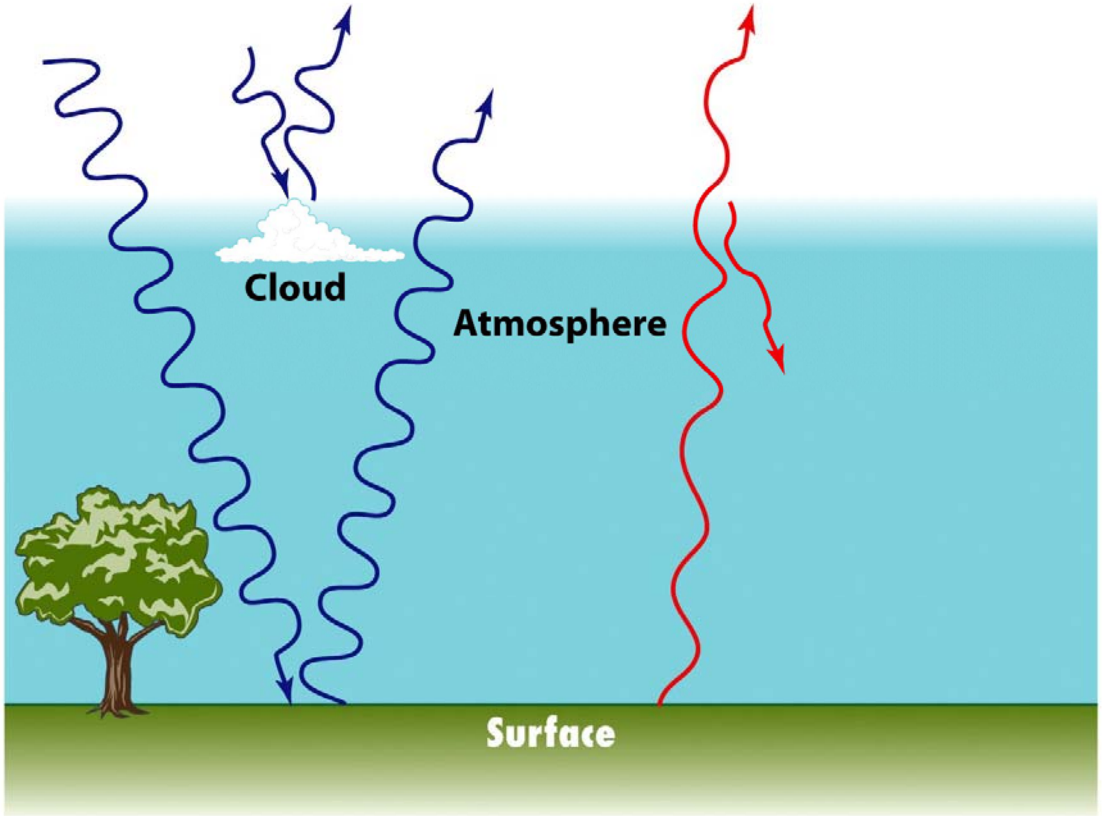
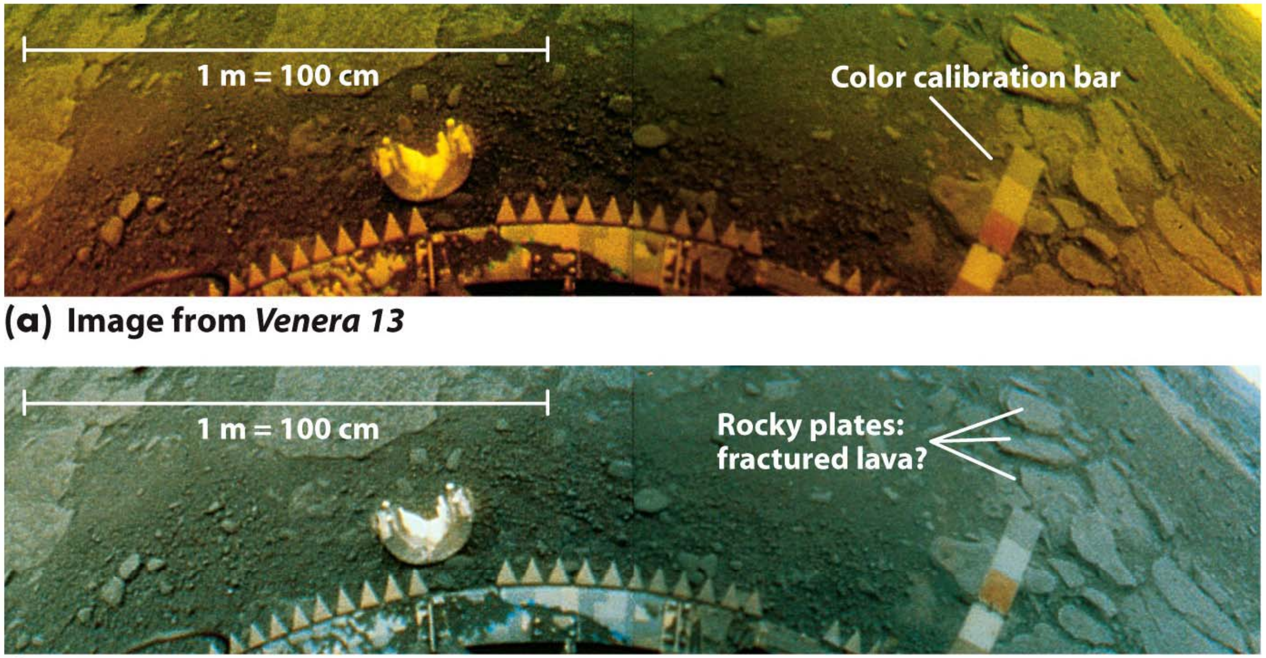


Figure 9-6
Universe, Eighth Edition

- **Venus and Earth's greenhouse effect compared**
  - **Earth's greenhouse boosts surface temperatures by about 33° C**
  - **Venus's greenhouse effects has boosted its surface temp. by 400° C**
  - **Result is that lead melts on the surface of Venus (and so do spacecraft)**
  - **Venus also has highly reflective clouds**
  - **If the clouds weren't there then the surface temperature would be 100s of degrees hotter**



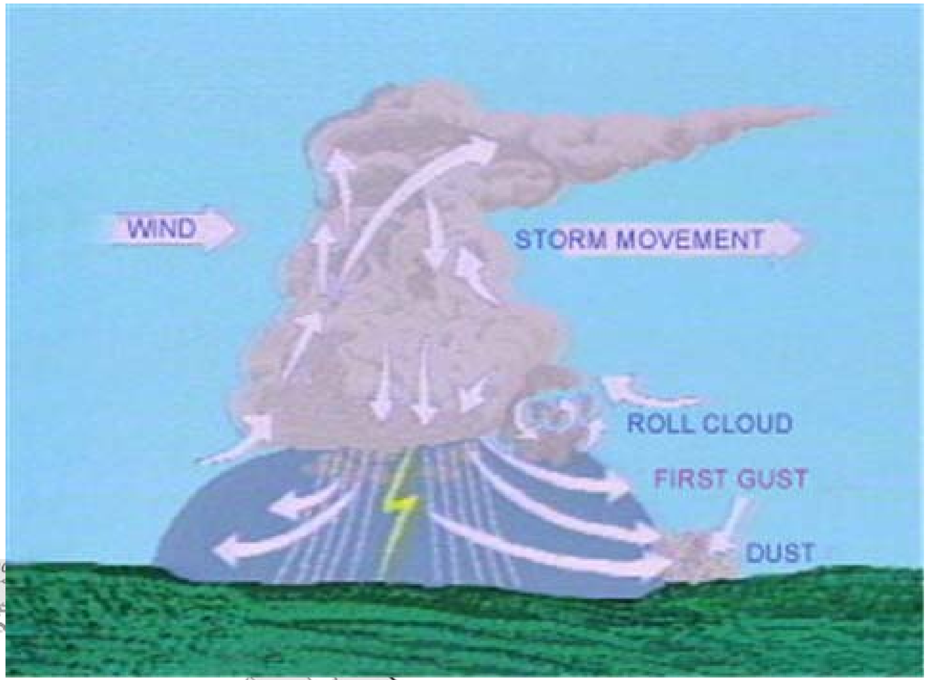
(a) Image from *Venera 13*

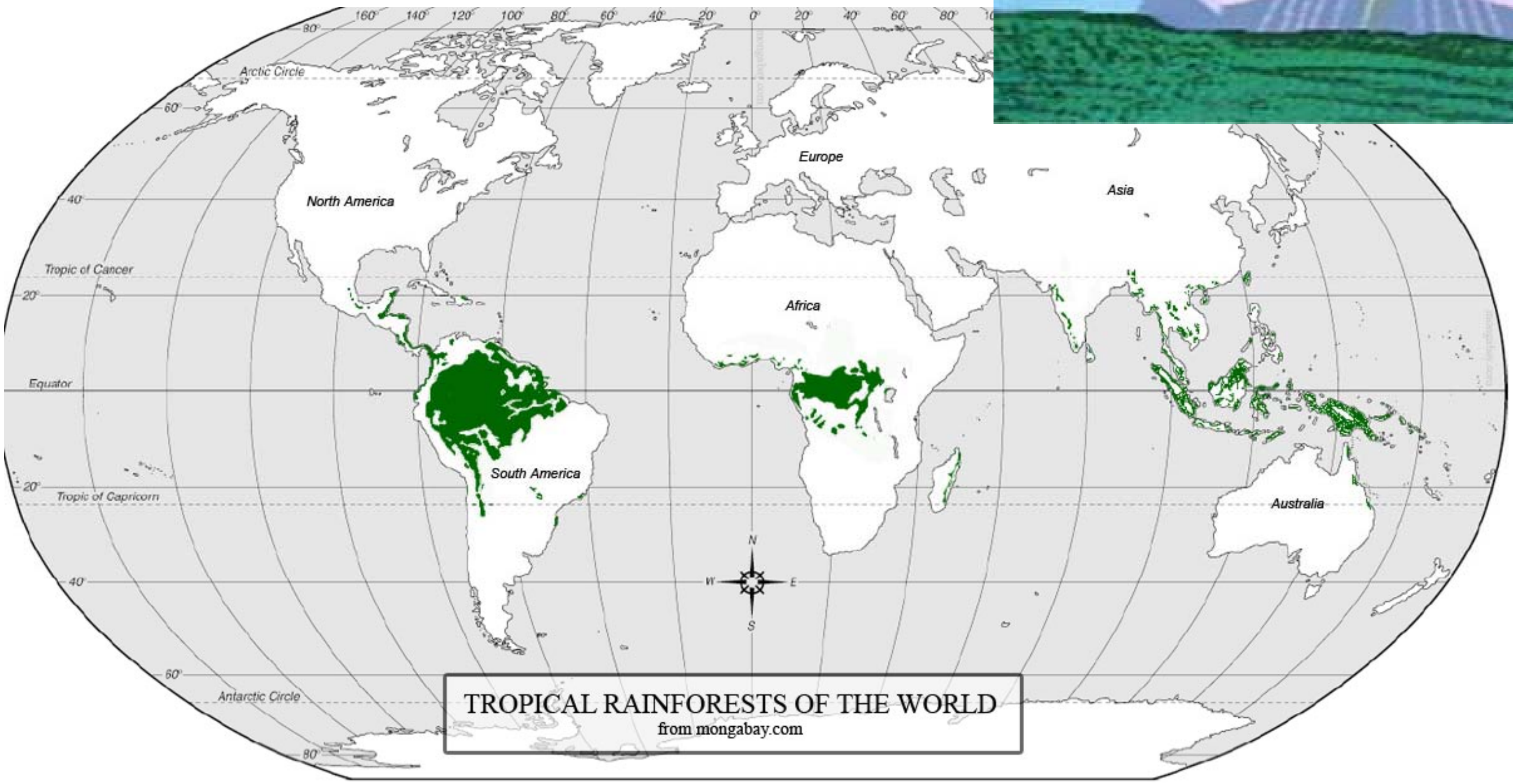
(b) Color-corrected image

Figure 11-26
Universe, Eighth Edition

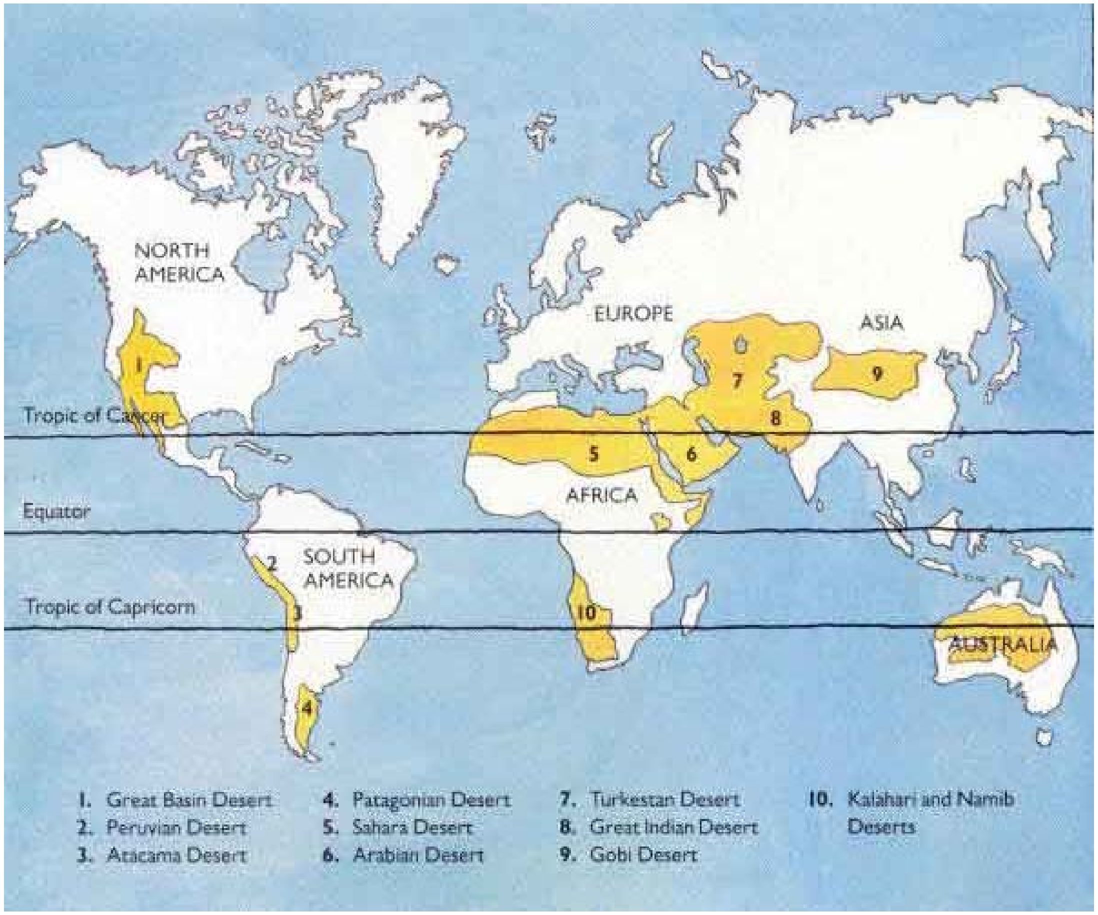
Circulation

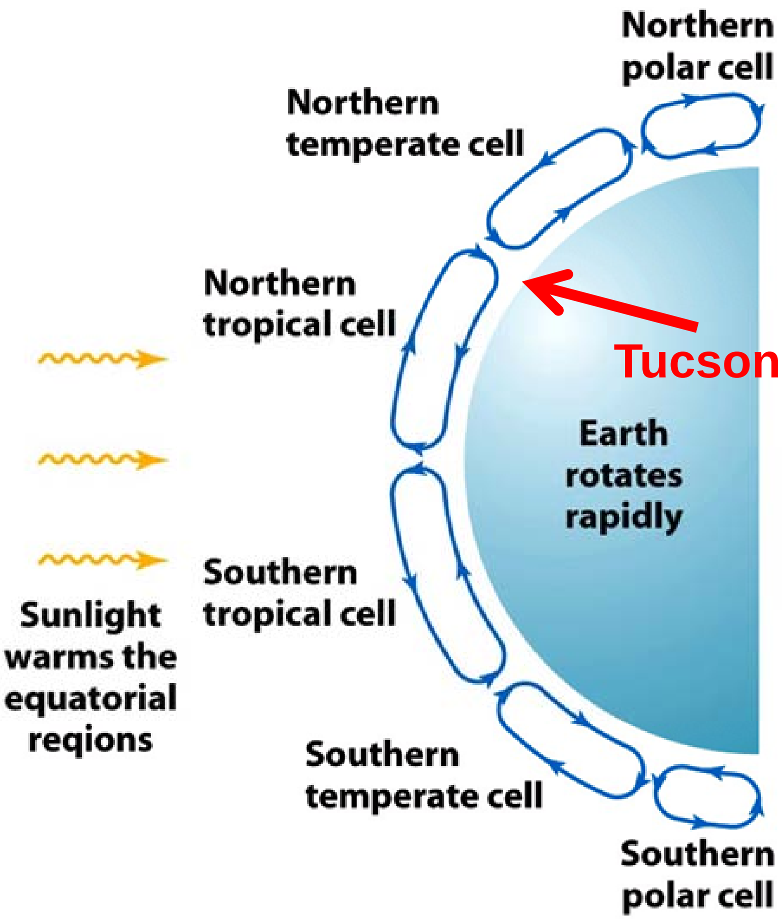
- **Air gets heated at the equator**
- **Hot air rises and cools off**
  - **Clouds form and lots of rain results**



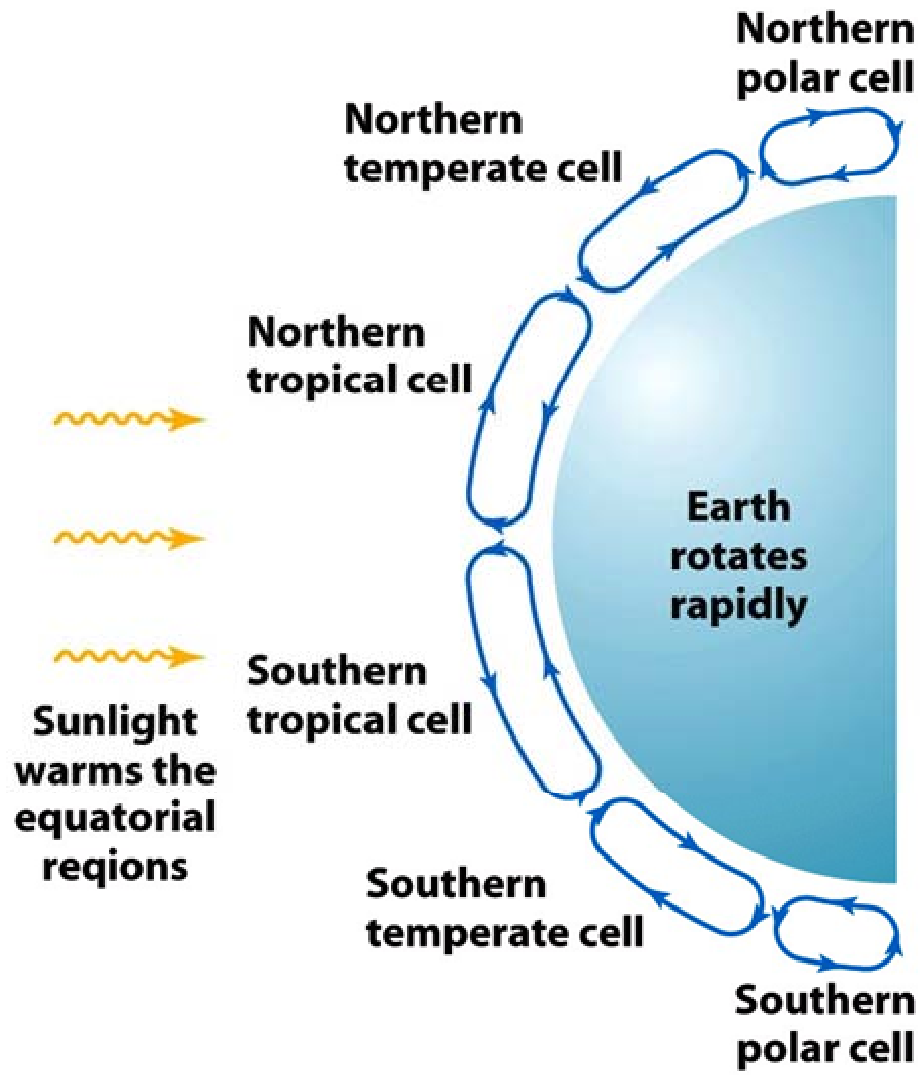


- **Hadley Cell circulation**
  - **Air (now dry) pushed aside from equator**
  - **Moves to the tropics (~30° latitude)**
  - **Descends to the surface and heats up – dry air creates deserts**



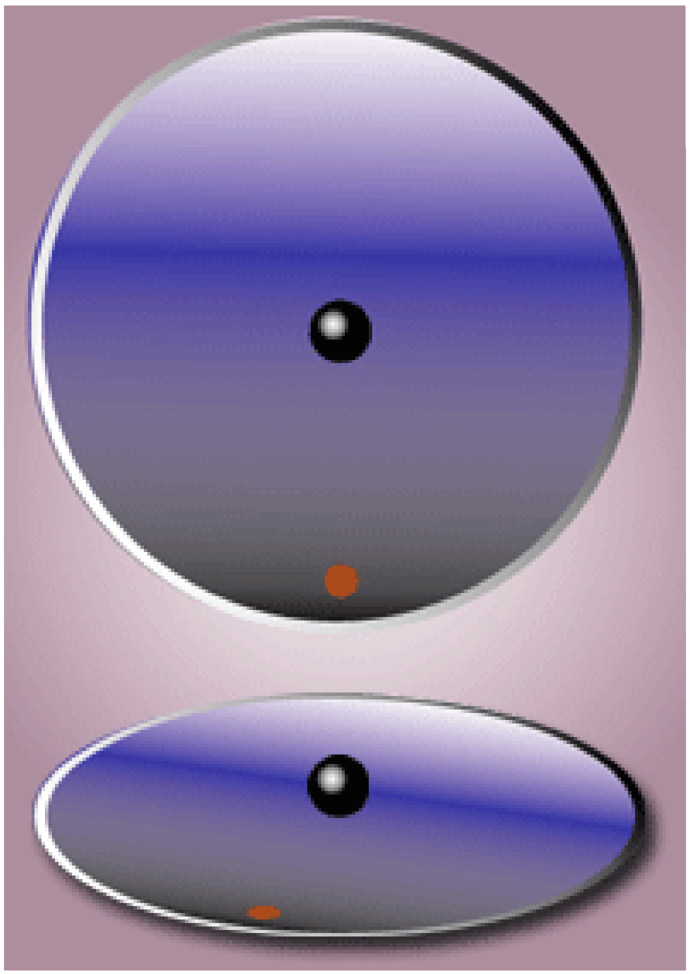


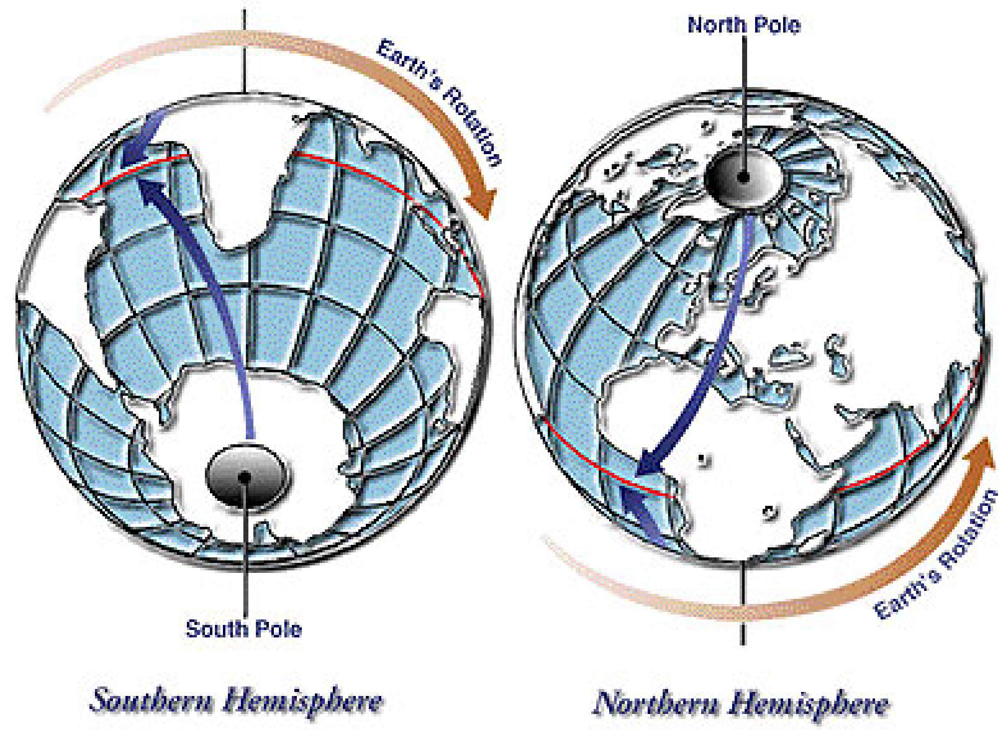
- Polar cell works the same way
  - …but in reverse
  - Cold air descends over the pole
  - Flows along the ground
  - Gets warmed up by being in contact with the surface
  - Rises around 60° latitude



- Ferrell cell
  - Sandwiched between the Hadley and polar cells
  - Driven by their motion

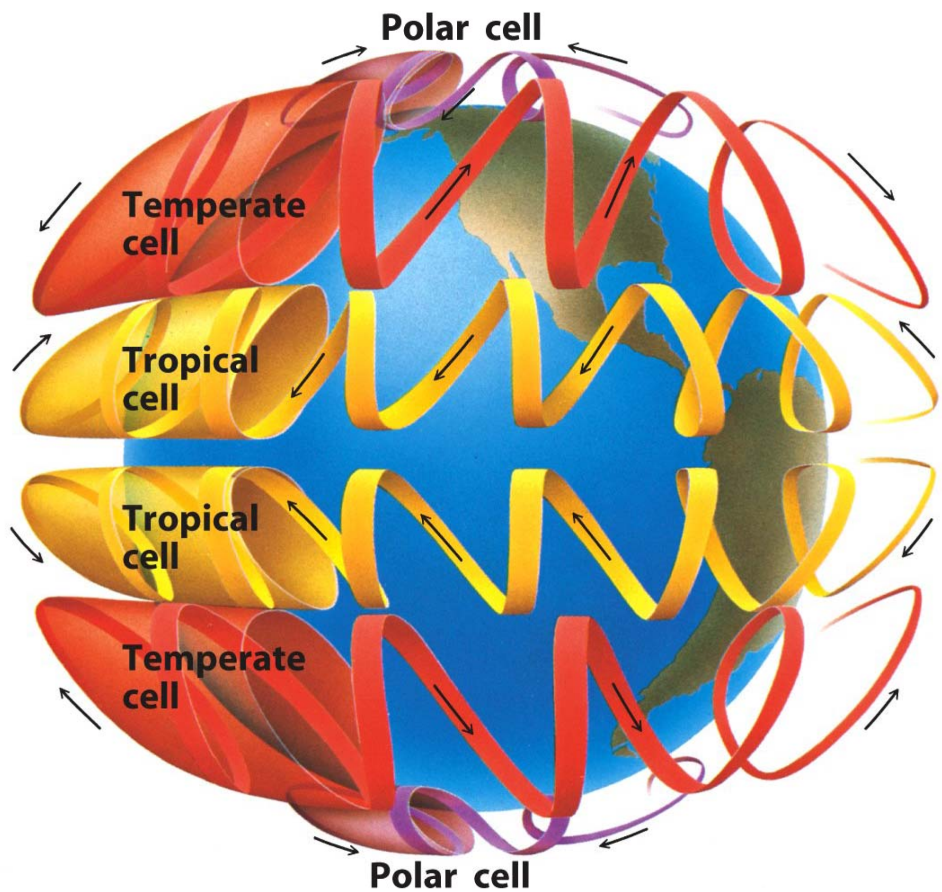
- **What's the complication?**
  - **The Earth is spinning**
  - **Things that move don't travel in straight lines**
  - **Called the Coriolis effect**





- **In the Northern hemisphere**
  - **Things are deflectedd to the right**
- **In the Southern hemisphere**
  - **Things are deflectedd to the left**

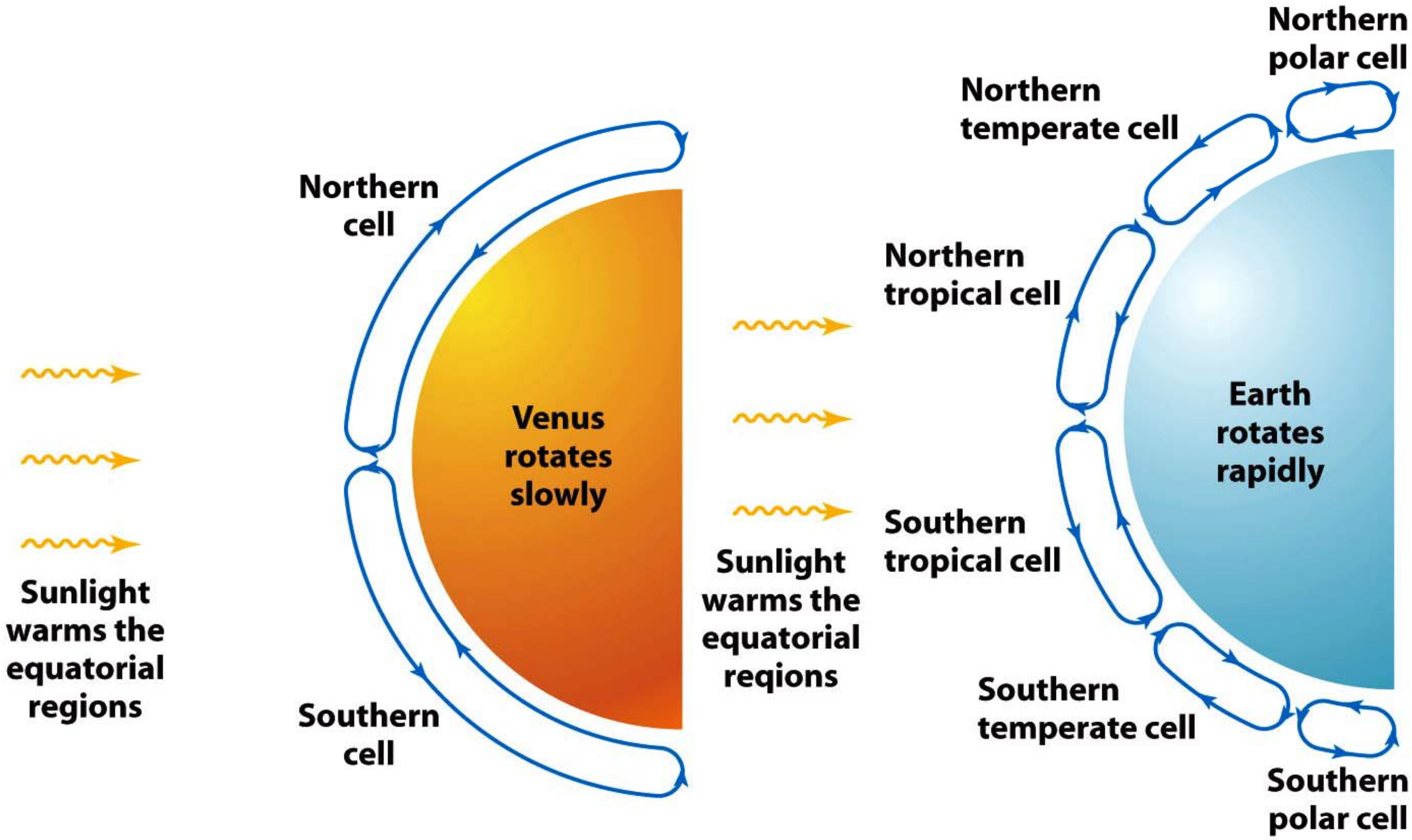
- **This deflects moving air into zonal winds**



Doldrums – winds conflict

Trade winds – blow west at surface

- **Planetary comparison?**
  - **Venus has a huge Hadley cell**
  - **Atmosphere is so thick that temperatures don't vary much between the pole and equator (or between day and night)**
  - **Rotation rate is very low so not much Coriolis deflection**



(a) Atmospheric circulation on Venus: two convection cells

(b) Atmospheric circulation on Earth: six convection cells

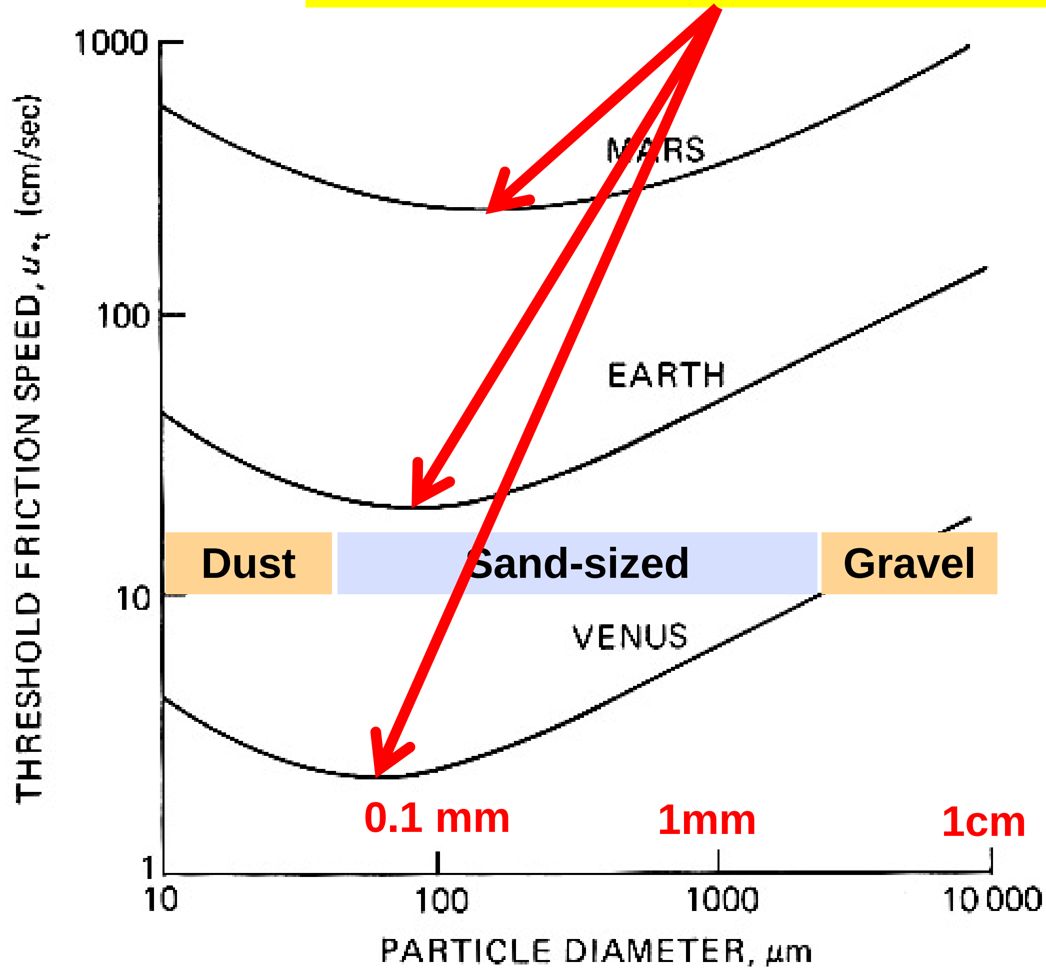
Figure 11-28
Universe, Eighth Edition

Surface features from the atmosphere

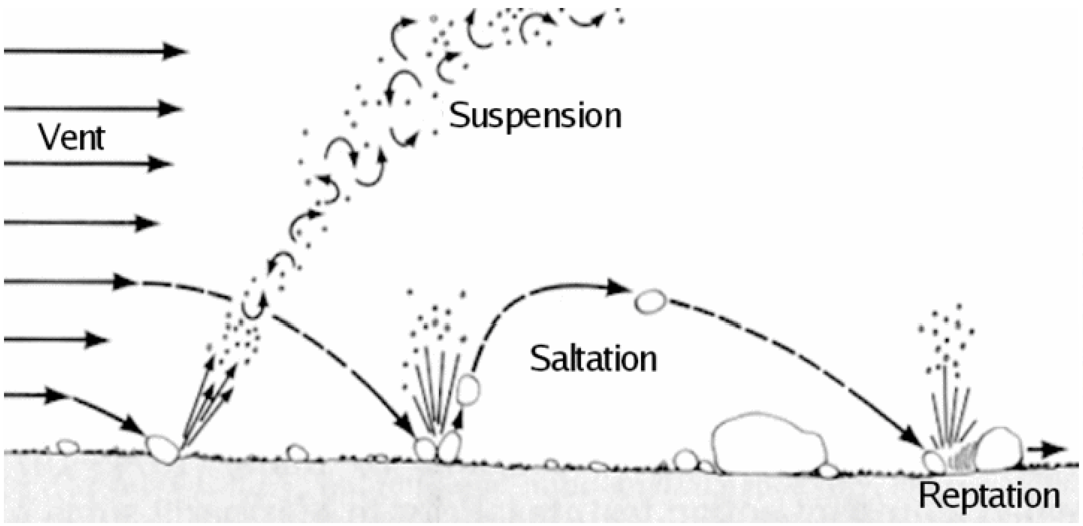
- **Particles classified by Udden-Wentworth scale**

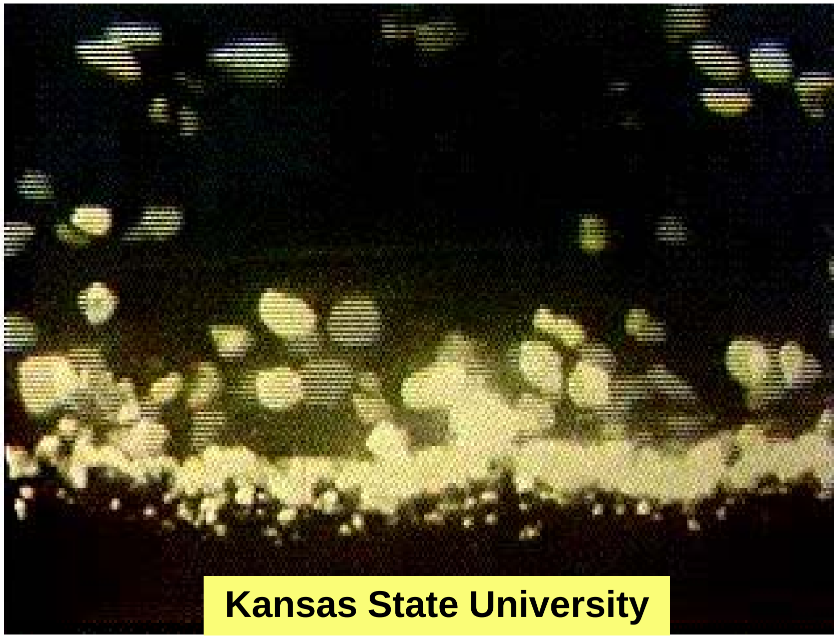
φ scale	Size range (metric)	Aggregate name (Wentworth Class)
< −8	> 256 mm	Boulder
−6 to −8	64–256 mm	Cobble
−5 to −6	32–64 mm	Very coarse gravel
−4 to −5	16–32 mm	Coarse gravel
−3 to −4	8–16 mm	Medium gravel
−2 to −3	4–8 mm	Fine gravel
−1 to −2	2–4 mm	Very fine gravel
0 to −1	1–2 mm	Very coarse sand
1 to 0	½–1 mm	Coarse sand
2 to 1	¼–½ mm	Medium sand
3 to 2	125–250 µm	Fine sand
4 to 3	62.5–125 µm	Very fine sand
8 to 4	3.90625–62.5 µm	Silt
> 8	< 3.90625 µm	Clay
>10	< 1 µm	Colloid

Easiest particles to move are sand-sized

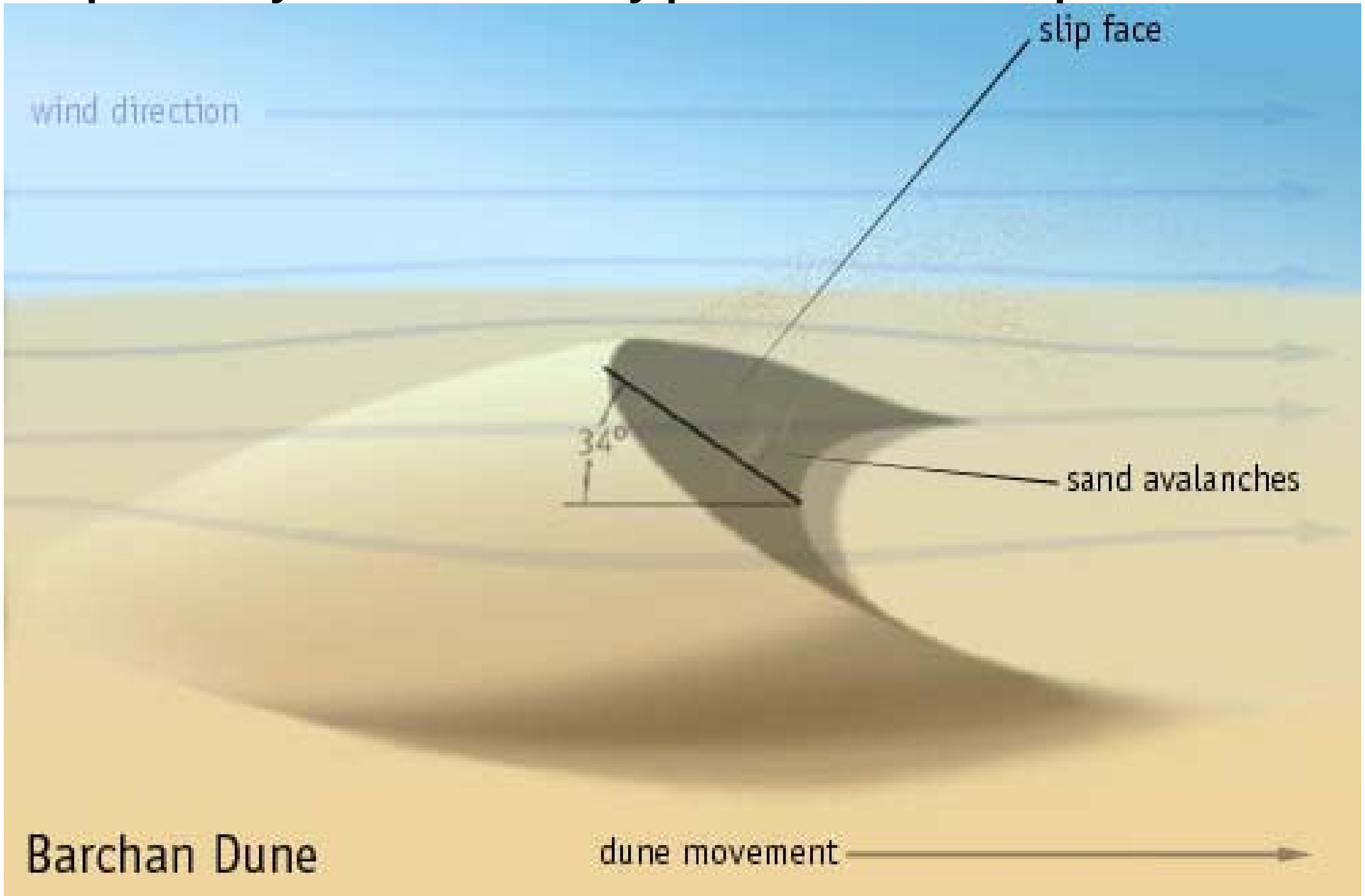


- **Grains travel by saltation**
  - **Impacting grains can dislodge new particles (reptation)**
  - **Impacting grains can push larger particles (creep)**

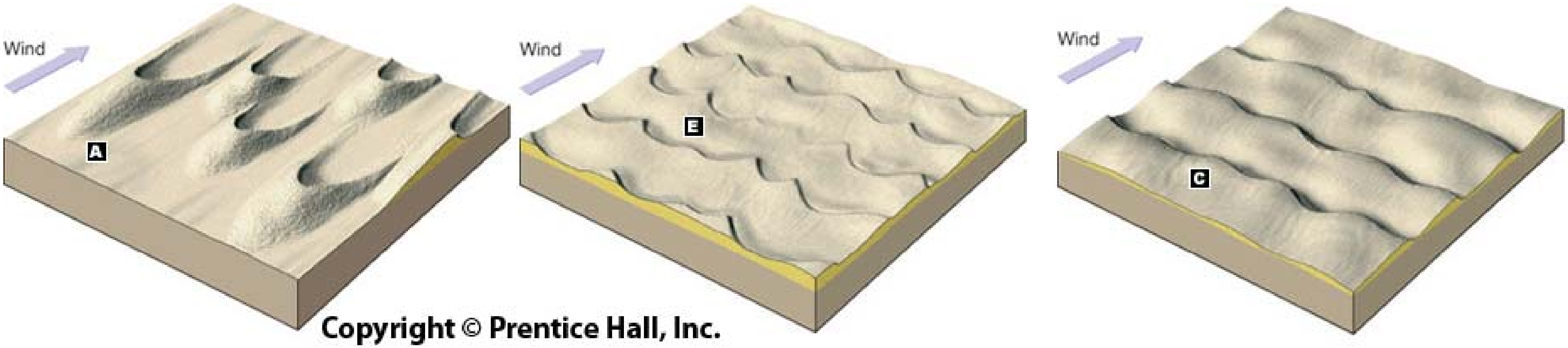




- **Saltating particles make many hops up the windward slope**
- **Wind disconnects from the surface at edge of dune**
- **Sand falls down the 'slip-face'**
  - **Slip face slope is the angle of repose**
  - **Angle of repose very similar for many particle-sizes and planets**

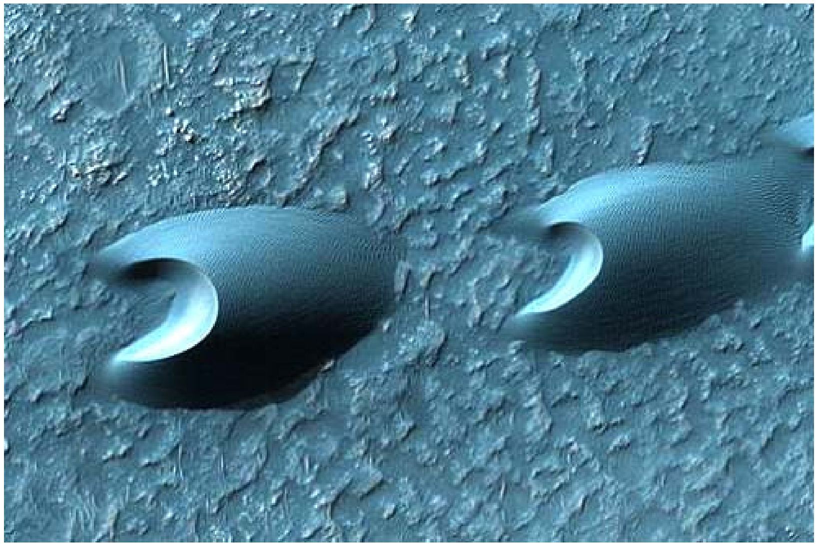


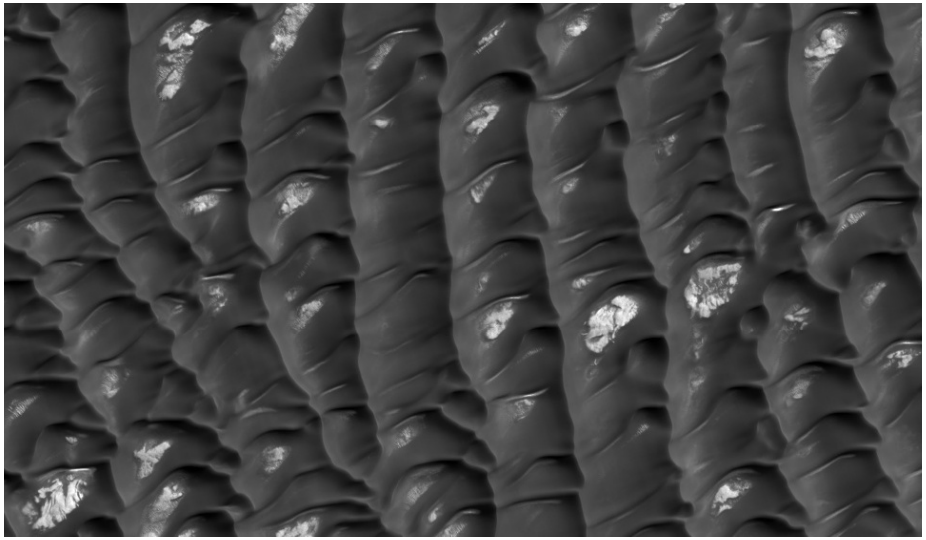
- **Unidirectional winds**
  - **Dune shape depends on sand supply**



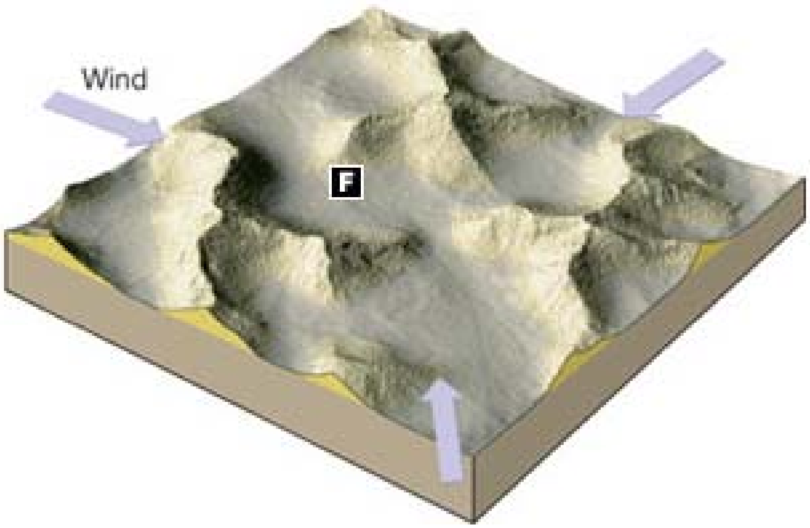
Barchan **Barchanoid ridges** **Transverse**

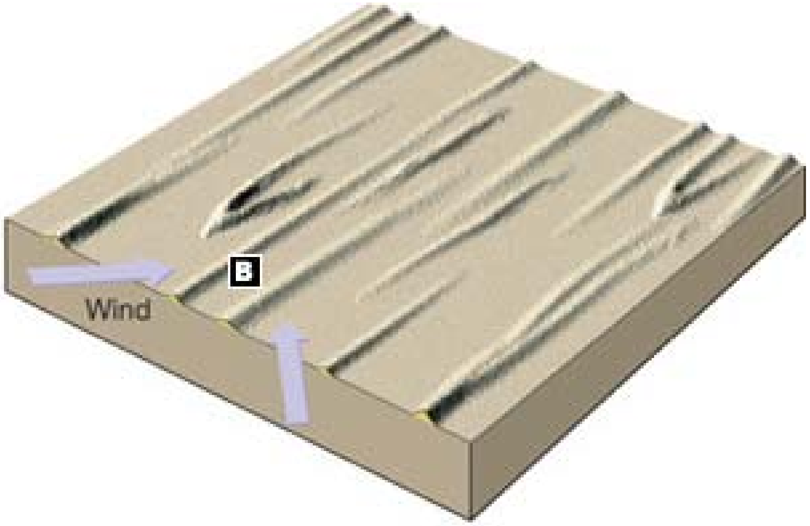
Increasing sand supply



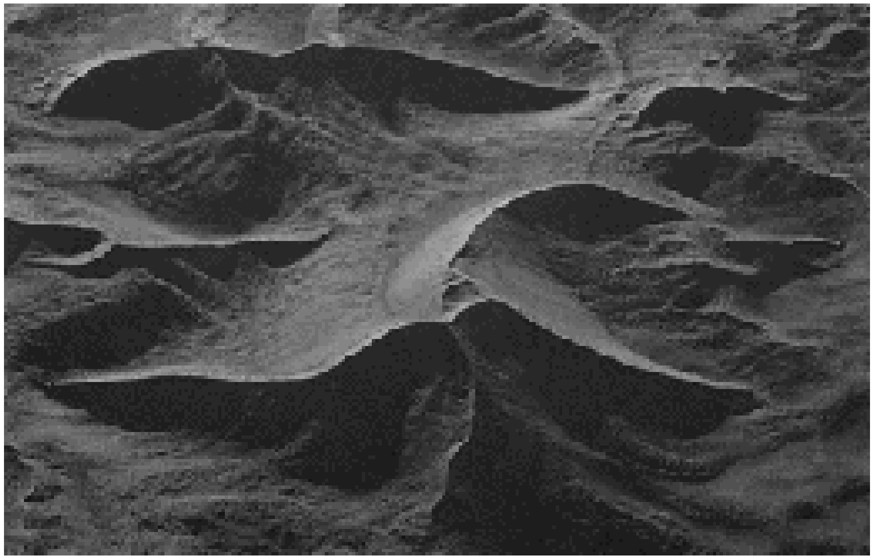


- **When wind directions vary**
  - **Linear dunes – a little variation**
  - **Star dunes – a lot of variation**



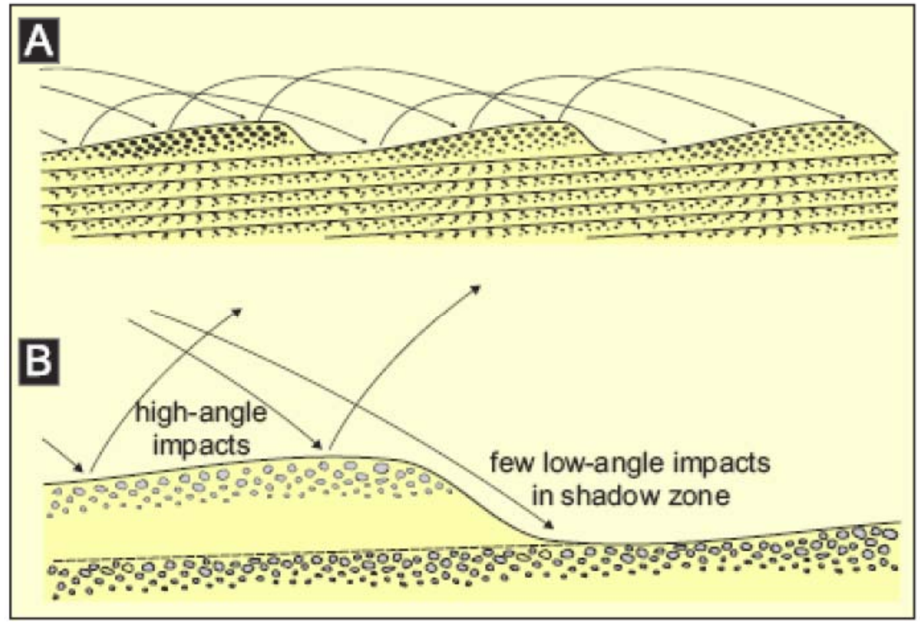


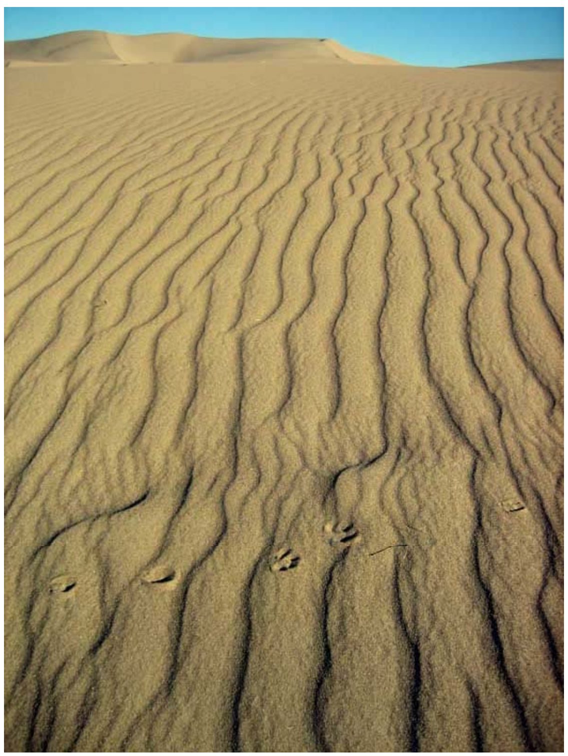
Star

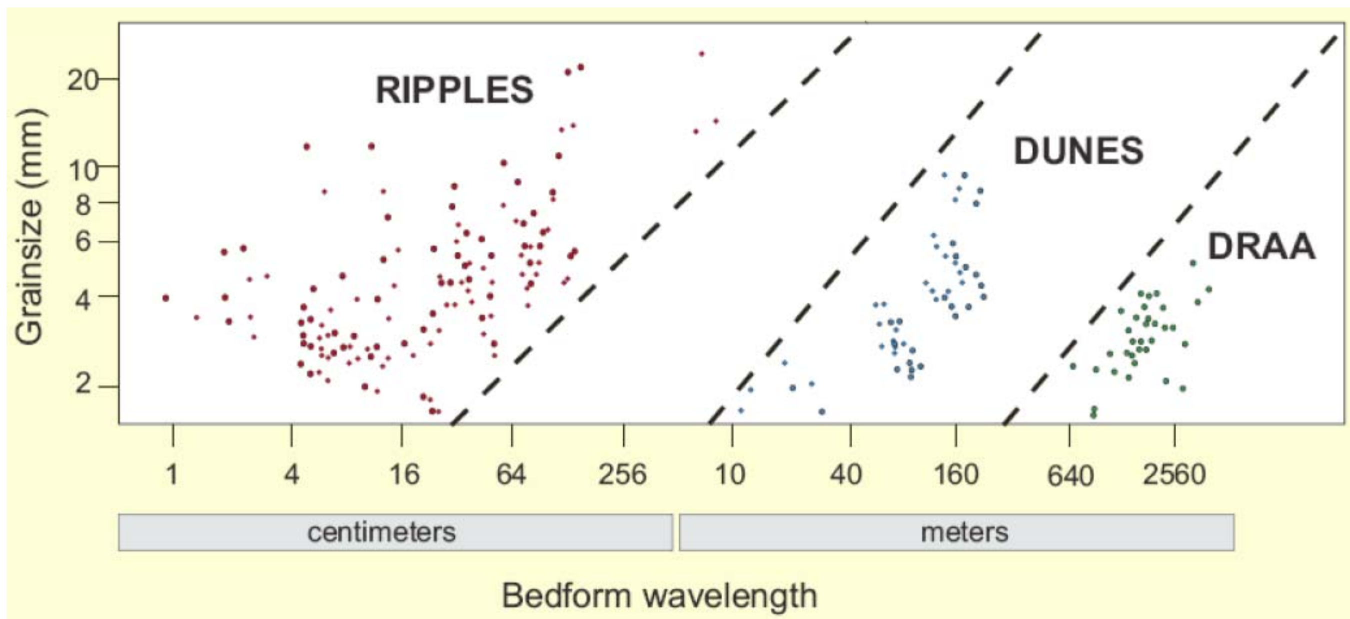


Linear/Longitudinal

- **Saltating particles can also form ripples**
  - **Much more dynamic than dunes**
  - **Asymmetric, 8-10 vs 20-30 degree slopes**
  - **Typical wavelengths 7-14cm, heights 0.5-1cm**

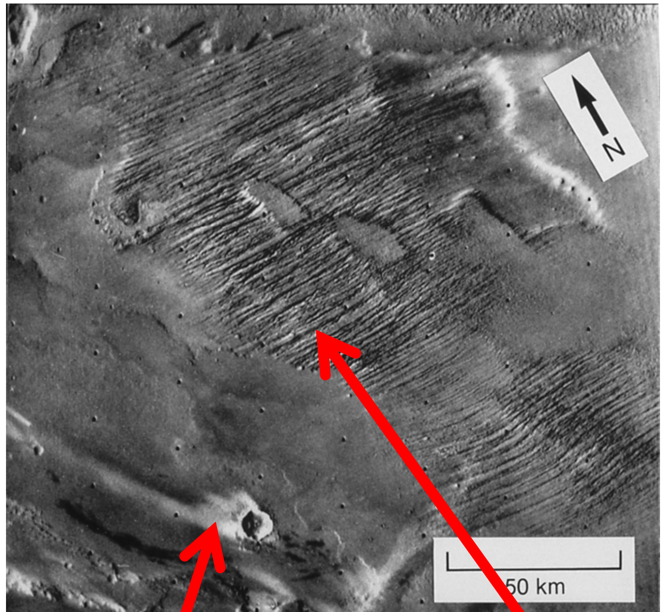






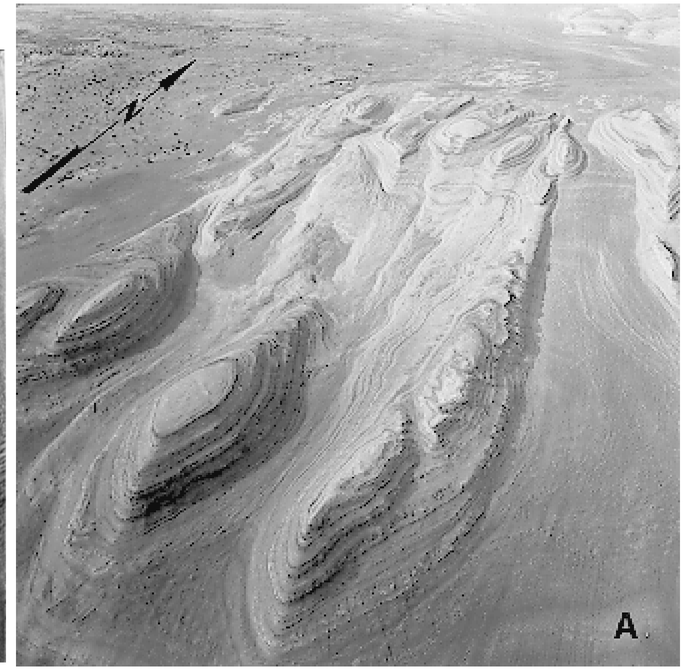
Aeolian Erosion

- Yardangs
  - Wind blown particles abrades surface
  - Erosion leaves elongated mounds as remnants
  - Requires strong, virtually unidirectional, wind.
  - Eroded material must be consolidated



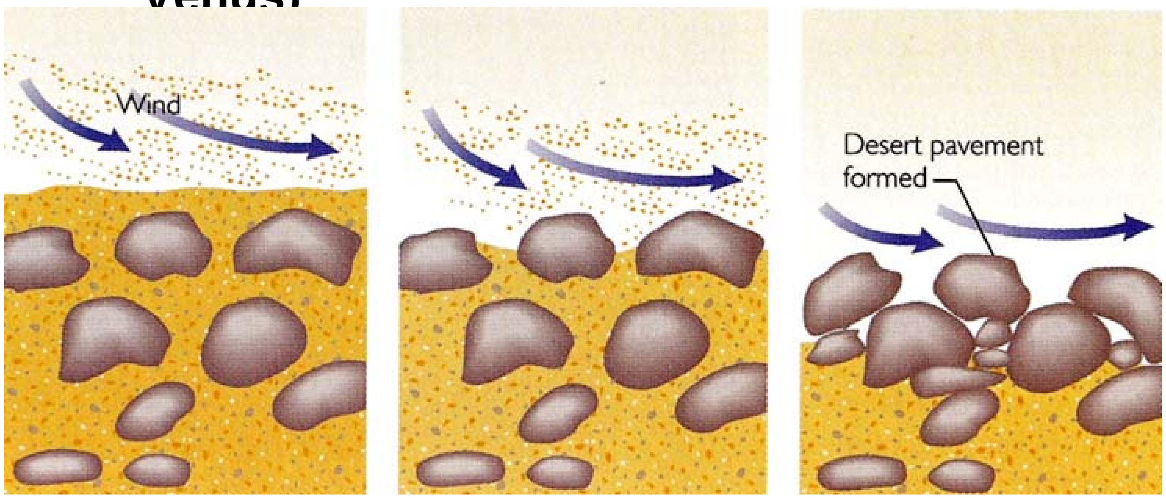
Recent wind action

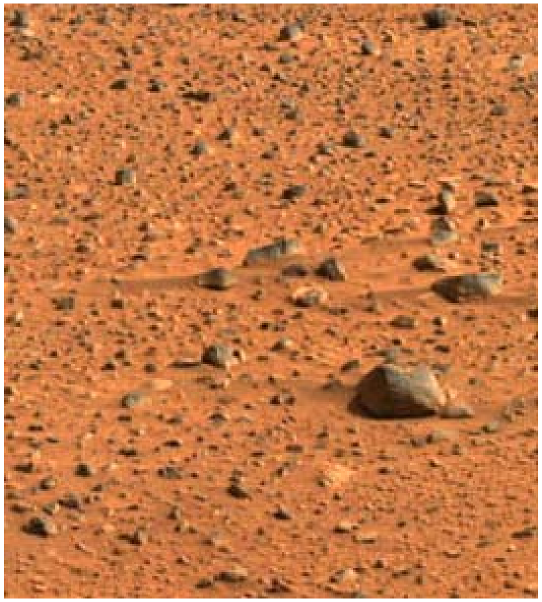
Older wind action

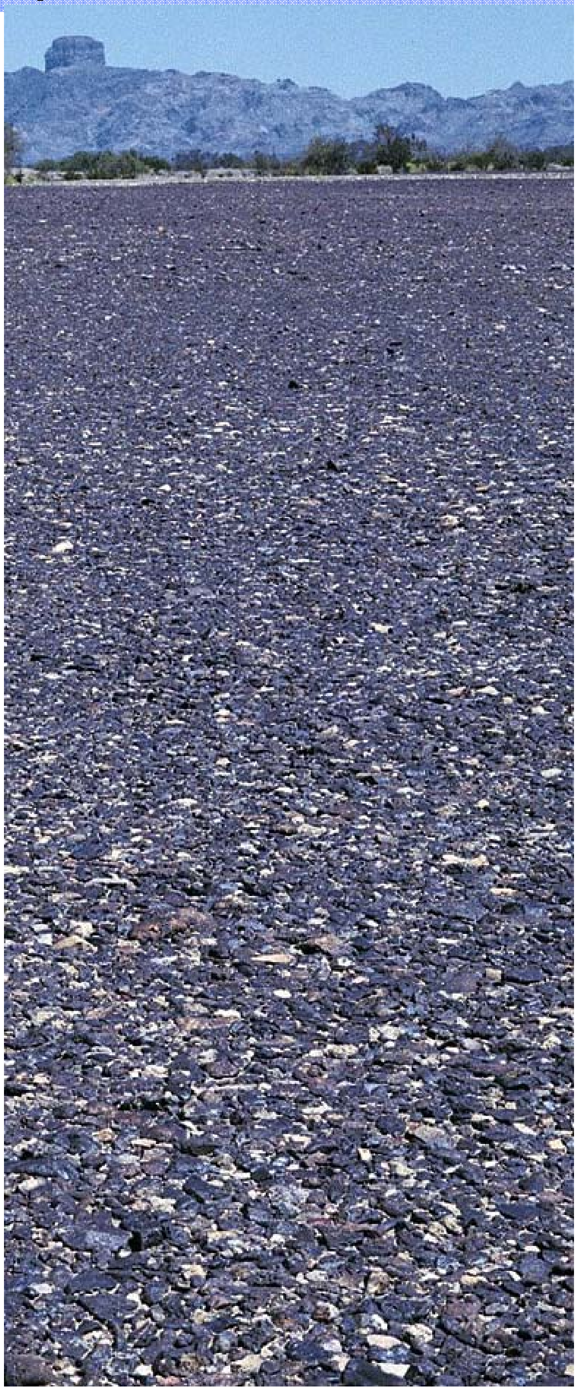


- Ventifacts
  - Elongated erosional marks on rocks
  - Usually works on originally circular vesicles
  - Used as paleo-wind direction indicators e.g. pathfinder landing site

- **Desert Pavement**
  - **Occurs frequently on Earth and Mars (and probably Venus)**

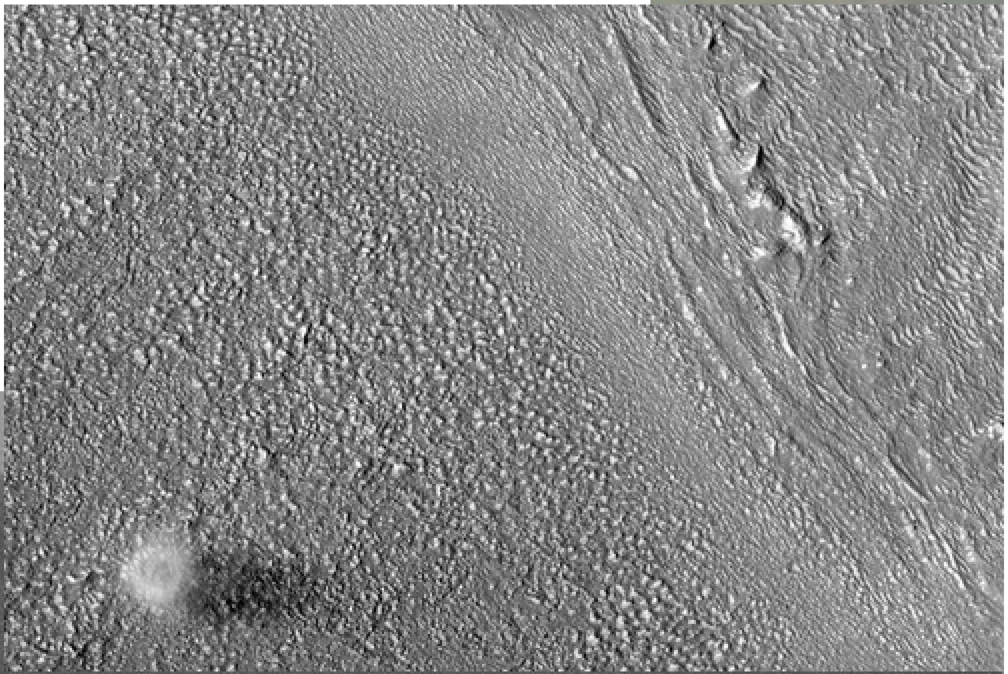


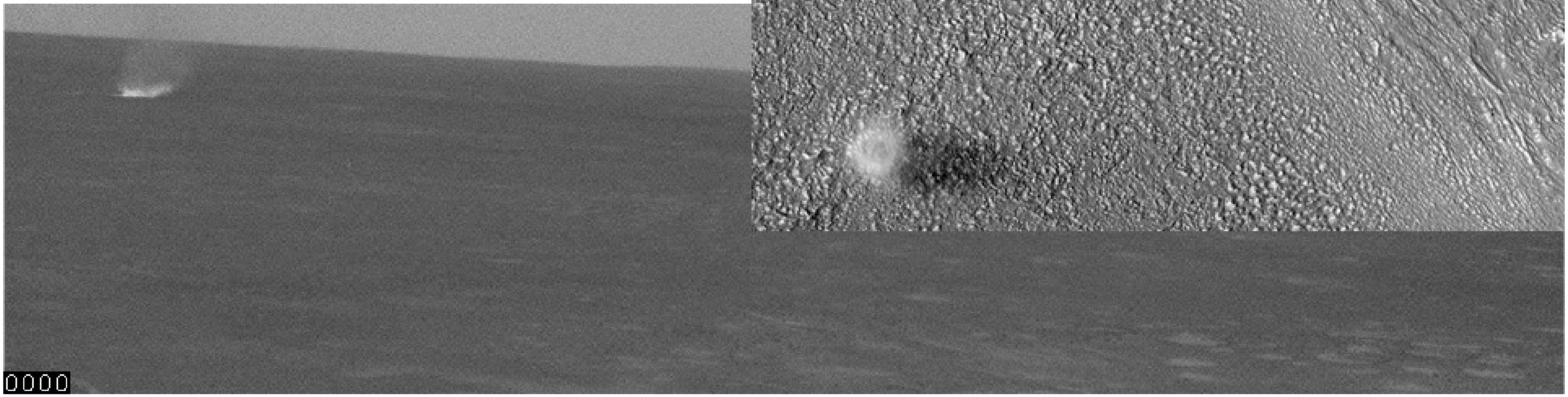




Dust Devils

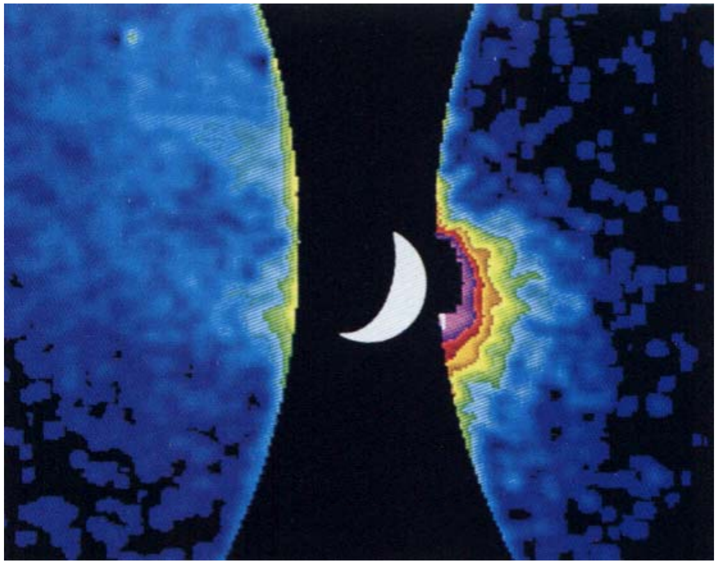
- **Plume of hot air rises**
- **Penetrates cooler atmospheric layer**
  - **gets stretched out vertically**
  - **Conservation of angular momentum starts column spinning**
  - **More hot air gets sucked in at the base to keep it self-sustaining**





'Atmospheres' of the Moon and Mercury

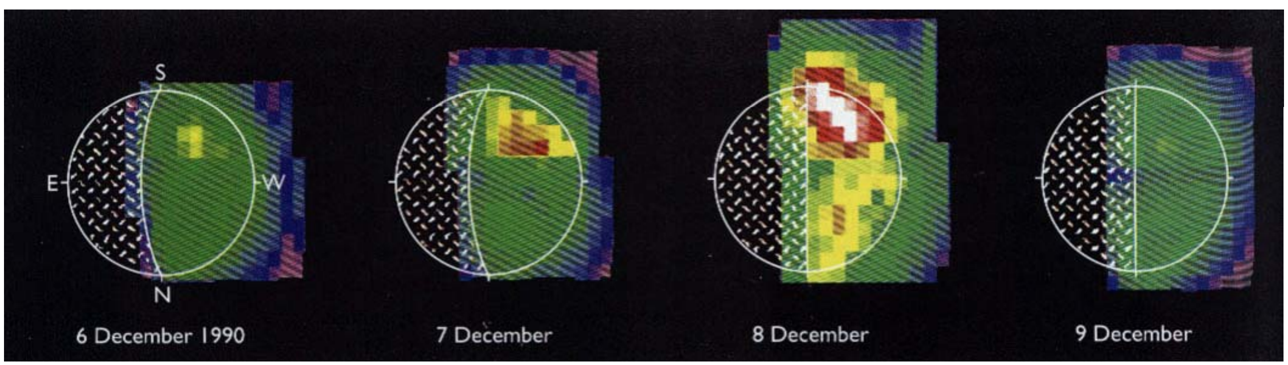
- **The Moon and Mercury both possess tenuous atmospheres**



Two Tenuous Atmospheres

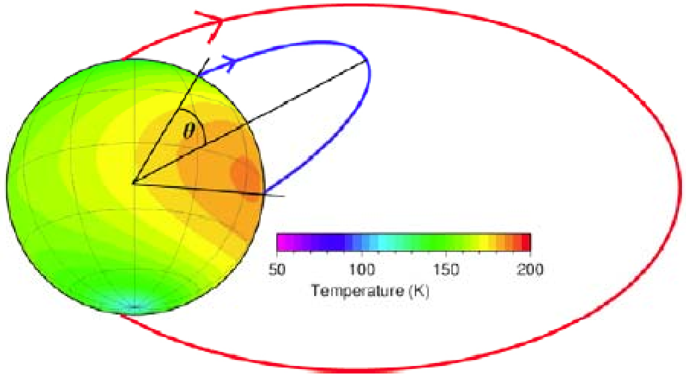
Species		*Mercury* *(atoms/cm³)*	*Moon* *(atoms/cm³)*
Hydrogen	(H)	200	< 17
Helium	(He)	6,000	2,000–4,000
Oxygen	(O)	< 40,000	< 500
Sodium	(Na)	20,000	70
Potassium	(K)	500	16
Argon	(Ar)	$< 3 \times 10^7$	4×10^4

Calcium now also seen at Mercury



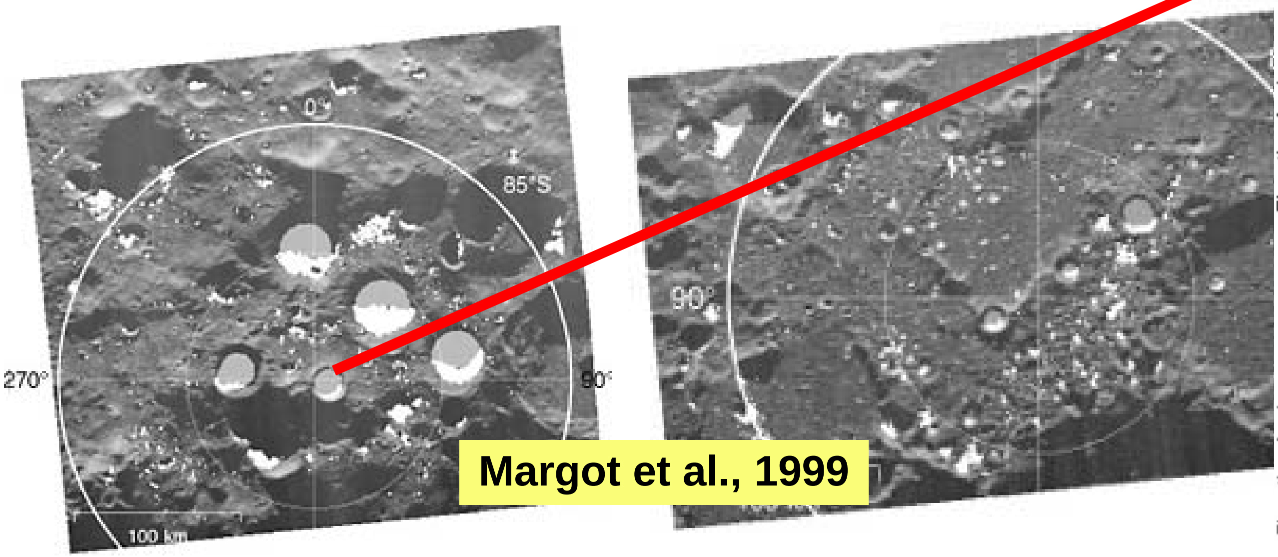
- **Sodium emission at the Moon and Mercury shows temporal changes**
  - **Stirring of regolith by small impacts**

- **Airless bodies do have 'atmospheres'**
  - **Surface bounded exospheres**
  - **Atoms collide more often with the surface than with each other**
    mean free path >> atmospheric scale height
    (really means that mean free path >> trajectory of a molecule)

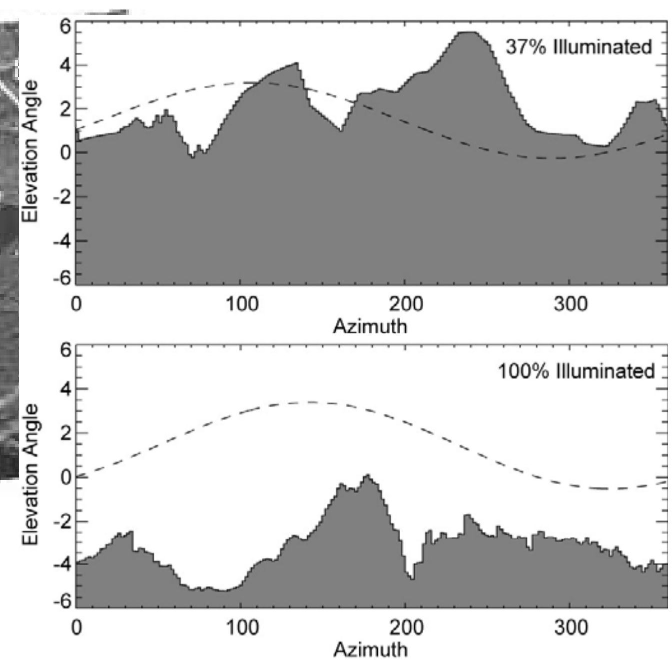


  - **Particles hop around until they find cold spots (e.g. night-side or shadowed area)**
    - **Ejection rate is slow & range is small**
  - **When the sun comes up they start hopping around again**

- **Do permanently shadowed regions exist?**
  - **Yes, Moon and Mercury have low obliquity**
  - **Solar elevations in the polar regions are always low**
  - **Even modest craters can have permanent shadow on their floors**

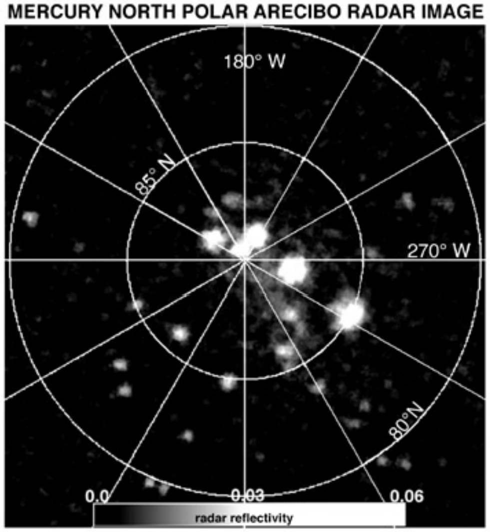


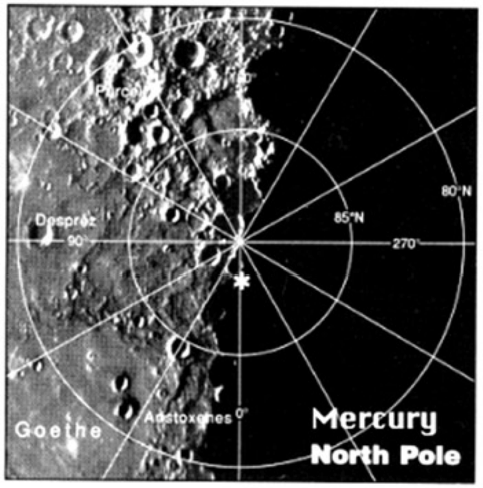
Margot et al., 1999



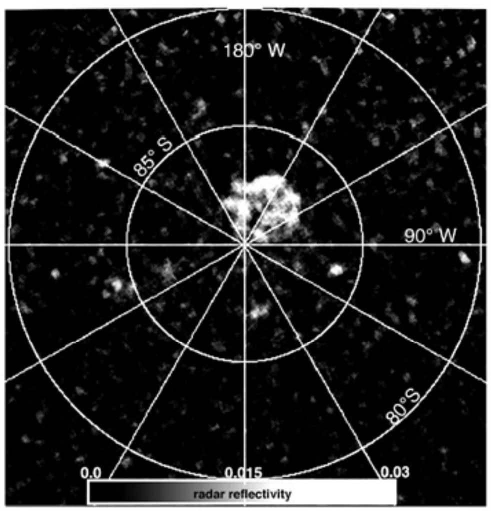
- **Evidence for ice in polar craters of the Moon and Mercury**
  - **Radar reflections show craters are filled with unusual material**
  - **Probably water ice**

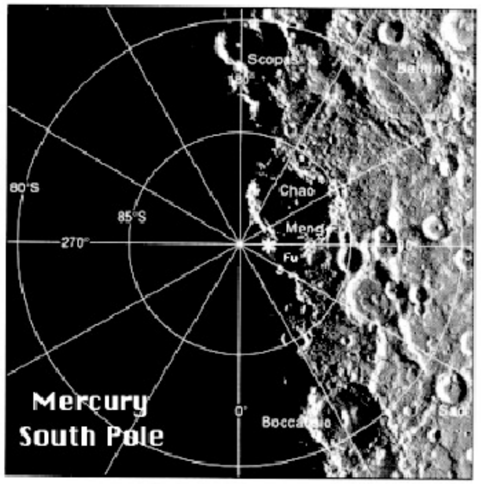
MERCURY NORTH POLAR ARECIBO RADAR IMAGE



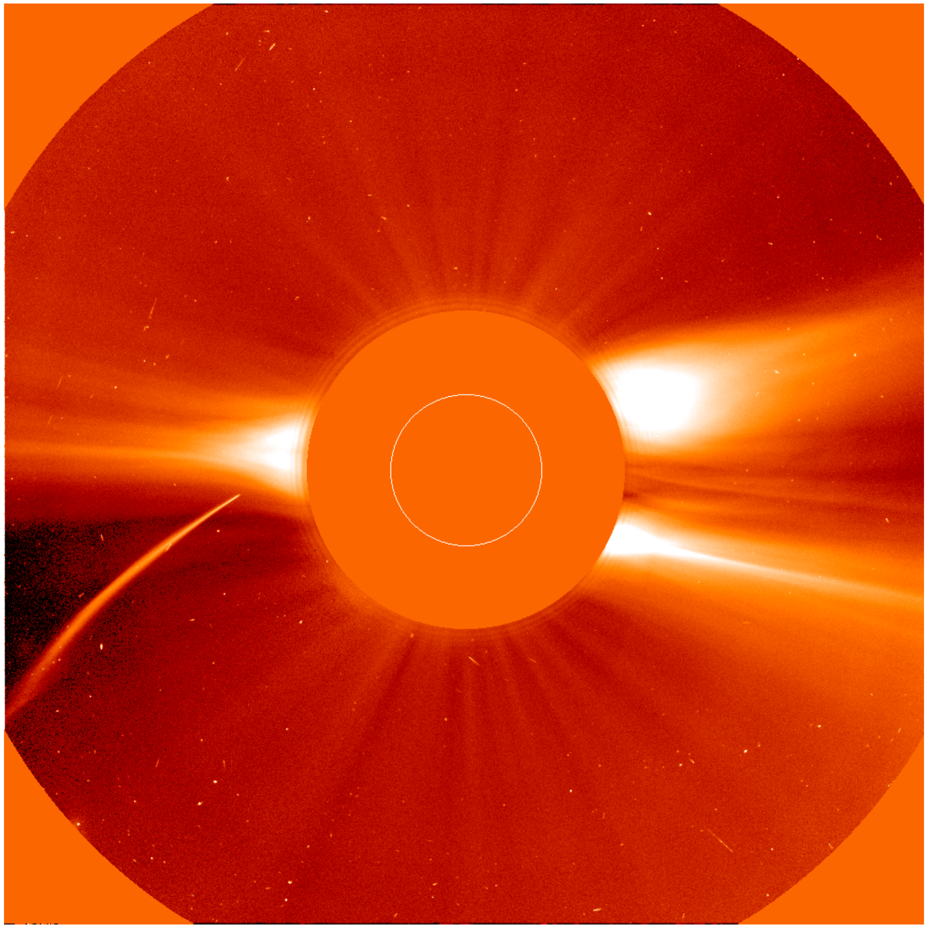


MERCURY SOUTH POLAR ARECIBO RADAR IMAGE



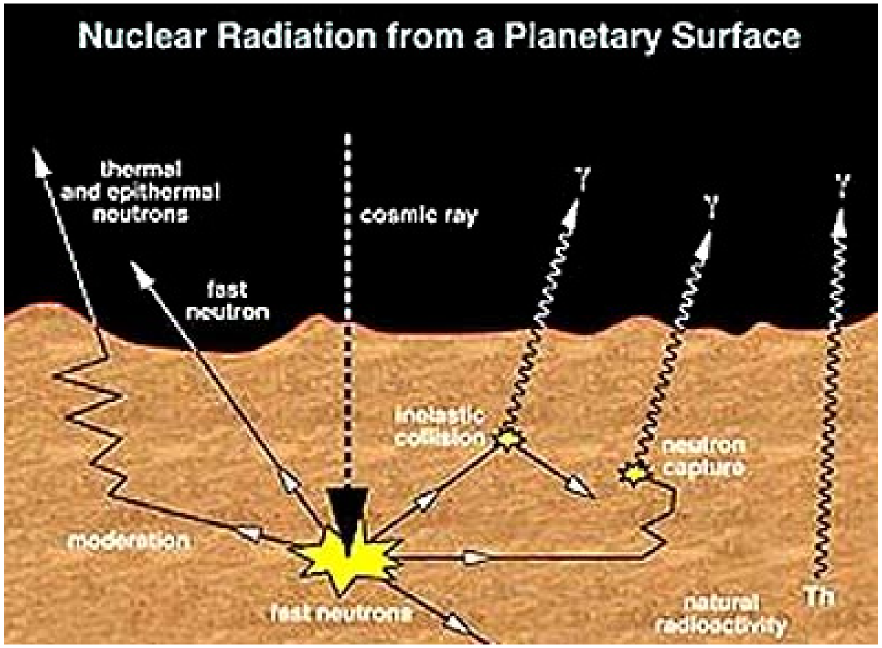


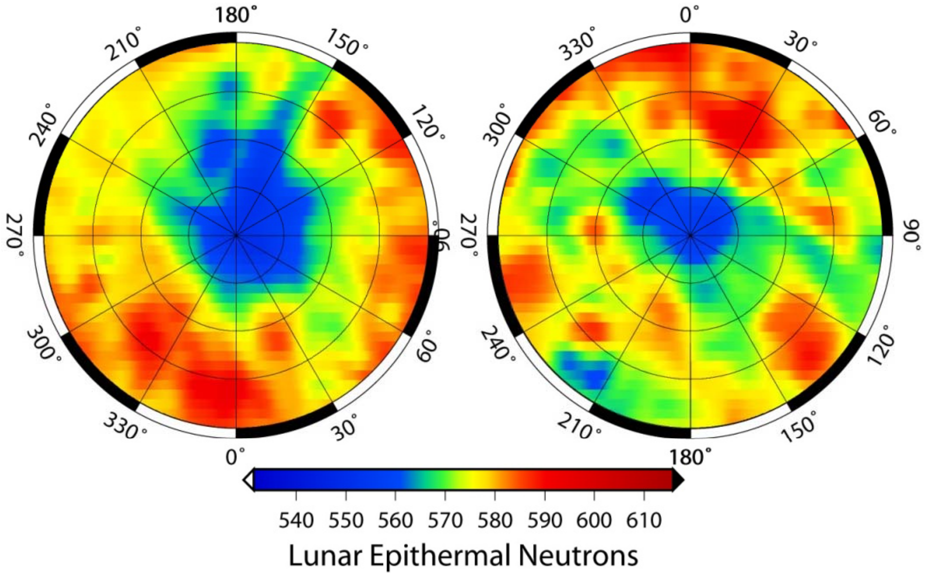
(Courtesy J. K. Harmon and M. A. Slade)



- **Source of the water?**
  - **Kreutz group – sungrazing comets**

- **Neutron spectrometer data**
  - **Cosmic rays hit the surface**
  - **Produce neutrons**
  - **Neutrons are easily scattered by hydrogen**
  - **Areas with low neutron counts have a lot of hydrogen**
  - **These areas correspond to the polar areas on the Moon**
  - **Hydrogen usually means water (ice in this case)**
- **Clementine bi-static radar**
  - **This evidence is pretty weak**
- **Lunar poles appear most empty of ice**
  - **No recent impacts?**





In this lecture…

- Introduction to atmospheres
  - Pressure, Temperature, Scale height
- Radiation and atmospheres
  - Clouds & Greenhouse effect
- Circulation
- Surface features from the atmosphere
  - Sand dunes and how they work
  - Eolian erosion
- ‘Atmospheres’ of Moon and Mercury
  - Ice in polar craters

Next: Venus

- Reading
  - Chapter 11-6 &11-7 to revise this lecture
  - Chapter 11-Venus sections for next lecture