# Earth: The Environment & Life.

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# Part I

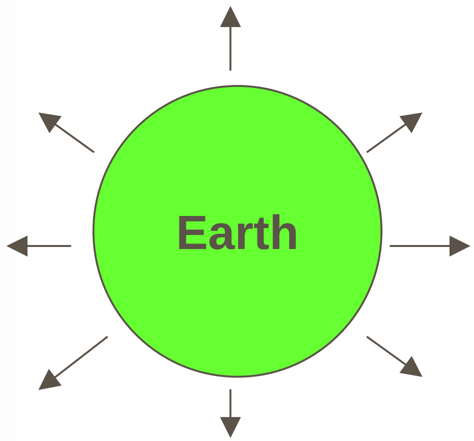
## The Environment.

***I cannot tell how the truth may be***
***I say the tale as it was said to me…***
***- Sir Walter Scott.***

# Planet Earth

- Third planet in the Solar system.
- Orbiting a Main Sequence G2 type star with surface temperature ~ 5600 K.
- Only planet known where life exists.
- Age ~ 4.55 Gyr.
- Oldest life fossils ~ 3.5 Gyr.
- Present atmosphere composed of $N_2$, $O_2$ and trace gases.
- Neighboring planets atmospheric compositions vastly different from Earth’s atmosphere today but similar to (what we believe) Earth’s composition at origin.

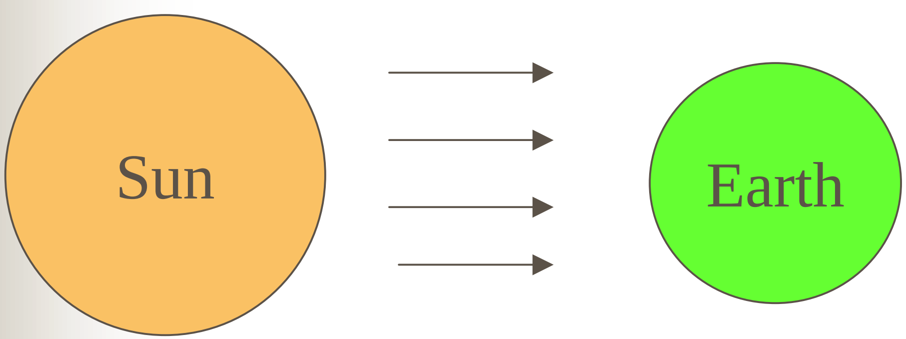
# Planet Earth : Radiative Balance.




$$P_{inc} = S * A \qquad S = 1380 W/m^2$$
$$P_{refl} = -\ a\ S * A \qquad A = \pi R_E^2$$
$$P_{eff} = S * A(1-a) \qquad a \sim 0.33$$

$$\therefore P_{eff} = 114 * 10^{15} Watts$$

$$Flux = \sigma T^4$$
$$P_{emit} = Flux * Area = \sigma T^4 * \pi R_E^2$$




$$P_{emit} = P_{eff} \Rightarrow \sigma T^4 * \pi R_E^2 = S * A(1-a)$$
$$\therefore T = \left(\frac{S(1-a)}{4\sigma}\right)^{1/4}$$

# Radiation Balance
# Steady State Assumption

$$T = [\frac{(1380)(1-0.33)}{4(5.7*10^{-8})}]^{1/4} = 252\,K = -21C$$

- Observed Earth temperature T=288K=15C !

# Earth’s Four Spheres

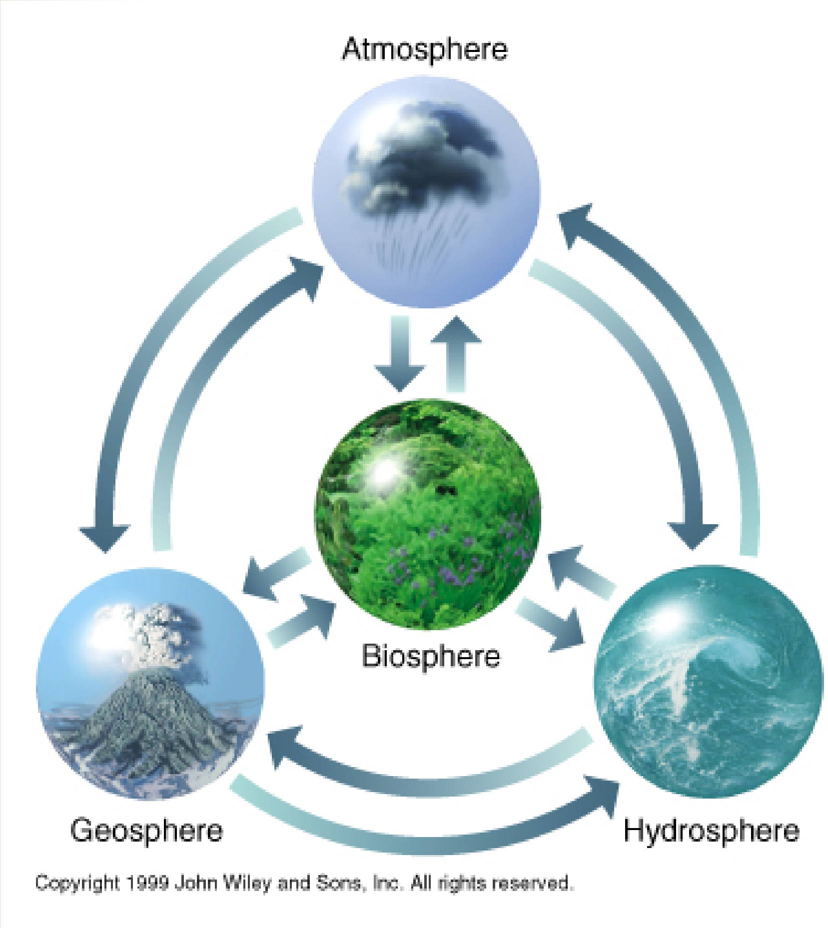
Geosphere: comprises the solid Earth and includes both Earth’s surface and the various layers of the Earth's interior.

Atmosphere: gaseous envelope that surrounds the Earth and constitutes the transition between its surface and the vacuum of space

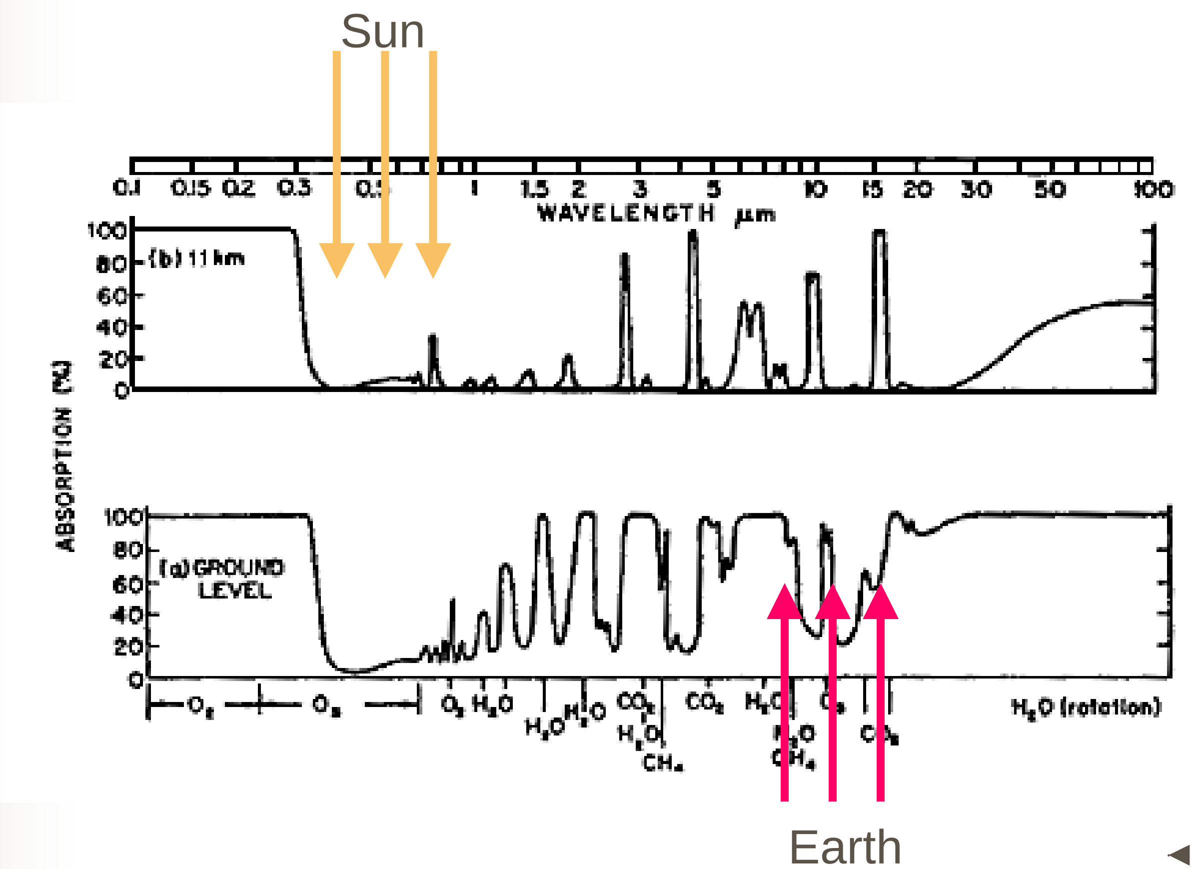
Hydrosphere: includes all water on Earth (including surface water and groundwater)

Biosphere: the life zone of the Earth and includes all living organisms, and all organic matter that has not yet decomposed.

# Planet Earth: The interacting spheres



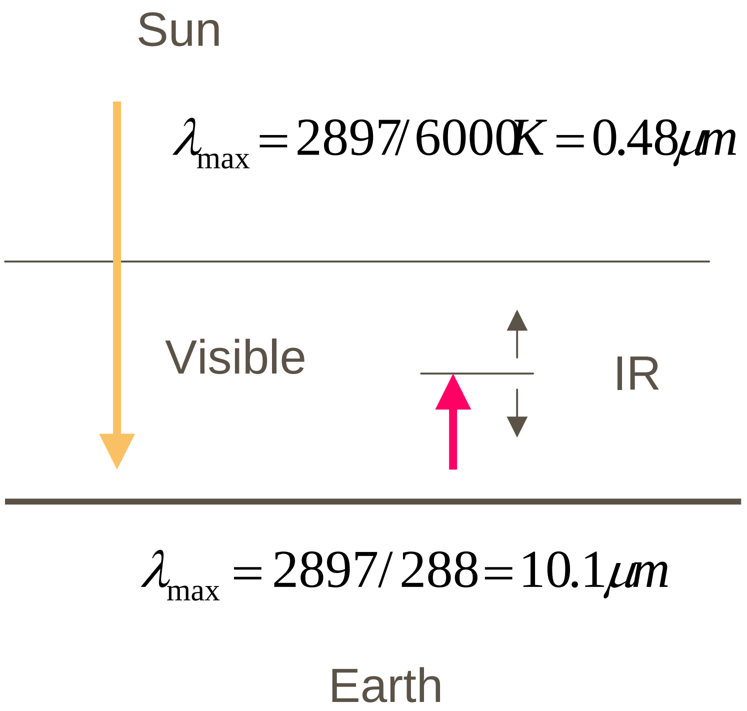

# Atmospheric absorption



# Greenhouse effect

- With no greenhouse effect:
  T ~ -21C
- With greenhouse effect :
  T ~ 15C
- This is the difference between solid ice and liquid water: no-life and life.
- Wien's Law:
  The wavelength of maximum emission depends inversely on the object's temperature.

$$\lambda_{max} = 2897 / T$$



# Planet Earth: Atmosphere.

Conditions at origin

- Sun surrounded by gas & dusty debris in disk; mostly hydrogen.
- accretion of debris into planets: Earth forms. Hydrogen in atomic or molecular form too light for gravity to hold onto, so most escaped.
- heating of surface by impact of leftover planetesimals, meteorites & comets.
- heating due to radioactive decay---inner parts become molten.

# Planet Earth: Atmosphere

<u>Formation of atmosphere</u>

- The gases of the early atmosphere were originally trapped within the solid crust of the Earth, and then released ("outgassed") either by volcanoes or by violent planetesimal impacts. Another alternative is hydrothermal vents on the ocean floor, which today cook up a lot of organic molecules.
- The early atmosphere was delivered by comets. Comets are ices + frozen gases and when they strike the Earth the ices melt and the frozen gases vaporize (become gaseous).
- Can explain the presence and amount of $H_20$, $CO_2$, $N_2$ at least partially. Cannot expain, $O_2$, $NH_4$ and $NH_3$.

# Greenhouse on other planets:

Assuming present conditions….

| Planet | Albedo | $T_{predicted}$ | $T_{actual}$ | Atmosphere |
|---|---|---|---|---|
| Venus | 0.71 | 244K | **700K** | Massive $CO_2$ |
| Earth | 0.33 | 252K | **288K** | $N_2$, $O_2$ and trace gases |
| Mars | 0.17 | 216K | **230K** | Thin $CO_2$ |

# Greenhouse effect & Life:

| | Planet | | | |
|---|---|---|---|---|
| Gas | Venus | Earth (without life) | Mars | Earth (with life) |
| $Co_2$ | 96.5% | 98% | 95% | **0.03%** |
| $N_2$ | 3.5% | 1.9% | 2.7% | **79%** |
| $O_2$ | Trace | 0.0% | 0.13% | **21%** |
| Ar | 70 ppm | 0.1% | 1.6% | **1%** |
| $CH_4$ | 0.0% | 0.0% | 0.0% | **1.7 ppm** |
| $T_s$ $^oC$ | 459 | 240-340 | -53 | **15** |
| P (bars) | 90 | 60 | 0.0064 | **1.0** |

*Source: The Ages of Gaia: James Lovelock.*

# Environment: The Young Sun paradox.

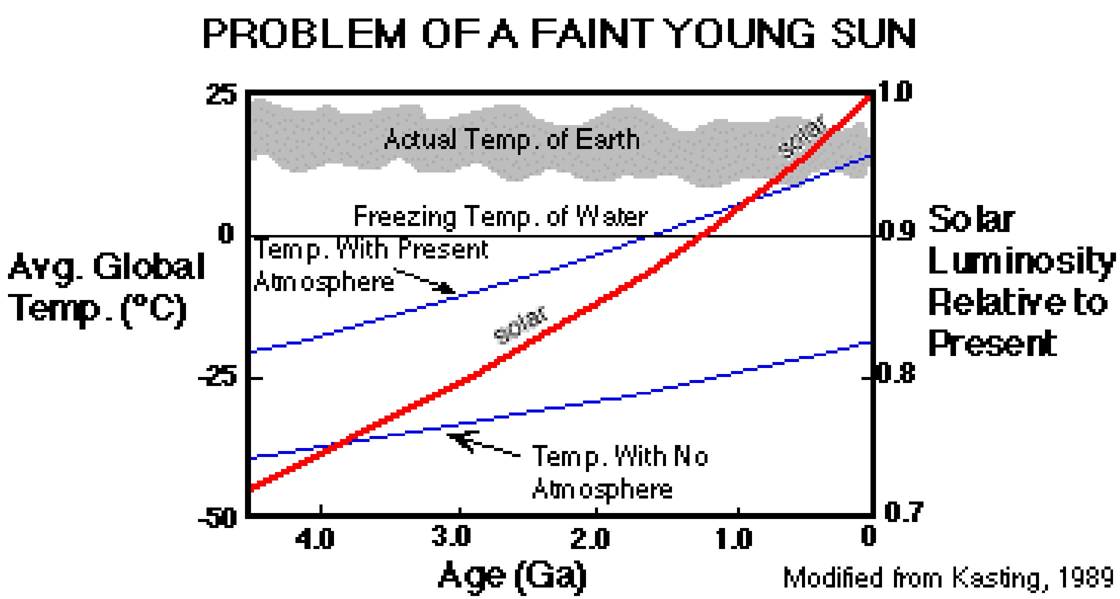



Figure 1.04. The change in the sun's luminosity is shown by the red line; two temperature histories for earth are also shown. In one case, the earth is presumed to have had an atmosphere with the same composition as todays (i.e., a greenhouse efficiency equal to today's); the other case shows what would have happened with no atmosphere at all (i.e., no greenhouse effect). These two cases differ substantially from what is presumed to have actually occurred; a more or less stable global temperature, with frequent but small variations, so that the global temperature stays within the shaded region in the figure (highly generalized).

# Part II

## Life.

***Outside the rain fell dark and slow,***
***While I pondered on a dangerous and irresistible pastime…***
***I took a heavenly ride through our silence,***
***I knew the moment had arrived,***
***For killing the past, and coming back to life…***

# Life: Intrinsic properties.

- All organisms alter their environment by taking in free energy, and excreting high-entropy waste products.
- Thus, life-forms maintain a low internal entropy at the expense of increasing the entropy of its surroundings.
- Organisms grow and multiply, usually in an exponential fashion, providing an intrinsic positive feedback to life.
- Life can exist only in a certain  range of a given environmental variable. Moreover, the growth of a particular organism is maximum at and around an optimal level of that variable.
- Once stable life-forms exist, which one of these dominates and hence leaves behind more descendants via competing for limited resources is determined by Natural selection as in standard theory.

# Life: Affects on Atmospheric composition

- First life forms probably Hyperthermophiles, capable of surviving in hydrothermal systems with T ~ 115 C, living almost exclusively around hot underwater vents and volcanoes.
- Life adapts to utilize $CO_2$ in the early atmosphere to generate energy via photosynthesis thus reducing dependence on unreliable supply of energy from fluids circulating in rocks.
- $O_2$ and $CO_2$ composition begins to change on abiotic factors (dissolving, chemical reactions etc) and on biotic factors (respiration, metabolic activity etc).

# Life: Clues towards biotic influences.

- Minerals *older* than 2.5 billion yrs are oxygen-poor.
- Stromatolites -- colonies of blue-green algae; appear at 2.0--2.3 billion yrs ago, not before. Current blue-green algae use oxygen.
- There is evidence for non-oxygenic photosynthesis at earlier times from fossil stromatolites.
- $CH_4$ presence in atmosphere is due to continuous replenishment by methane producing bacteria – methanogens.

# Life

# Part III

## Daisyworld

*KATHLEEN: I love **daisies**.*

*JOE: You told me.*

*KATHLEEN: They're so friendly. Don't you think that **daisies** are the friendliest flowers?*

*JOE: I do…*

# Gaia: Introduction

- Together with scientist Dian Hitchcock, James Lovelock examined the atmospheric data for the Martian atmosphere in the late 1960’s and found it to be in a state of stable chemical equilibrium, which they interpreted as an indication of lifelessness (and correctly so).
- The Earth was shown to be in a state of extreme chemical disequilibrium. Gases such as methane, Oxygen and ammonia have “no business” being present in the atmosphere in a steady state.
- In that same year, Lovelock began to think that such an unlikely combination of gases such as the Earth had, indicated a homeostatic control of the Earth biosphere to maintain environmental conditions conducive for life, in a sort of cybernetic feedback loop, an active (but non-teleological) control system.

# Gaia: Introduction

- Lovelock calls this the science of geophysiology - the physiology of the Earth (or any other planet).

In the most extreme interpretation of this idea:

- Earth is a super-organism
- Biota and physical environment are so tightly coupled they are considered a single organism.
- The climate and chemical composition of Earth are kept in homeostatis at an optimum by and for the biosphere.
- Life supporting conditions are maintained by this super-organism for its own benefit and the benefit of its constituents.

# Gaia: The hypotheses.

- **Strong version**: The strong Gaia hypothesis states that life creates conditions on Earth to suit itself. Life created the planet Earth, not the other way around.
- **Weak version**: Individual traits determined primarily by natural selection, do have a global effect on the environment. Collectively life has a significant impact on the environment.

# Gaia Hypothesis

Goes beyond simple interactions amongst biotic and abiotic factors

**Influential Gaia**
Life collectively has a significant effect on earth’s environment

**Homeostatic Gaia**
Atmosphere-Biosphere interactions are dominated by negative feedback

**Coevolutionary Gaia**
Evolution of life and Evolution of its environment are intertwined

**Geophysiological Gaia**
Biosphere can be modeled as a single giant organism

**Optimizing Gaia**
Life optimizes the abiotic environment to best meet biosphere’s needs

# Strong & Weak Gaia:

**Drawbacks of Strong version:**

- Almost impossible to put to test.
- Teleological: requires foresight and planning by biota.
- Is not falsifiable.

**Strengths of Weak version:**

- Makes definite predictions.
- Mathematically accessible via Daisyworld-type toy models.
- Is falsifiable, and in Popper's sense is a "good" scientific theory. Even though it may be proven "incorrect" eventually, the positives derived from the research it fuels, will prove its worth by itself.

# Daisyworld: A Toy model.

- Inhabited by single species of biota, daisies:

  i) Black daisies —dark in colour, lower albedo (reflectivity) than soil.

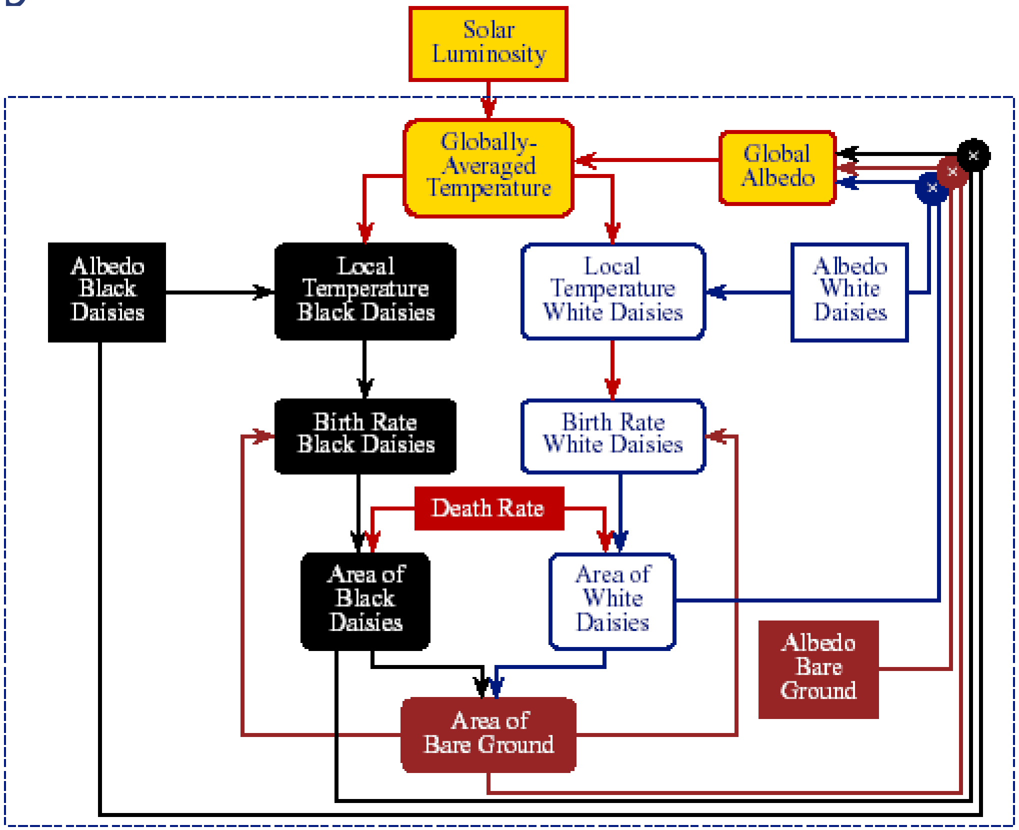
  ii) White daisies —light in colour, higher albedo than soil.

- Environmental conditions suitable for daisy growth over entire planet surface.
- Daisy growth influenced by surface temperature: Too cold (< 5C) or too hot (> 40C)—daisies die — material immediately recycled;
- Optimum temperature for growth 22.5C.
- Changes in surface temperature controlled by solar luminosity and surface albedo.

# Daisyworld: Assumptions

- *Heuristic* — seeks to describe ways in which mechanisms and feedbacks *might* work.
- Planet same size as Earth illuminated by star of same mass and luminosity as Sun, at same distance as Earth from Sun.
- Atmosphere free from clouds.
- All rain falls at night.
- ‘Greenhouse’ gases constant and negligible effect on climate.
- No seasonality in climate or latitudinal variation in solar radiation received.

# Daisyworld




*Source: http://stress.swan.ac.uk/~mbarnsle/teaching/envmod04/*

# Daisyworld: Equations

$T_c =$ effective temperature,
$A_i =$ albedo of $i^{th}$ specie,
$a_i =$ fractional coverage by $i^{th}$ specie,
$\beta_i =$ variable growth rate,
$\gamma_i =$ death rate,
$x =$ fraction of barren ground on Daisyland,
$q =$ constant relating the albedo to temperature.

$$T_c = \left(\frac{SL(1-A)}{\sigma}\right)^{0.25} - 273$$

$$A = xA_g + a_iA_i$$

$$T_i = q(A - A_i) + T_c$$

$$\beta_i = (1 - 0.00326(22.5 - T_i)^2)$$

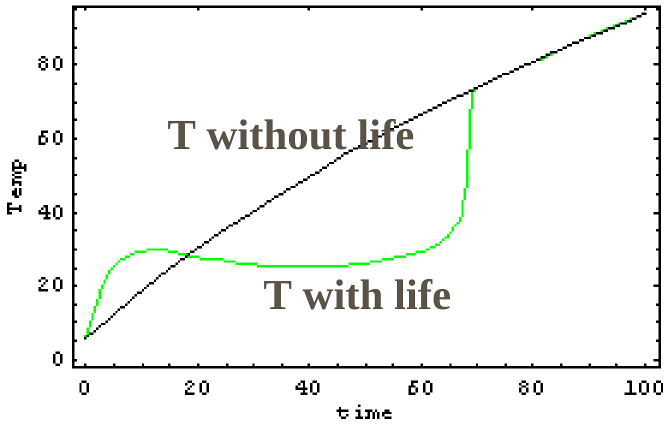
$$\frac{da_i}{dt} = a_i(x\beta_i - \gamma_i)$$

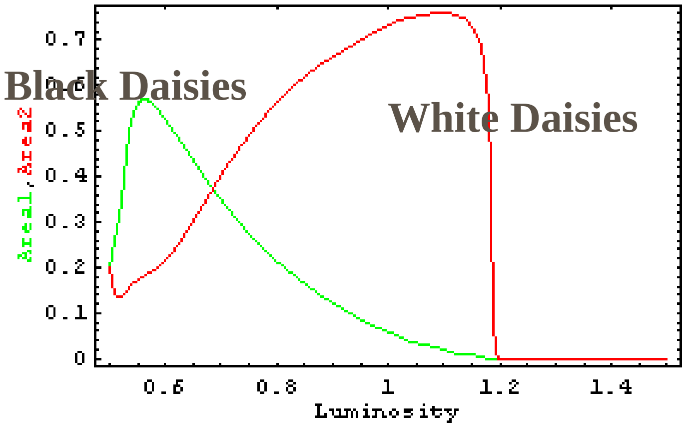
$$x = 1 - (a_1 + a_2 + \dots a_i)$$

*Source: A numerical model for biodiversity – Lovelock, Phil. Tans. R. Soc. Lond. B, **338**, 383-391.*

# Daisyworld: Results

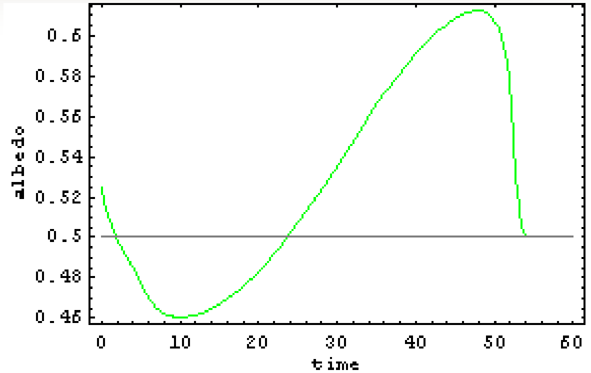
- Temperature on surface of planet rises as the Sun's luminosity increases.
- Initially, surface temperature is below optimal, and so the Black daisies with lower albedo are favored since they are 'warmer'.
- The population of white and black daisies evolves so as to maintain the temperature closest to optimal.
- Eventually, as the temperature exceeds the optimal, the white daisies dominate.

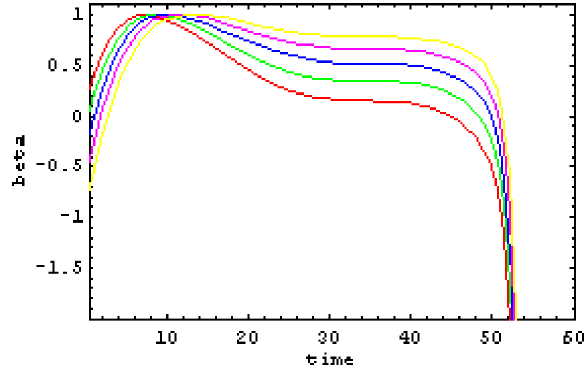


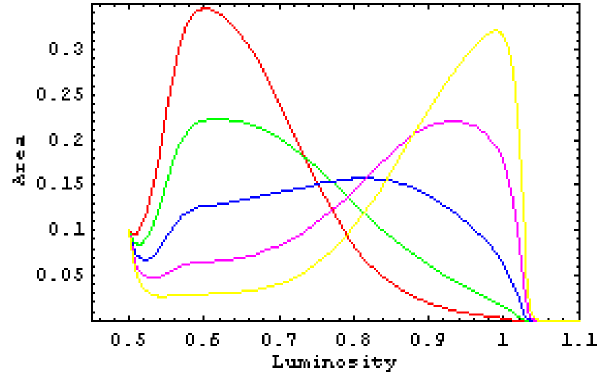



# Daisyworld: Results.

- A Daisyworld with 5 daisy phenotypes, defined by albedo's ranging from 0.35 to 0.75 in steps of 0.1.
- The effective albedo of the planet changes so as to maintain optimal temperature on surface.
- Beta = Growth rate of daisies. As the temperature increases above ~ 50 C, all daisies die out.
- Relative areas covered by the daisies reflecting their populations. Lower albedo daisies dominate when the temperature is below optimal and vice versa. The blue curve corresponds to a = 0.55 which seems best adapted to the particular set of conditions imposed.



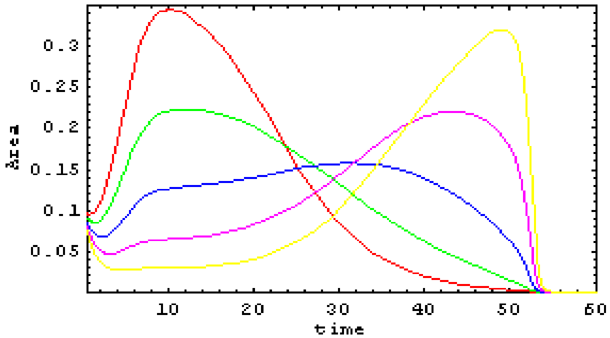



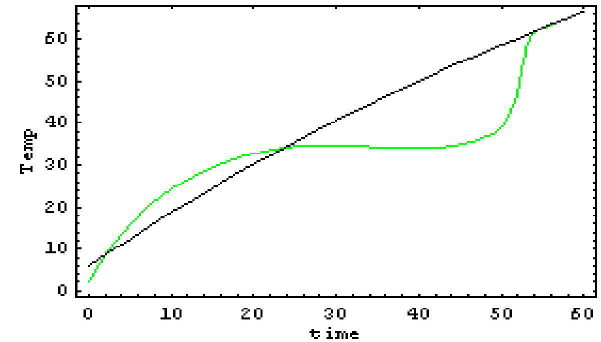
# Daisyworld: Results

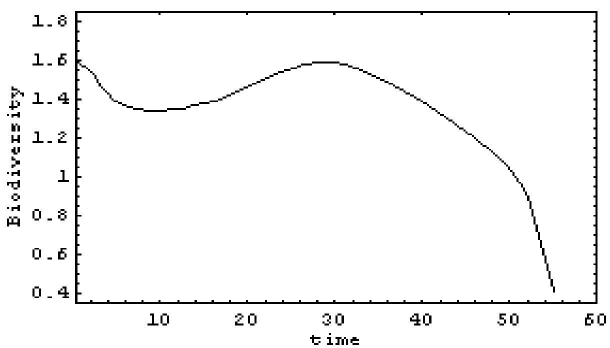
- Same as earlier, 5 daisies with varying albedo.
- The biodiversity index is defined as:

$$\mathbf{H} = -\sum_{i=1}^{s} p_i \log_e p_i$$

- H = the **Shannon biodiversity index,**
- $p_i$ = proportion of each species in the sample (relative abundance),
- s = the number of species in the community.
- Biodiversity is maximum when the system is least strained, ie,when the Temperature of the system would be the same as it would be without life.

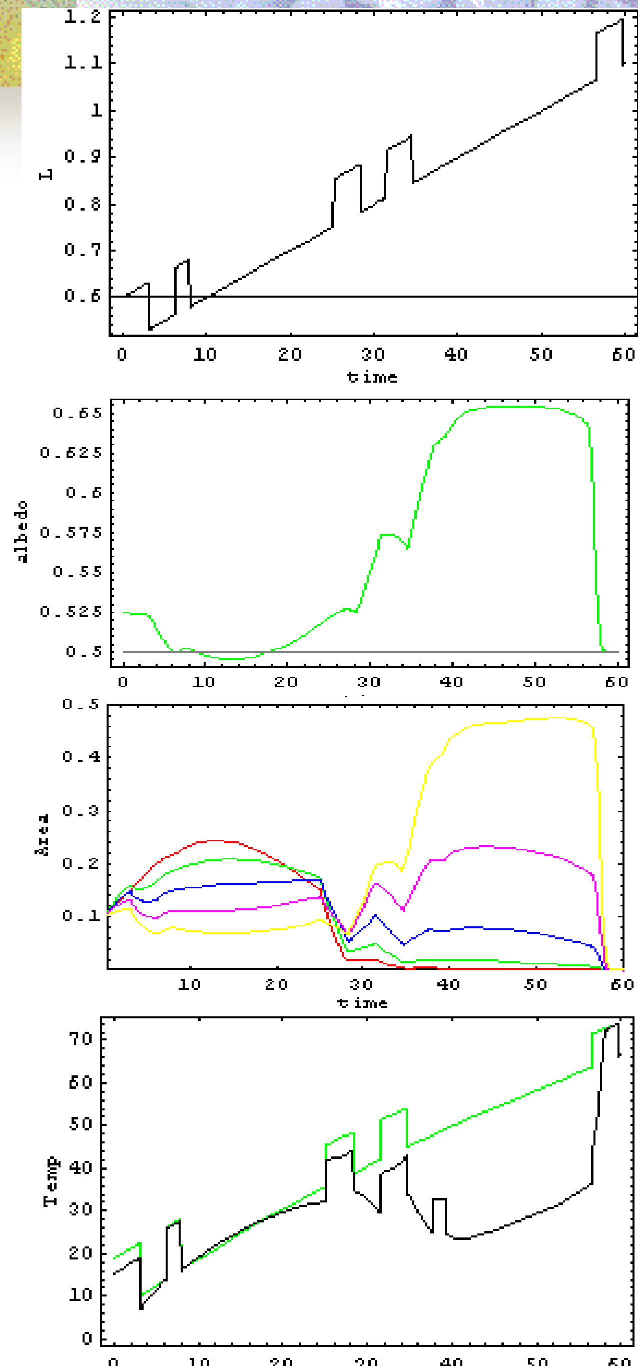


# Daisyworld: Toying

- To study the effects of random perturbations, we introduce perturbations in the driving term, the solar luminosity function.
- It is seen that the magnitude of the effect is different, depending on what state the perturbation occurs at.
- In any case, there is clear evidence that the system tends to recover almost immediately from the perturbation to self-regulated steady state.



# Daisyworld: Toying with the model

$$\mathrm{d}a_i/\mathrm{d}t = a_i(\beta_{ia}x_a - \gamma_{ia} - B) \quad \text{plants,}$$
$$\mathrm{d}b_i/\mathrm{d}t = b_i(A\beta_{ib}x_b - \gamma_{ib} - C) \quad \text{herbivores,}$$
$$\mathrm{d}c_i/\mathrm{d}t = c_i(B\beta_{ic}x_c - \gamma_{ic}) \quad \text{carnivores.}$$

Where (A, B and C) are the populations of each of the three levels, and ($x_a$, $x_b$ and $x_c$) is the space unoccupied by each of these populations.

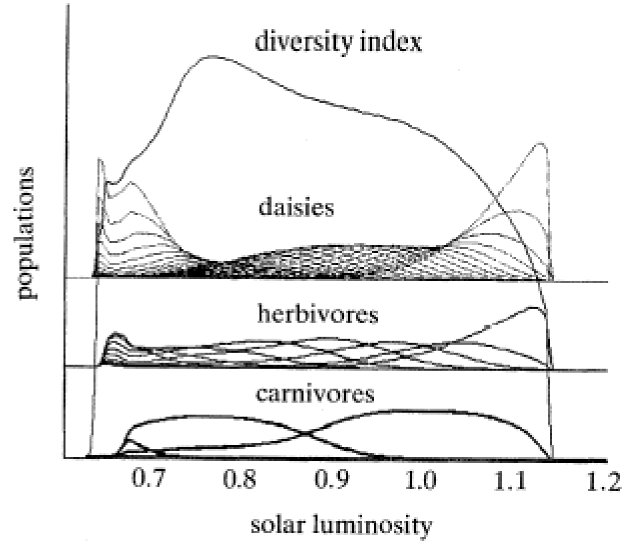



Figure 12. A three trophic level model with 30 daisy types, 10 rabbit types and three fox types. The evolution of the model was followed from birth to death as the star heated up from 0.6 to 1.2 solar luminosities. The populations of each of the three levels have been separated on the diagram in the interests of clarity. Note the peak of the diversity index at the solar luminosity (0.76) where the system is most stable. Temperature regulation, not shown, was very similar to that illustrated in figures 5 and 6.

# Daisyworld: Implications from model

- Temperature regulation achieved by cycles of positive and negative feedback.
- Self regulated systems are capable of recovering from violent, short-lived perturbations.
- Biodiversity is highest when the system is “least stressed”.
- Daisyworld is completely consistent with natural selection: individual traits can have global effects.

# Daisyworld: Observational clues

- Oxygen, trace gases and temperature regulation.
- Biological amplification of rock weathering.
- Dimethyl Sulphide (DMS) and marine phytoplankton.

# Oxygen and Gaia: a closer look.

- Negligible amounts of Oxygen before origin of life in the Hadean era.
- Oxygen mainly a by-product of Oxygenic photosynthesis:

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

- Aerobic respiration is the reverse reaction, liberating energy utilized by organisms for metabolism.
- Anaerobic organisms cannot use free $O_2$ since it is toxic, and respire indirectly.
- Once $O_2$ levels reach a sufficiently high level, Ozone, which is a potent greenhouse gas, is formed in the high stratosphere:

$$CO_2 + h\ f \rightarrow O + O$$

$$O + O_2 + \rightarrow CO_3$$

# Oxygen and Gaia:

- Prior to 2.2 Gyr ago, $pO_2$ was maintained at about 0.0008 atm by a combination of biotic and abiotic factors.
- Around 2.2 –2.0 Gyr ago, Oxygen production began to exceed consumption: reasons unclear, but probably because of oxidation of most of the exposed reduced material.
- The rate of exposure of reduced material from Earth’s interior was falling off, due to reduced impacting, and reduced volcanic activity.
- Oxidation amplified by organic carbon burial.

# Oxygen and Gaia:

- Between 2.0 and 0.8 Gyr ago, $pO_2$ ~ 0.002 – 0.02 atm.
- Somehow, the Oxygen level was maintained at low levels, indicating a negative feedback mechanism, i.e., increased oxygen creation would generate increased removal.
- The “set point” for $pO_2$, according to Gaia theory, was then at a comparatively low level.
- The “set point” is thought to have been continually updated upward, as organisms with improved tolerance to Oxygen had evolved.

# Oxygen and Gaia: Bottom line

- The residence time of Oxygen is only 3.25 Myr.
- It is remarkable that over the past 350 Myr, the level of Oxygen in the atmosphere, $pO_2 \sim 0.21$, has been almost constant.
- In other words, the whole reservoir of Oxygen has been replaced a 100 times, and yet, its size has been maintained.
- The oxidative weathering sink is presently saturated. Thus, Oxygen regulation is now almost entirely biotic.
- Oxygen is maintained at an optimal level by this mechanism, above $pO_2 \sim 0.25$, the toxicity and inflammability of Oxygen, will by severely destructive.

# Summary of Gaia and Daisyworld

- That the onset of life and its consequent resilience has dramatically altered the "spheres" is almost self-evident from the presence of Oxygen, ammonia and methane along with other volatile trace gases.
- Gaia theory takes us a step further by hypothesizing that the environment and life conspire via a hierarchy of feedback mechanisms to maintain conditions conducive to life.
- Philosophically, Gaia can be viewed as a generalization of Darwinian evolution, tying in the evolution of the environment with the evolution of biota, at least weakly coupled (weak Gaia hypothesis) if not as a strongly coupled single entity (strong Gaia).
- At the very least, Gaia theory has fuelled immense amount of cross-disciplinary research and co-ordination amongst geologists, biologists, chemists and archeologists. This in itself, is an worthy achievement.

# Summary: Contd.

- Gaia theory provides us with the possibility of an exciting experiment: to appropriately “seed” Mars (or any other reasonable planet) and let it evolve to a steady state.
- The spirit on the Gaia theory is “good news” for detection of life on other planets. The probability of detection definitely is helped by the stabilizing affect of life on its own survival and sustenance.
- Daisyworld is a simple, yet revealing toy model to illustrate that self-regulation is effective, stabilizing and non-teleological. Moreover, in its complicated avatars it can form the basis for not only self-regulation, but also to explain bio-diversity and other ecological properties.

# Part IV

## Life on other planets.

*Hamlet: There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy….*

# Implications: detection of Life

- terrestrial atmospheres: degassing
- transition to life: ~ 4 billion years ago
- photosynthetic cyanobacteria: ~ 2 by

from photodissociation of $H_2O$

$CO_2 + H^+ \rightarrow \text{organics} + O_2$

photosynthesis

Biological activity

760 nm tracer (but Earth $O_2$-free until -2 Gyr)

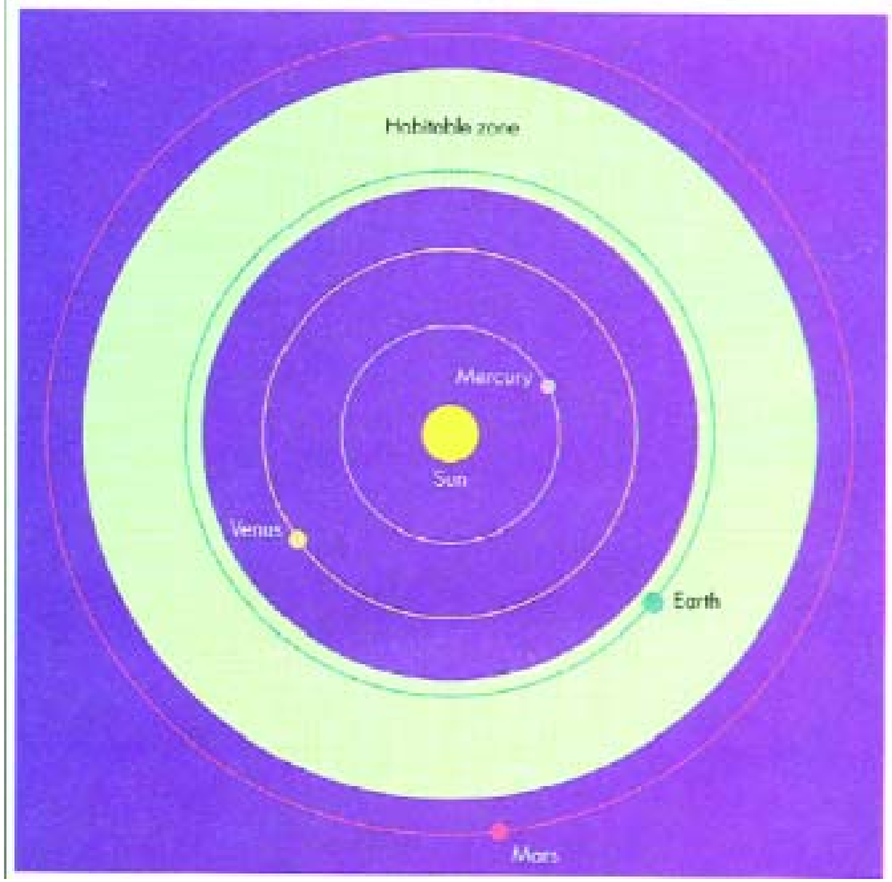
anaerobic decomposition of organics; combines with $O_2$

$O_3$ ($O_2$ tracer): 9.6 μm
$H_2O$: 6-8 μm
$CH_4$: 7.7 μm (or shorter)
$CO_2$: 15 μm

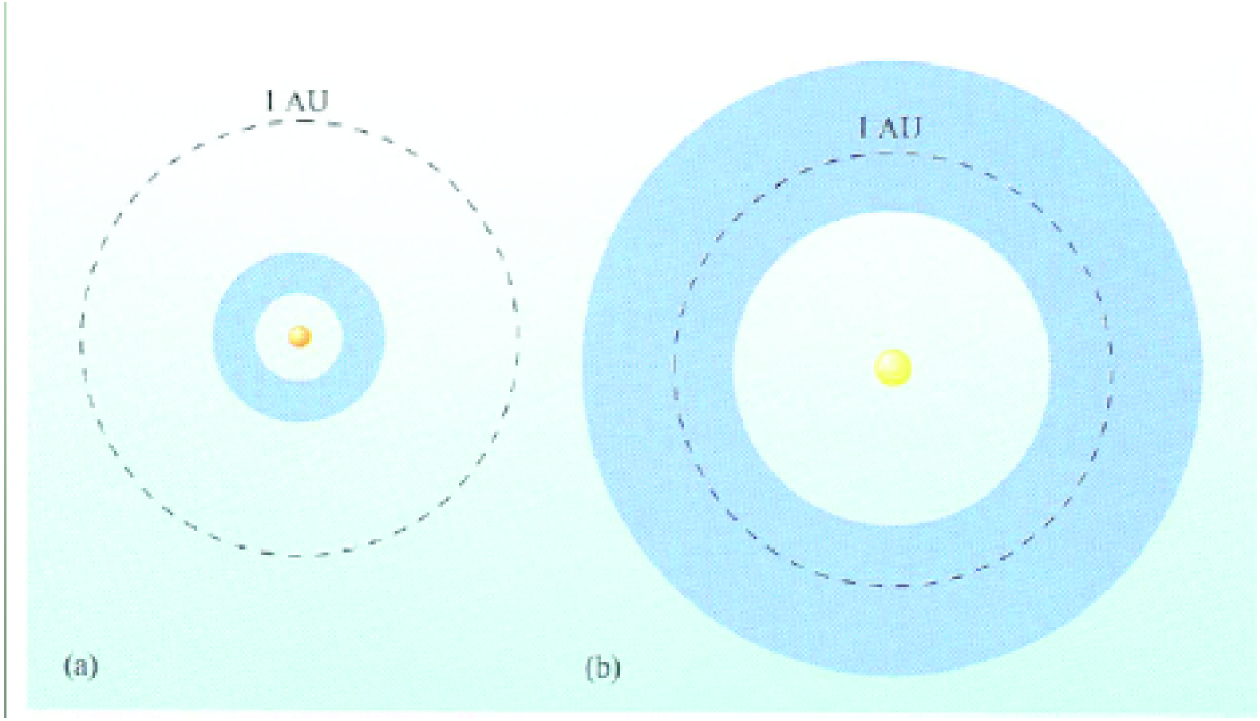
- Absence of $O_2 \neq$ absence of life
- Simultaneous detection of $CH_4 + O_2 \Rightarrow$ life?
- Simultaneous detection of $H_2O + O_3 \Rightarrow$ photosynthesis?
- Detection of vegetation signature?

# Habitable Zones: Liquid water

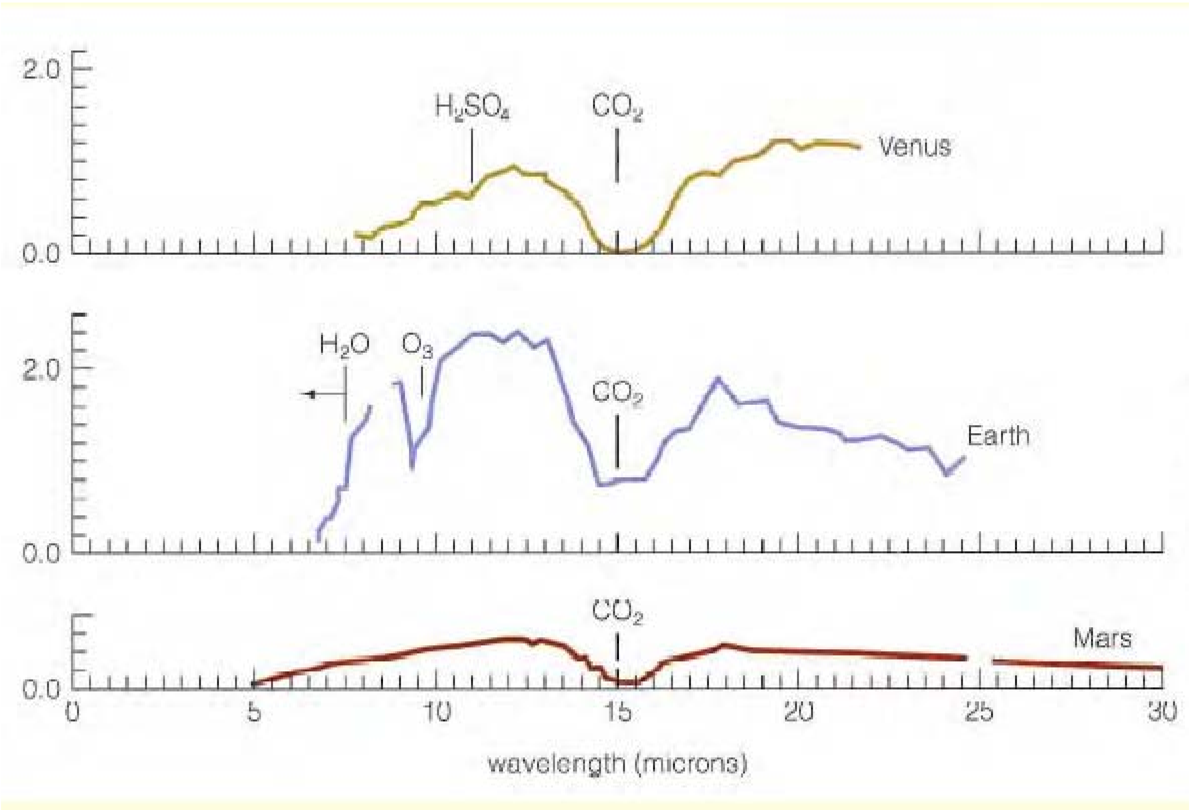
- Naively, based on distance alone, there exist a certain zone around a star at a particular temperature in which water can exist as a liquid, which we deem essential for life.
- From our earlier discussion, it is clear that other factors, like the greenhouse effect, play a role as well.



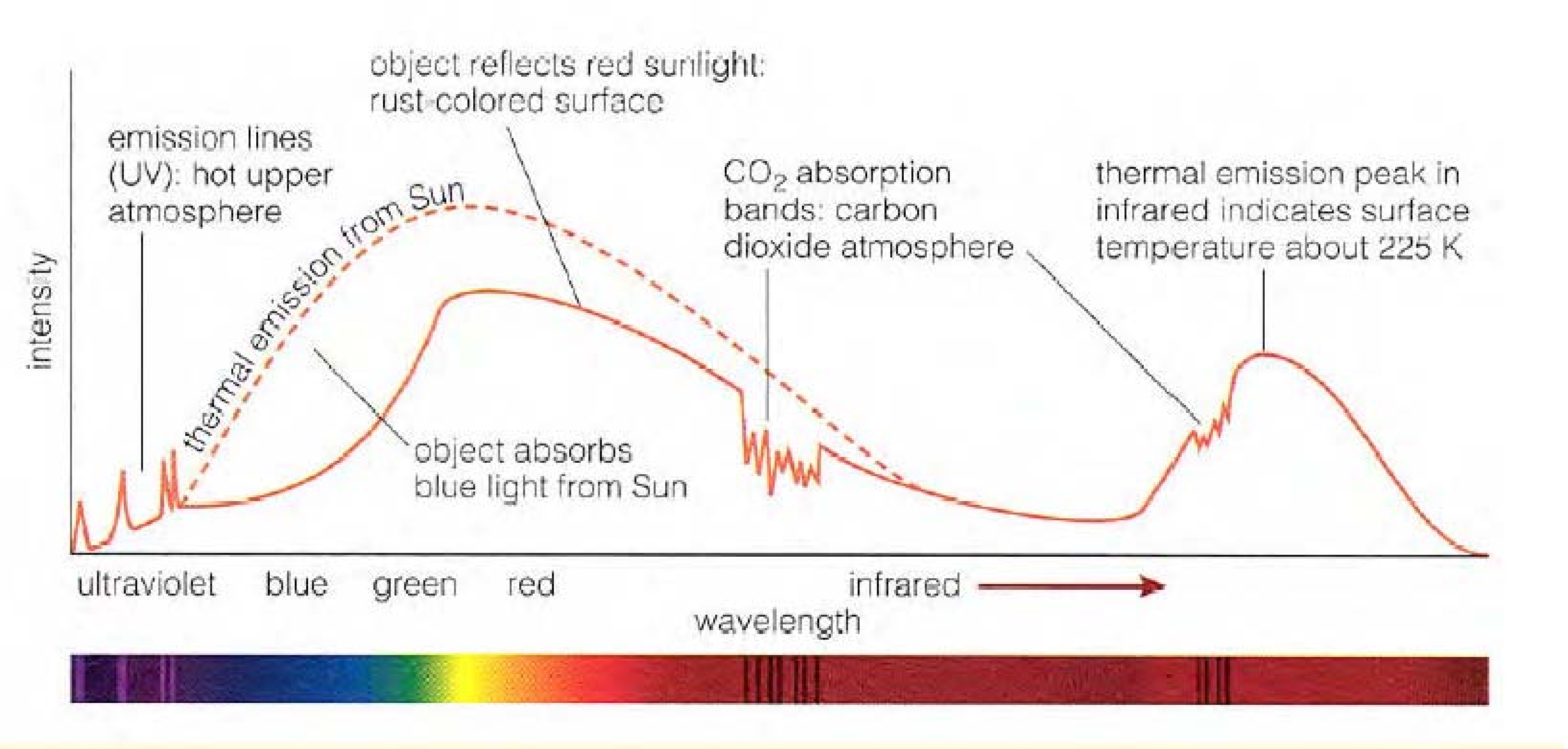
# M-star and G-star comparison.



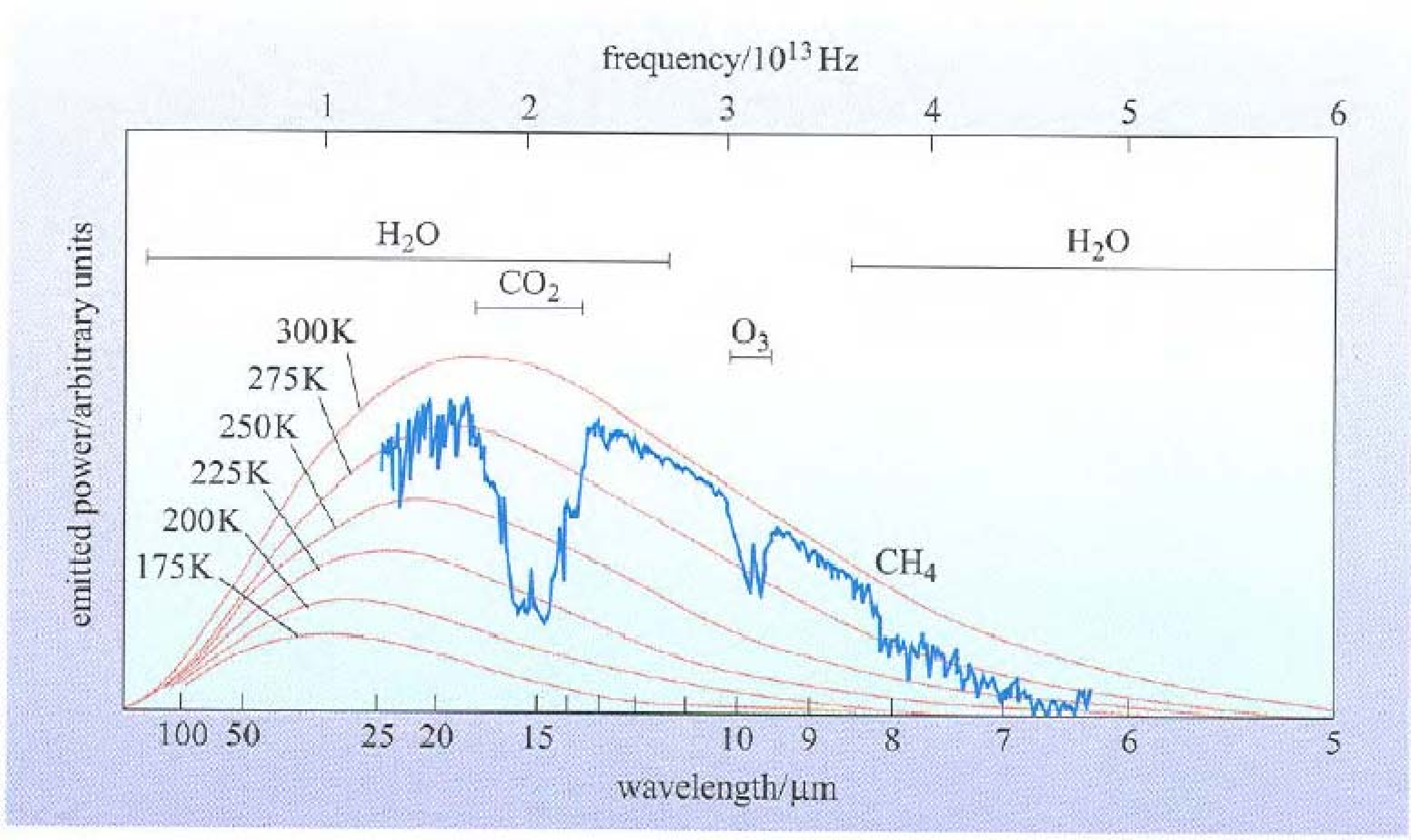
# Spectra: Venus, Mars & Earth



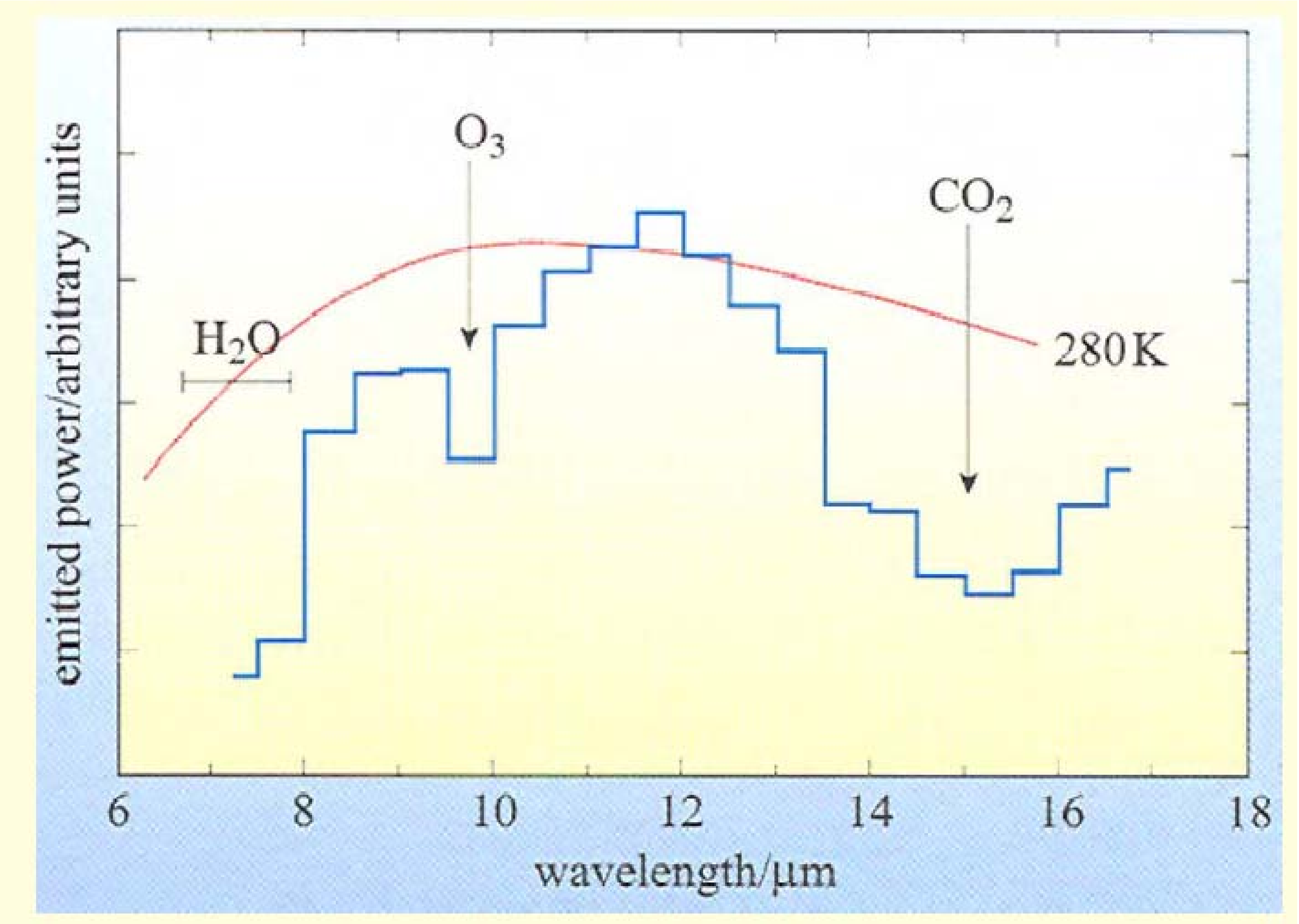
# Star and Planet Spectra



# Earth Spectrum: Detail



# Earth: 10 pc away, TPF 40 hr exposure.



# Part V

## Global Warming.

*JULES: …. And I will strike down upon thee with great vengeance and furious anger those who attempt to poison and destroy my brothers. And you will know my name is the Lord when I lay my vengeance upon you….*

# Earth Feedback

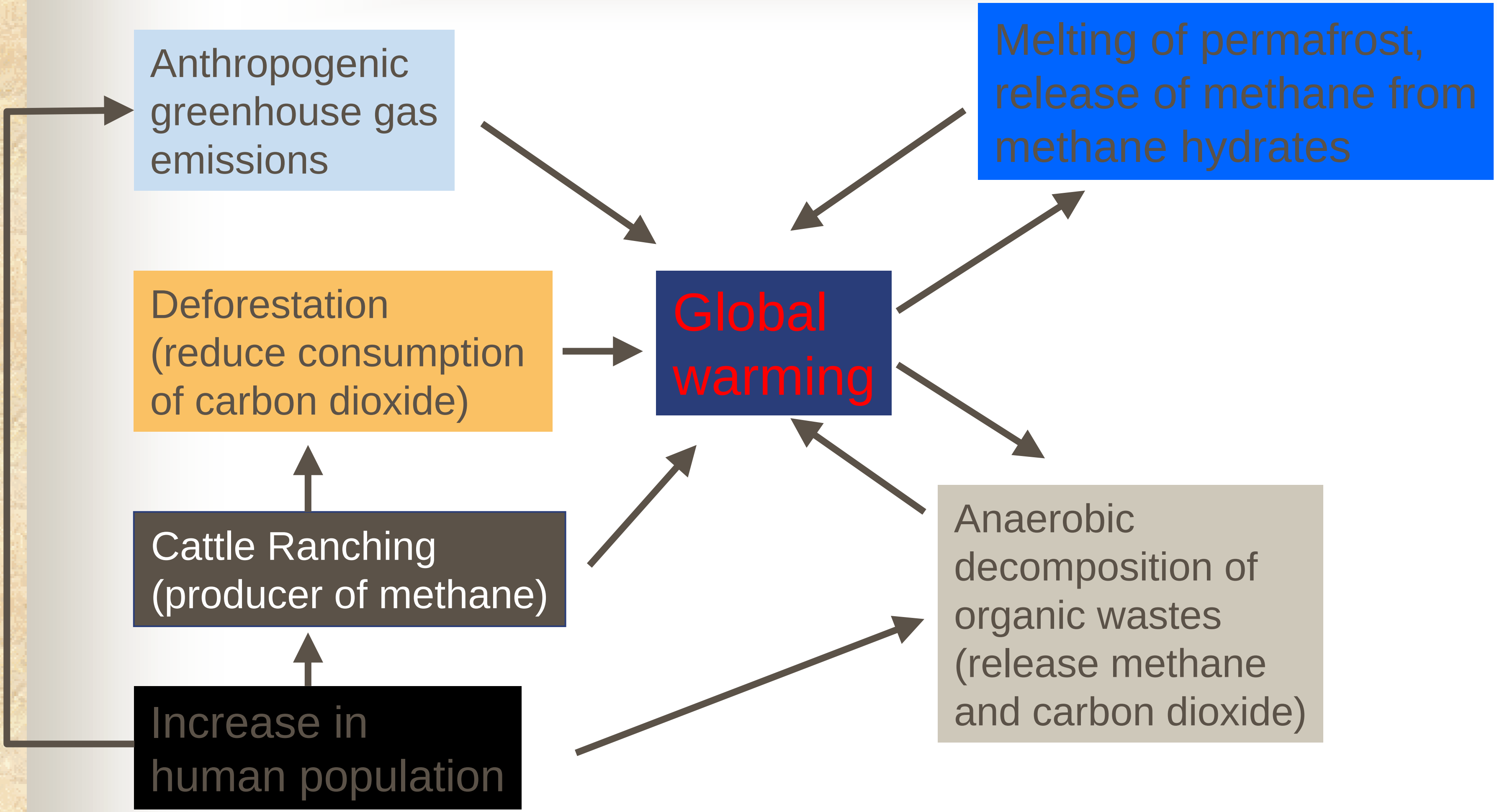
In the act of adjusting to disturbances in the system, small changes can become big changes.

Because Earth is a system, a change in one component may result in the adjustment of other components.

Also, in some cases, small changes in Earth System components (and in features within these components) can result in BIG changes in the system

For example, what are some implications of human population growth ? Human-related global warming might give some insight on this.

# An Example: Global Warming - How bad can it be ?




The complex interaction of Earth processes makes the issue a bit more serious than what it first appears

# Conclusions:

- In the steady state, in optimal conditions or a mild secular perturbation, the biosphere manages to manipulate the environment to match its needs.
- In case of a calamity, either local or global, natural selection decides which specie dominates: only the most (genetically) versatile survive, the less versatile perish in adversity.
- This probably explains why evolution seems to occur in bursts rather than as a continuous process.
- Gaia theory provides us with the possibility of an exciting experiment: to appropriately “seed” Mars (or any other reasonable planet) and let it evolve to a steady state.
- The spirit on the Gaia theory is “good news” for detection of life on other planets. The probability of detection definitely is helped by the stabilizing affect of life on its own survival.