Class 1
What Determines Earth's Temperature?

OLLI

L809 Climate Change

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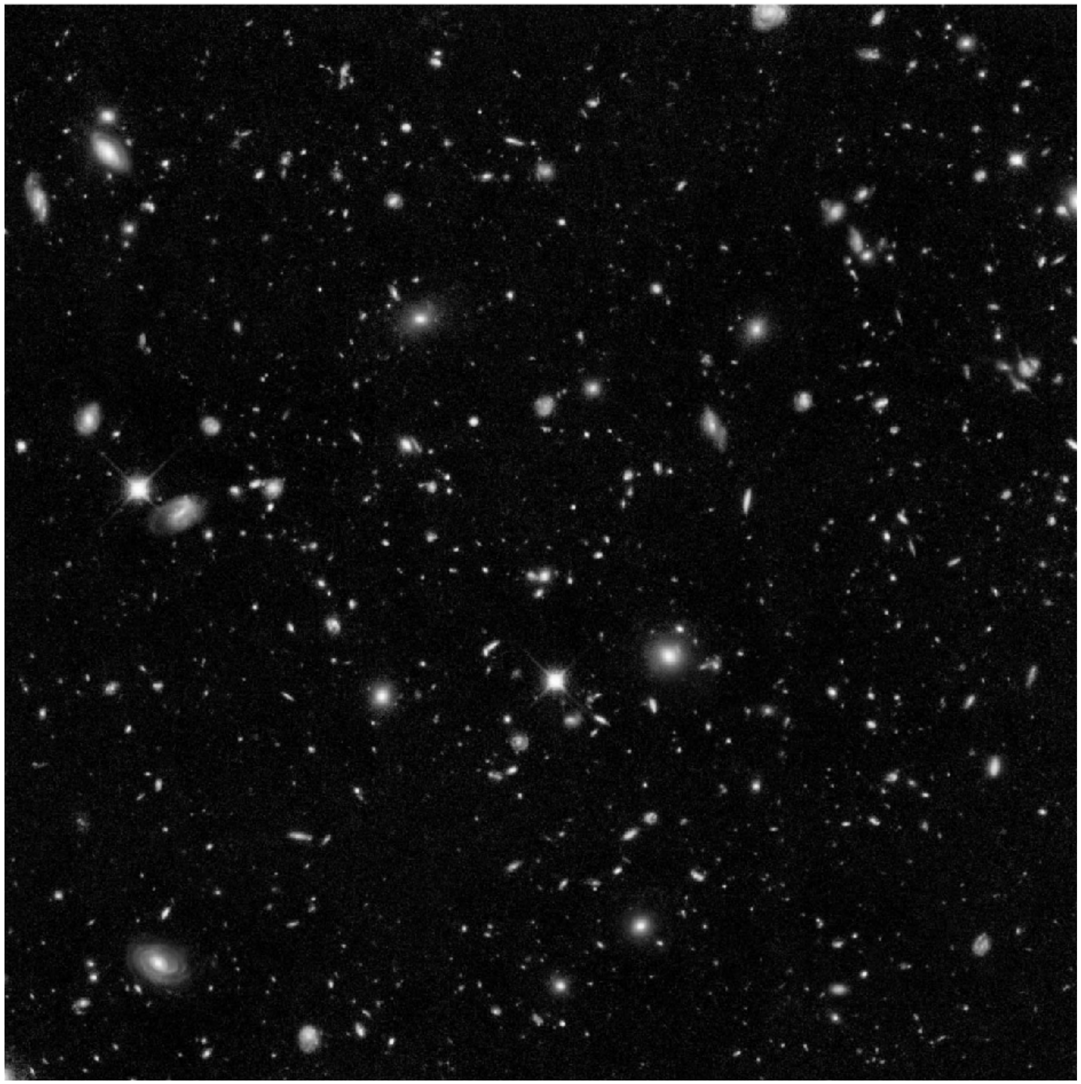
EARTH’S ENVIRONMENT

Earth and Other Planets

- About a thousand confirmed exoplanets
- Most within 1,000 light years of Earth – compare Milky Way diameter of 100,000 light years
- Milky Way is one of more than 100 billion galaxies in the observable universe

Hubble Ultra-Deep Field

Diameter: 3 arc-minutes = tenth diameter of full moon



Focus Shifts

- What are the planets' characteristics?
- Could they support life?
- Reference point: conditions that permitted or promoted life on Earth

The Layers

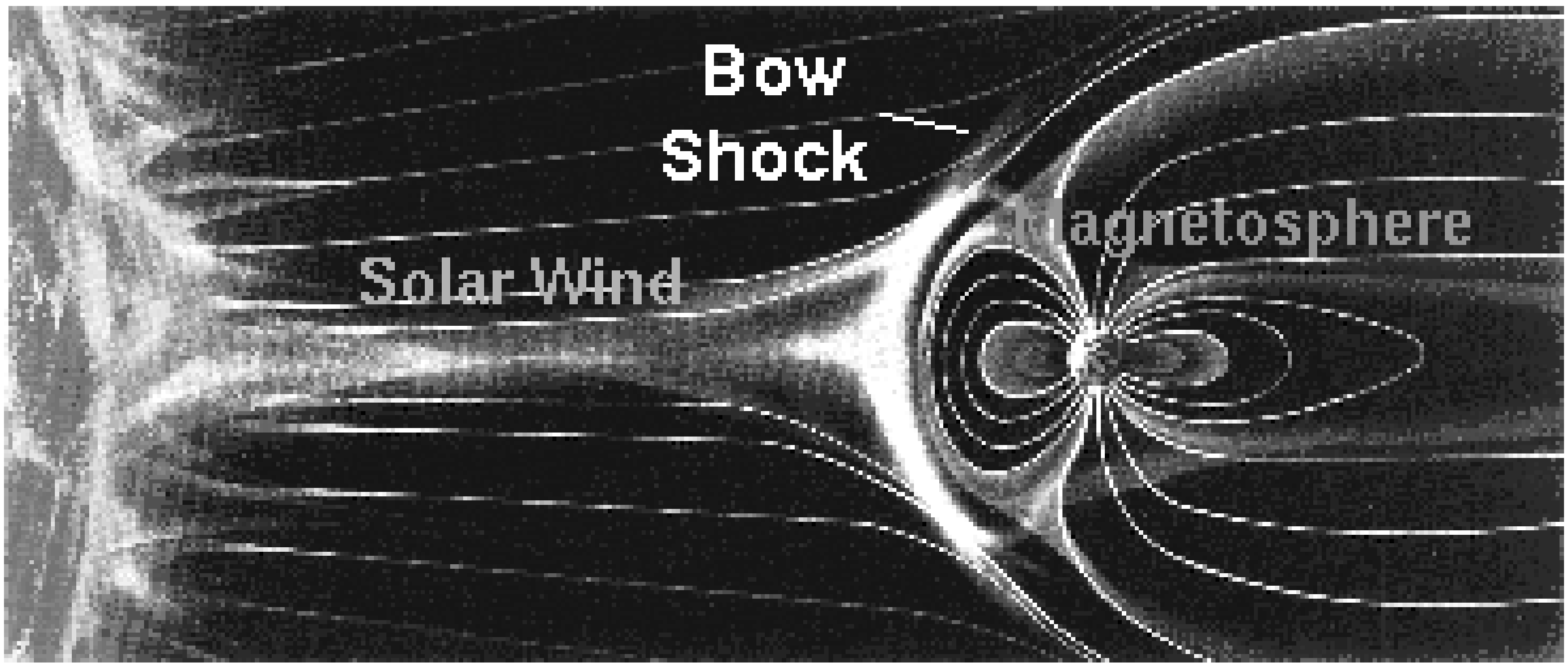
- Earth's Moon
- Earth's magnetic field
- The ozone layer
- Greenhouse gases

Earth's Moon

- High moon/planet mass ratio stabilizes Earth's rotational axis within range of less than 3^o
- Previous view: Without moon, up to 90^o variation and climate instability inconsistent with evolution of life
- Recent studies: Perhaps 20^o – 25^o variation and life probably would have taken a different course
- Consistency with life versus consistency with life as it has in fact evolved

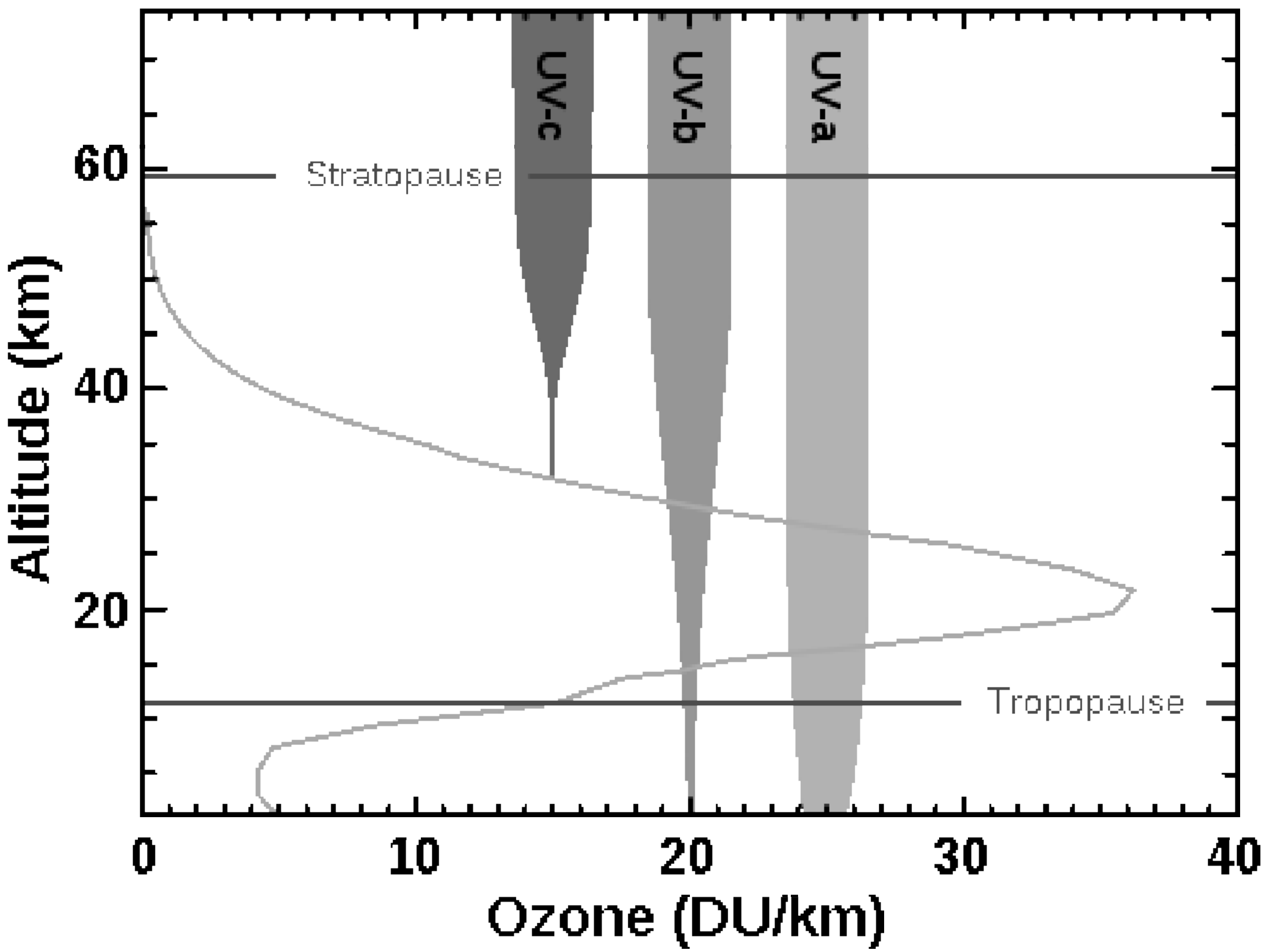
Earth’s Magnetic Field

- Created by rotating molten iron outer core
- Shields atmosphere from most of charged particles of the solar wind
- Lack of magnetic field may have contributed to loss of Martian atmosphere


Bow
Shock
Solar Wind
Magnetosphere

Ozone Layer

- Very thin stratospheric layer of ozone (O_3)
- Absorbs most powerful ultraviolet rays
- Effect of no ozone layer
  - Cancer
  - Genetic damage


UV-c
UV-b
UV-a
Stratopause
Tropopause
60
40
20
Altitude (km)
0
10
20
30
40
Ozone (DU/km)

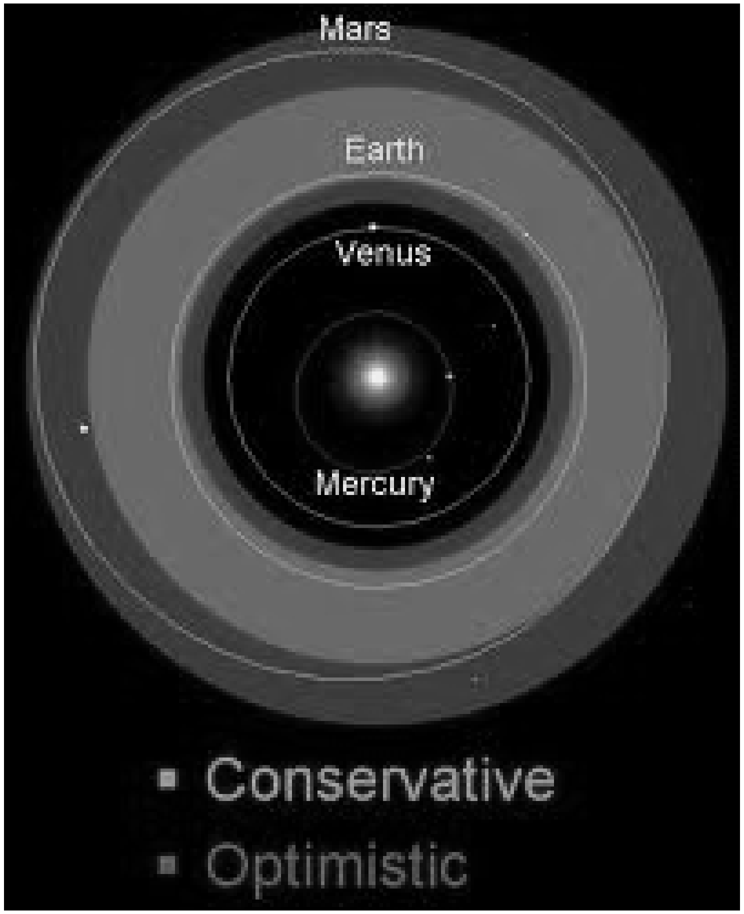
Greenhouse Gases

- Absorb outgoing low-energy radiation and re-emit part back to surface
- Result: Higher surface temperature
- Without greenhouse gases, Earth would not be within "habitable zone"

The "Habitable Zone"

- Assumes:
  - Life needs liquid water
  - Stellar radiation is the source of energy
- Determinants
  - Stellar radiation output and orbital radius
  - Atmospheric pressure
  - Greenhouse gases
- Carbon chauvinism?

The Sun's Habitable Zone



WHAT DETERMINES EARTH'S TEMPERATURE?

Basic Principles

- Temperature measures kinetic energy of system's molecules or atoms: <u>thermal energy</u>

- Energy gain ≠ energy loss: temperature change

- Gain = loss: equilibrium temperature

Applying the Principles to a Planet

- Receiving and losing thermal energy on Earth
  - Conduction
  - Convection
  - Radiation

- Planets: only radiation

- Imbalance between incoming and outgoing radiation: <u>radiative forcing</u>

Long ago in a galaxy far away
Planet Keeling ejected from its system

- Heat from home star lost during journey
- Insignificant internal source of heat
- Dull black – reflects nothing
- No atmosphere

Keeling Arrives

- Captured by Sun-like star in near-circular orbit of 150 million km radius

- Incoming solar radiation:
  - Cross-section: 1366 watts/meter^2
  - Average for Keeling's surface: 342 watts/meter^2

- Initial outgoing radiation: ~none

- Radiative forcing: 342 watts/meter^2

Now What?
The Path to Equilibrium

- Radiative forcing adds energy → Planet Keeling's temperature rises
- Higher temperature → more outgoing radiation
- More outgoing radiation → less radiative forcing
- No radiative forcing when incoming and outgoing radiation are equal: 279^{o} K = 6^{o} C

For the Curious

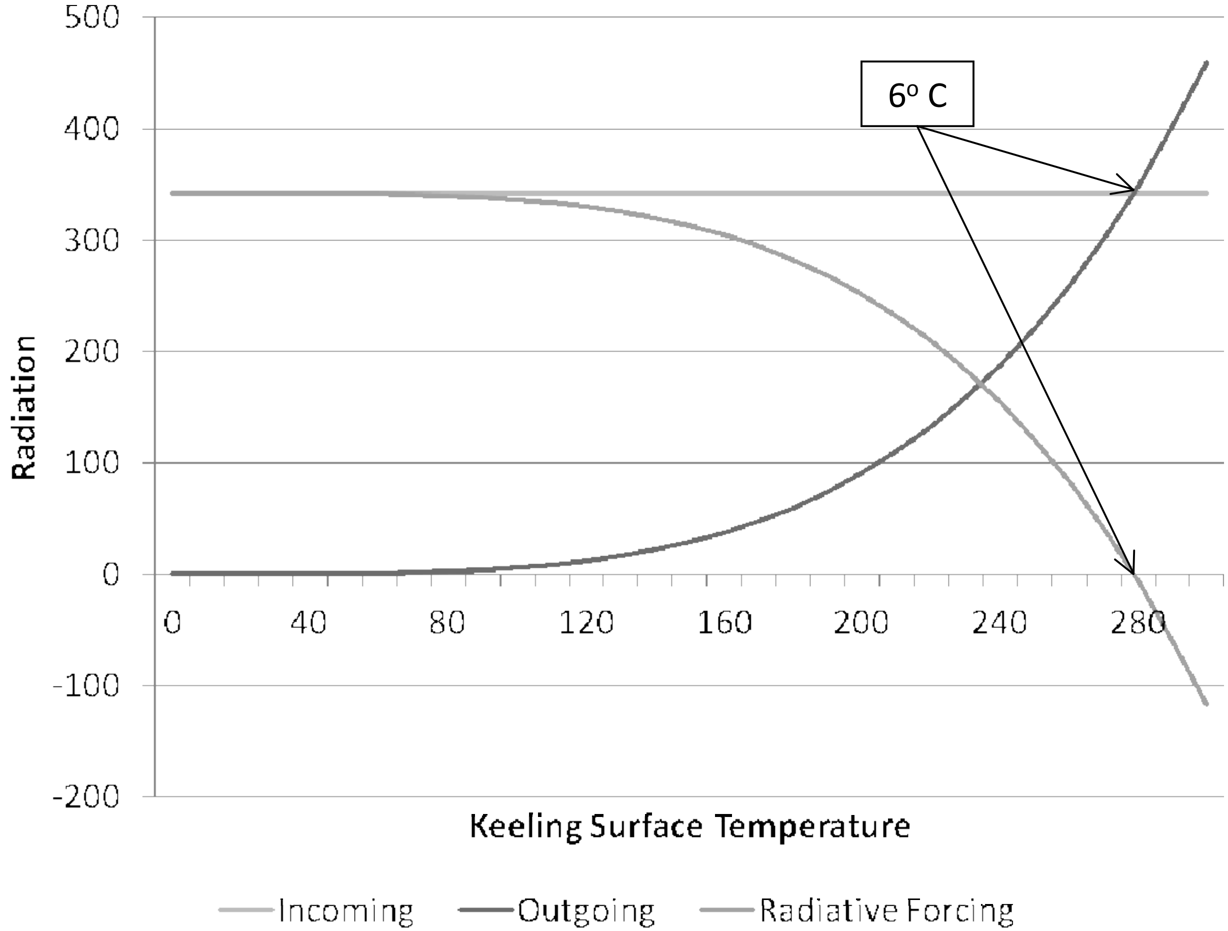
- Radiation = σT^4
  - Radiation is in w/m^2
  - Temperature is in degrees Kelvin (centigrade + 273)
  - $\sigma = 5.67 \times 10^{-8}$ watts

- Task: Solve for T for $\sigma T^4 = 342$

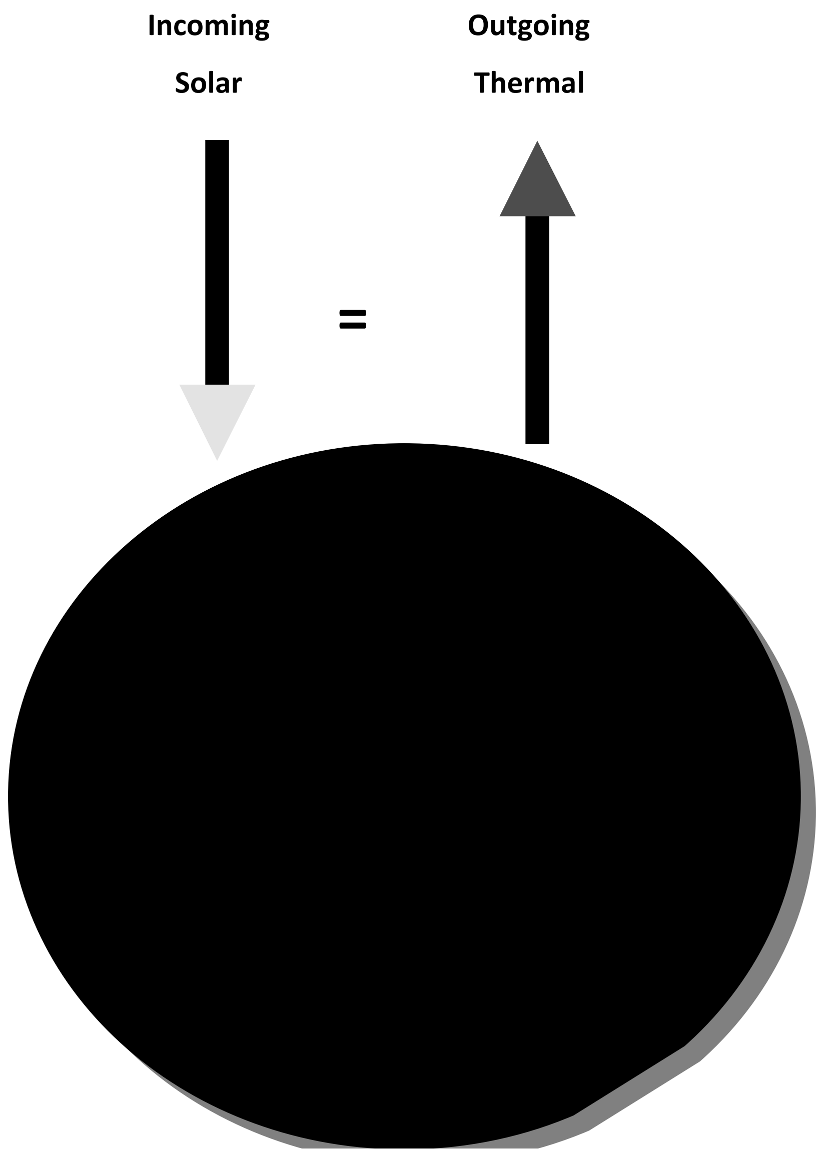
- Some algebra: $T^4 = 342/(5.67 \times 10^{-8})$

- And more : $T = (342/5.67)^{1/4} \times (10^8)^{1/4} = 2.79 \times 100 =$ 279^o K = 6^o C

The Path to Equilibrium



Equilibrium for Planet Keeling I



Good (19^{th} century) Physics

But Wrong Answer:

Earth is Warmer than 6^o C

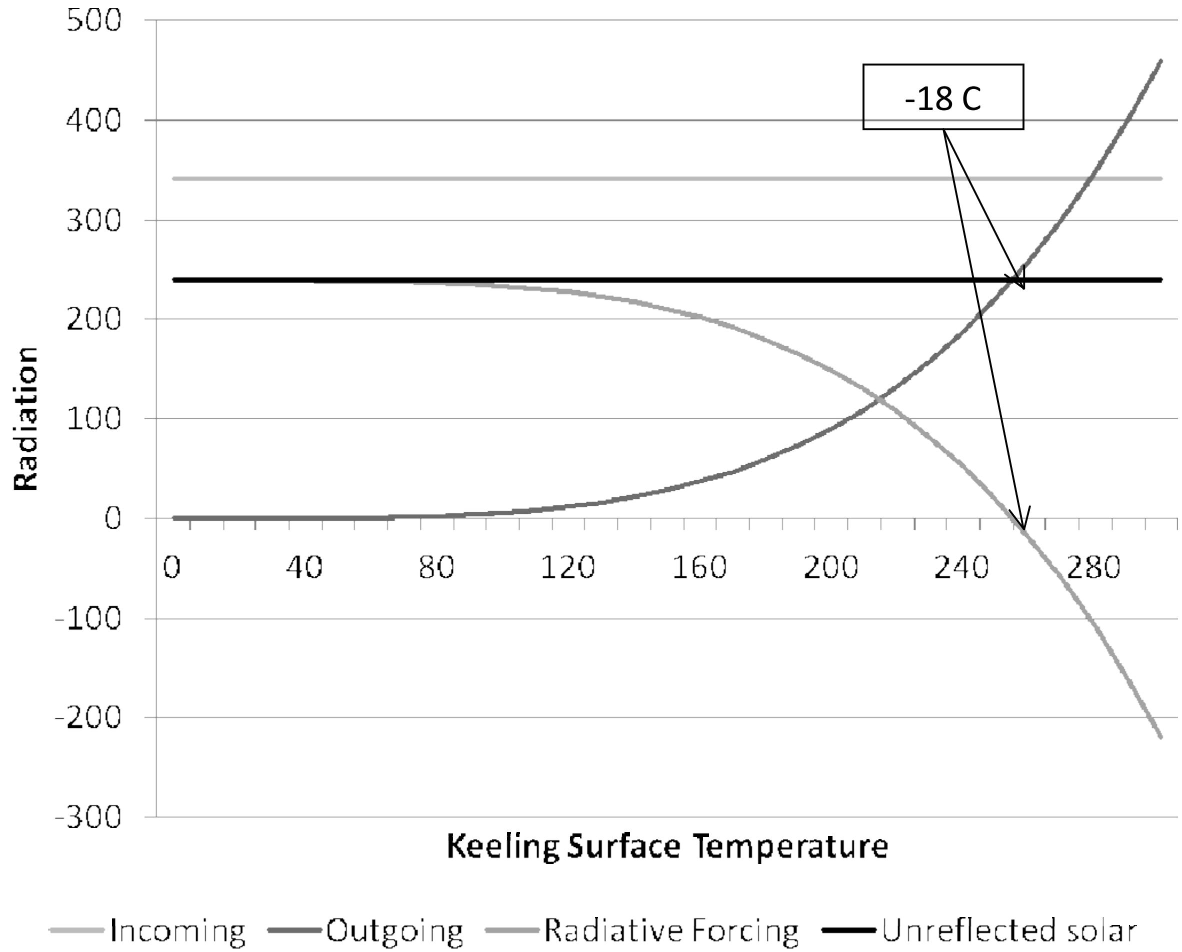
Planet Keeling Mark II: Add Albedo

- Reflects 30% of solar radiation (0.3 albedo)

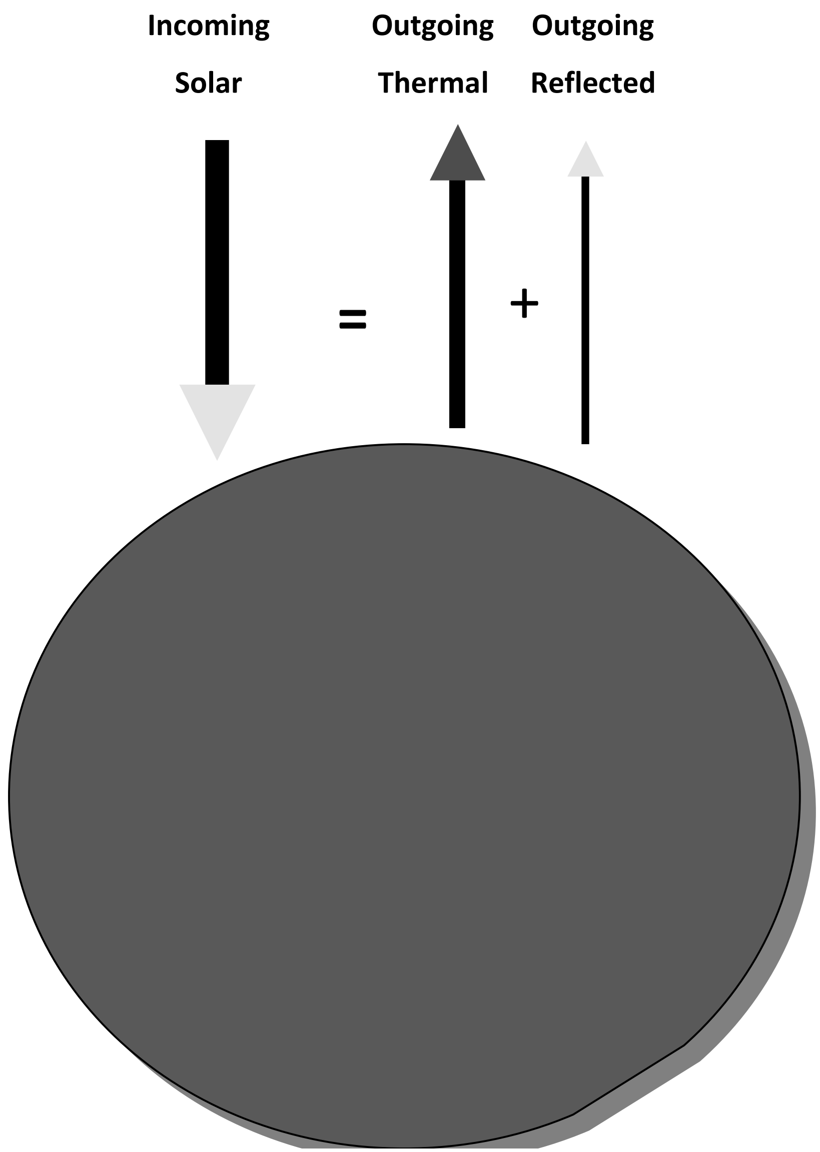
- Solar radiation now balanced by:
  - Keeling's own thermal radiation <u>plus</u>
  - Reflected solar radiation

- Equilibrium requires less thermal radiation → reached at lower temperature

The New Path to Equilibrium



Equilibrium for Planet Keeling II



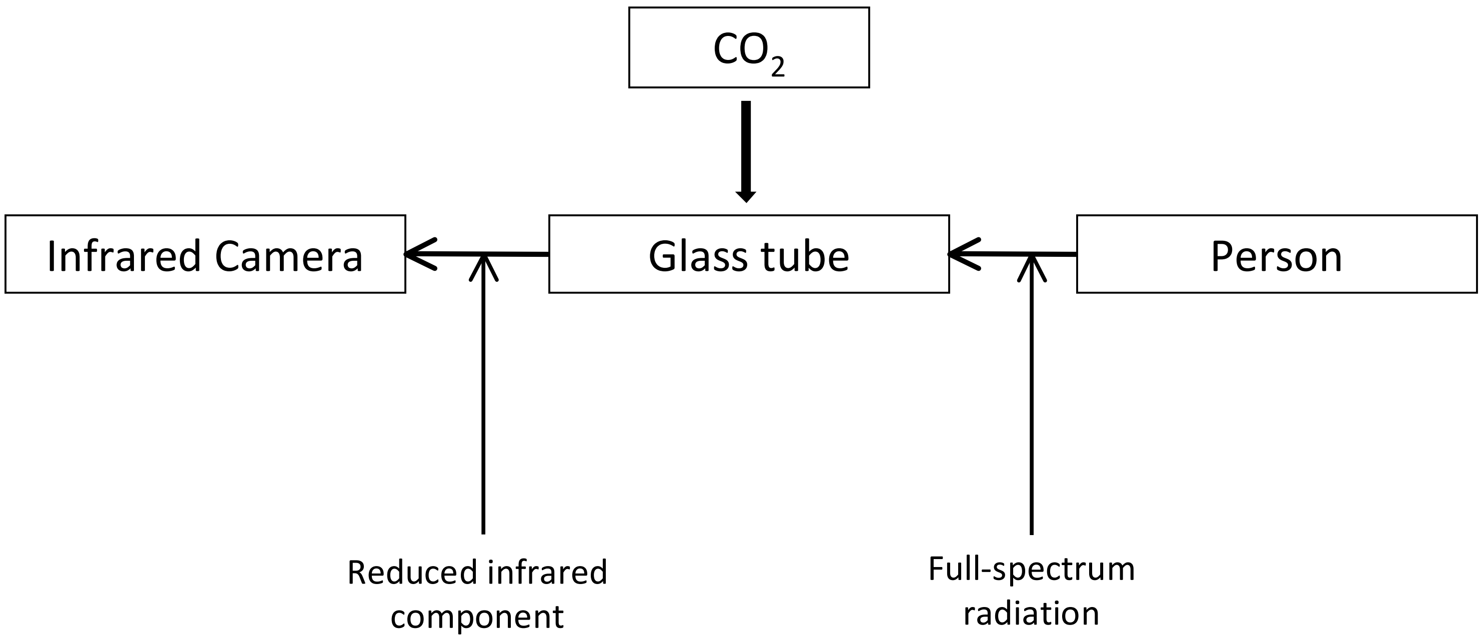
The Model is More Realistic
But the Answer is More Wrong:
Earth Isn't a Snowball

THE GREENHOUSE EFFECT

The Missing Piece

- Fourier (1824): Atmosphere must trap heat
- But (1) what part of atmosphere does this and (2) how does it do it?
- Tyndall (1859) answers the first question
  - Oxygen and nitrogen (99% of atmosphere) are transparent to infrared radiation
  - Water, CO_2 and methane (CH_4) are not

Tyndall Experiment: Modern Version



Infrared Image of Face with Normal Atmosphere

Add CO_2 to Tube – And More and More

Why?

- For Tyndall: an empirical result
- Explanation requires 20th century physics
  - Electromagnetic radiation
  - Interaction of radiation and gas molecules

1. Electromagnetic Radiation

- Includes X-rays, visible light, thermal radiation, radio waves
- Behaves as particles (photons) <u>and</u> waves
- High/low-energy photons = short/long wavelength

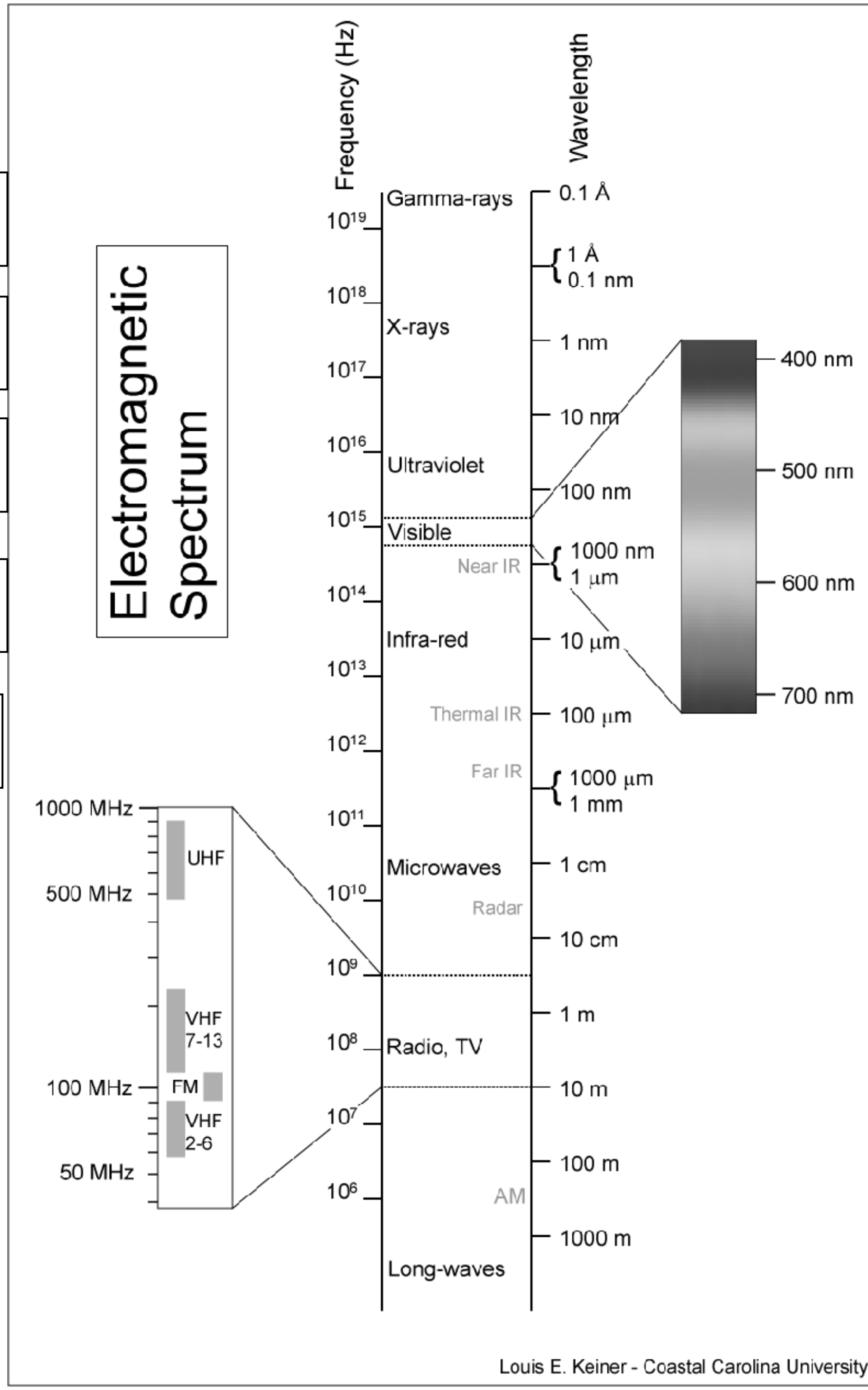
Angstrom (A):
10-billionth of a meter

Nanometer (nm) :
Billionth of a meter

Micrometer (μm):
Millionth of a meter

Millimeter (mm):
Thousandth of a meter

Centimeter (cm):
Hundredth of a meter



Shorter wavelength
=
More energetic photons

Sun and Earth

- Source temperature determines photon energy/ wavelength
- Incoming solar radiation: high energy photons/short wavelength
- Outgoing radiation:
  - Reflected solar radiation: unchanged
  - Earth's thermal radiation: low energy photons/long wavelength

Solar Radiation And Earth's Thermal Radiation

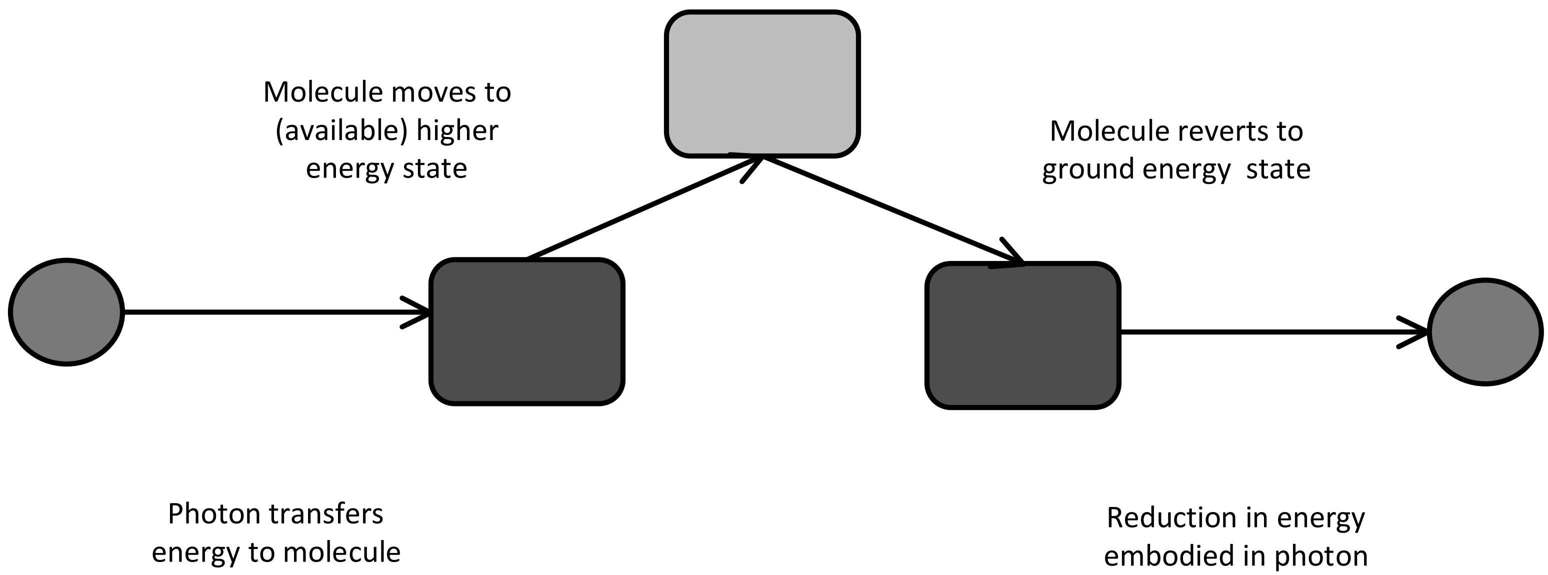
2. Molecules and Greenhouse Gases

- Molecules can only occupy certain energy states
- Absorb a photon if its energy matches an interval between available energy states
- Greenhouse gases absorb low-energy photons of Earth's thermal radiation

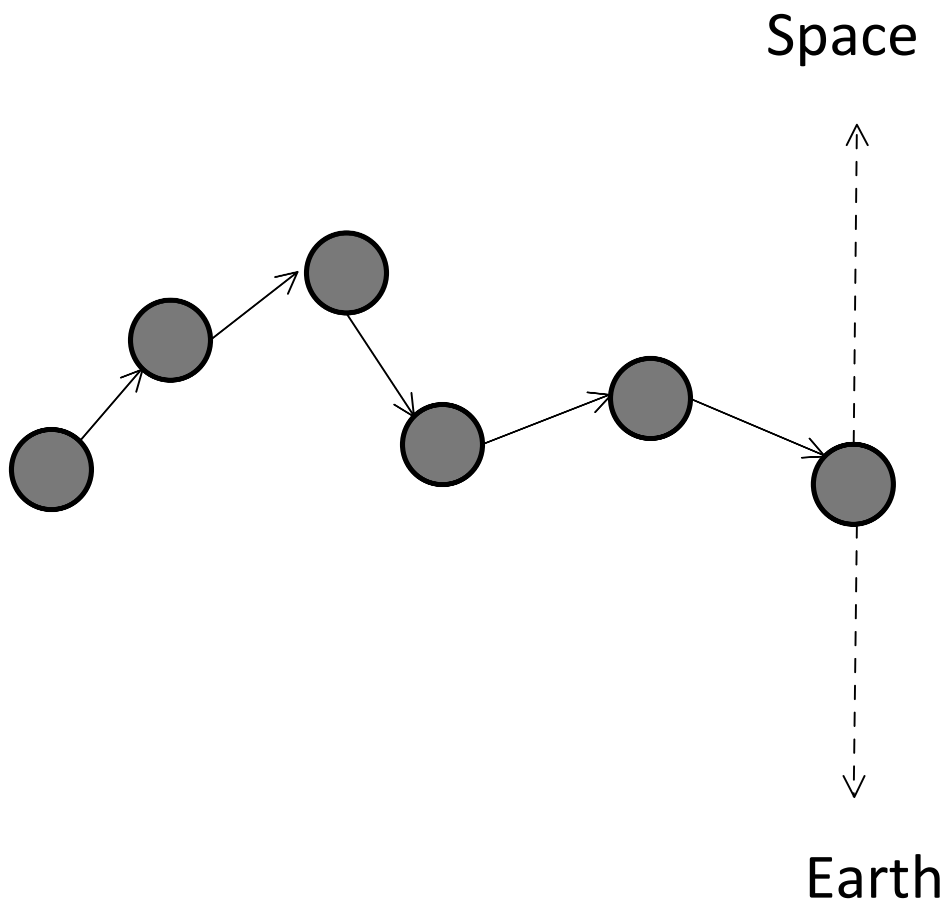
The Process Continues

- Molecule drops back to original energy level
- Emits photon <u>in random direction</u>
- Further collisions repeat process
- Ends when photon escapes into space OR strikes Earth's surface

From Photon to Photon: Nothing Lost, Nothing Gained



Molecular Bumper Cars



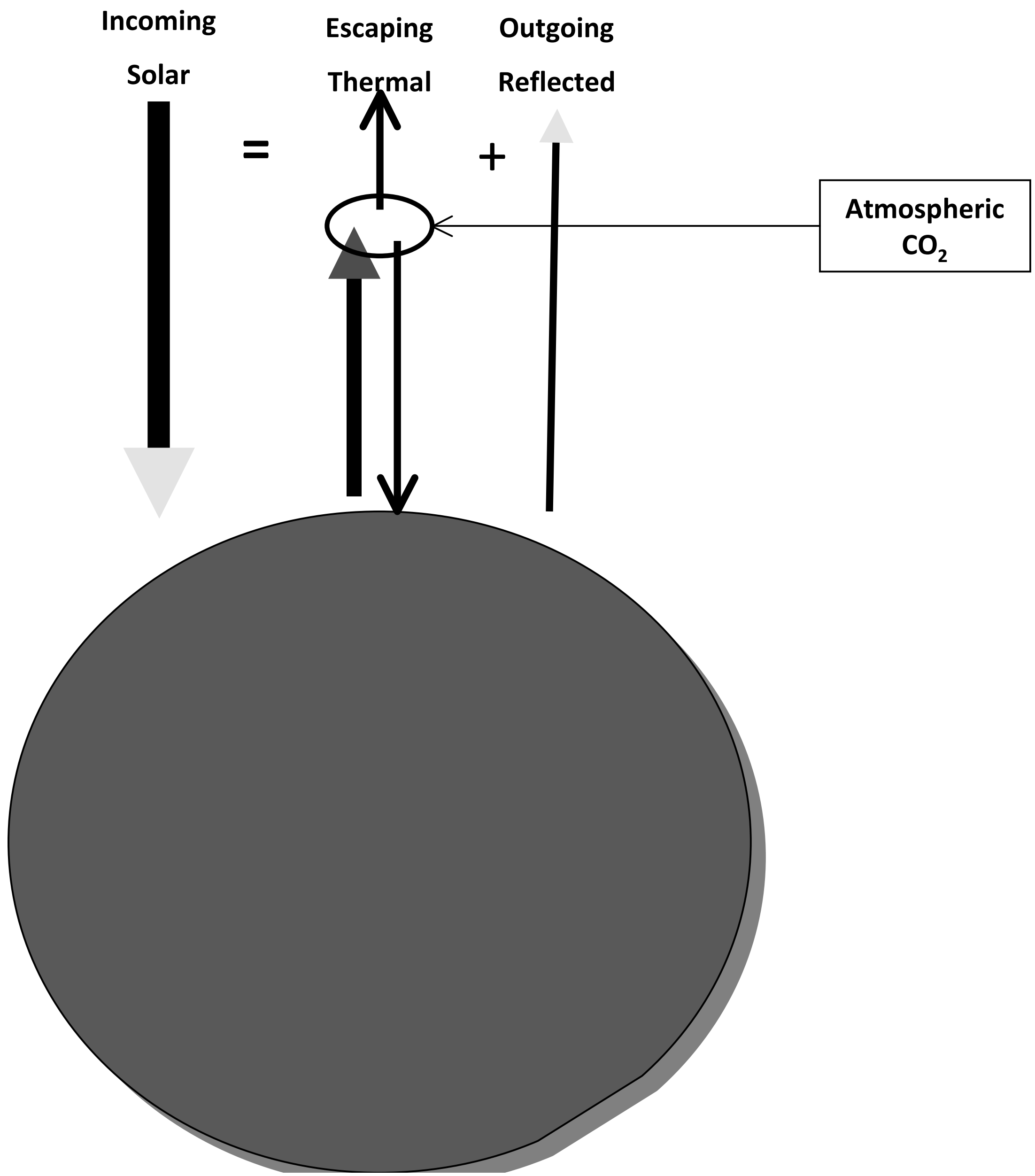
Planet Keeling Mark III (preliminary edition)

- Add CO_2 to atmosphere
- Part of outgoing radiation re-radiated back to surface
- Higher surface temperature

The New Equilibrium

- Warmer surface → increased thermal radiation from surface
- Radiation escaping into space increases
- Warming continues until escaping thermal plus reflected solar equals incoming solar

Planet Keeling III (preliminary)



With Earth's CO_2 Concentration: Surface Temperature Higher But Not Enough Higher

Just Add Water

- Water vapor is a greenhouse gas: roughly doubles warming effect of CO_2
- But a feedback: atmospheric water vapor determined by temperature
- CO_2 is the control knob: without it, planet's water vapor would be surface ice

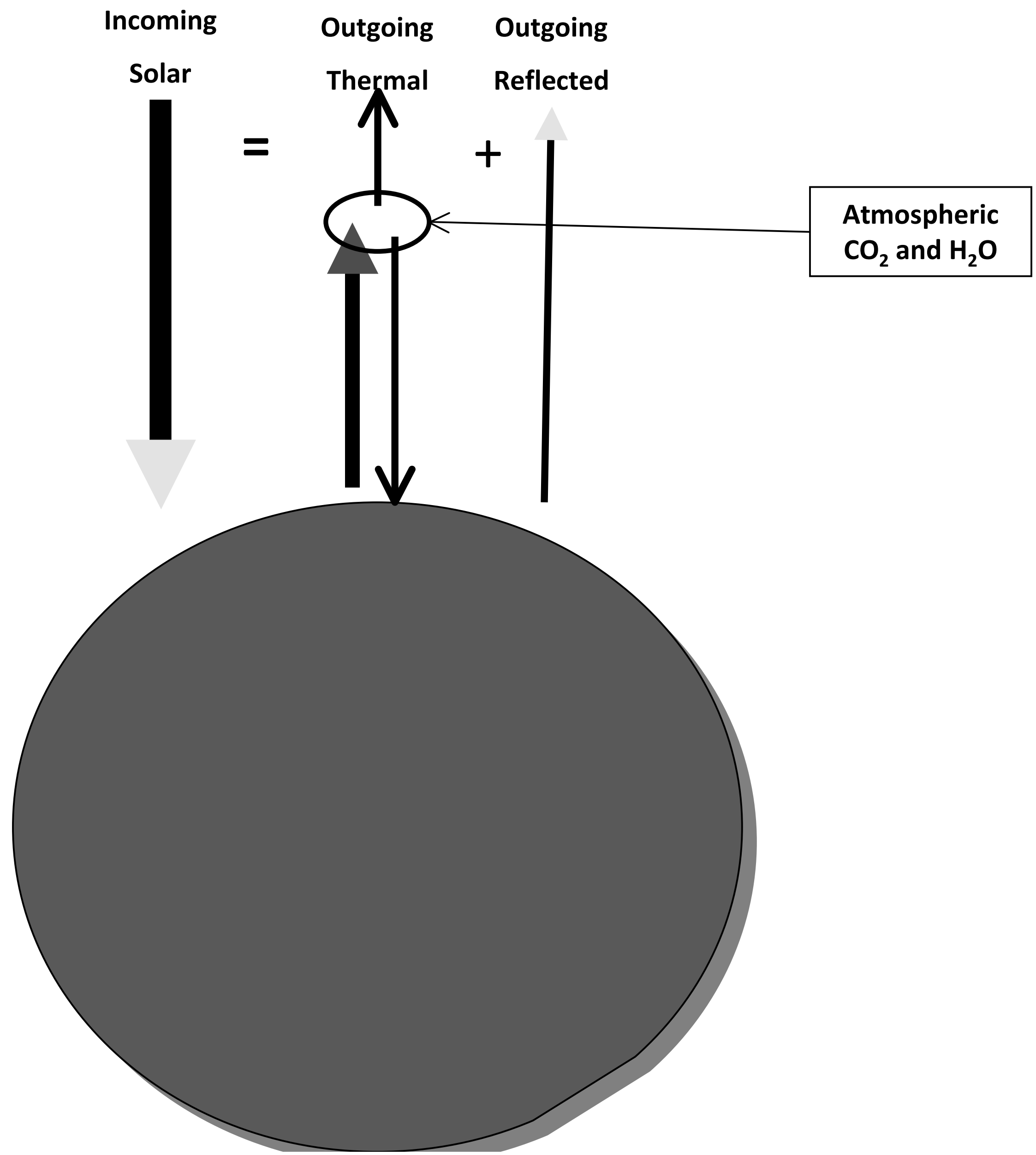
Feedbacks

- System change produces effect that increases or reduces the change
- Negative feedback: more CO_2 → more plant growth → absorbs some of CO_2
- Positive feedbacks for higher temperature
  - Reduced ice cover → lower albedo
  - Release of arctic methane → increased greenhouse effect

Planet Keeling Mark III: Mostly CO_2 and Water Vapor

- Radiation into space now consists of:
  - Reflected solar radiation
  - <u>Part</u> of thermal radiation from Earth's surface
- Equilibrium requires making up thermal radiation trapped by greenhouse gases:
  - Thermal radiation from surface must increase
  - Requires higher temperature
- Equilibrium: 18^o C or 65^o F

Planet Keeling III



Equilibrium

- Equilibrium reached in all cases: Keeling I, II, III (preliminary) and III (final)

- Difference: temperature needed to reach it

- Lower if part of incoming solar is reflected

- Higher if only part of surface thermal radiation escapes into space

A Tale of Two Houses

- Two houses on dark side of Mercury identical except House A is insulated and House B is not.
- Only source of heat: identical 1000-watt heaters that run continuously
- At end of year , thermal radiation from each house is measured.

What is the relationship between two houses' radiation?

Radiation from A is greater?

Radiation from B is greater?

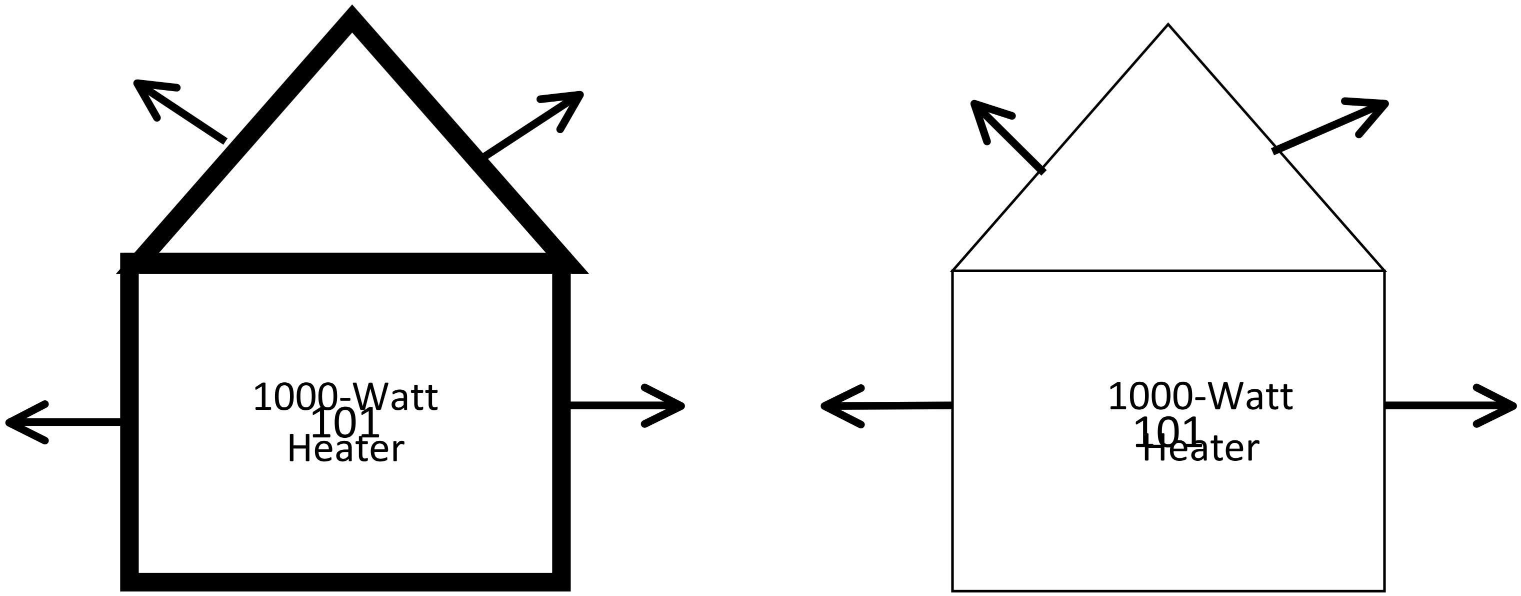
Equal radiation?

Two Houses

A > B?

B > A?

A = B?



House A

House B

THE DISCOVERY OF GLOBAL WARMING: THE BEGINNING

1890s Setting: What's the Question?

- 19th century uniformitarianism:
  - Scientific principles operating in the past are the same as those operating today
  - Today's world results from gradual change over long periods

- Second assumption challenged by evidence of past global glaciations

- Leads to question: What caused global <u>cooling</u>?

Svante Arrhenius (1896)

- Perhaps fewer volcanic eruptions: Less CO_2 → cooler → less water vapor → still cooler

- To be complete, looks at the reverse: more eruptions → more CO_2 → more water vapor → warmer world

Also Quantifies Impact of Doubling CO_2

- Science: CO_2 and water vapor feedback
- Data: atmospheric absorption of thermal radiation from Langley experiments
- Tools: pen and paper
- Result: 5^o-6^o C warming – within range of modern calculations
- Moral: Basic idea of global warming isn't complicated

But is there a problem? Two questions

- Is Arrhenius correct about effect of doubling CO_2?
  - Angstrom fils: atmosphere already saturated with CO_2
  - Wrong

- When (if ever) will CO_2 double?
  - Large emissions far in the future
  - Even large emissions would have limited effect on atmosphere: oceans would absorb most CO_2

Roger Revelle

- Grant to study ocean chemistry (1957)
  – Expects to find that ocean absorb CO_2
  – It does but (surprise) most pops back out again
- Eliminates <u>one</u> reason for putting problem far into the future
- But still expects slow growth in emissions

Now We Need Measurements

- Is atmospheric concentration of CO_2 rising?
- Are global temperatures rising?
- What is the quantitative relationship between CO_2 concentration and global temperature?

Review of Processes

- Radiative forcing changes average temperature of Earth system
- Under constant conditions, temperature change eliminates radiative forcing: a negative feedback
- Albedo reduces equilibrium temperature because reflected solar partly balances incoming solar
- CO_2 raises equilibrium temperature because not all thermal radiation escapes into space