Gaia Hypothesis & The Biosphere Project

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Ast 281

Biosphere I – The Living Earth

- Biomass
  - 2.5 trillion tons
  - 99% plants, 1% animal
  - 10% annual renewal
  - Oceans produce 1/3 of biomass
- Volume
  - <1% of geophysical volume
  - Habitats: ~38,000 to ~29,000 ft
  - Oceans cover 78%, average depth 3.5 km
- Energy used – 0.5-3 W m⁻²
  - 1360 W m⁻² from sun
  - Surface area of Earth = 4πr² = 5.1x10¹⁴ m²
  - Average incoming energy is 1.7x10¹⁷ W
  - Average world power use is 15 terawatts / yr
    - 1 terawatt = 10¹² W
    - 80-90% is fossil fuels

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 environment
    - organisms that leave the most off-spring survive (Darwinism)
    - organisms affect their physical and chemical environment
    - constraints establish the limits of life

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.
  - Life uses nutrients to maintain physical environment
  - The atmosphere, oceans, climate and crust are regulated in a state comfortable for life
  - 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
- Rain 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

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 50% (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 drastic 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.

The Archean World

The atmosphere
- Reddish orange chemical haze (blue sky that we have now is evidence of the presence of substantial oxygen)

Ocean waves in a shallow sea reveal
- Stromatolites (silt + CaCO₃ – calcium carbonate deposits from cyanogens)
- Inland pools: blackish mats of bacteria

Sounds
- Wind
- Slow bursting of CH₄ bubbles from 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 E → produce O₂ from CO₂
  - In a reducing atmosphere
  - Little O₂ exists — only near sources
  - Rapidly combines with other chemicals

**Maintaining the Greenhouse**
- Cyanogens could use CO₂ in ~10⁵ yr
- Why didn’t oceans freeze?
  - 3.5-4.0 Gya 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 by making greenhouse gases (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 2.3 Gy & 850 Myr ago
  - CH₄ disappears → cooler temps
- Largest pollutant Earth has known
  - Life survived
  - But it was different life

**Snowball Earth –850-635Myr– The Cryogenian**

- Major glaciation
  - Global cooling accelerates with more ice cover (high albedo)
  - Life dies → CO₂ decreases
  - World gets colder → more glaciers
- Escape from glaciation
  - Volcanoes re-supply CO₂
  - No plants to use CO₂
  - Greenhouse effect increases → ice melts
  - Hardy survivors
    - Triggers rise of complex life forms
    - Cambrian Explosion of life

**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 biota”
- Life alters the world to be suitable for life
  - This represents a complex, interconnected feedback system
- Daisy World: a simple mathematical models to explain feedback
  - Applied this to Early earth environment, and punctuated changes in life
  - Applied to a future view of Earth (Ward and Brownlee)
- Highly relevant to artificial 100% self contained biospheres
  - This is 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, H₂O, bacteria algae, sunlight
    - Man: uses O₂ exhales CO₂
    - Algae expel O₂ & use CO₂
    - Man drinks H₂O → pees
    - Bacteria: algae break down urine
    - Man eats algae → excretes
    - Algae / bacteria grow on waste
    - Import: light, export: heat.
**Bios 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 – El Nino → cloud cover excess
  - 5/92 – Major O₂ decline → 0.3% / month
  - 1/13/93 – Added O₂ to bring to 19% (from 14%)
- 1994 Operations differences – joint venture dissolved
- 1994 Aug – Begin short-term research
- 1996 Turned over to Columbia Univ: 5 yr
  - Ecosystems study
- 2000 10 year lease for Columbia Univ.
- 2003 Columbia pulls out (expense)
- 2007 Operated by the University of AZ

**Biosphere II**

- **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

**The Laboratory**

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**Biosphere II Biomes**

- **Rainforest** [2070 m² / 35222 m³]
  - Oxygen production in summer
  - Food
- **Ocean** [2500 m² / 41500 m³]
  - Oxygen & food
- **Marsh**
  - Water recycling
- **Savanna**
  - Species at high and low T
- **Desert** [1400 m² / 18000 m³]
  - Oxygen production in winter
- **Agro-Forestry** [2000 m² / 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 → fog machine
- **Experiments**
  - Water cycles

**Savannah Biome**

- **Grassland**
  - Variety of plants growing in different seasons
- **Stream**
  - 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 invertebrates

**Ocean Monitors**
**Marsh Biome**
- **Purpose**: Filter between biomes, Water recycling
- **Research**: Wetland – marine estuary, Comparison with Everglades
- **Technology**: Environmental adjustments, Daily rainfall, Water desalination

**Desert Biome**
- **Dimensions**: 37 x 37 x 23 m
- **Features**: 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**
- **Dimensions**: 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**
- **Dimensions**: 22 x 74 x 23 m
- **Features**: 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
- **Resources**: 10 apartments & 5 bathrooms, Communal dining area, Meeting space, Laundry facilities: electric washers, biodegradable soap, Library and Observatory

**Living Facilities**
- **Dimensions**: 22 x 74 x 23 m
- **Features**: 10 apartments & 5 bathrooms, Communal dining area, Meeting space, Laundry facilities: electric washers, biodegradable soap, Library and Observatory
Biosphere II Lungs

- **48 x 48 x 15 ft**
- **Purpose**
  - Air Exchange
  - 51,137 m³ air
  - As air heats, it expands → needs some place to go as T increases

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 → 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 CO₂ sink)
  - Earth rainforests T: 86°F (biosphere 90-105°F)
- Coral reefs (secondary CO₂ sink)
  - CaCO₃ saturation inversely related to atm CO₂ concentration
  - High atm CO₂ dissolves in ocean (makes it acidic)
  - Coral grows best around pH 8.2-8.4
  - Coral algae use HCO₃⁻ and Ca²⁺ to build the skeleton:
    - Ca(OH)₂ + CO₂ → CaCO₃ + H₂O
    - CaO + H₂O → Ca(OH)₂
    - CaCO₃ + CO₂ + H₂O ↔ CaHCO₃²⁻ + 2HCO₃⁻

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 . . .

Life & Death of Planet Earth

- Habitability of Earth is short over its 12 Gy life for plants & animals
  - Have we reached max capacity for people?
- Earth history: episodes of stressed environments reaching new equilibria
  - Chemical stresses
  - Environmental T
  - Earth today is atypically warm
    - Current interglacial period: width allowed rise of civilization
    - Normal state is cold glacial
    - Now have <5% of CO₂ as when first appeared (weathering)

P. Ward & D. Brownlee 2002
Plate Tectonics & Habitability

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

Solar Luminosity

- Increasing T of sun \(\rightarrow\) increase in weathering, remove CO\(_2\)
  - Too little CO\(_2\) 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 \(\rightarrow\) increase in CO\(_2\) and greenhouse
  - O\(_2\) levels plummet
  - Loss of animals \(\rightarrow\) age of bacteria
- Sun continues to warm
  - 1 Billion years in future mean global T \(\sim\) 70C (160F) \(\rightarrow\) extremophiles

Future: Few x 10\(^8\) 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