The Gaia Hypothesis & The Biosphere Project

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Ast 281

James Lovelocks: Mars & Gaia

1961 – NASA Viking Mission
- Asked to provide advice on life detection – how to recognize it
- A life-bearing planet will exhibit an atmosphere which is far from chemical equilibrium
  - if there is life, it will be pervasive (there can’t just be a little bit of life)
  - life uses liquids and atmosphere to “communicate” or interact by sharing nutrients, wastes & evolution,
  - Thus the chemistry of the environment is constantly changing.

Prediction:
- Life will not be found on Mars – because atmosphere was in equilibrium

Biosphere I – The Living Earth

<table>
<thead>
<tr>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
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</thead>
<tbody>
<tr>
<td>N₂ &lt; 2%</td>
<td>N₂ ~ 77%</td>
<td>N₂ &lt; 3%</td>
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<tr>
<td>CO₂ ~ 95%</td>
<td>CO₂ ~ 0.3%</td>
<td>CO₂ ~ 95%</td>
</tr>
<tr>
<td>No O₂</td>
<td>O₂ ~ 0%</td>
<td>No O₂</td>
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<tr>
<td>Chemical eqm</td>
<td>Disequilibrium</td>
<td>Chemical eqm</td>
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The Gaia Hypothesis

- Lynn Margulis – (Boston Univ.)
  - microbiologist – eukaryote origins
- James Lovelock – (UK) – independent scientist & inventor

Homeostasis
- The ability of a cell or organism to maintain equilibrium by adjusting physiological processes
- As a theory, homeostasis involves
  - Living organisms exploit environmental opportunities
  - organisms that leave the most offspring survive (Darwinism)
  - organisms affect their physical and chemical environment
  - constraints establish the limits of life

The Gaia hypothesis says: “The temperature, oxidation state, acidity, and certain aspects of the rocks and waters are kept constant, and that this homeostasis is maintained by active feedback processes operated automatically and unconsciously by the biota.”

Gaian Perspective & Implications

- “Complex, stable … and evolving biospheres will be a necessity if life is to inhabit other parts of space permanently”
- “Only with full scientific exploration of Gaian control mechanisms can we expect to implement self-supporting living habitats in space” – Lynn Margulis & Dorian Sagan
- “We tend to think of this planet as life-infested rock, which is as absurd as thinking of the body as a cell-infested skeleton” – Alan Watts
Environmental Feedback Systems

- The Earth is alive
  - Gaia = Earth Goddess, the name of this "entity"
- The evolution of species and environment are coupled
  - Life alters environment by using mobile media to carry waste & nutrients, chemistry moves away from equilibrium.
  - The atmosphere, oceans, climate, and crust are regulated in a state comfortable for life because of the behavior of organisms
  - Long periods of stability are punctuated by abrupt and sudden change (J. E. Gould)
- Geophysiology – all ecosystems are related
  - There is a homeostasis, or "wisdom of the body" involved, meaning that the system is self-regulating: many important properties of the Earth are maintained essentially constant by the presence of life.
  - Does not require conscious control . . .

Daisy World

- Simple Illustrative Feedback Model
  - Some characteristics represent the real Earth
- Parameters
  - Earth-sized Planet orbits solar type star at 1 AU
  - Slowly increasing luminosity (as we saw for our early solar system)
  - 2 life forms:
    - Low albedo daisy (black)
    - High albedo daisy (white)
  - Can only survive 5-40°C
  - Grow best at 20°C
  - No cloud cover during day
  - Rains only at night
  - Starting conditions
    - Even mix light & dark daisy seeds
    - T = 5°C
    - Only warm enough for life at equator

Simple Daisy World Model

- Numerical model results
  - Life stabilizes surface T
- Daisies thrive best at 20°C
  - Both populations present at 20°C
  - Greatest population diversity occurs at optimum temperature
  - Low albedo daisies best at low T
  - Warm the atmosphere
  - High albedo daisies best at high T
  - Cool the atmosphere

Complex Daisy World

- Add a 3rd species
  - Grey daisies – cannot alter T
  - Energy tax on pigmented daisies
- Results
  - Grey do best when no T control is needed
  - Different species grow when environment is best suited to them
- 20 Daisy Model
  - Diversity greatest when least stress
  - Under stress, darkest or lightest (not grey) have advantage, fewer species

Lotka and Volterra Model

- New Constraints
  - Daisies grazed by rabbits
  - Rabbits eaten by foxes
  - Catastrophically destroy the daisy population by 30% (4x)
- Results
  - When the system is healthy → little effect on ability of the system to regulate the environment!
- New Constraints
  - 10 species
  - Recurrent destruction (effects all colors) - kills 10% of daisies
- Results
  - Fluctuations in T most dramatic when # of species the least, farthest from ideal T

Lessons from the Models

- In a many species system, it is relatively immune to perturbations unless near the beginning or the end of the stability zone.
- You cannot have a planet with partial life – it wouldn’t survive any catastrophe.
- Need to have at least 20% cover before planet is self-regulating.
- From the point of view of Solar System exploration, won’t have to look hard to find life on a planet – if you do, it isn’t there.
For Discussion: Does this mean that we don’t need to worry about pollution, Earth will take care of itself and come to equilibrium?

**The Archean World**
- The atmosphere
  - Reddish orange chemical haze
  - Blue sky is evidence of the presence of oxygen
- Ocean waves in a shallow sea reveal
  - Stromatolites (CaCO₃ - calcium carbonate deposits from cyanogens)
  - Inland pools contain blackish mats of bacteria
- Sounds
  - Wind
  - Slow bursting of CH₄ bubbles from these ponds
- Punctuated by large planetary impacts

**Self Regulating Systems:**

**Archaean Earth**
- Methanogens - scavengers
  - Feed on organics
  - Produce CO₂ and CH₄ → strong greenhouse gases
- Cyanobacteria - photosynthesizers
  - Convert solar energy → produce O₂ from CO₂
  - In a reducing atmosphere
  - O₂ exists only in small pockets near source
  - Otherwise rapidly combines with other chemicals

**Maintaining the Greenhouse**
- Cyanogens use CO₂
  - Use all atm CO₂ in ~10⁶ yr
  - Why didn’t oceans freeze?
    - 3.5-6 Gyr sedimentary rocks (Greenland, Australia) → Earth was never entirely frozen
  - Methanogens returned CH₄ to atm
  - CH₄ unstable, reactive in sunlight
  - Creates photochemical smog
  - Greenhouse & UV absorbers
  - A self-regulating system
    - Photosynthetic life → keep cool with CO₂ use (white daisies)
    - Decomposers → keep warm with greenhouse gas (dark daisies)

**Use of CO₂ by cyanogens**
- Eating the greenhouse blanket
- Should continuously build up O₂ level
- Eventually aerobic organisms evolve
- Rapid transition to an oxidizing atmosphere

**Major glaciation 2.3Gy ago**
- CH₄ disappears → cooler temps
- Largest pollutant Earth has known
- Life survived
- But it was different life

**Snowball Earth – 600-800 Myr**
- Namibia – no Fossils 10 Myr

**Summary of Gaia**
- Developed (1961) for the Viking mission – how to search for life
- Lovelock’s Gaia hypothesis:
  - “The temperature, oxidation state, acidity and certain aspects of the rocks and waters are kept constant and that this homeostasis is maintained by active feedback processes operated automatically and unconsciously by the biosphere”
- Life alters the world to be suitable for life
  - This represents a complex, interconnected feedback system
  - Life, if present, will be abundant or it cannot survive catastrophe
- Daisy World: a simple mathematical model to explain feedback
  - Applied this to Early Earth environment, and punctuated changes in life
  - Applied to a future view of Earth (Ward and Brownlee)
- Relevance to artificial 100% self contained biospheres
  - Such as what will be needed for long-term survival in space.
Misinterpretations & Uses of Gaia

- 1970’s & 1980’s criticism
  - Homeostasis impossible without communication
  - Implication of conscious control
- Gaia = Earth Goddess
  - Gaia is not a living entity in the conscious sense, rather a complete balanced system
  - Some interpreted Gaia as a religion
- Applications to artificial ecosystems
  - Lessons from development of biospheres

Biosphere History

- Understanding planetary systems
  - Environments
  - Colonies
  - Terraforming
- Early Biospheres
  - V. Vernadsky – 1926
    - Soil properties can't be understood without taking into account life's influence
    - Mineral diversity due to life
    - Life on Earth: a global chemical reaction
  - McHarg’s Cubicle – 1960
    - Man, air, H\textsubscript{2}O, bacteria algae, sunlight
    - Man: uses O\textsubscript{2}, exhales CO\textsubscript{2}
    - Algae expel O\textsubscript{2} & use CO\textsubscript{2}
    - Man drinks H\textsubscript{2}O, "pees"
    - Bacteria, algae break down urine
    - Man eats algae, "excretes"
    - Algae / bacteria grow on waste
    - Import: light, export: heat

Biosphere 3 Project

- Test effects of space on cosmonauts
  - J. Gitelson; Built 1965-1972; Krasnoyarsk, Russia
  - Clandestine closed ecosystem experiment
- 315 cu meter habitat for 3 people
  - 4 habitat areas: crew, 3 food areas
  - Algae (Chlorella) cultivator for air recycling
  - Water recycling
  - 80% of diet from closed system
  - Meat brought in, waste stored (not recycled)
- Experiments
  - First experiments 1968
  - Ten manned experiments conducted
  - Longest experiments in 1972-1973 – 180 days
- Gave valuable input to Biosphere 2

Space Biospheres Ventures

- Goals
  - To build a completely closed recycling ecological system
  - Serve as a test model for closed colonies in space
  - Model for scientific study of Earth feedback systems
  - Designed to last 100 years
- Specific Science Goals for Earth systems
  - How to maintain food production without harmful chemical fertilizers and pesticides
  - How to restore endangered ecosystems
  - How to recycle all air, water and waste
- Cost - $200M from 1984-2007
  - Largest completely closed ecological system ever built

Space Biospheres Ventures

- 1984 Project Began
- 1986 Construction Began
- 1990 Component testing
- 1991 Sep 26 – Completed; sealed for 2 yrs
  - Fall 1991 – fierce El Nino -> cloud cover excess
  - 592 – Major O\textsubscript{2} decline – 0.3% / month
  - 1/13/93 – O\textsubscript{2} added to bring to 19% (from 14%)
- 1994 Operations differences – joint venture dissolved
- 1994 Aug – Begin short-term research
- 1996 Turned over to University of Arizona: 5 yr
  - Ecosystems study
- 2000 10 year lease for Columbia Univ.
- 2003 Columbia pulls out (expense)
- 2007 Operated by the University of Arizona
Biosphere II

The Laboratory
- Volume: 203,760 m³
- Size: 3.15 acres
- Space frame: 32.2 km
- Panels: 6,600 panels of 3/4 inch glass
- Species: 4,000 imported – scientists believe there are more now
- Energy: sunlight & electricity (generators)
- Sensors: Global monitoring via 1,000 sensors scanned every 15 min
- Operations: monitor 4000 sensor inputs / hr
- Biomes: 5

Biosphere II Biomes
- Rainforest
  - Size: 44 x 44 x 28 m
  - Hollow 50 ft mountain (tools, technology)
- Ocean
  - Size: 6500 m³ / 18000 m³
  - Oxygen & food
- Marsh
  - Water recycling
- Savannah
  - Species at high and low T
- Desert
  - Size: 1400 m² / 18000 m³
  - Oxygen production in winter
- Agro-Forestry
  - Size: 2000 m³ / 35222 m³
  - Food production
  - Lungs
  - Pressure maintenance
  - Habitat & Laboratories

Rain Forest
- Size: 44 x 44 x 28 m
- Hollow 50 ft mountain (tools, technology)
- Atmospheric gases
  - Primary O₂ production
  - Removal of CO₂
- Climate
  - Temperature: 90-105°F (32-41°C)
  - Humidity → fogger machine
- Experiments
  - Water cycles

Savannah Biome
- Grassland
  - Variety of plants growing in different seasons
  - Stream
- Purpose
  - Ecosystem boundary between wet and desert regions
**Ocean Biome**
- 45 x 48 x 15 m
- Largest man-made ocean
  - 1 million gallons
  - 7.6 m deep
  - Temp: 24-26°C
  - Wave generation
  - 5% of land area
- Ocean Species
  - 30 species Blue green algae
  - Coral reefs
  - 25 species, Fish, turtles
  - 100 species invertabrates

**Marsh Biome**
- 28 x 19 m
- Wetland – marine estuary
  - Represent 32 km of Everglades
  - Fresh → salt water
- Purpose
  - Filter between biomes
  - Water recycling
- Research
  - Wetland – marine estuary
  - Comparison with Everglades
- Technology
  - Environmental adjustments
  - Daily rainfall
  - Water desalination

**Desert Biome**
- 37 x 37 x 23 m
- Seasonal Heavy growth
  - O₂ production in cooler months
- Research
  - Studies of CO₂ uptake and O₂ production
  - Competition with species from neighbor biomes
  - Desertification process & loss of diversity

**Agriculture**
- 41 x 54 x 24 m
- Purpose
  - Food production
  - Fed 8 people with 1 acre
  - Usually requires 4-8 acres / person
- Research
  - Soil management
  - Fertilization & Pest control
  - High yield crops
  - Species diversity
    - 72,000 species edible, man uses 7 for 75% of food

**Habitat**
- 22 x 74 x 23 m
- Laboratory with equipment that did not emit toxic gases
- Computer command room
- Medical facility
- 2 Kitchens Food Preparation
  - one for refining raw materials, 1 for cooking
- 10 apartments & 5 bathrooms
- Communal dining area
- Meeting space
- Laundry facilities
  - Electric washers, biodegradable soap
- Library and Observatory
Living Facilities

Biosphere II Lungs
- 48 x 48 x 15 ft
- Purpose
  - Air Exchange
  - 51,137 m³ air
  - As air heats, it expands \( \rightarrow \) needs some place to go as \( T \) increases

Biosphere 2 Behind the Scenes
- Continuous trace gas monitoring systems
- Temperature, chemical, water cycle loggers

Water Cycles
- Computers control the water system & simulate seasonal changes
- Sunlight driven evaporation
- Air pressure too low for clouds
  - condensation onto glass
- Water funneled to a sprinkler system to simulate rain
- UV + hydrogen peroxide treatment \( \rightarrow \) drinking water
- Marshes were used also to treat water
  - water hyacinth and canna can be used to take pollutants out of water.
- Problems
  - Condensation was so great that there was a lot of dripping over the desert, so the desert became too lush.
### Carbon Cycles
- **Rainforests**
  - Primary sink of CO₂
  - Earth rainforests T: 86°F (biosphere 90-105°F)
- **Coral reefs**
  - Secondary sink of CO₂
  - CaCO₃ saturation inversely related to atm CO₂ concentration
  - If high, hard to precipitate CaCO₃
  - Ca(OH)₂ + CO₂ → CaCO₃ + H₂O
  - CaO + H₂O → Ca(OH)₂
  - CaCO₃ + CO₂ + H₂O → CaCO₃ + HCO₃⁻ + H₂O
  - CO₃²⁻ + H₂CO₃ ↔ HCO₃⁻ + CO₂
  - CaCO₃ bicarbonate
  - CO₂ carbonate
  - H₂CO₃ carbonic acid
- Coral algae use HCO₃⁻ and CO₂ in photosynthesis

### Energy Cycles
- **Heat management**
  - Outside T reaches 120°F
  - Without cooling → 150°F inside
  - 4 cooling towers
  - Water cooled electrically
  - Passed through pipes to cool air
  - Pumps circulate air
  - Works like “swamp coolers” – not great in high humidity

### Energy Cycles
- **UV problem**
  - Glass didn’t transmit UV shorter than ~ 0.4 microns
  - Bees use UV to navigate ~ near 0.35-0.4 microns
  - Crew had to hand pollinate the food

### Biosphere 2: Failure or Success?
- Many problems
  - Low oxygen
  - Overgrowth in desert
  - High pH in ocean
  - Over-run of ants
  - Not as high crop production
  - Psychological problems . . .

### Success or Failure?
- "New Age drivel masquerading as science . . .
- "The most exciting scientific project to be undertaken in the U.S. since President J. F. Kennedy launched us toward the moon"
- "Not enough science on confined environment psychology"
- "As with all experiments, whether considered successes or failures, the results have proved informative; in the case of Biosphere 2, the experimenters learned that small, closed ecosystems are complex and vulnerable to unplanned events. This lesson will almost certainly be applicable in the more hazardous environment of space."

### Other Biosphere Efforts
- **Mars 500**
  - Psycho-social isolation experiment 2007-2011
  - Russia, ESA, China
  - For Mars space missions
- **Eden Project**
  - Open in 2001
  - Located in Cornwall, UK
  - Public facility, environmental education
Tying this back to Life and Death of Planet Earth

Recall how we opened the semester . . .

Plate Tectonics & Habitability

- Mechanism for plate mobility
  - Heat gradients in Earth → convection
- Effects of tectonics
  - Cycling of organic & inorganic carbon
  - Cycling of greenhouse gases
- Effects of a new supercontinent
  - Climate change – humid, hot everywhere
  - Oceans unmixed – less life, mass eruptions of toxic gas
  - Interior of continent large T extremes
  - Mass extinction

Solar Luminosity

- Increasing T of sun → increase in weathering, remove CO₂
  - Too little CO₂ plants die
  - Diversity is already decreasing
- 150 ppm most plants die (some grasses survive until 10 ppm)
  - 500-700 My Earth turns brown
- Change in weathering → increase in CO₂ and greenhouse
- O₂ levels plummet
- Loss of animals → age of bacteria
- Sun continues to warm
- 1 Billion years in future mean global T ~ 70°C (160°F) → extremophiles

Future: Few x 10⁸ years

- Continents reddish brown-atm thick with dust
- Greyish yellow sky
- No visible life outside ocean edges
- No more mammals
- Humidity 90%, oxygen thin
- Oceans are evaporating

Far Future – 4-7 Billion years
References