Comparative Planetary Atmospheres

- Qualitative Structure: for each atm….
  - Composition: what's it made of?
  - Density, pressure structure: how thick is it?
  - How hot? Mean temp., and temp. profile.

- Observational techniques: How do we find out?

- Atmospheric Physics:
  - The exponential atmosphere.
  - Gaseous escape processes.
  - Energy budgets: input, output, greenhouse effects

- Origins and later Evolution

Why the big differences between the planet's atmospheres?

Venus - Earth - Mars Atmospheres

Bulk Composition (by number of molecules).

Venus:

CO_2	96 %	
N_2	3.5	
SO_2	0.015	
H_2O	0.01	(lower atm.)
Ar	0.007	

Earth:

N_2	78 %
O_2	21
Ar	0.93
CO_2	0.33
H_2O	0-4 %

Mars:

CO_2	95 %
N_2	2.7
Ar	1.6
O_2	0.13
CO	0.07
H_2O	0.03

Why is Earth so different?

Planetary Atmospheres:

Surface Conditions

	T (K)	P (Pa)	g (m/s^2)
Mercury	100 – 700	Tiny: some He, Ar, O, Na	3.7
Venus	730	9.2×10^6	8.9
Earth	290	1.0×10^5	9.8
Mars	214	636	3.7
Titan	94	1.5×10^5	1.3

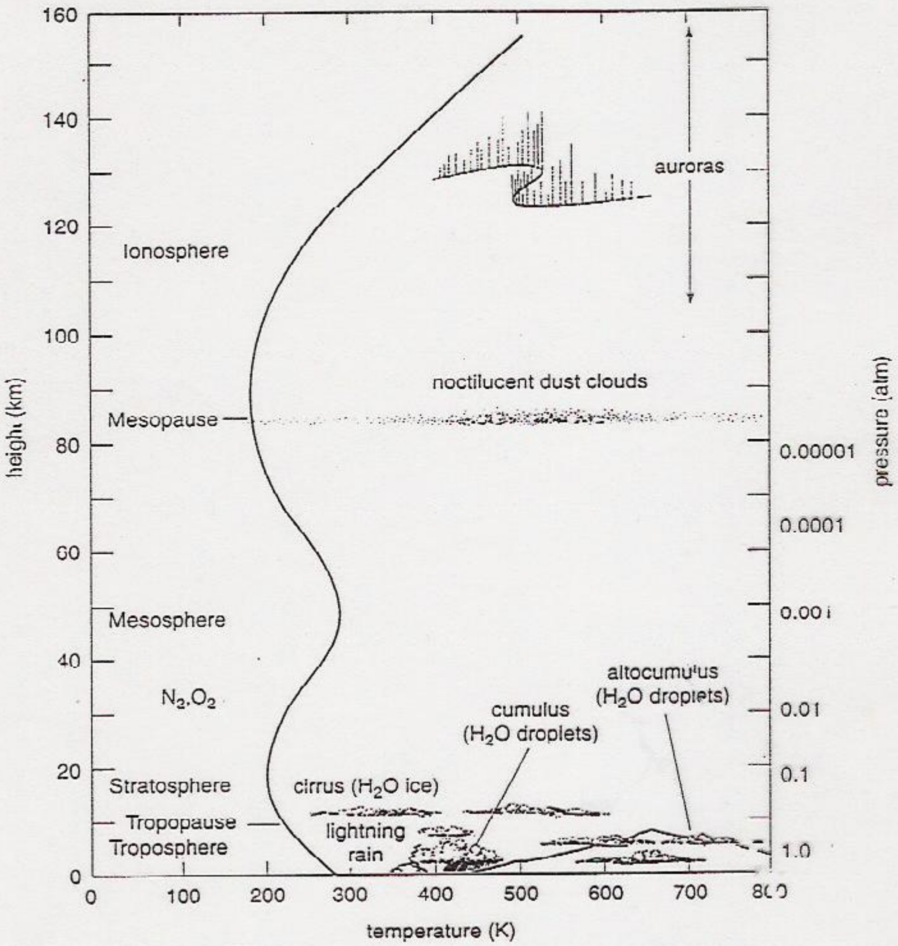


Figure 11-13. Structure and features of Earth's atmosphere.

Jupiter

Magnetosphere: Huge! 50 - 100 radii.

- Strongest planetary dipole field ≈ 4 Gauss at the 'surface'. $B \propto 1/r^3$.

  (Surface radius ≈ 11 Earth radii.)

- Charged solar wind particles decelerate between the bowshock and magneto-pause, in high temperature magneto-sheath (300-400 x 10^6 K).

- Powerful radiation belts = regions where magnetic field traps particles (torii). Slow leakage of particles to tenuous plasma sheet.

- Charged particle sources include:
  - solar wind and galactic cosmic rays.
  - hot gases from Io (orbits within radiation belts).

Atmosphere:

- Consists of light zones and dark belts.
- Bulk composition - generally like the Sun.
  O - a bit depleted, C - compounds enhanced. Tar like formation?
- Belts and zones variable, with periods of days to years. These are jet streams of varying velocity. Most go from west to east.
- Jets get energy from small spots (eddies), which get theirs from convective turbulence.
- Convection in lower layers expected from temperature profile (extrapolated & from Galileo probe).
- Belts & zones = cloud tops. Clouds of NH_3, NH_4SH, and H_2O ices depending on altitude.

- Colors due to trace compounds whose abundances depend sensitively on temp. and altitude.
  - Exact composition not known, but darker, more colorful belts in deeper, warmer layers.
- Also aurora and spectacular lightening displays.

Giant Planets of Our Solar System
P. Irwin (2003)

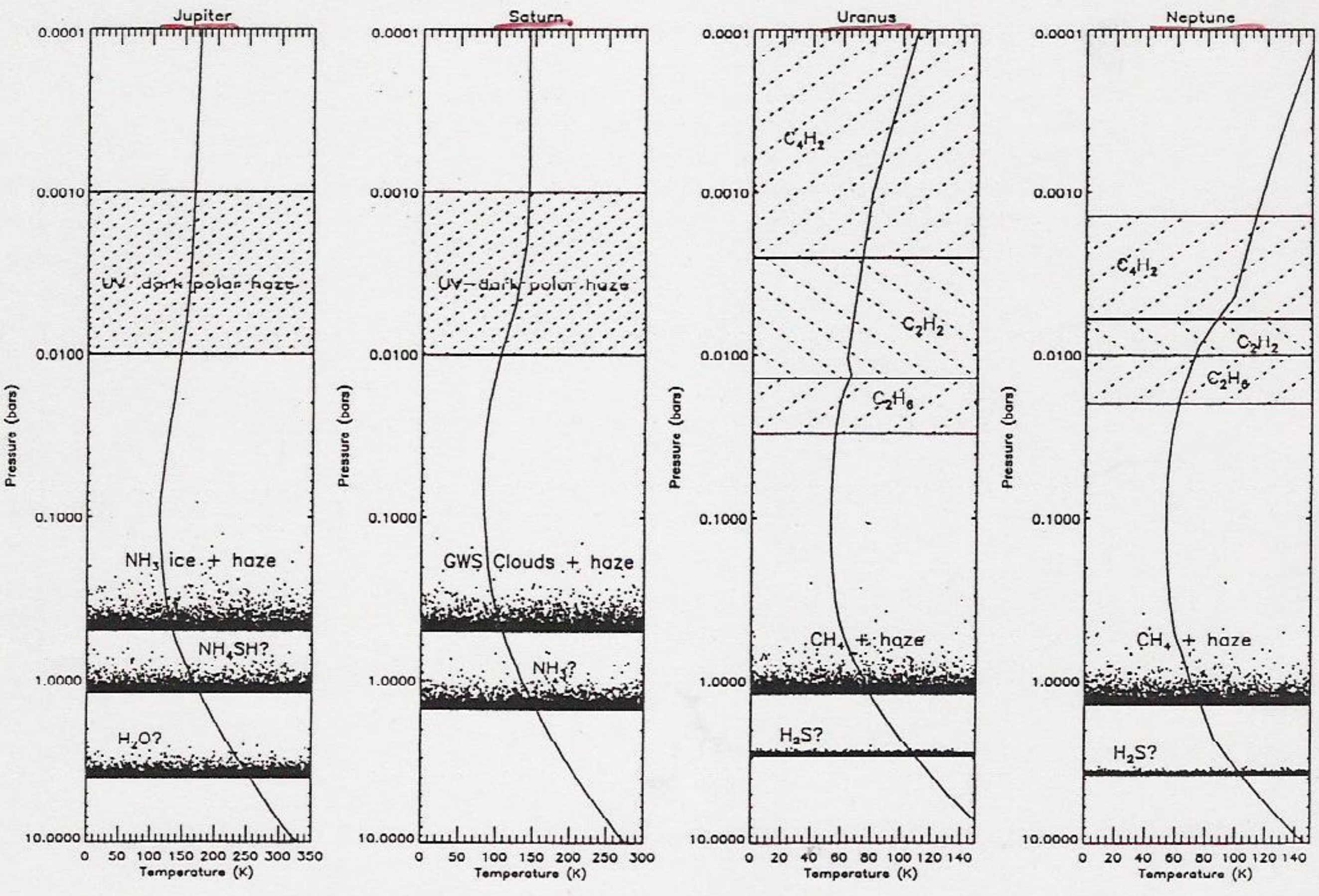


Figure 4.13 Mean observed/modelled cloud profiles of the giant planets.

~~(Preliminary)~~ Galileo Probe Results

- Lasted for 57.6 min. from the 0.35 bar to the 23 bar levels.
  - Went down 200 km below cloud tops (T = 152 C).

Discoveries -

- New (inner) radiation belt, located between atmosphere and ring.
  - Made up of He ions of "unknown origin".
- Upper atm. temperature, density higher than expected.
  - Lower atm. as expected, except low water fraction, 1/10 - 1/5 solar.
  - Greater visibility, no thick clouds. Where are they? Is this location the Jovian desert?

- Strong winds persist to great depth.
  - Suggests continuous low-to-high convection.
- Weird lightening.
  - Little optical, lots of radio.
- Low abundances of: H_2O, CH_4, HS, Ne, He.
  - Suggests more fractionation than expected.
  - Plenty of NH_3, however.

Atmospheric Composition - Jovian Planets

(From - The Planetary Scientist's Companion, 1998)

Jupiter	H_2	86.2 ± 2.6 %	
	He	13.6 ± 2.6 %	
Methane	CH_4	0.[illegible]18 %	
Ammonia	NH_3	0.026 %	
	H_2O	$\lessapprox 0.057$	(Galileo probe dry result)
	+ many trace gases		
Saturn	H_2	96.3 ± 2.4 %	
	He	3.25 ± 2.4 %	
	CH_4	0.45 %	
	NH_3	≈ 0.01 %	
	+		
Uranus	H_2	$\approx 82.5 \pm 3.3$ %	
	He	15.2 ± 3.3 %	
	CH_4	~ 2.3 %[1]	
	NH_3	< 0.01 %[2]	

[1] Carbon enriched upper atm.?

[2] N poor atm.? Or NH_3 bound up in clouds?

Saturn

Much like Jupiter, <u>except:</u>

Magnetosphere:

- Very extensive HI torus.

  H & N probably come from Titan's atmosphere.

- Also an inner H_2 torus.

  Essentially an atmosphere around the rings, derived from icy ring particles.

Atmosphere:

- Faster jet streams than J. Why?
  Possibilities include:

  1) greater relative internal heat flow - Saturn's is 2-3 times the solar constant.

  2) smaller size --> greater temperature 'gradients', larger scale circulations.

- Clouds deeper in Saturn's troposphere.

  Thin haze above obscures clouds, and belts & zones.

Composition:

- Why less He in atmosphere than J.?

  Greater differential settling possible because S. cooled more rapidly. Enhanced settling could also provide energy for high heat flow.

Interior:

- Liquid, metallic H probably extends closer to the center than on J.

  Consistent with weaker magnetic field.

Uranus

Like other Jovian planets, <u>except:</u>

- It's tilted (obliquity) 98°!

  Hard to understand.... but maybe an Earth-sized planet collided with Uranus at some point.

- Strange abundances of N & C.

Atmosphere:

- Probably continues trend begun from J. to S. where clouds form at lower fractional radius in smaller, colder Jovian planets.

  Does a relatively thick stratospheric haze hide <u>brightly colored bands below?</u>

Figuring Out Planetary Atmospheres
(Observational Techniques)

1. Albedo – fraction of radiation reflected relative to incident

- Clouds have high albedo, oceans and rocky surfaces have low albedo.

Planet	Albedo		
Mercury	0.06		
Venus	0.76		
Earth	0.3-0.5	Moon	0.07
Mars	0.16		
Pluto	0.5		

- Very important factor in surface energy balance.
- Variations observable for Earth and Mars, that is, Seasons!

2. Reflectance Spectra

Can observe absorption lines due to a variety of atoms and molecules. The strength of the features varies with the angle of the Sun relative to the line-of-sight → estimates of relative abundances.

3. Emission Spectra

Continuous thermal spectra reveal the surface temp.

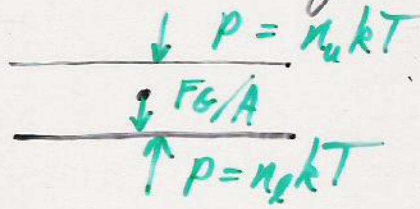
4. Direct Sampling

Send a space probe! Lot of info. when possible.

The Exponential Atmosphere (after Feynman)

To have equilibrium must have force balance!

Consider a layer in the (quiet) atmosphere:



$$F_G/A = \frac{(mnV)g}{A} = nmg\,dh \quad \text{(grav. per unit area)}$$

$$\therefore \quad n_\ell kT = n_u kT + nmg\,dh$$

$$\text{or} \quad (n_u - n_\ell)\,kT = kT\,dn = -nmg\,dh$$

$$\frac{dn}{n} = \frac{-mg}{kT}\,dh$$

$$\int_{n_0}^{n} \frac{dn}{n} = -\int_0^h \frac{mg}{kT}\,dh$$

If atm. is isothermal: $n = n_0\, e^{-\frac{mgh}{kT}} = n_0 e^{-h/H}$.

Why is the Earth's Atm. So Different?

- Surface repositories:
  - Great quantities of CO_2 in:
    - the **oceans** as bicarbonates (H_2CO_3).
    - **sedimentary rocks** as carbonates (CO_3...).

Conclusion: <u>life</u> changed the Earth's atmospheric composition.

- Composition of early atm. probably resembled that of volcanic gases.
  - Mostly H_2O, but much CO_2, & N & S oxides.
  - Little O_2, maybe 100 times as much CO_2.

- Geologic evidence shows beginning of O_2 increase 2 billion years ago. (Cause: <u>photosynthetic organisms</u>.)
  - Present abundance of O_2 reached 270 Myr. ago.

What about the other composition differences with Mars & Venus?

- Can understand as result of different escape rates.

1) Light molecules can acquire enough energy in collisions to escape planet's gravity.

2) Why? Tendency to "equipartition" where all molecules have same average kinetic energy, $mv^2/2$.

3) Also molecules have wide range of speeds and energies around average, some collisions transfer much more than average energy.

Over time light molecules can escape from (warm) planetary atmospheres!

Atmospheric Escape

Can formulate in terms of an escape time or escape rate.

Two important velocities:

R.M.S. molecular velocity: $v_{RMS} = \sqrt{\frac{3kT}{m}}$

where k is Boltzmann's const., T is the temp., and m is the mean molecular weight.

Escape velocity: $v_{esc} = \sqrt{\frac{2GM}{R}}$.

For high values of the ratio v_{esc}/v_{RMS} (the retentivity) → low escape probability.

Define: $Y = \frac{GM}{kT_x R} \approx \frac{3}{2}\frac{v_{esc}^2}{v_{RMS}^2}$, where T_X is the temp. of the 'exosphere.'

The classical Spitzer escape timescale is,

$$t = \frac{\sqrt{6\pi}}{3}\frac{v_{RMS}}{g}\frac{e^Y}{Y},$$ where g is the surface grav.

----

de Pater and Lissauer use a variable λ_{esc}, which is the same as Y to within a factor of order unity, and give an escape rate that is closely related to the inverse of the Spitzer timescale,

$$\Phi_J = \frac{N_{ex} v_o}{2\sqrt{\pi}}(1 + \lambda_{esc})e^{-\lambda_{esc}} \quad atoms\, cm^{-2}\, s^{-1}.$$

See text. In reality, escape may be orders of magnitude faster. Other processes are involved.

Earth's Atmosphere and Climate

(1) <u>Atmosphere</u>

- Structure and composition
- Transmission of radiation
- Energy balance
  - Greenhouse effect
  - Ozone depletion
  - Clouds & dust (Why is the sky blue?)

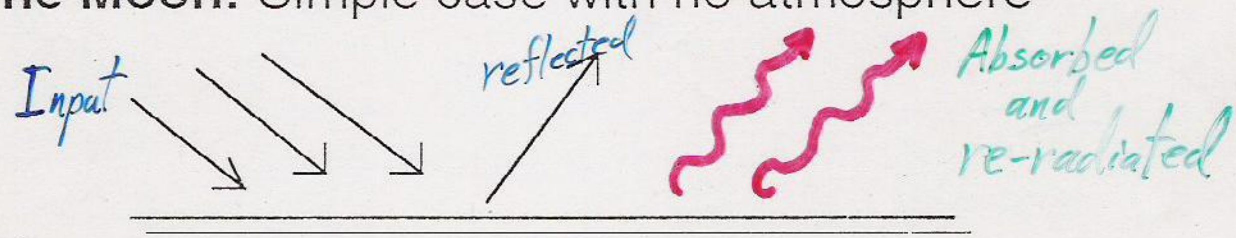
(2) <u>Changing Climate</u>

- Seasons
- Historical record
- Long-term changes

Planets (or local areas on planets) **are Thermal Radiators too.**

- **Heat balance:**
  - Average heat received = average heat lost
    solar constant = 1,370 Watts/m^2

- **The Moon:** Simple case with no atmosphere



  - Albedo = fraction reflected = (reflected flux)/(input)
  - Large temperature variations on lunar surface

- **The Earth:** many complications
  - extensive convection in atmosphere and oceans
  - Heat storage in oceans, rocks, atmosphere
  - Heat of vaporization of water
  - Absorption, scattering and reflection by: clouds, dust, smoke, etc.

Yet, complex balance ⇨ **relatively, stable, liveable climate**

Energy Balance (in a nutshell)

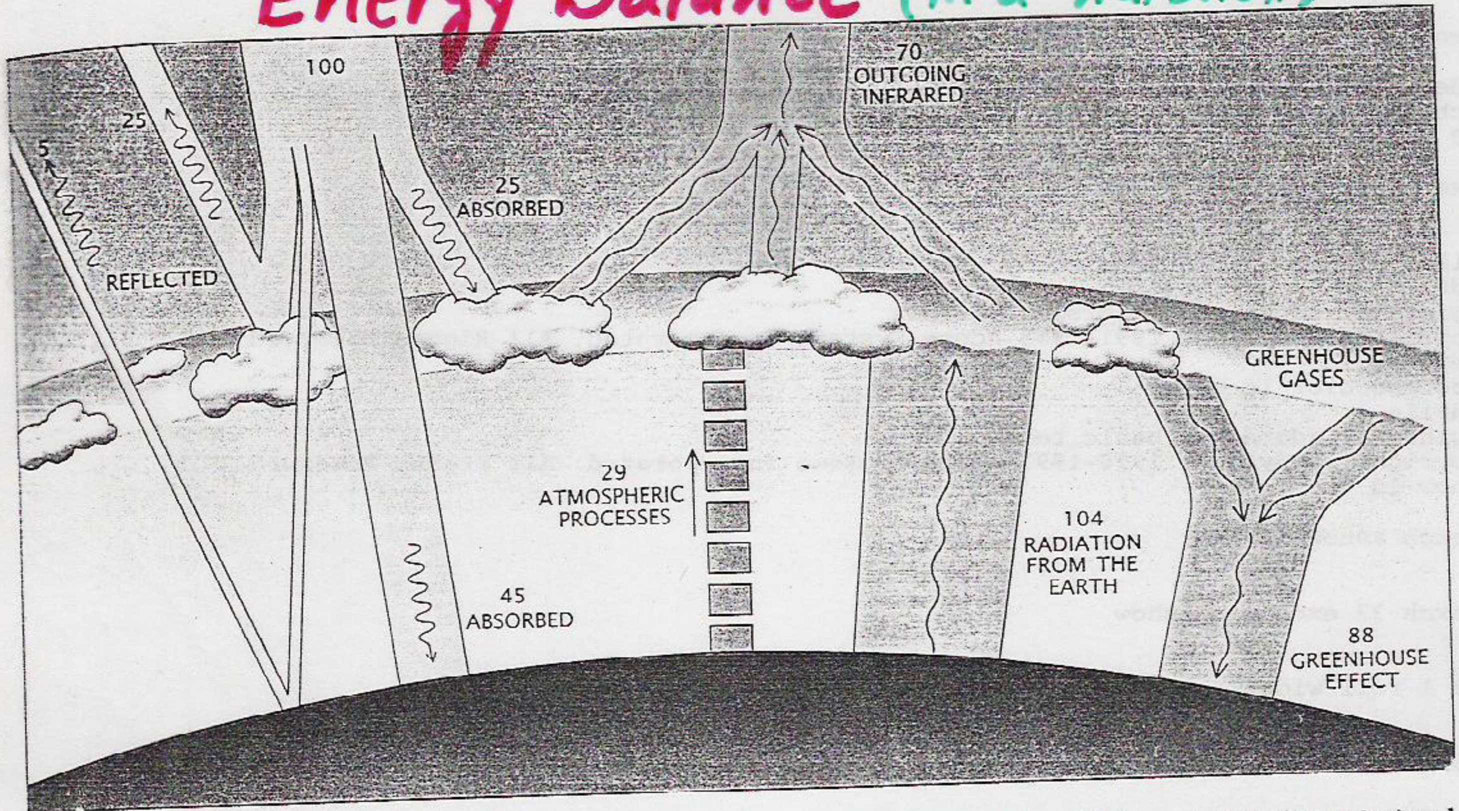
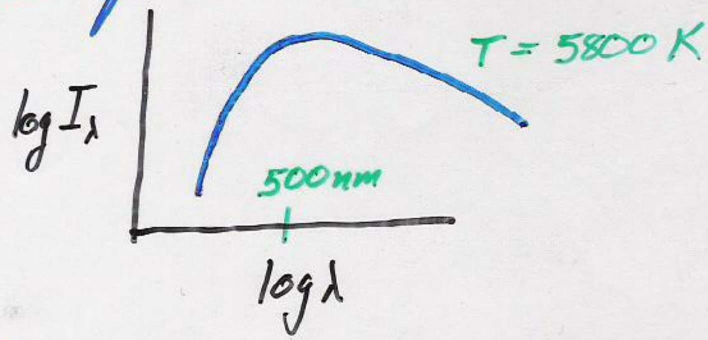


Figure 3.2 HEAT TRAPPING in the atmosphere dominates the earth's energy balance. Some 30 percent of incoming solar energy is reflected (*left*) either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70 percent is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.

From Managing Planet Earth

Planetary Radiation Budgets & the Greenhouse Effect.

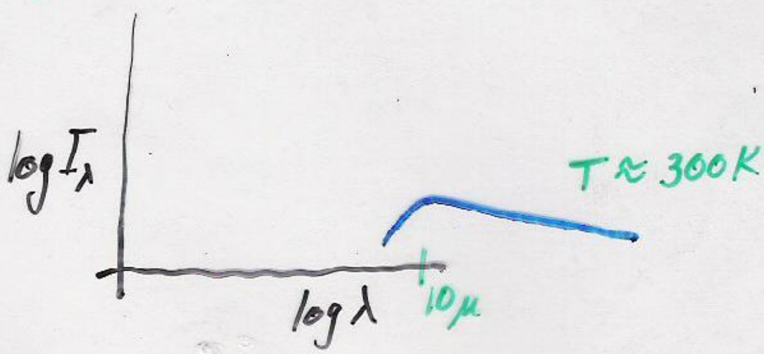
1. Begin with the solar spectrum.



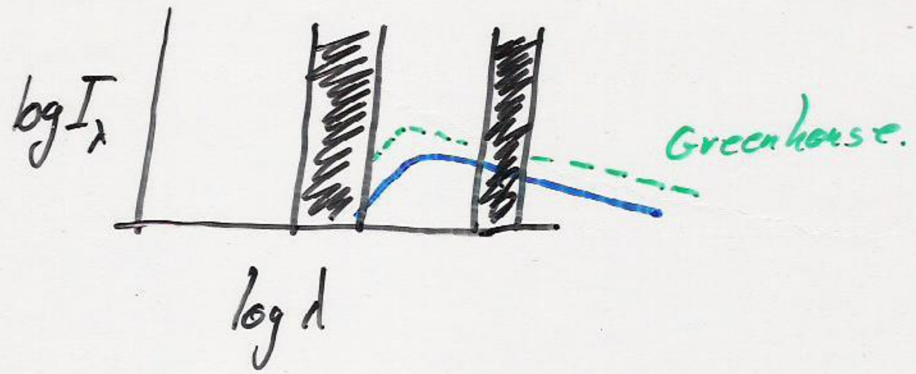
2. Reduce the solar luminosity by the surface area factor - $(\pi R^2_{planet}) / (4\pi r^2_{orbit})$, and multiply by (1 - albedo) to get planet's luminosity.

3. Energy is redistributed to achieve new thermal equilibrium temp., appropriate to the planet's L:

$$T_p^4 = L / 4\pi R^2 \sigma .$$



(4) Greenhouse effect: Some wavebands are opaque. Therefore, must go to a higher T Planck curve to squeeze out the same L.



Seasonal temperature changes –

Why ?

1- Sun's altitude ⇒ Power / Area
(See following diagram.)

2- Sun's altitude ⇒ Path length through atmosphere

3- Day length

4 - Snow cover (+ other surface effects)

5- Weather – clouds, haze, dust, ...

6- Distance from Sun – but
we are closest to Sun about January 1 (9 a.m. Jan. 3 in 1992)
(variation ≈ ± 1.7%)

Note also – Effects of nearby water
– Circulation patterns in oceans + atmosphere
– etc.

Seasons

Venus Small obliquity ($\simeq 3°$)

+ very circular orbit + highly insulating atm.

$\Longrightarrow$ no seasons

Mars Significant obliquity + elliptical orbit

+ transparent atm.

$\Longrightarrow$ seasons

We observe seasonal variations in wind patterns (dust storms), size of polar caps, etc.

Long-term Climate Changes

Actually many timescales, from years to billions of years....

- **Evidence:**
  - Historical records
  - Archaeological records
  - Geological:
    - » Sedimentation rates
    - » Isotopic variations, e.g. ^{18}O in ocean cores $\propto$ ice covering.
    - » Ice cores
    - » Stromatolites

- **Possible Causes:**
  - **External:**
    - » Perturbed Earth Orbit (Milankovich)
    - » Changing Solar Flux?
    - » Impacts
  - **Internal:**
    - » Atmospheric changes (e.g. composition)
    - » Changing circulation patterns in the:
      - atmosphere
      - ocean
      - interior

Climate Change

- Earth:
  - Large amount of CO_2 in early atm.
  --> <u>strong greenhouse effect.</u> Either Earth much hotter, or Sun cooler.

  - Small changes in Earth's orbit due to tidal effects, may have effected climate. E.g., generated ice ages (Milankovich). Or comet showers?

- Mars: some evidence of long term climate change.
  - Heavier weathering of craters before 3 billion yrs. ago.

  - Dendritic (water) channels concentrated near equator, not near poles or geologically active sites.

Liquid water a stable phase in past!

Warmer, denser atm. then? Need 200x present CO_2

- Venus:

  - If Earth moved to Venus' orbit it would have a similar atm., but much more water. Did Venus have more in past? Where'd it go?

  - Unlikely to be lost to space or stored near surface. Also need more H_2O to initiate runaway greenhouse effect with faint early Sun.