IDEASWORTHPOLLINATING

Space
Earth
Life

A Rapid, Low-Cost Approach to Permanently Extend Life Beyond Earth

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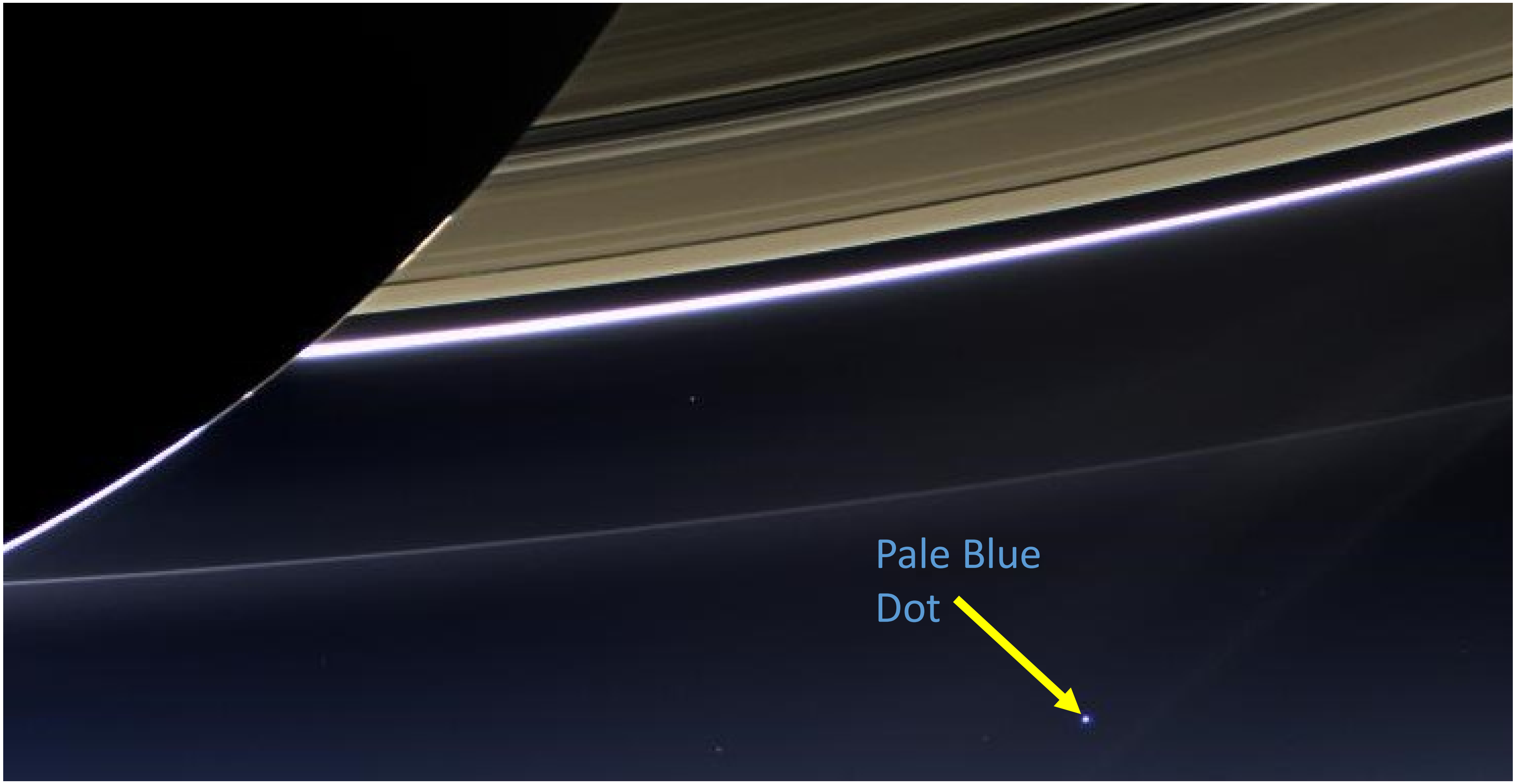
Outline

- The value proposition for permanently extending life beyond Earth
- Closed ecosystems
- An approach to study sustainable, closed ecosystems
- The problem of long-term life in space
- A mission design concept to study long-term life in space
- Next steps

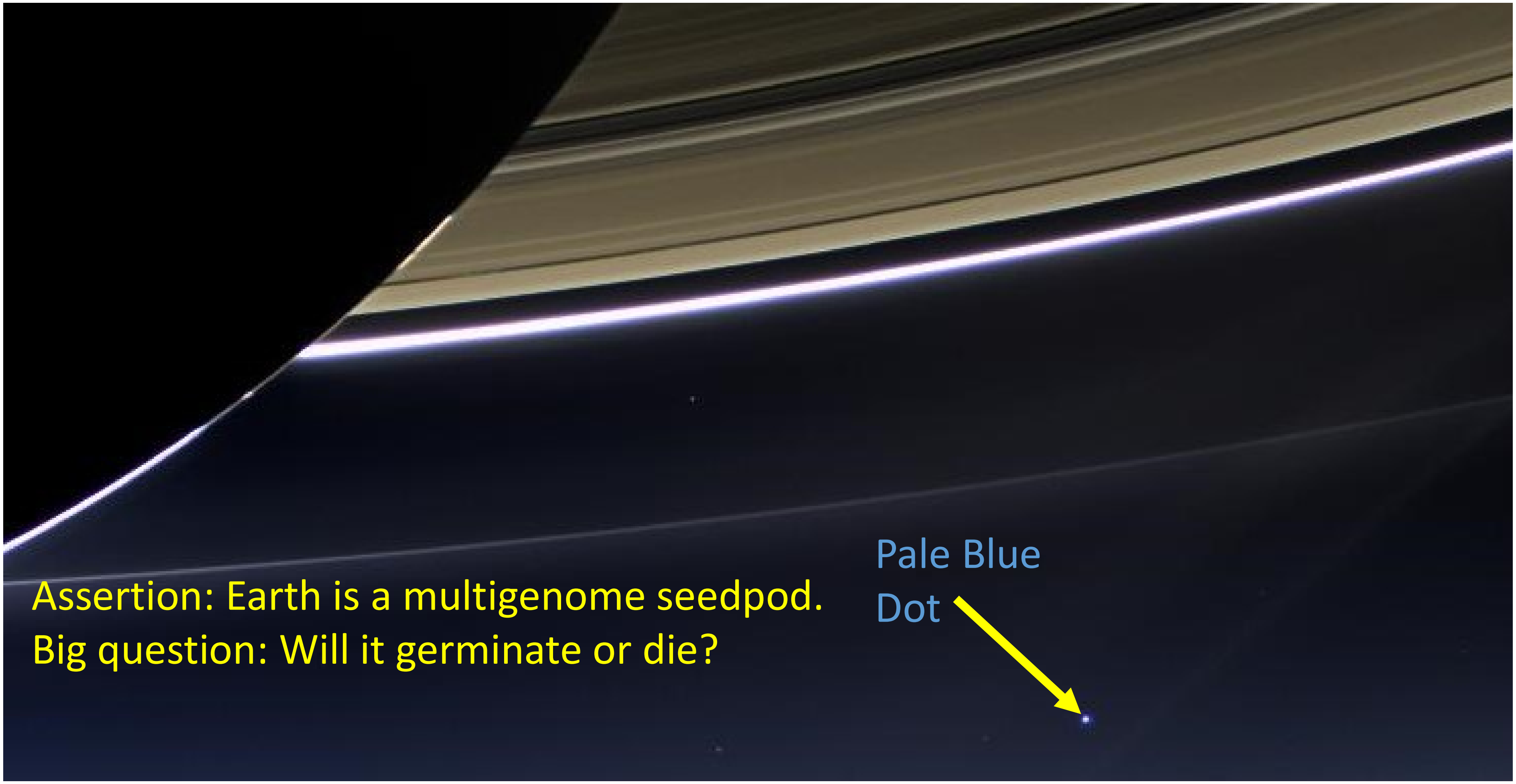
Notable Cassini Image 7/19/2013

Cassini Spacecraft: Launched 1997, Saturn orbit insertion 2004, and impacted Saturn 2017.

Location of All Known Life in the Universe



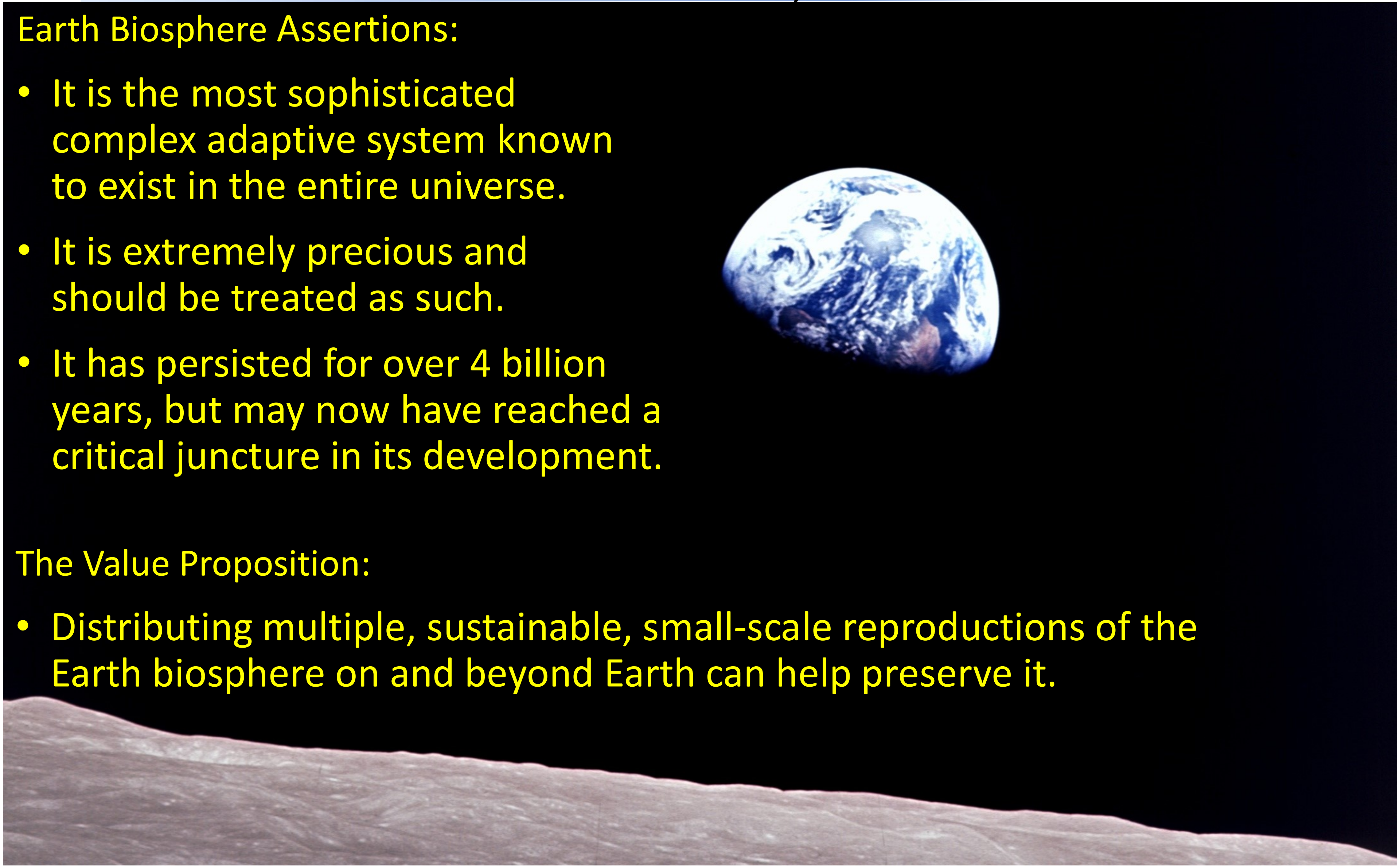
Location of All Known Life in the Universe



Assertion: Earth is a multigenome seedpod.
Big question: Will it germinate or die?

Fundamental questions of space biology:
- What happens to life from Earth, beyond Earth?
- Can a self-sufficient biome persist beyond Earth?

Apollo 8: Earthrise
December 24, 1968



Earth Biosphere Assertions:

- It is the most sophisticated complex adaptive system known to exist in the entire universe.
- It is extremely precious and should be treated as such.
- It has persisted for over 4 billion years, but may now have reached a critical juncture in its development.

The Value Proposition:

- Distributing multiple, sustainable, small-scale reproductions of the Earth biosphere on and beyond Earth can help preserve it.

This image is credited with stimulating environmental movements world-wide.

Wheel of Misfortune

Really bad things have happened on Earth and can happen with little notice (at least 5 mass extinction events).

Earth’s next mass extinction event will be caused by ? (place your bets):

Does it really make any sense for Earth life to literally keep all its eggs in one basket if there is an alternative?

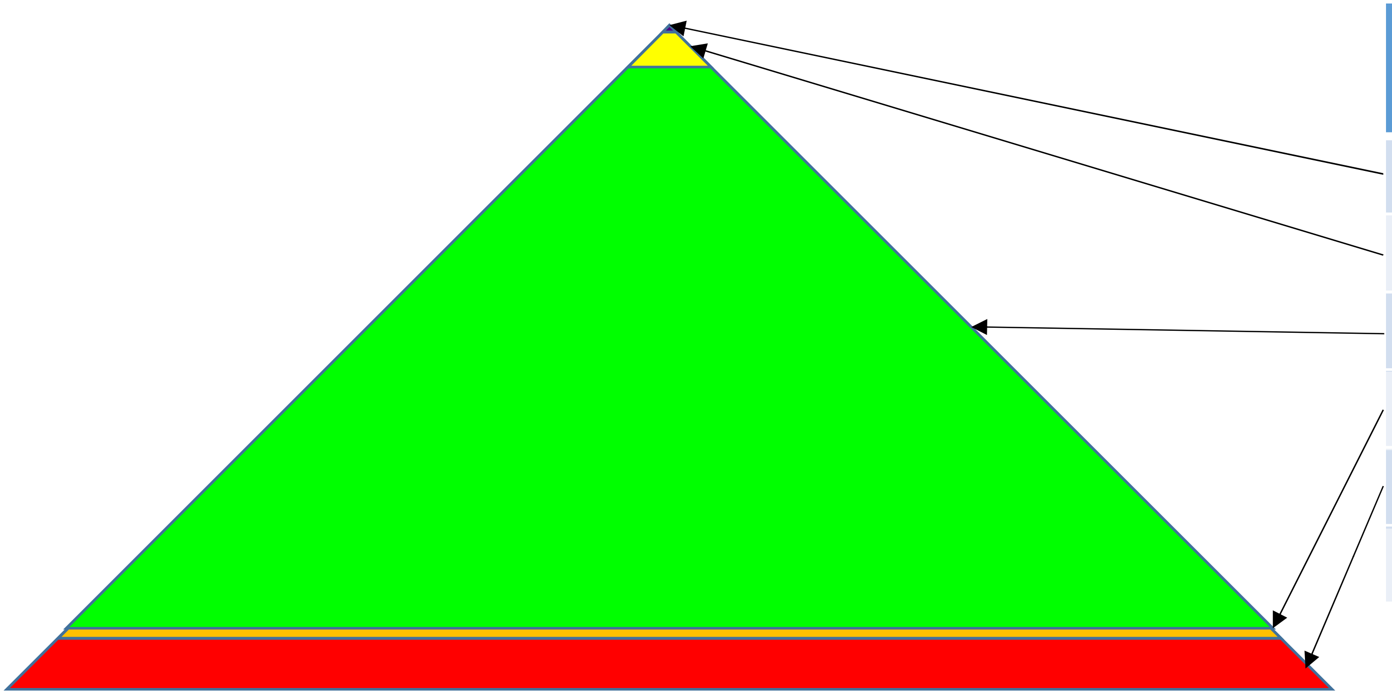
Stephen Hawking and many other highly-educated people are passing away questioning if humanity is on the verge of extinction.

- Mystery Disaster
- Nuclear War
- Bioengineered Disaster
- Pandemic
- Super Volcano
- Asteroid Impact
- Coronal Mass Ejection
- Neighborhood Nova
- Radical Climate Change
- Rise of the Machine

Earth Life Limits

- Total biomass on Earth may have peaked during the Carboniferous period over 300 million years ago.
- There is a growing consensus that the Earth would be better off with fewer people that live more frugal lives.
- Understanding how to optimize closed ecosystems can benefit all life (Earth is a nearly-closed ecosystem).
- The nomadic drive in humans is strong and has spread humanity across the Earth, but most astronauts have not lived in space for more than a few months (human record: 438 days set in 1995).

Current Total Biomass Carbon Estimate by Type



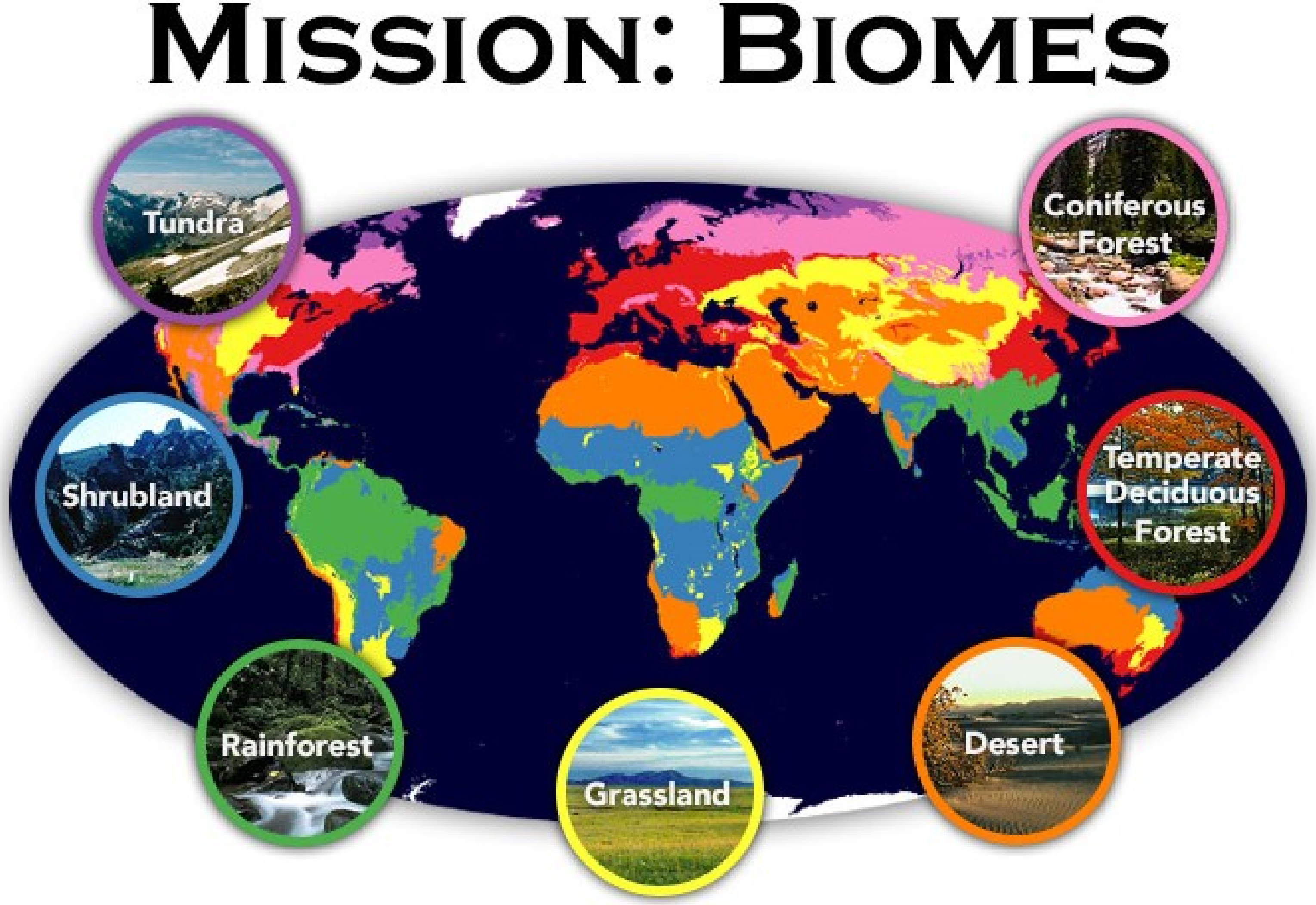
Type	Mass Gt C
Humans	0.06
Animals (other)	2
Plants	450
Fungi	12
Microbes	81.2
Total	545.3

- The total Earth biomass carbon is currently estimated at 545 billion metric tons and is distributed as depicted above.
- Humans (top predator) are 0.01% of Earth's total carbon biomass.
- Earth has a long history of replacing top predators (unstable position).
- Too many trees and not enough people? Sustainability is the answer.

Notes: Each human is approximately 15% carbon by mass.
Gt C is Gigatonnes of Carbon where 1 Gt = 1 trillion kilograms.

Source: http://www.pnas.org/cgi/doi/10.1073/pnas.1711842115

Earth’s Terrestrial Biomes: Diversity Increases Robustness

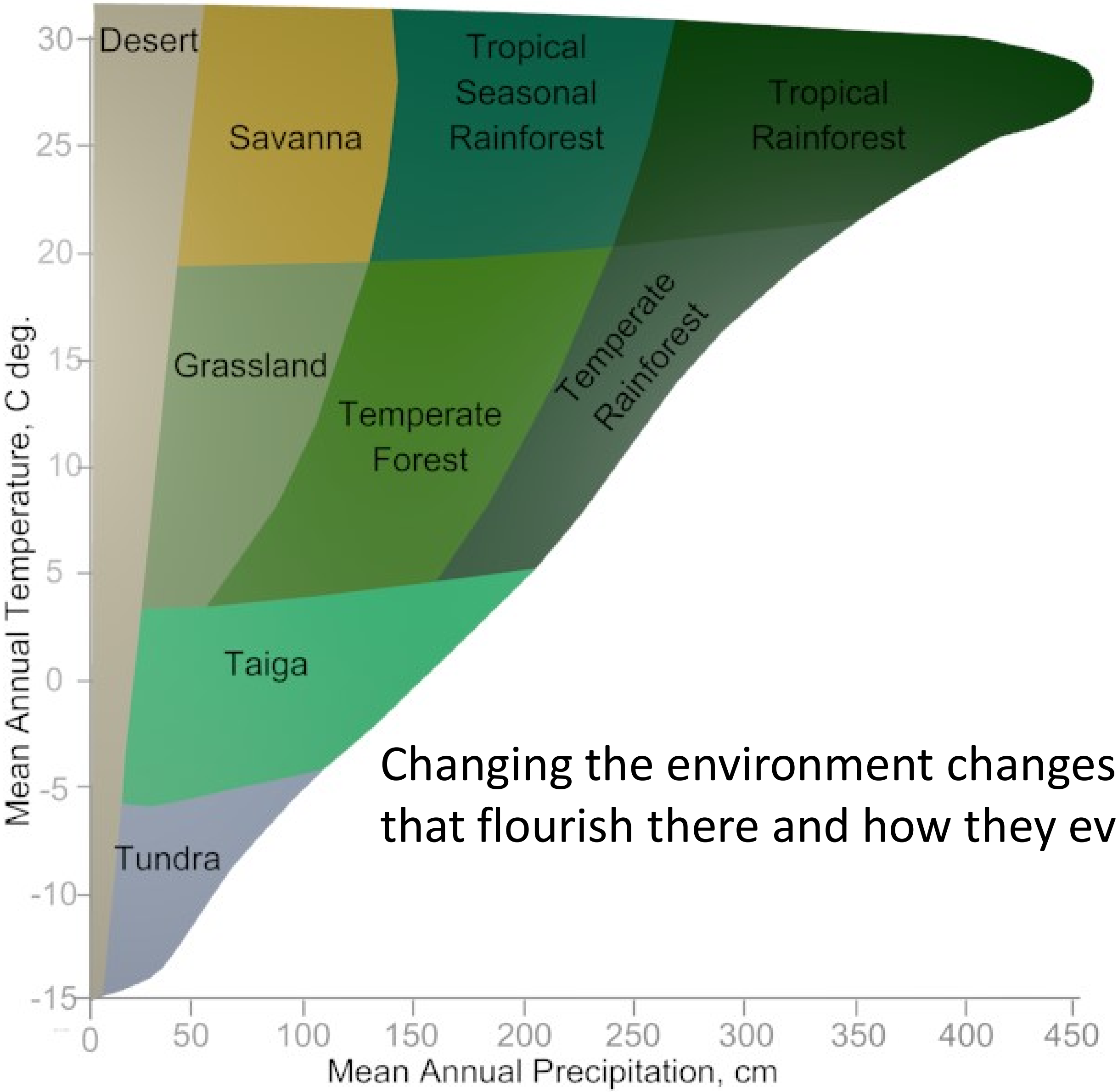


A Biome is a region characterized by similar coexisting plants and animals.

The Earth’s loosely coupled biomes enable life to more effectively adapt to changes.

Source: https://earthobservatory.nasa.gov/experiments/biome

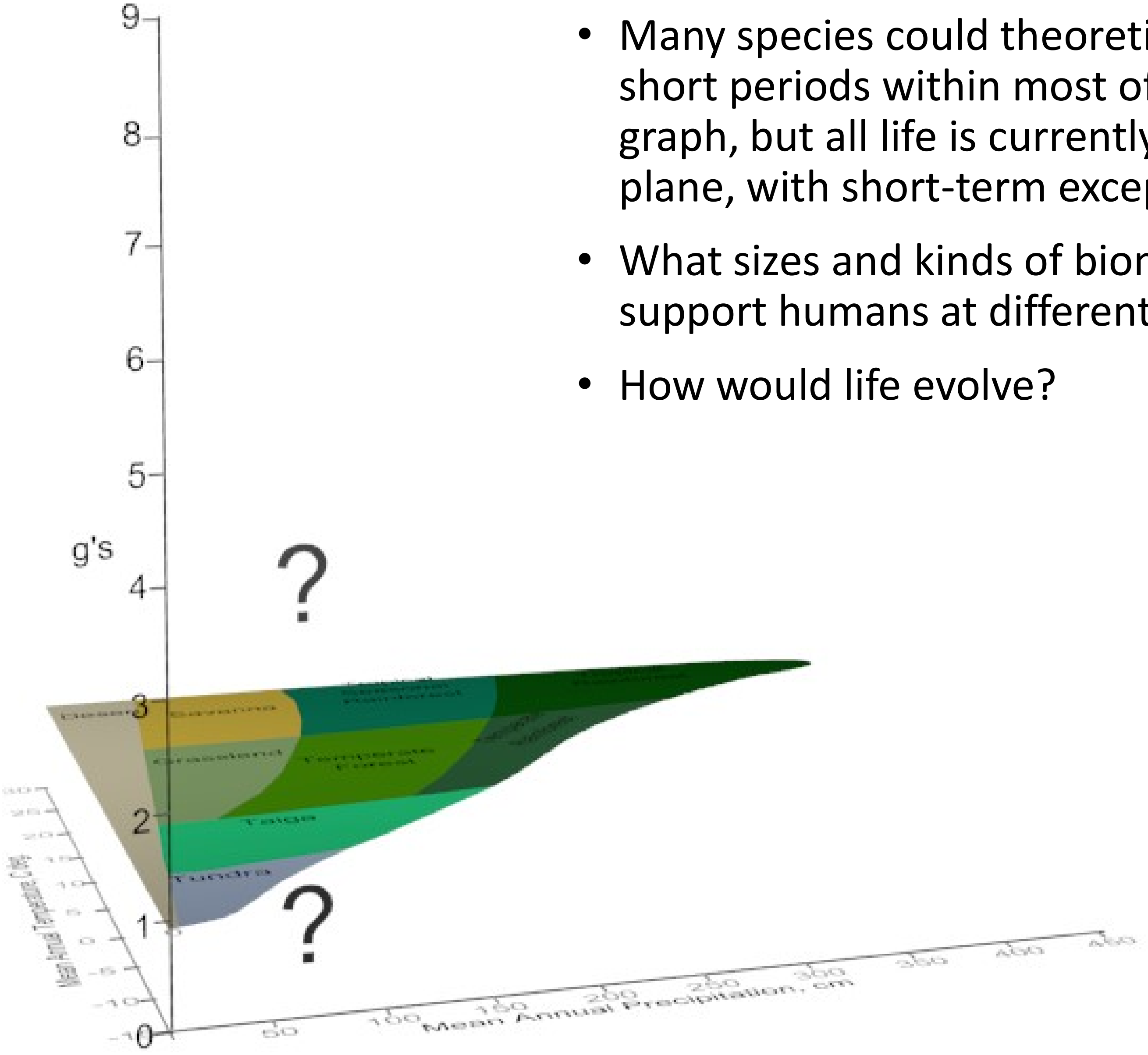
Earth Surface Biomes by Precipitation and Temperature



Changing the environment changes the species that flourish there and how they evolve.

Source: modified version from Whittaker, R., *Communities and Ecosystems*, 2nd ed., NY: MacMillan, 1975.

Earth Surface Biomes by Gravity, Precipitation, and Temperature



- Many species could theoretically survive for at least short periods within most of the volume of this graph, but all life is currently confined to the 1g plane, with short-term exceptions.
- What sizes and kinds of biomes could robustly support humans at different mean gravity levels?
- How would life evolve?

Note: 1g = 9.8 m/s^2, the Earth's surface gravity level

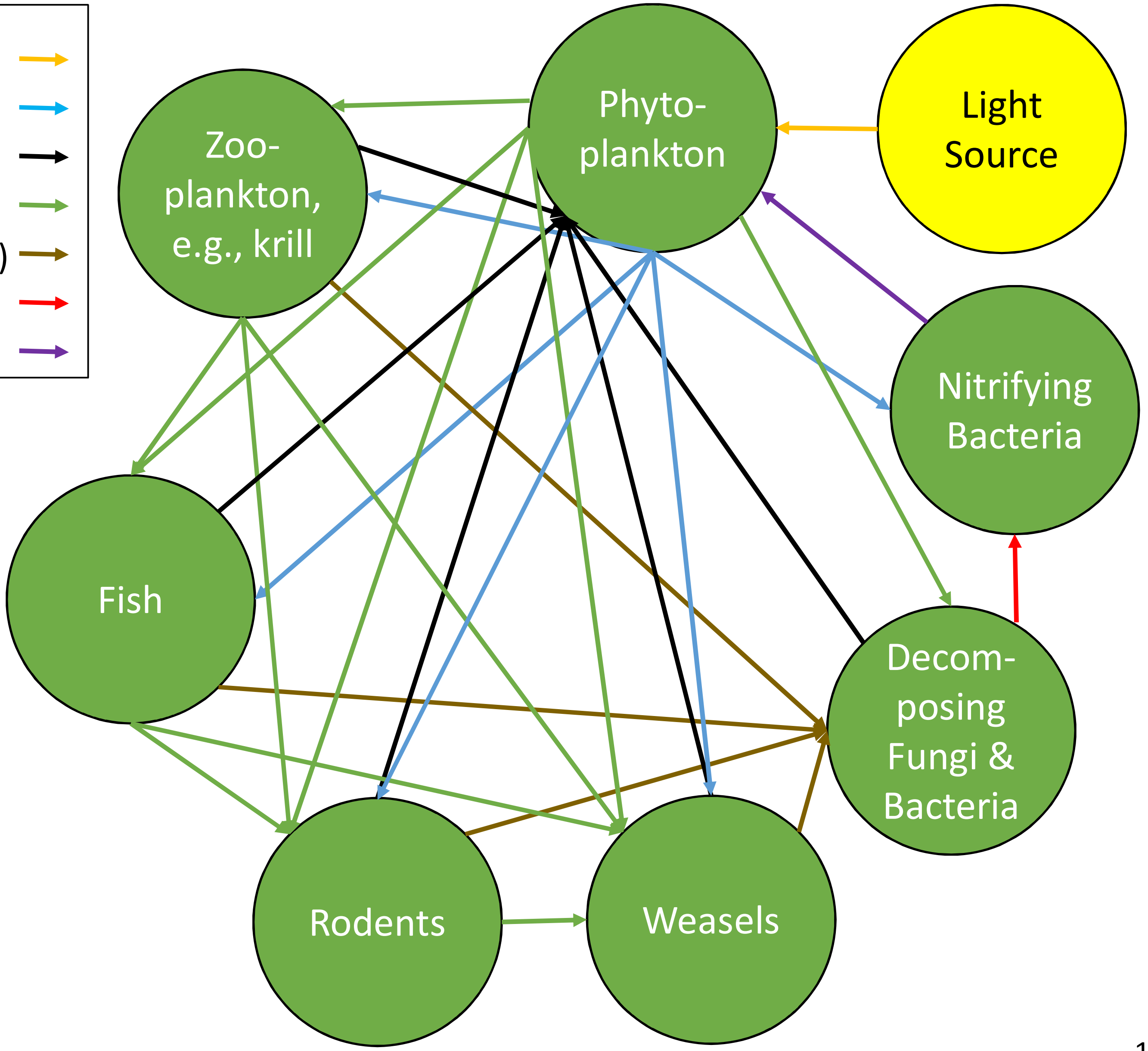
Closed Ecosystems

- A Closed EcoSystem (CES) is a community of organisms that persist in a sealed volume such that mass is not added or removed.
- The mass required (food/air/water) by the CES organisms is continually recycled from the mass produced (waste) by the organisms.
- Energy and information may be transferred to and from a CES.
- CESs that can support mammals indefinitely remain speculative (other than the Earth itself). The combinations of minimum required mass, volume, and species (recipes) for mammalian CESs are unknown.
- A CES is a useful spacecraft payload because of the scarcity and high value of mass in space. Resupplying the payloads with products from Earth and disposing of waste byproducts are not required.
- CESs capable of supporting mammals significantly reduce the costs of space habitats enabling very long-term research of mammals subject to various gravity and radiation levels.
- CESs hold the prospect of permanently establishing life beyond Earth.

Closed Ecosystem Example

Key

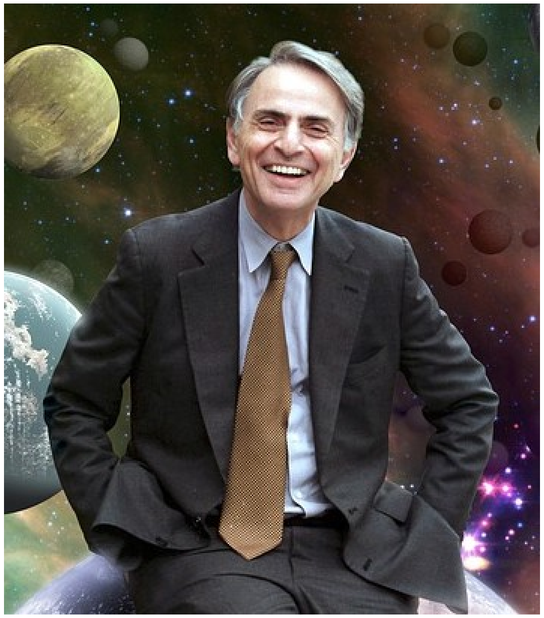
Light →
Oxygen →
Carbon Dioxide →
Organic Compounds (Food) →
Organic Compounds (Wastes) →
Ammonia →
Nitrates →



A NASA Closed Ecosystem Effort

- In the early 1980s NASA funded an effort in small, self-contained ecosystems and the 1982 Workshop on Closed System Ecology.
- One system at the workshop was licensed by NASA to a small business, which has sold approximately 1 million units since then (see image).
- In 1986, Carl Sagan (renowned astronomer, author of "Cosmos" and "A Pale Blue Dot") wrote a magazine article titled, "The World that Came in the Mail" about this ecosystem, in which he stated: *"Such systems are being perfected and will play a key role in future human exploration of the solar system."*
- The next step is to increase the system complexity as well as instrument and control a wide variety of such systems.

EcoSphere



Dr. Carl Sagan

EcoSphere image courtesy of Ecosphere Associates, Inc., Tucson, AZ, USA

Closed System Ecology Workshop, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19820024011.pdf

NASA ecosystem license article, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020090822.pdf

C. Sagan Ecosphere review, https://eco-sphere.com/carl-sagan-review-of-the-ecosphere/

Closed Ecosystem Equipment

Sensor candidates

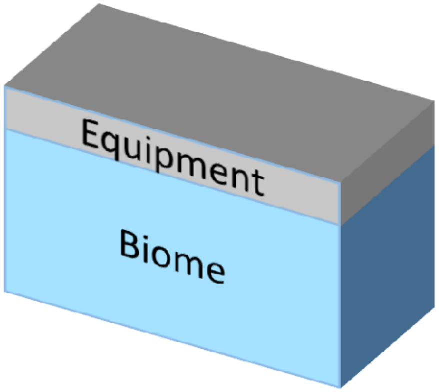
- Temperature Sensors
- Microscopes
- Imagers, variable frame rates
- Multi-spectral Light Sensors
- Pressure Sensors
- 6-axis Accelerometers
- GPS/location sensors
- pH Sensors
- Humidity Sensors
- Spectrometers
- Genomic Sensors
- Magnetometers
- Radiation Detectors

Actuator candidates

- Multispectral Lighting
- Heaters & Coolers
- Humidifiers/Evaporators
- Dehumidifiers
- Brine Collectors
- Precipitation Mechanisms, e.g., Misters
- Water pumps & valves
- Air pumps & valves
- Organism gates
- Fans
- Robotic arms
- Sampling Mechanisms
- Electromagnets
- Lasers
- Vibrators
- Augers

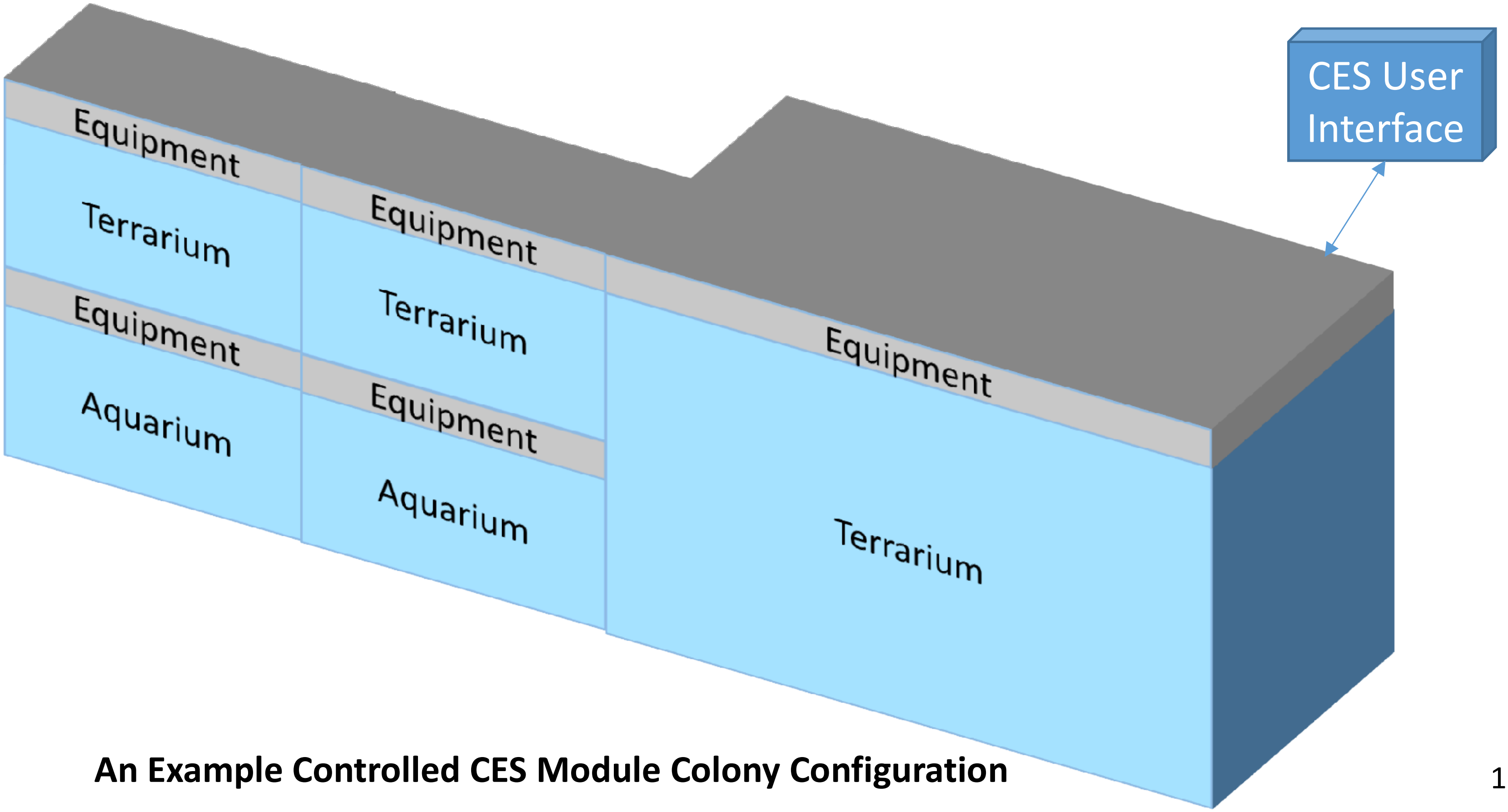
Other

- CPUs
- Memory Storage
- USB Ports
- Actuator Controllers
- Analog/Digital Converters
- Internet Controllers
- Power Supplies



Controlled Closed Ecosystem Modules

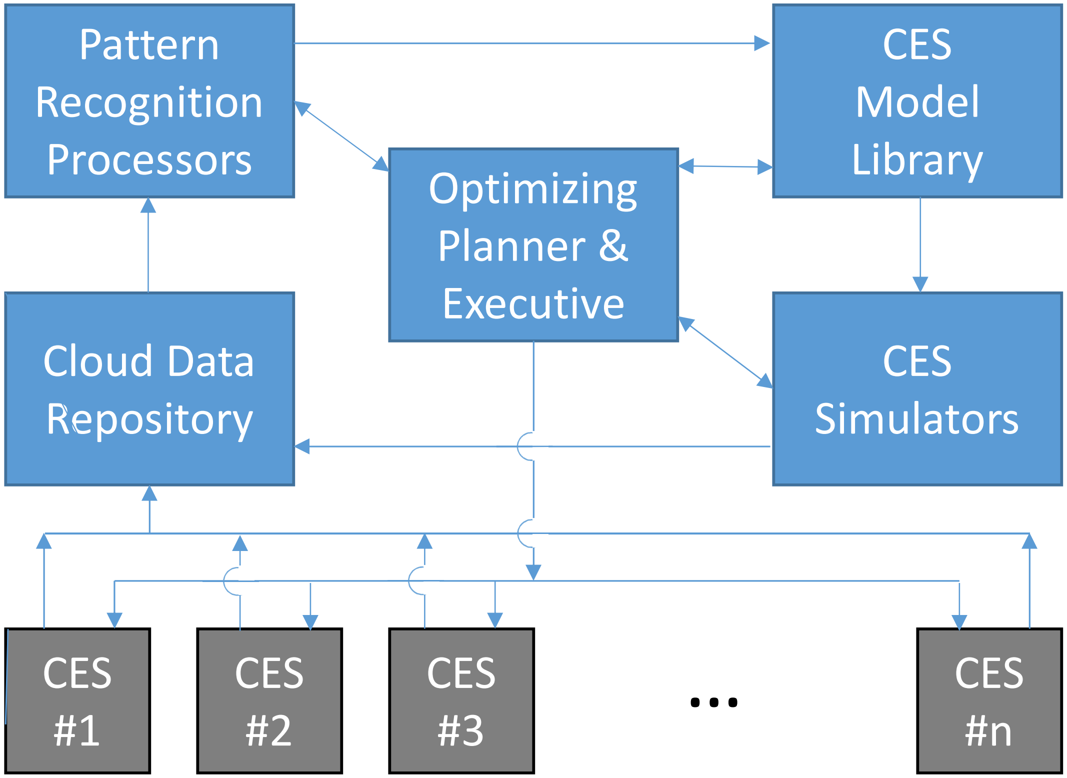
- CES Modules can be attached together in a wide variety of configurations to increase specimen variety, size, capacity, and sustainability.
- The transfer of gas, water, and specimens can be controlled (e.g., some modules may be designed to produce excess oxygen and others to produce excess carbon dioxide.)



An Example Controlled CES Module Colony Configuration

Closed Ecosystem Self-Optimizing Network

- The data collected from each physical CES and the CES simulators are used to optimize the individual CESs and the CES Model Library Artifacts.
- The CES Simulators run much faster and simulate many more variations of CES systems than the physical CESs, which are used to validate the simulations.



CESs to Repository

- Sensor Data
- Command Logs

Library Artifacts

- Organism Models
- Environment Models
- CES Recipes
- Resource Recipes
- Inter-Module Configurations
- Intra-Module Configurations
- Control Algorithms
- Heuristics
- Simulation Scenarios
- Simulation Histories
- CES Predictions

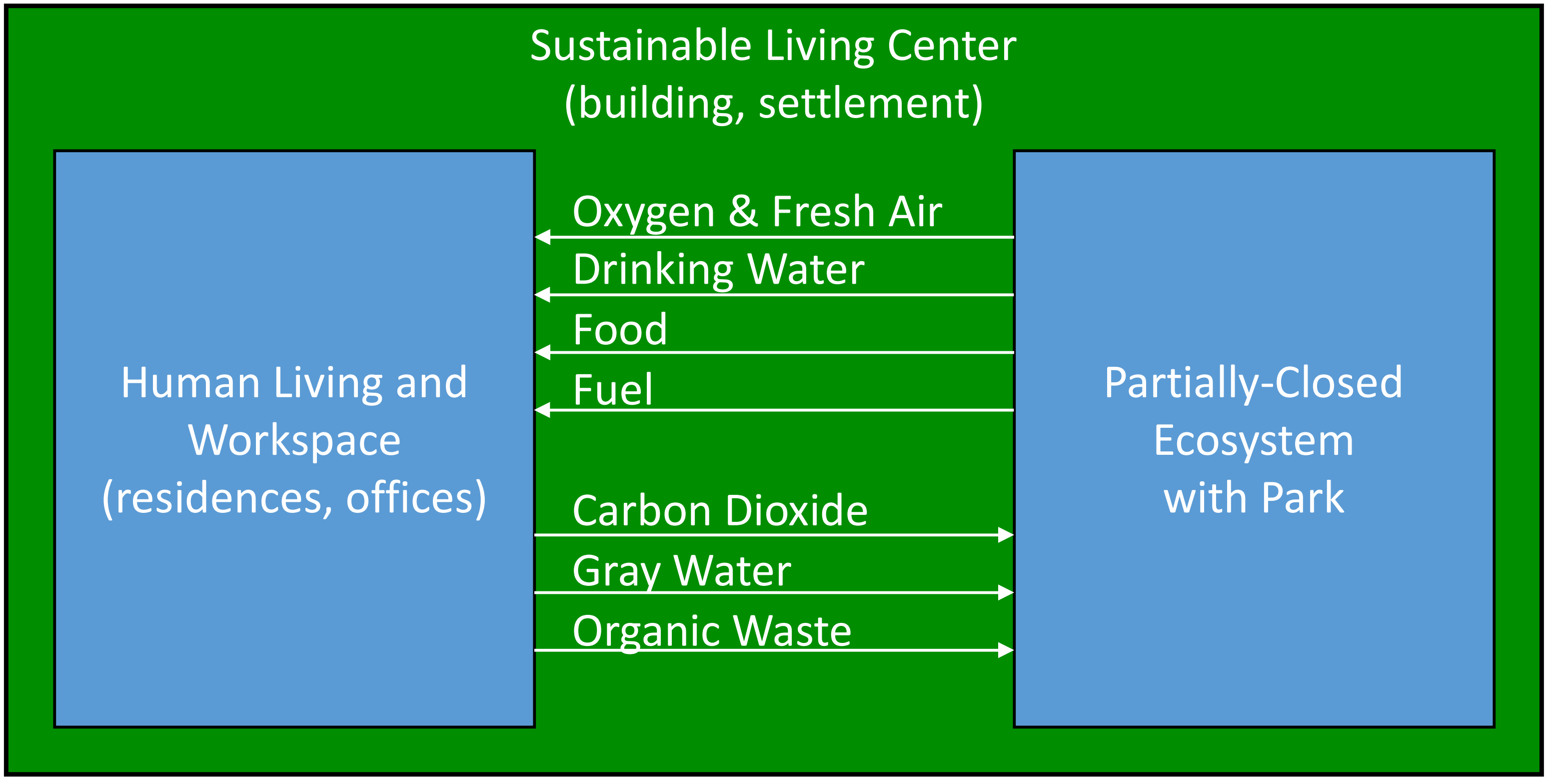
Planner/Executive to CESs

- Command Sequences
- Control Advisories
- Status Reports
- Software Updates

Source: Dorais, G. A., An Evolutionary Computation System Design Concept for Developing Controlled Closed Ecosystems: An Intelligent Systems Approach to Foster Gravitational Ecosystem Research for Developing Sustainable Communities in Space and on Earth , NASA TM -2018-56787, 2018. https://ntrs.nasa.gov/

Sustainable Living Centers

- Growing closed ecosystems will enable sustainable cities on orbit and on and inside the Moon, Mars, and asteroids.
- People can live sustainably just about anywhere on and inside the Earth in much higher densities with much lower impact on the other life on Earth.



Sustainable Living Center
(building, settlement)

Human Living and
Workspace
(residences, offices)

Oxygen & Fresh Air ←
Drinking Water ←
Food ←
Fuel ←

Carbon Dioxide →
Gray Water →
Organic Waste →

Partially-Closed
Ecosystem
with Park

U.S. Space Policy Directive-1 of 12/11/2017

The U.S. National Space Policy was updated to read:

''The Administrator of NASA shall: Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;''

Drives new requirements for:

- Understanding the very long-term effects of radiation and fractional gravity
- Very long-duration artificial-gravity spacecraft to study these effects
- Bioregenerative life-support (closed ecosystems) for:
  - ✓ atmosphere processing
  - ✓ water purification
  - ✓ food production
  - ✓ waste recycling

https://www.federalregister.gov/documents/2017/12/14/2017-27160/reinvigorating-americas-human-space-exploration-program

Is Long-Term Life Beyond Earth Feasible?

<u>3 Top Concerns:</u>

- **Radiation**
- **Microgravity**
- **Atmosphere**

Space Travel Has 'Permanent Effects,' Astronaut Scott Kelly Says

By HAYLEY WALKER · Jun 15, 2016, 7:18 PM ET

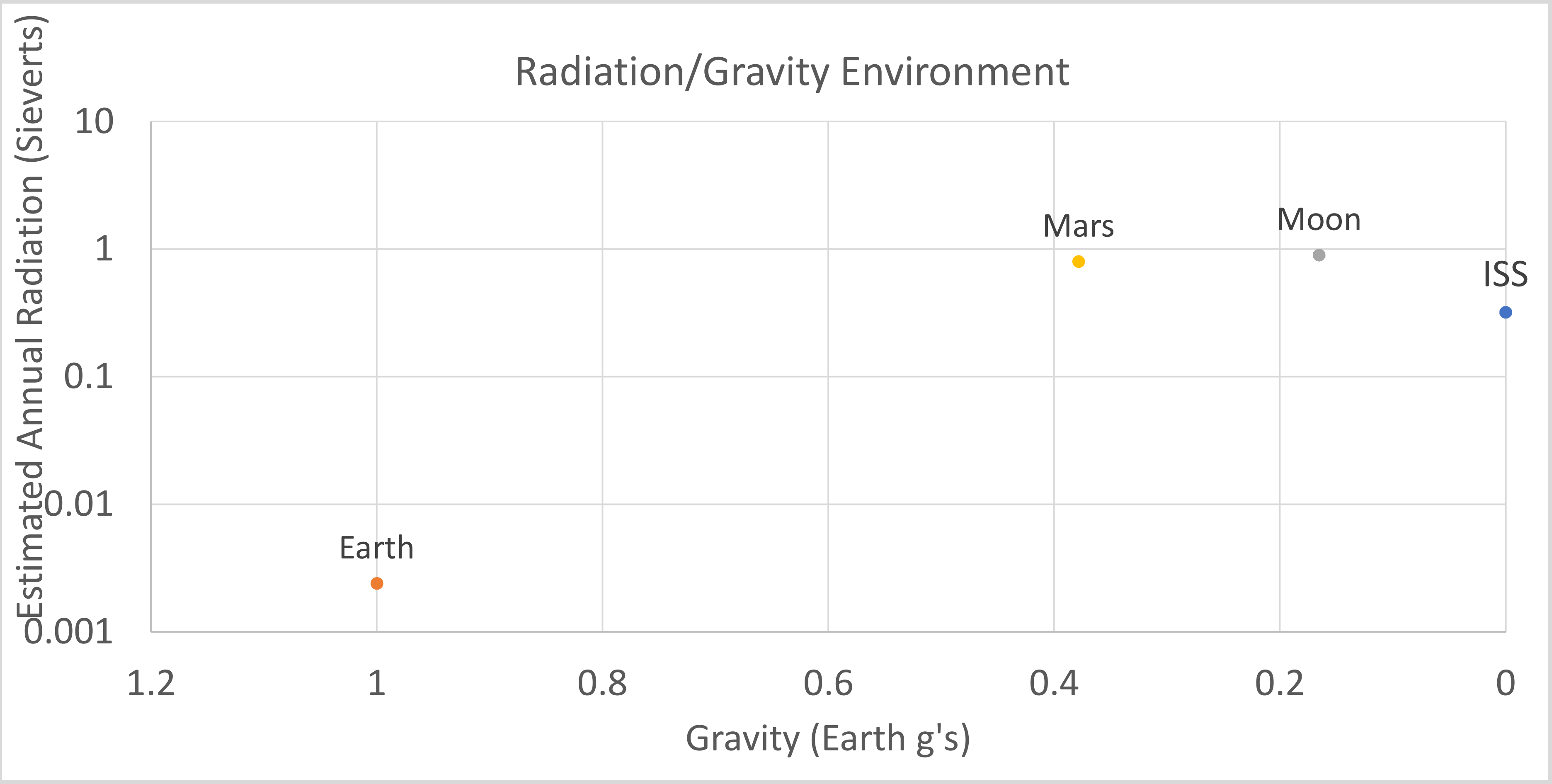
WATCH | Scott Kelly's Mission: 340 Days in Space

Astronaut Scott Kelly, who spent 340 days aboard the International Space Station, said that being in space appears to have "permanent" effects that aren't fully understood.

Longest time in space by a human: 438 days set in 1995.

Source: http://abcnews.go.com/US/space-travel-permanent-effects-astronaut-scott-kelly/story?id=39884104

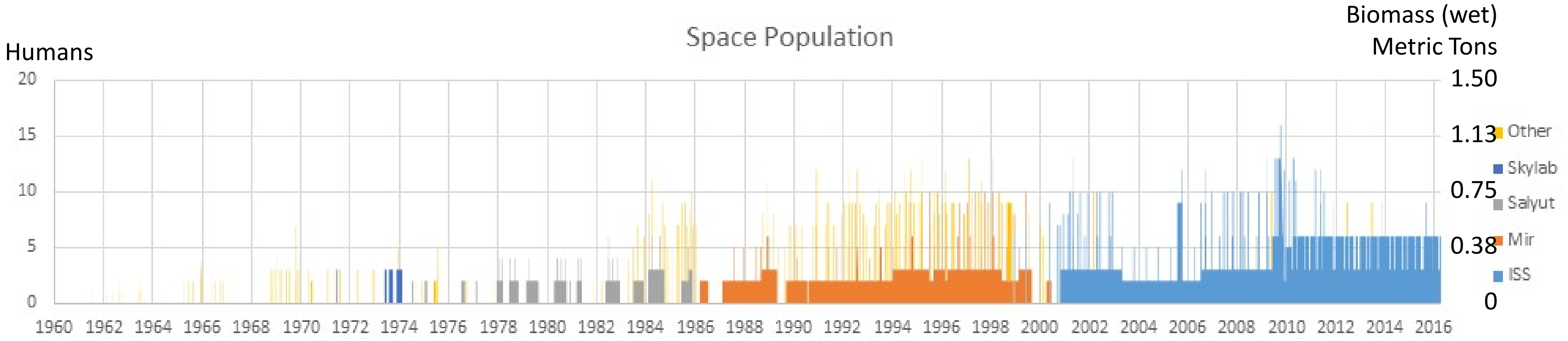
Solar System Radiation/Gravity Environment



- Other than nearby the Earth data point, the viability of long-term life is unknown.
- Deep-space artificial-gravity bioscience missions could answer this question.

Note: Estimated radiation levels exclude Solar Particle Events, which can increase unshielded daily radiation levels by 3 orders of magnitude off Earth.
Sun radiation varies by 4X through 11-year solar cycle.

Orbiting Biomass

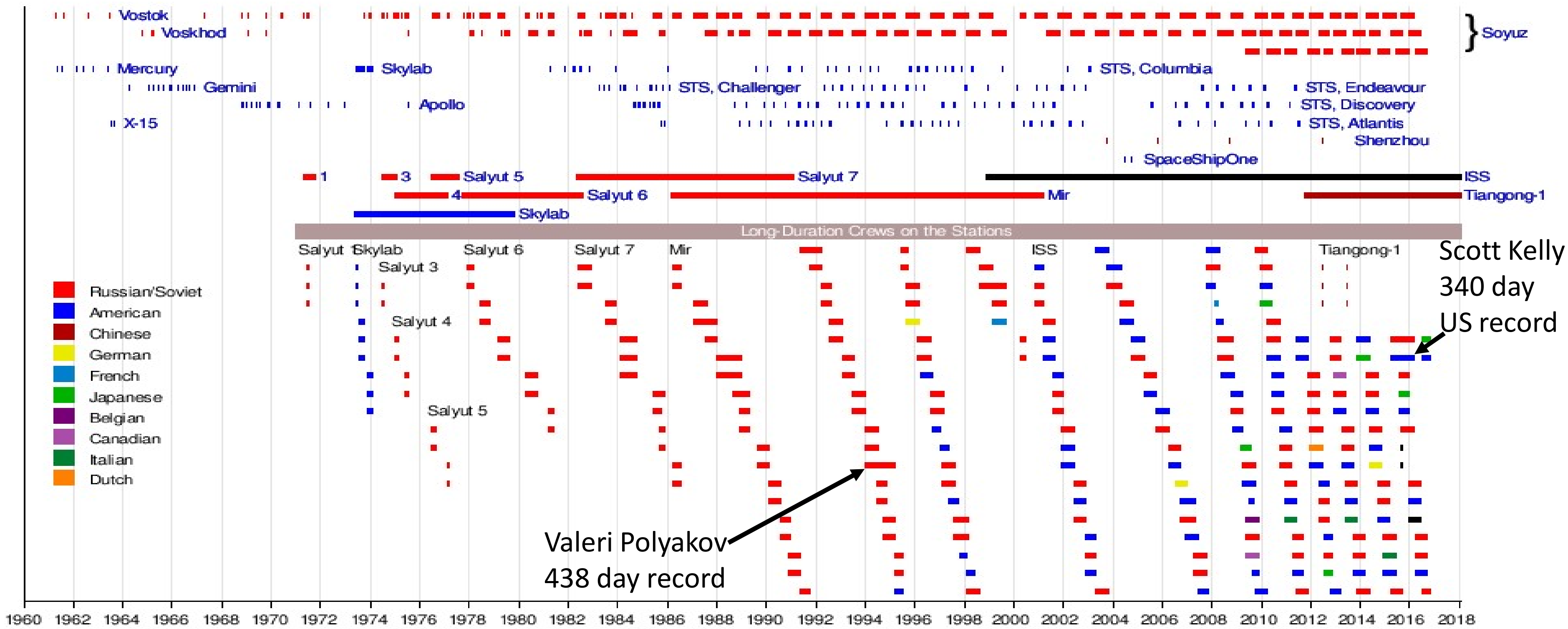


- Over 99.9% of the known biomass in space is human.
- In contrast, 99.99% of the biomass on Earth is not human.
- Maximum biomass in space occurred in 2009 (approx. 1.2 metric ton of biomass).
- Space biomass capacity is primarily dependent on ISS.

Note: Total wet biomass is approximated at 75kg per person, which is ~14kg carbon biomass.

Source: https://en.wikipedia.org/wiki/List_of_human_spaceflights

Timeline of Humans in Space



Scott Kelly
340 day
US record

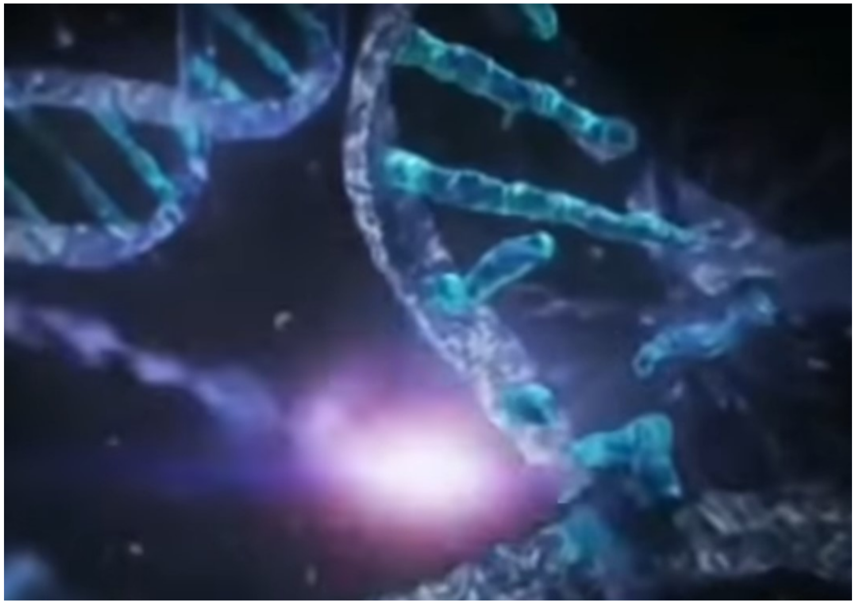
Valeri Polyakov
438 day record

- Humans are migratory in space.
- Total biomass in space is not increasing because almost all of it returns to Earth within 6 months.

Source: https://en.wikipedia.org/wiki/List_of_human_spaceflights

Types of Radiation: Waves & Particles or Ionizing & Non-ionizing

- Radiation is often classified as ionizing and non-ionizing radiation. Upper-ultraviolet, X-ray, gamma frequency waves, and particle radiation are ionizing radiation since they have sufficient energy to ionize atoms they strike and break chemical bonds.
- Electromagnetic Wave radiation: deep infrared through gamma frequencies
- Particle radiation: 99% protons and alpha particles (2 protons and 2 neutrons), but larger nuclei are also common up to nickel
- Galactic Cosmic Rays (GCRs) are particle radiation; most travel at speeds between 43%-99.6% of the speed of light (GCRs have relativistic effects, e.g., 10X mass)
- Almost all radiated particles from the Sun travel at speeds less than 1% of the speed of light (0.16% speed of light on average: 3.5 days to reach Earth)



Radiation Particle Breaking DNA Strand Illustration

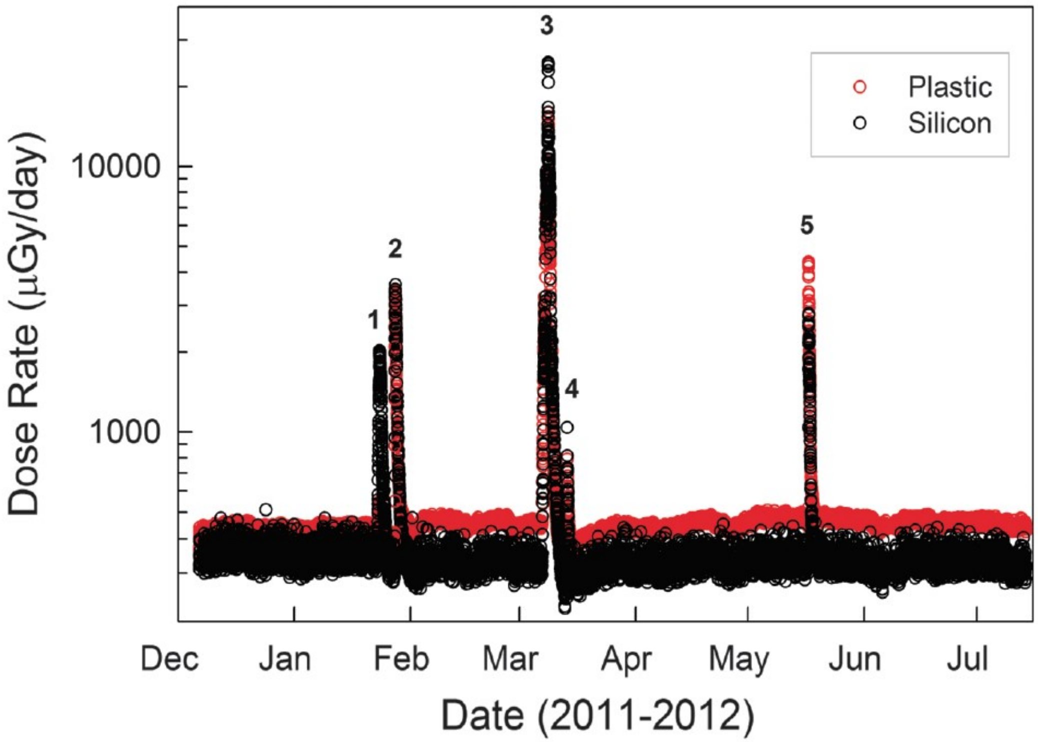
Similar damage is done to neurons, blood vessels, organs, tissues….

Image source: https://youtu.be/cz5tSegU16E

Secondary Particle Radiation

- Ionizing radiation (particles and waves) can increase the radiation particle count, called Secondary Particle Radiation.
- Increasing shielding monotonically reduces wave radiation, but increasing shielding initially increases particle radiation due to secondary particle radiation.
- Some particles can pass through objects without collisions. The greater the mass, the lower the probability.

Mars Science Laboratory (MSL) Cruise Phase Radiation



- GCR dose equivalent rate of 1.84 +/- 0.33 mSv/day (without Solar Particle Events (SPEs) – the spikes)
- Annual public artificial radiation limit per year is 1 mSv (50 mSv for radiation workers)
- The GCR radiation exposure beyond the Van Allen Belts is 2-3X LEO levels
- SPEs in deep space are much worse than in LEO and frequently cause electronic failures. A single SPE can result in well beyond 1 Sv (1000X annual public limit).

Notes:

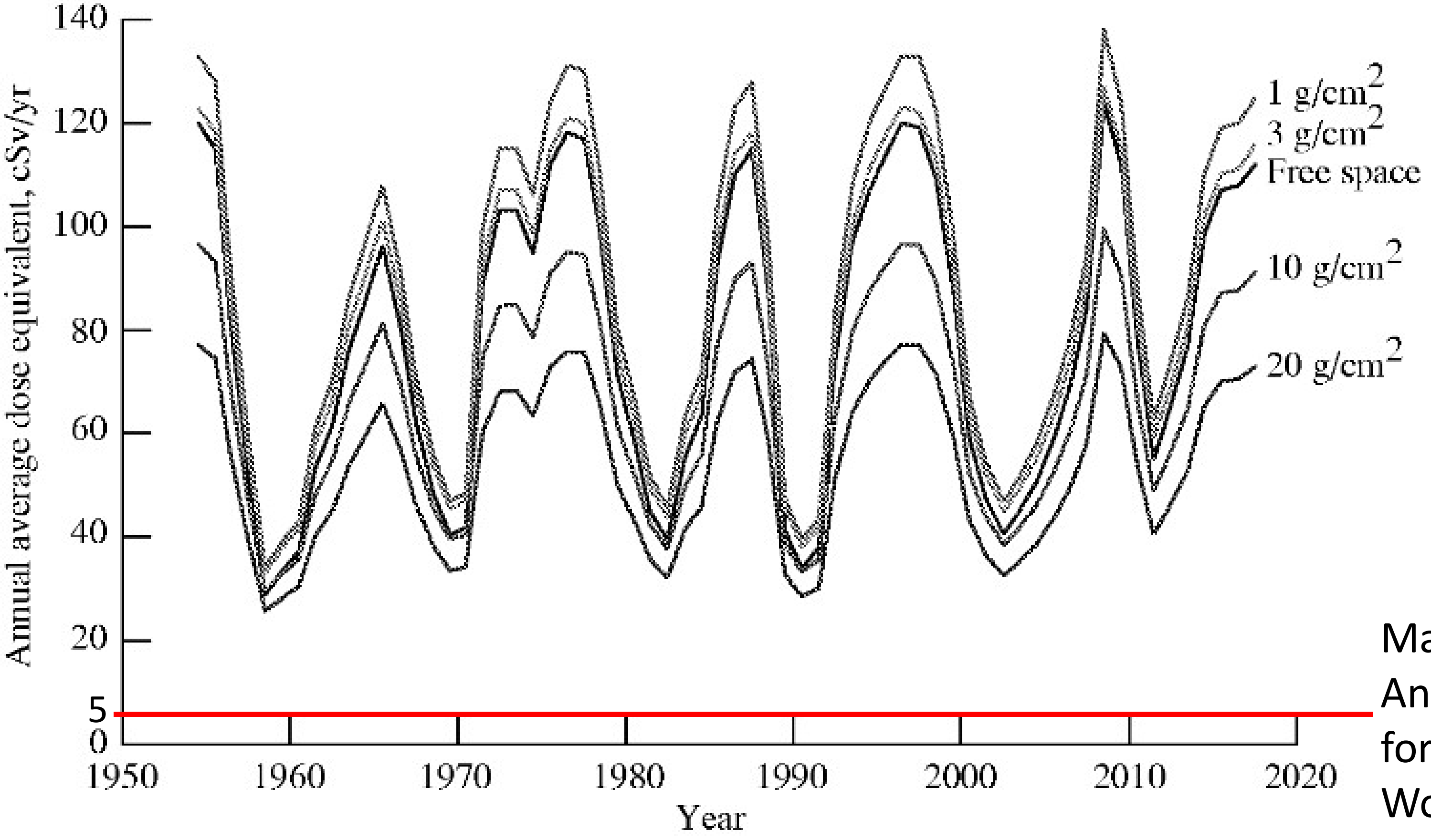
- Integers indicate Processor Single Event Upsets.
- Doses averaged over 15.5 minute intervals
- Sensors just measure particle radiation
- Shielding between < 10g/cm^2 and 80g/cm^2
- Y-axis is exponential.
- Average Quality Factor Q = 3.8 +/- 0.25 for conversion between Grays and Sieverts (e.g., 1 Gy of Alpha = 20 Sv, 1 Gy of Gamma = 1 Sv, Alpha 20X more dangerous than Gamma radiation)
- Plastic Sensor composition is closer to human tissue

Radiation Units of Measure

1 Gray (Gy) = 100 rad = 1 Joule/kg
1 Sievert (Sv)= 100 rem (equivalent human dose)
Sieverts = Grays x Q
where Q: Average Quality Factor of radiation
Q = 1 for pure gamma radiation

Source: Zeitlin, C., et al., Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory, Science, May 2013. https://www.researchgate.net/publication/236977793

Solar Cycle Radiation



Maximum Annual Dosage for Radiation Workers

- Sunspots are also highly correlated with GCR: increased solar wind associated with increase sunspots decreases the GCR effects within the solar system by 4X.
- Less than ~3.5 grams per cm^2 of aluminum shielding (~13mm thick) increases radiation exposure due to the secondary particles.
- ISS Shielding ~20 grams per cm^2
- Earth atmosphere ~1kg per cm^2, equivalent to 10m of water, which is 10 metric tons per square meter.

Image source: Wilson et al., "Solar Cycle Variation and Application to the Space Radiation Environment," NASA TP-1999-209369, Sept., 1999.

Negative Microgravity Effects on Humans

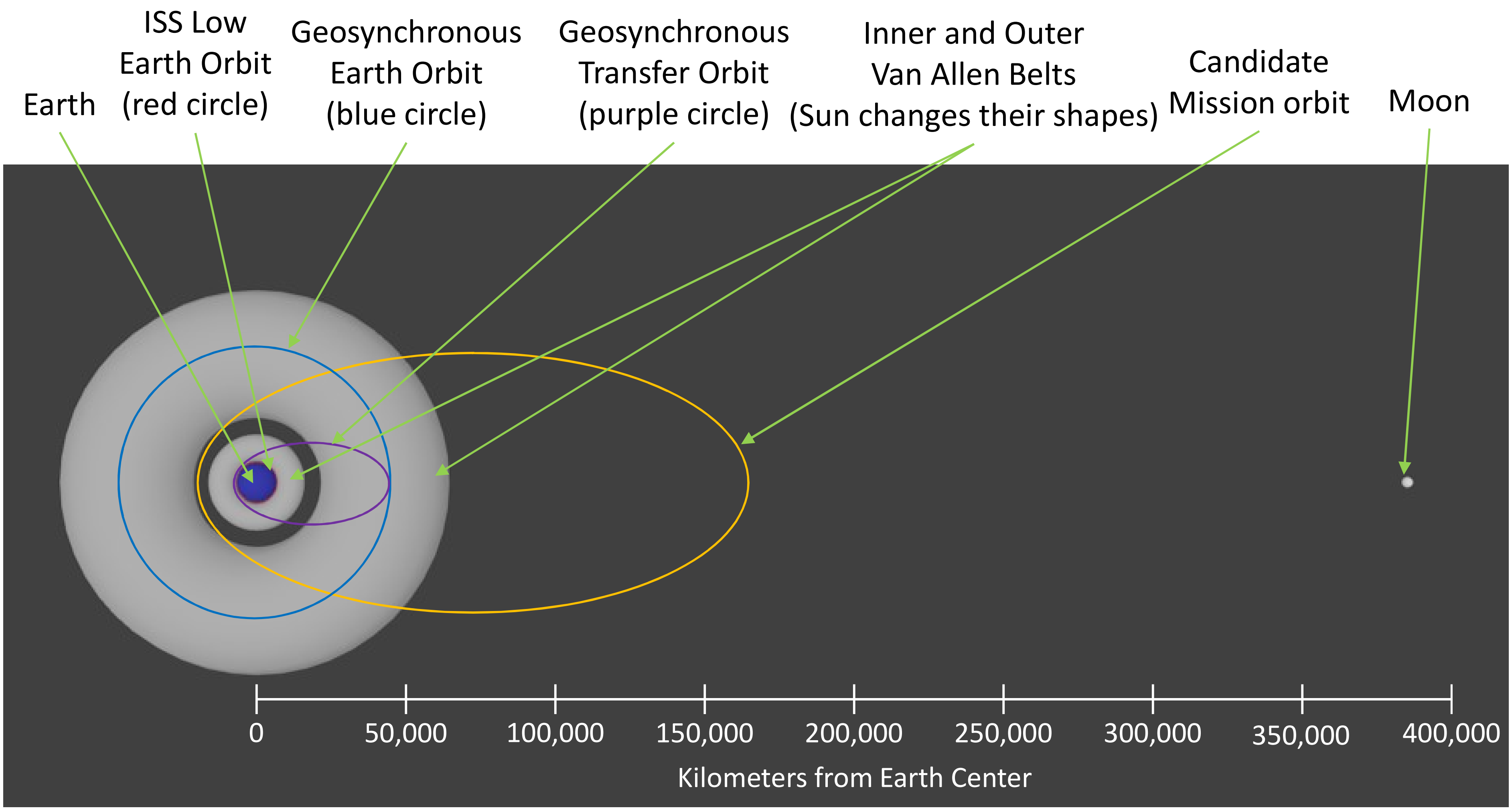
<u>A non-exhaustive list of known negative effects of microgravity:</u>

- Decreases Bone Density (0.5% – 2% per month)
- Decreases Muscle Mass
- Decreases Immune System Effectiveness
- Decreases Organ Mass
- Decreases Coordination
- Decreases Cardiovascular Conditioning
- Decreases Resistance to Unconsciousness Due to Acceleration
- Increases in Neurological Anomalies
- Increases Disorientation
- Increases Nausea
- Increases Intraocular Pressure Degrading Vision and Potentially Injuring Eyes
- Induces Skin Atrophy, Itching, Dryness, Irritation, and Susceptibility to Scratches

Orbiting Modular Artificial-Gravity Spacecraft (OMAGS) Mission Concept

Operate in cislunar orbit an unmanned spacecraft, with a 150cm-radius centrifuge that simultaneously produces Earth and/or multiple fractionated gravity levels for approximately 2,000kg and 3,000 liters of bioscience payloads, with in situ science capability and sufficient radiation shielding for the closed-environment biospecimen populations to persist for at least 5 years.

Cislunar Space (to scale)



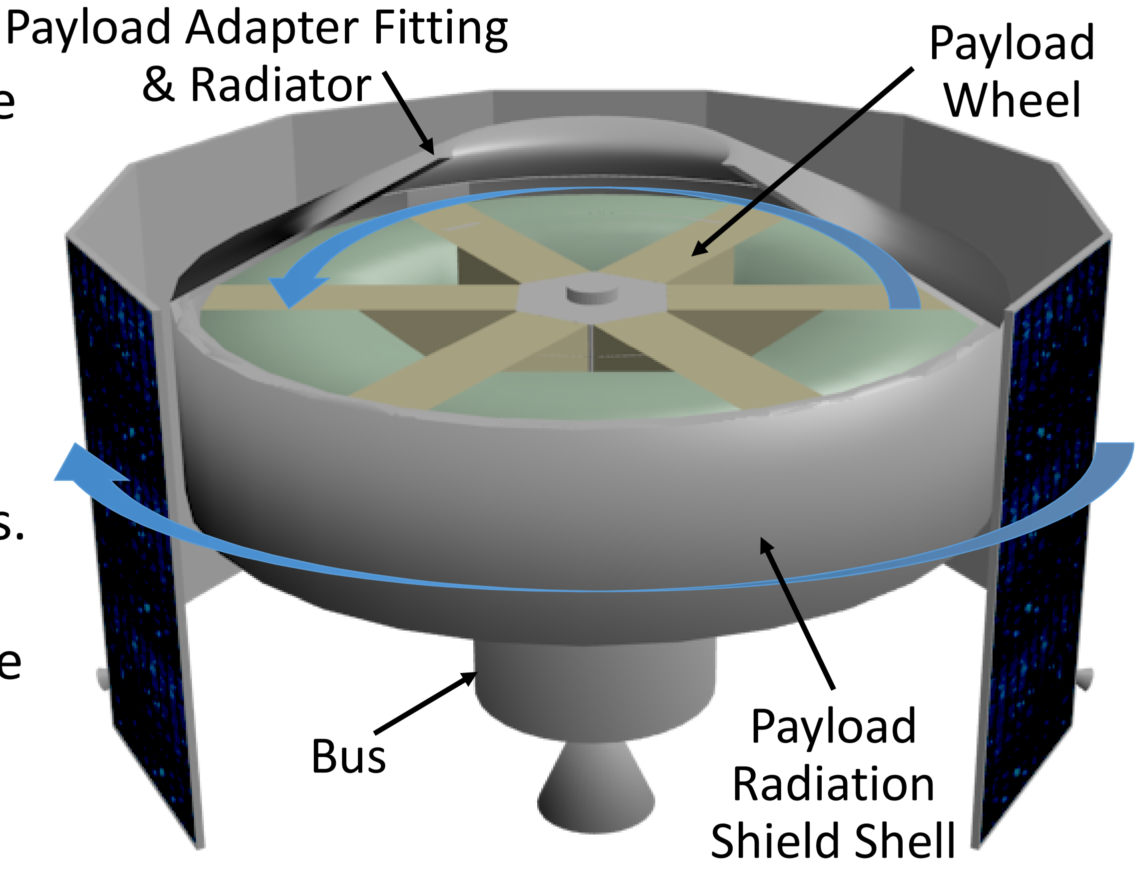
OMAGS External View

Preliminary Concept Drawing

OMAGS Cutaway View

The Spacecraft and Payload Wheel counter-rotate resulting in net zero angular momentum and zero gyroscopic forces.

- Artificial-gravity level can be changed without requiring propellant to change total angular momentum
- The spacecraft attitude can be changed without having to compensate for centrifuge gyroscopic forces.
- Spacecraft mass without Payload Wheel is ~12X more than the Payload Wheel mass so the spacecraft counter-rotates an order of magnitude more slowly than the Payload Wheel.



Multi-Payload Rationale

Spacecraft accommodates the following Artificial Gravity (AG) payloads:

(6) rim 350-liter payloads at 100% nominal AG
(6) spoke 54-liter payloads at 80% nominal AG
(6) spoke 54-liter payloads at 60% nominal AG
(6) spoke 54-liter payloads at 40% nominal AG

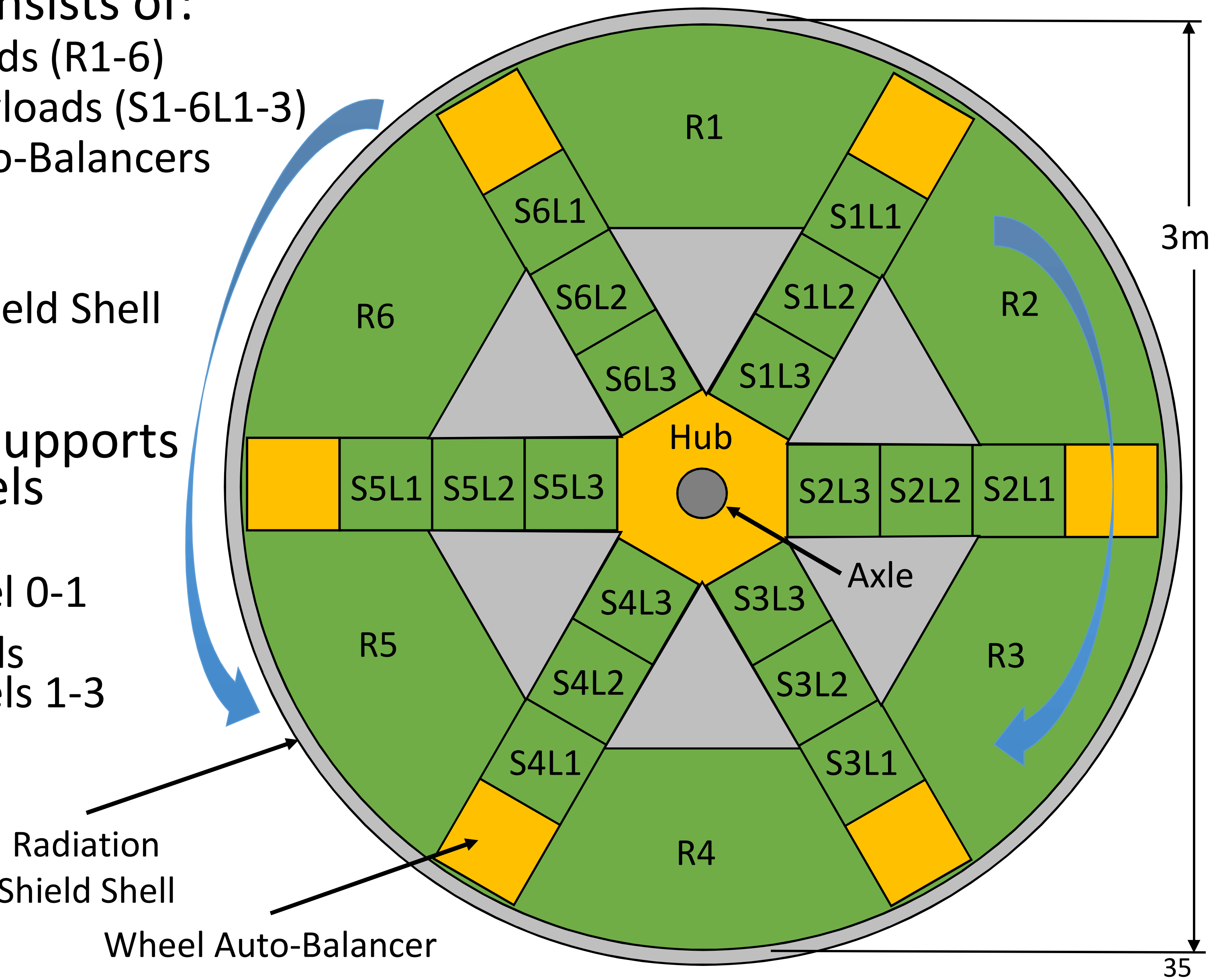
- Experiment Variety, answer multiple questions
- Experiment Repeatability
- Experiment Biospecimen Separation
- Experiment Equipment Redundancy
- Vary radiation shielding of otherwise identical payloads
- Vary gravity level of otherwise identical payloads
- Increase stakeholders, multiple payload science organizations

OMAGS Centrifuge Top View

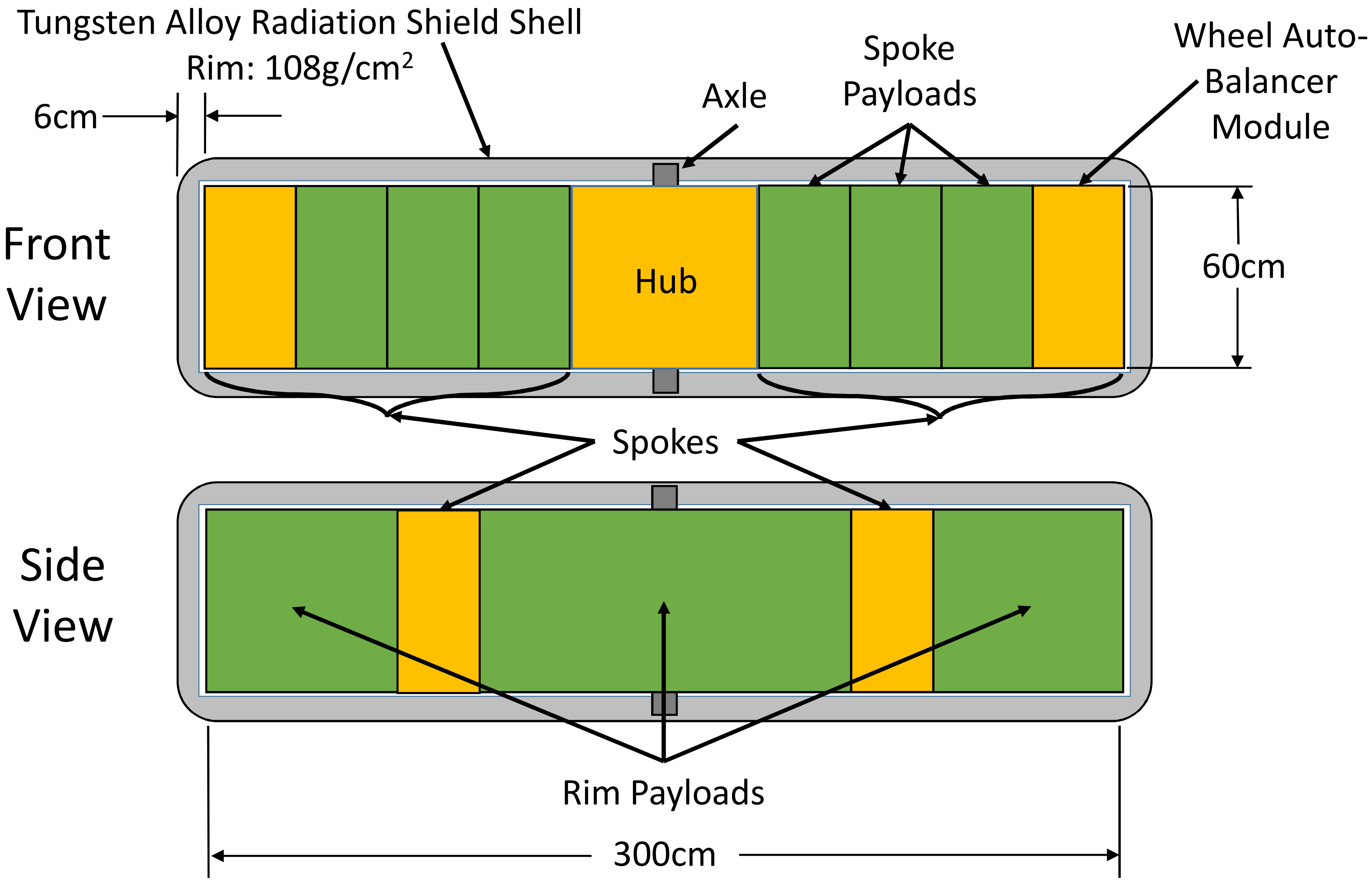
Centrifuge consists of:

- 6 Rim Payloads (R1-6)
- 18 Spoke Payloads (S1-6L1-3)
- 6 Wheel Auto-Balancers
- Avionics Hub
- Axle
- Radiation Shield Shell

- Centrifuge supports four AG levels
- Rim Payloads are all AG level 0-1
- Spoke Payloads (SxLy) are levels 1-3 where:
  x = Spoke #
  y = AG level #



Centrifuge Front & Side Cutaway Views



Artificial Gravity

- The spacecraft generates Centripetal Acceleration (a_c) by rotating the Payload Cab Wheel according to the formula:

$$a_c = v_T^2/r = (\text{RPM}\ \pi)^2 r/900$$

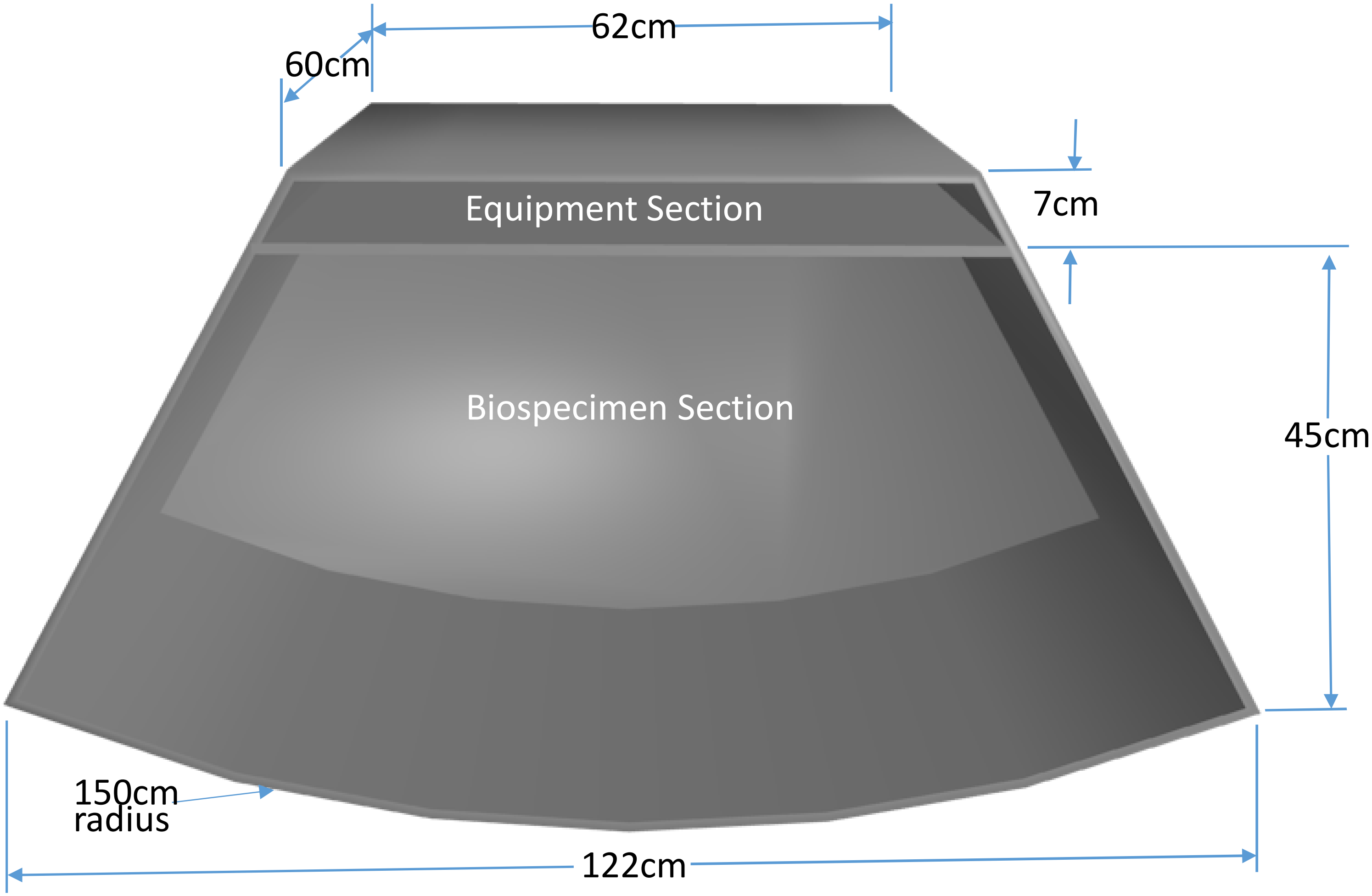
where:

- v_T (m/s) = the tangential velocity at the Payload floor
- r (m) = radius, the distance from the Payload floor to the axis of rotation
- RPM = Revolutions Per Minute = $30v_T/\pi r$
- a_c changes linearly with radius, but quadratically with RPM
- a_c is conserved due to the Law of Conservation of Angular Momentum
- example: Earth gravity = 1g = 9.8(m/s^2) = $(24.4\ \pi)^2$ x 1.5(m)/900

RPM	Level 0g	Level 1g	Level 2g	Level 3g
24.4	1.00	0.80	0.60	0.40
14.0	0.33	0.26	0.20	0.13

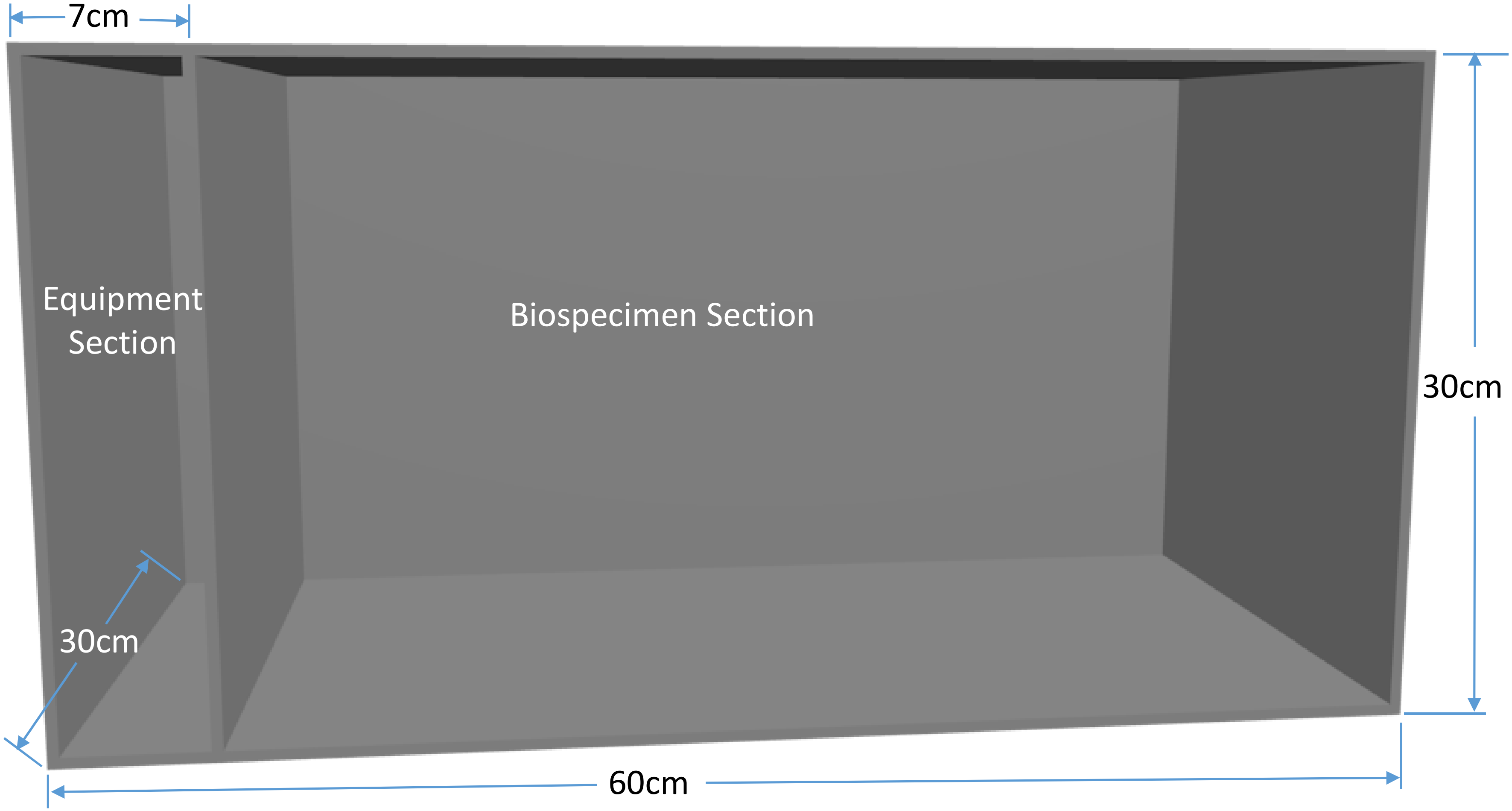
Payload Rim Module Cutaway View

- 350 liter (92 gallons) volume,
  including 27 liter equipment section



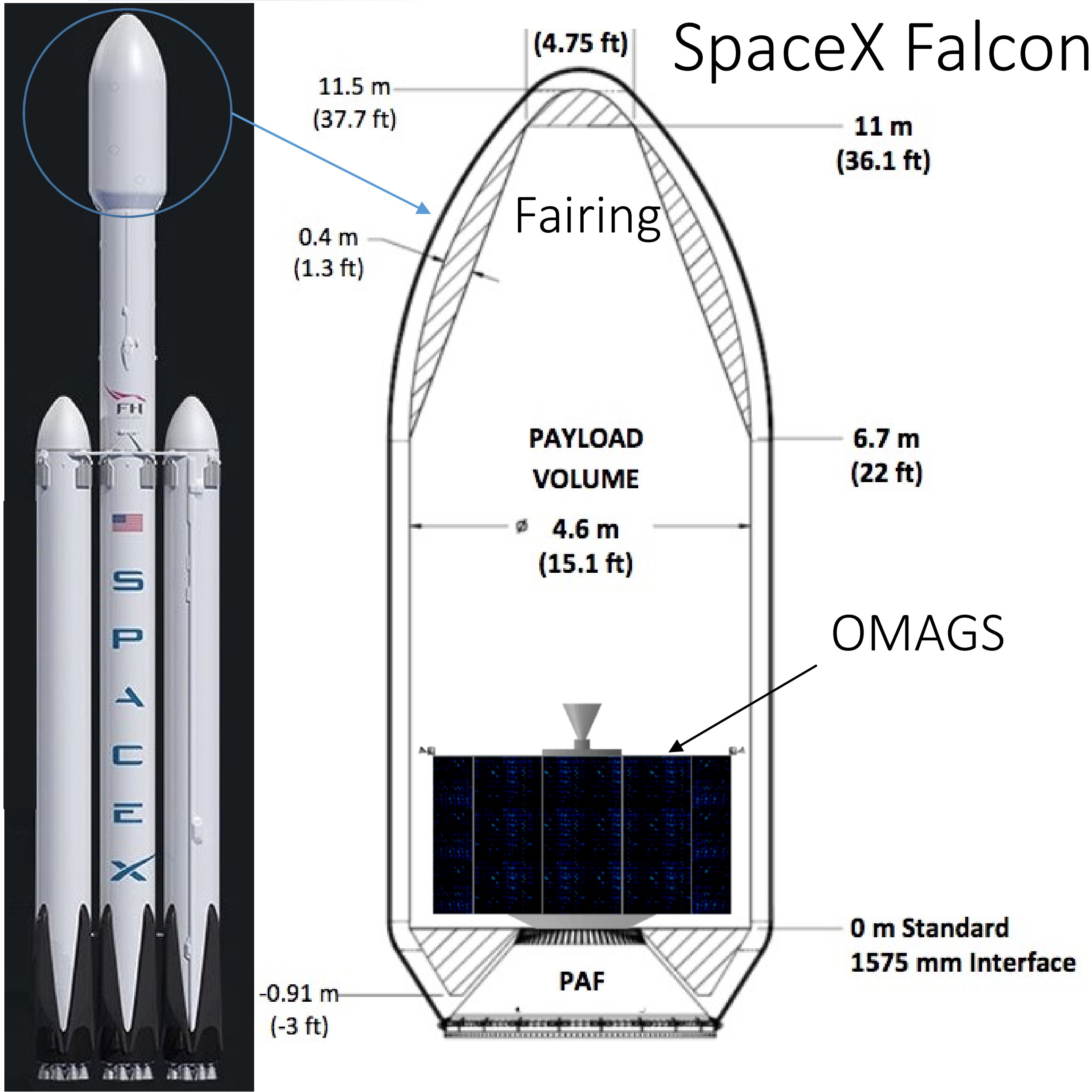
Payload Spoke Module Cutaway View

- 54 liter (14.3 gallons) volume, including 12.6 liter equipment section



OMAGS Launch Vehicle

SpaceX Falcon Heavy



Geosynchronous
Transfer Orbit (GTO)
27 degree inclination
payload mass: 26,700kg

Source: http://www.spacex.com/about/capabilities

Next Steps

Ultimately, expanding life beyond Earth will not be inexpensive, but it is worth the investment and will improve our understanding of Earth life and our environment. However, inexpensive next steps are:

- Develop and evolve several small closed ecosystems to collect data for optimizing the systems and to demonstrate the feasibility of remotely maintaining the viability of biomes over several years and remotely studying their organisms (can be done online).
    - By creating multiple biomes, their variances can be determined and payloads can be flight-ready with control groups that stay on ground.
- Form a small and focused Science Definition Team to:
    - Devise goals and measurement objectives for the mission
    - Consider candidate payloads and partners
    - Engage the National Academy of the Science Committee for the Decadal Survey on Biological and Physical Sciences in Space Space Studies Board
    - Develop a space bioscience mission study report regarding the long-term effects of space radiation and fractional gravity on life.
      LADEE Science Definition Team Study Report example:
      https://lunarscience.arc.nasa.gov/files/LADEE_SDT_Report.pdf

Summary

- Closed Ecosystems (CESs) can be used as spacecraft payloads to study the long-term effects of various gravity and radiation environments on life.
- A population of small CESs on Earth can be used to generate data without direct human interaction and be continually optimized by an intelligent system modeling the CESs based on the data.
- Small CESs can be combined and/or expanded to very large sizes, large enough for human populations enabling people to live almost anywhere on Earth with much lower impact on each other and other life.
- Once CESs are demonstrated to reliably persist in space, within specified gravity and radiation limits, it is a small step for similar CESs to persist just about anywhere in space (Earth orbit, Moon, Mars, Earth-Mars cycler orbit, asteroids, …) enabling life to permanently extend beyond Earth and grow exponentially.
- The Power of Small: the above can all begin by collecting data from Worlds that come in the Mail (Carl Sagan, 1986).

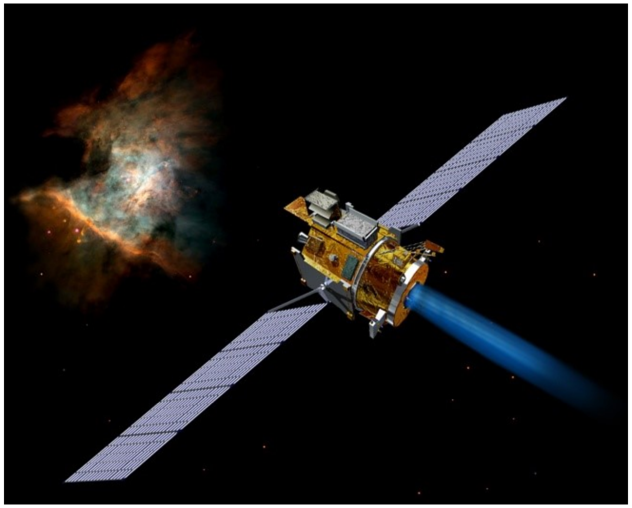
Questions?

Consider the Dandelion as an existential metaphor for the Earth and humanity's search for meaning with regard to future of life in the cosmos.

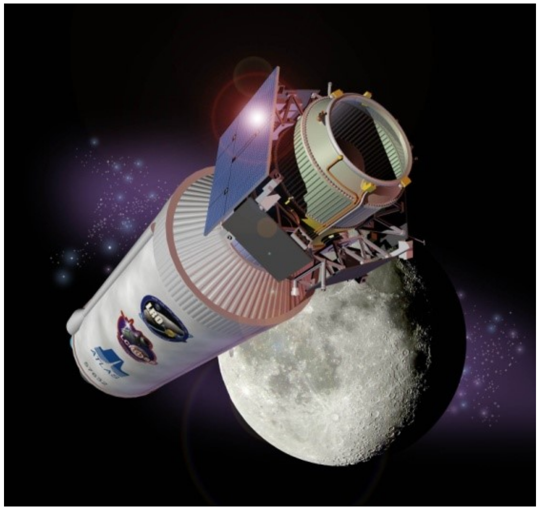
Backup

Brief NASA Biography

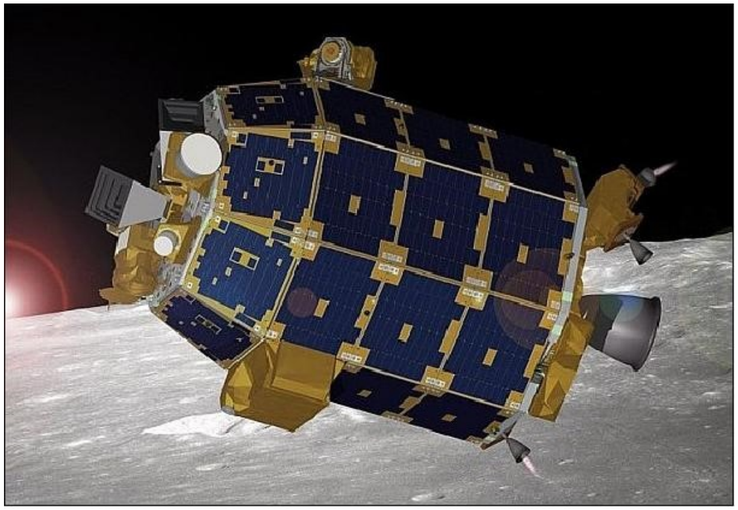
Greg Dorais received his Ph.D. in Intelligent Systems and has served in the NASA Ames Research Center Intelligent Systems division (TI) since 1997. Space Mission team member on:



Deep Space 1 (DS1)



Lunar CRater Observation and Sensing Satellite (LCROSS)

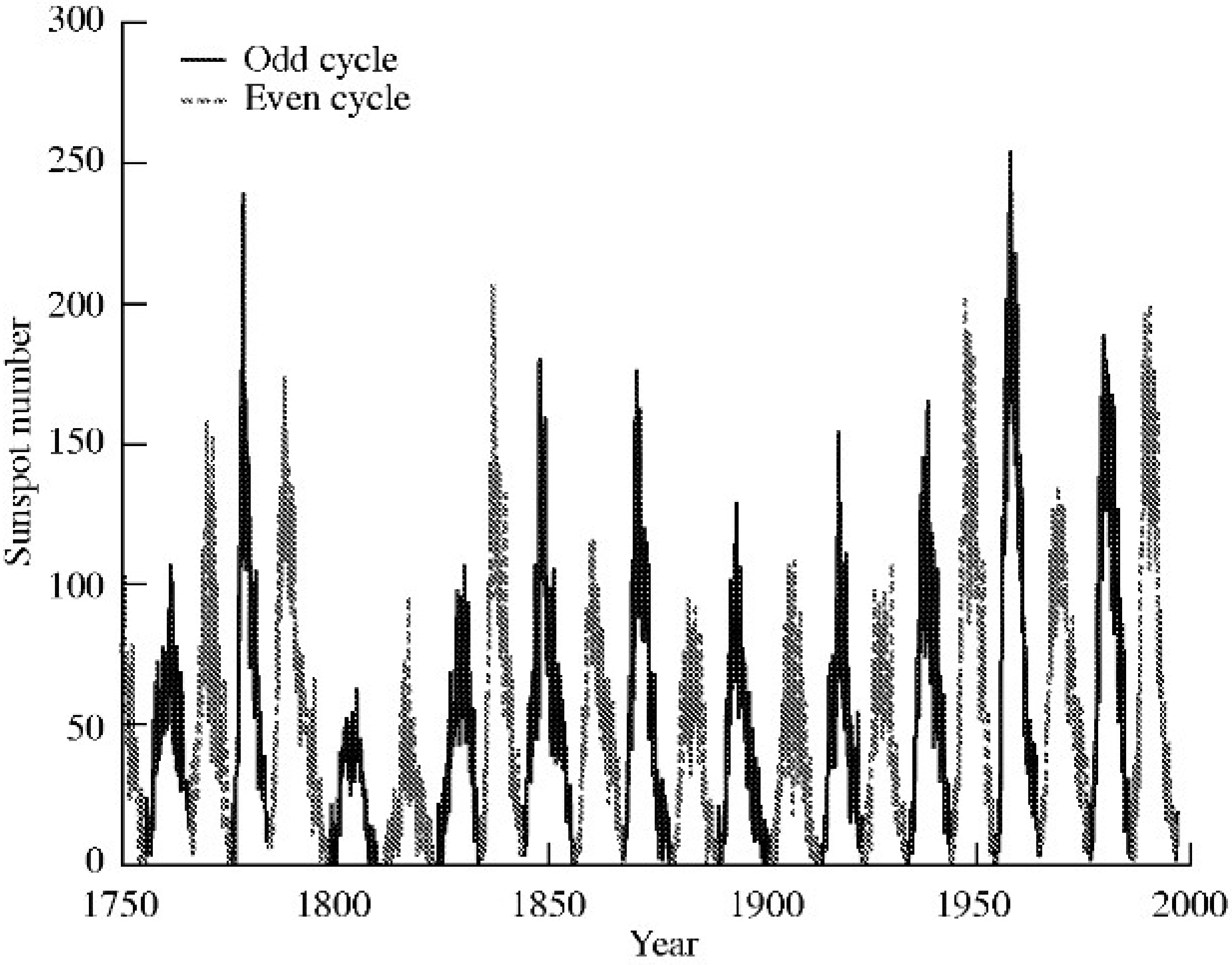


Lunar Atmosphere and Dust Environment Explorer (LADEE)

Program Office team member:

- Design for Safety
- Engineering Complex Systems
- Small Spacecraft Technology

Sunspots per Year



- Sunspots are highly correlated with the Sun’s 11-year magnetic field cycle
- Sunspots decrease GCR but increase Solar Particle Events (SPEs)
- The largest SPE on record (a Coronal Mass Ejection) occurred in 1859 during a Solar Minimum

Image source: Wilson et al., “Solar Cycle Variation and Application to the Space Radiation Environment,“ NASA TP-1999-209369, Sept., 1999.

Spacecraft Propulsion Analysis

- Provides delta-V to achieve cislunar orbit
- Provides torque to desaturate reaction wheels used for attitude control
- Hydrazine Propellant Specific Impulse (I_{sp})= 230 seconds
  - Propellant Specific Impulse is the change in momentum per unit of mass (kg)
- delta-V = ln(StartMass/EndMass) * I_{sp} * EarthGravity
  272 m/s = ln(26,400kg/23,400kg) * 230s * 9.8m/s^2

Radiation Shield Materials

Shield Material	Density g/cm^3	Pros	Cons
Polyethylene	0.9	Inexpensive, shields neutrons & electrons	Very low density
Water	1.0	Inexpensive, multi-purpose, shields neutrons & electrons	Very low density, low boiling point & high freezing point
Aluminum	2.7	Inexpensive, standard spacecraft shield	Low density, Ineffective neutron & electron shield
Iron	7.9	Inexpensive, can be magnetized	Medium density, Ineffective neutron & electron shield
Lead	11.6	Dense	Soft, low melting point (328 C), toxic, Ineffective neutron & electron shield
Tungsten Alloy	**18.0**	**Very high density, Extremely high melting point (3422 C)**	**Moderately expensive, Ineffective neutron & electron shield**
Platinum	21.5	Very high density	Very expensive, Ineffective neutron & electron shield

- Combinations of shield materials are often used to effectively shield against multiple types of radiation.